WOODHEAD PUBLISHING IN TEXTILES

Cotton: Science and technology

Edited by S. Gordon and Y-L. Hsieh

CRC
The Textile Institute
WP

Cotton: Science and technology

Related titles:

Total colour management in textiles
(ISBN-13: 978-1-85573-923-9; ISBN-10: 1-85573-923-2)
Managing colour from the design stage to the finished product can be a difficult activity as colour perception is subjective and can therefore be inconsistent. *Total colour management in textiles* covers all aspects of managing colour from the design stage to the final product ensuring that the designer's vision is fulfilled in the finished colour. Many new developments in the area of colour measurement and colour perception are discussed, including the sensory effect of colour for design and use in product development, and digital colour simulation.

Digital printing of textiles
(ISBN-13: 978-1-85573-951-2; ISBN-10: 1-85573-951-8)
At present the textile industry produces the majority of its 34 billion square yards of printed textile fabric by screen printing. However, in the digital age new developments in the digital printing of paper are now being adapted for the textiles market. This collection gives full coverage of all the current developments in digital textile printing. It is divided into four parts covering printer and print head technologies, printer software, digital printing colouration, and design and business for digital printing. It contains fundamental technical explanations along with current research.

Recycling in textiles
(ISBN-13: 978-1-85573-952-9; ISBN-10: 1-85573-952-6)
An increasing amount of waste is generated each year from textiles (including carpets and clothing) and their production. For economic and environmental reasons it is necessary that as much of this waste as possible is recycled instead of being disposed of in landfill sites. On average approximately ten million tonnes of textile waste is currently dumped in Europe and America each year. *Recycling in textiles* is the first book to bring together textile recycling issues, technology, products, processes and applications for all those in the industry who are looking for ways to recycle their textile waste.

Details of these books and a complete list of Woodhead's titles can be obtained by:

- visiting our web site at www.woodheadpublishing.com
- contacting Customer Services (e-mail: sales@woodhead-publishing.com;
  fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext.30; address: Woodhead Publishing Ltd, Abington Hall, Abington, Cambridge CB21 6AH, England)

Cotton: Science and technology

Edited by

S. Gordon and Y-L. Hsieh

The Textile Institute

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge, England

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited, Abington Hall, Abington
Cambridge CB21 6AH, England
www.woodheadpublishing.com

Published in North America by CRC Press LLC, 6000 Broken Sound Parkway, NW,
Suite 300, Boca Raton, FL 33487, USA

First published 2007, Woodhead Publishing Limited and CRC Press LLC
© 2007, Woodhead Publishing Limited
The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN-13: 978-1-84569-026-7 (book)
Woodhead Publishing ISBN-10: 1-84569-026-5 (book)
Woodhead Publishing ISBN-13: 978-1-84569-248-3 (e-book)
Woodhead Publishing ISBN-10: 1-84569-248-9 (e-book)
CRC Press ISBN-13: 978-0-8493-9101-9
CRC Press ISBN-10: 0-8493-9101-6
CRC Press order number: WP9101

The publishers' policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elementary chlorine-free practices. Furthermore, the publishers ensure that the text paper and cover board used have met acceptable environmental accreditation standards.

Project managed by Macfarlane Production Services, Dunstable, Bedfordshire, England
(e-mail: macfarl@aol.com)

Typeset by Replika Press Pvt Ltd, India
Printed by T J International Ltd, Padstow, Cornwall, England

Contents

Part I The structure and properties of cotton

Part III Quality and other issues

Contributor contact details

(* = main contact)

Editors

Dr Stuart Gordon
CSIRO Textile and Fibre Technology
P.O. Box 21
Belmont, VIC 3216
Australia

E-mail: stuart.gordon@csiro.au

Dr You-Lo Hsieh
Division of Textiles and Clothing
University of California
One Shields Avenue
Davis, CA, 95616-8722
USA

E-mail: ylhsieh@ucdavis.edu

Chapter 1

Dr You-Lo Hsieh
Division of Textiles and Clothing
University of California
One Shields Avenue
Davis, CA, 95616-8722
USA

E-mail: ylhsieh@ucdavis.edu

Chapter 2

Professor John W. S. Hearle
The Old Vicarage
Mellor
Stockport
Cheshire SK6 5LX
UK

E-mail:johnhearle@hearle.eclipse.co.uk

Chapter 3

Dr Stuart Gordon
CSIRO Textile and Fibre Technology
P.O. Box 21
Belmont, VIC 3216
Australia

E-mail: stuart.gordon@csiro.au

Chapter 4

Sharon Orford,* Sven Delaney and Jeremy Timmis
School of Molecular and Biomedical Science
The University of Adelaide
South Australia 5005
Australia

Email: sharon.orford@adelaide.edu.au
jeremy.timmis@adelaide.edu.au

Chapter 5

Dr Phillip J. Wakelyn*
National Cotton Council
1521 New Hampshire Ave
NW Washington, DC 20036-1205
USA

E-mail: PWAKELYN@cotton.org

Dr M. Rafiq Chaudhry
International Cotton Advisory Committee
1629 K Street, Suite 702
Washington, DC 2006
USA

E-mail: rafiq@icac.org

Chapter 6

Mr W. Stanley Anthony
USDA-ARS Cotton Ginning Research Unit (Retired)
2750 Ascot Place
Greenville, MS 38701
USA

E-mail: anthonywsa@aol.com

Chapter 7

Professor C. Lawrence
School of Design
University of Leeds
Woodhouse Lane
Leeds LS2 9JT
UK

E-mail: c.a.lawrence@leeds.ac.uk

Chapters 8 and 12

Dr Lawrance Hunter
CSIR and Nelson Mandela Metropolitan University
P O Box 1124
Port Elizabeth 6000
South Africa

E-mail: lhunter@csir.co.za
lawrance.hunter@nnmu.ac.za

Chapter 9

Nuray Uçar
Istanbul Technical University
Faculty of Textile Technology and Design
Textile Engineering Department
nönü Caddesi 87
Gümü suyu 34437
Beyo lu
Istanbul
Turkey

E-mail: ucarnu@itu.edu.tr

Chapter 10

Ms Indra Doraiswamy* and
Dr Arindam Basu
The South India Textile Research Association
Post Box No. 3205
Coimbatore Aerodrome Post
Coimbatore – 641 014
India

E-mail: sitra@vsnl.com

Chapter 11

Dr David King
CSIRO Textile and Fibre Technology
Textile & Fibre Technology – Belmont
Colac Road
Belmont VIC 3216
Australia

E-mail: David.king@csiro.au

Chapter 13

Mr Terry Townsend
Executive Director
International Cotton Advisory Committee
1629 K Street, N.W., Suite 702
Washington DC 20006-1636
USA

E-mail: terry@icac.org

Chapter 14

Dr Phillip J. Wakelyn
National Cotton Council
1521 New Hampshire Ave
NW Washington, DC 20036-1205
USA

E-mail: PWAKELYN@cotton.org

Chapter 15

Dr Billie J. Collier*
Dean
College of Human Sciences
242 Sandels Building
Florida State University
Tallahassee, FL 32306-1490
USA

E-mail: bcollier@fsu.edu

Dr Simioan Petrovan
The University of Tennessee
432 Dougherty Engineering Building
1512 Middle Drive
Knoxville, TN 37996-2200
USA

E-mail: petrovan@utk.edu

Dr John R. Collier
Department of Chemical and Biomedical Engineering
A-156 Engineering
FAMU-FSU College of Engineering
2525 Pottsdamer Street
Florida State University
Tallahassee, FL 32310-6049
USA

E-mail: john.collier@eng.fsu.edu

Dr Ioan I. Negulescu
Louisiana State University Center
232 Human Ecology Building
Louisiana State University
Baton Rouge, LA 70803
USA

E-mail: Inegulescu@agcenter.lsu.edu

Chapter 16

Dr Gajanan Bhat
The University of Tennessee
204 TANDEC Building
1321 White Avenue
Knoxville, TN 37996-2200
USA

E-mail: gbhat@utk.edu

Introduction

Cotton fiber is the purest source of cellulose and the most significant natural fiber. The economic significance of cotton in the global market is evident by its majority share (over 50%) among fibers for apparel and textile goods. Both the market value and the quality of cotton products are directly related to fiber quality. Competition with other fibers is affected by innovations and commercialization of other fibers including microdenier (polyesters and nylons), elastomeric (spandex), and lyocell fibers, among others. Fundamental understanding of the fibers (structural formation during development, chemistry, physics), significant improvement in fiber quality as well as in process innovation and product differentiation are critical to uphold the inter-fiber competitiveness of cotton fibers and the share of cotton fibers in the global apparel and other textile markets.

Part I of this book focuses on the chemical and physical properties of cotton fibers. The most essential cotton fiber qualities related to mechanical processing, i.e. traditionally yarn spinning, weaving, and knitting, are length, strength, fineness and their distributions. The ranking importance of these fiber qualities varies with the type of yarn spinning method, such as ring, rotor, and air-jet. These fiber qualities also determine the yarn strength, yarn regularity, handle and luster of fabrics. For chemical processing such as scouring, dyeing and finishing, fiber structure related to maturity, or the level of development, plays a major role. This is largely due to the impact of the noncellulosic cell wall components and the cellulose in the secondary cell wall on these chemical processes.

In order to develop effective strategies for fiber quality improvement and for innovative processing and product development, the developmental linkages between these chemical and physical properties and particular fiber qualities need to be identified. The relationship between cell wall development and fiber structure and properties has only gained attention more recently. Findings from some of these systematic studies linking fiber structures and strength with stages of fiber development and genotypes are detailed in Chapter 1. Chemical properties of cotton are discussed in both Chapters 1 and 2. The chemical structures and reactions are detailed in Chapter 1 whereas the effects of moisture, mercerization, swelling and resin-treatments are included in Chapter 2.

The strength of cotton fibers is attributed to the rigidity of the cellulosic chains, the highly fibrillar and crystalline structure, and the extensive intermolecular and intramolecular hydrogen-bonding. Chapter 2 includes detailed discussion of mechanical properties, including tensile strength, fracture and fatigue, and structural mechanics as well as other physical properties such as thermal, electric, friction and optical. The majority of strength data have been based on bundle strength, such as that generated by the Stelometer or high volume instruments (HVI) in recent years.

The understanding of structural origins of fiber properties such as strength and dyeability is fundamental to competitiveness and future development of quality cotton goods. However, significant challenges remain today partly due to the variability of the cotton fibers, a common characteristic of a natural product. Even the complex strength relationships between single fibers and bundles or fibers and yarns are not completely clear. For example, fibers shorter than 12.7 mm make little contribution to yarn strength. Fiber elastic behavior (elongation) and inter-fiber frictional characteristics may also contribute to yarn strength, but their association with strength has not yet been systematically studied.

The fiber properties that determine the market value of cotton are discussed in Chapter 3 along with the test methods used to measure these properties, and caveats associated with each method. Currently around 30% of the world's cotton is objectively tested using HVI[1]. The remaining 70% is largely classed subjectively by humans against physical cotton standards. The USDA Universal Cotton Standards are used in over twenty countries to class and determine the value of cotton for trade and spinning. Other national standards and merchant 'shipper type' standards are also used to ascribe value to traded cotton. International efforts to expand the use of objective testing and to develop fast and accurate test methods for important properties such as fiber fineness and maturity, trash content, neps and stickiness continue. Other important qualities to the spinner and dyers such as the wax layer that envelopes the fiber, moisture uptake and microbial decay are also discussed in Chapter 3.

In Part II, the production (growing of cotton) and processing of cotton fiber and fabric are described. Genetic modification or transformation of cotton plants via molecular genetic approaches has resulted in the introduction of pest-tolerant, and herbicide-resistant traits to cotton. A brief history and introduction to the science behind genetic modification of cotton, including traditional plant breeding is given in Chapter 4. The new traits introduced to cotton via molecular genetic modification have improved crop productivity and significantly reduced the reliance by cotton on some insecticides. Around a third of all cotton grown in the world is now genetically modified. However, despite the potential of genetically modified crops, there remain significant technical hurdles to overcome before many of the promises and claims made for genetically modified cotton are realized. Genetic transformation, that is the artificial insertion of a single foreign gene or a few genes into a plant's genome, requires two fundamental steps: Introduction of the new gene and regeneration of intact plants. Both steps have numerous constraints, and not least is the understanding of the role inherent genes have in their own chromosome set. Future genetic manipulation of cotton is aimed at realizing better fiber quality, increased resistance to pests and diseases, and improving the ability of the cotton plant to grow under adverse water, heat and nutrient conditions.

Like genetically modified cotton, organic cotton generates much debate on its worth to society. There continues to be worldwide interest in organic cotton on the basis that it is an environmentally friendly and cost-effective way to produce cotton. Production of organic cotton has recently increased to about 0.1% or about 110,000 bales of world cotton production, mainly due to increased production in Turkey as well as India, China and some African countries. Based on the facts available, growing organic cotton is more expensive to produce than conventional cotton if the same nutrient and pest management equivalents are used to ensure comparative yield and quality outputs. Viewed from this perspective organic cotton production practices are not necessarily more environmentally friendly or sustainable than current conventional practices. Management of organic cotton, from production through textile processing, is discussed in Chapter 5 and compared with conventional practices. How organic cotton is certified and organized as an industry segment is also discussed, along with the limitations of organic cotton production practice that need to be overcome if organic cotton is to become more than a small niche product.

Harvest and ginning processes are discussed in Chapter 6. These processes, which represent the first steps in the conversion of fiber to fabric, have a significant influence on the quality of the fiber realized from a crop. Enormous differences exist in harvest and ginning processes across the cotton world. Harvest methods range from totally hand-harvested crops in some countries to totally machine-harvested in others with only the United States, Australia and Israel harvest methods being fully mechanized. The principal function of the cotton gin is to separate lint from seed and produce the highest monetary return for the resulting lint (fiber) and seed under the marketing conditions that prevail. Currently the market rewards whiter, cleaner cotton with a certain traditional appearance of the lint known as preparation. Preparation is a relative term describing the amount of cleaning or combing given to cotton so that it matches official (USDA) physical grade standards upon which cotton is valued. However, these properties are more often not as important to the final product as the focus at the gin and across the merchant desk would attest. The majority of spinners prefer fiber that is long, even in length, strong, fine and without high proportions of nep and short fiber. These last two parameters are unfortunate characteristics of cotton harvested and ginned by mechanized means. Whilst not included in existing classification systems for cotton, the presence of nep and short fiber seriously affects the attractiveness of some cotton produced in the USA and Australia, which utilize automated harvesting and ginning systems.

Cotton accounts for the bulk of the raw material used in the very large short-staple spun yarn market, despite rapid incursion of synthetic fibers into the textile market over the last 35 years. The proportion is considerably less in the non-woven market, although the potential for increased use on the basis of cotton's natural attributes is high. Opening and carding, spinning, knitting, weaving and non-woven production processes are described respectively in Chapters 7 to 10 and 16. Whilst the basic mechanics of these processes, which evolved from hand-operated machines and tools, some used over 6000 years ago, have not changed greatly, speed, efficiency and thus productivity have increased dramatically. For example, cotton carding machines processing fiber at 70 kg per hour just over ten years ago now process fiber in excess of 200 kg per hour, and modern yarn spinning technologies, like the Murata Vortex Spinner (MVS) enable yarn to be spun at speeds in excess of 400 m per minute. Likewise the productivity of knitting and weaving machines has increased. Chapters 7 and 8 cover the various processes and technologies involved in the conversion of raw cotton fiber into yarn suitable for subsequent fabric manufacturing. Chapters 9, 10 and 16 cover the major cotton fabric formation processes, which are most commonly knitting and weaving processes, as well as the newer non-woven processes. In the last few decades non-woven fabrics have become more popular, and currently represent the fastest growing sectors of textile materials, particularly in the market for single use, or disposable products.

Coloration of cotton is a well-developed industrial process to add value. Chapter 11 discusses the common classes of dyes and dyeing and printing metholodogy. Dyeing involves the diffusion of dyes into the non-crystalline regions of the highly crystalline cellulose structure in the cotton fibers, thus favoring elongated and coplanar dye structures. Retention or substantivity requires strong secondary forces and/or chemical bonding with the hydroxyl functional groups of cellulose. Improvement of dye affinity to cotton, reduction of chemical effluents from dyeing as well as development of dyes that serve other functions are among some of the current trends.

Survival in today's textile market relies on knowledge of raw material costs, the maintenance of product quality, health and safety issues and recycling (cradle-to-grave) processes associated with the manufacture of cotton products. Part III of this book provides insight into the science and technology that influences and is used in these areas. In the highly competitive global textile market, the survival of a textile company depends greatly upon its ability to meet demanding quality specifications within acceptable price and delivery time frames. Chapter 12 deals largely with the objective or instrument testing of yarn and fabric physical and related properties inasmuch as they relate to their subsequent performance in textile processing and end-use performance. Whilst, generic or general testing of yarns and fabrics is carried out irrespective of their end-use to ensure consistency in production, specific tests are also conducted to determine the performance of fabric or yarn for specific and especially critical end-uses. For example, for fabric to be used in children's nightwear, flammability is of paramount importance, whereas for fabrics used in parachutes, bursting and tear strength, impact resistance and air permeability are critically important.

Chapter 13 covers world cotton and cotton textile production and the influence of technological advances on productivity, and on consumer supply and demand for cotton. Government subsidies have a significant and distorting influence on production and the final price paid for cotton. The distorting effects of these subsidies, which are created in response to local political pressures in each country, are also discussed. World cotton production and consumption are currently trending higher under the influence of new technologies, including the use of genetically modified cotton varieties. World cotton production reached 26 million tons in 2004/05 with the cost of production for most producers falling between 50 and 60 US cents per pound. International cotton prices have declined in real terms over the last six decades because of advances in technology, and this process is continuing. In the 20 to 25 years to the mid-1990s, the average world price of cotton was 70 cents per pound, but the average international price during the current decade is expected to stay between 50 and 60 cents per pound, in line with the costs of production for most producers.

Health and safety are key components of responsible production and processing of cotton and of a responsible management system for cotton operations. Workers handle and process cotton in many work operations from planting the cottonseed, to the finished cotton textile, i.e. from production, harvesting, ginning, yarn and fabric manufacturing, and preparation, through to dyeing and finishing. Each cotton industry sector has its own particular health and safety considerations. Chapter 14 covers the pertinent health and safety issues for each sector of the cotton industry.

Environmental conservation from the perspective of preserving expensive produced cotton, reducing disposed wastes and regenerating new usage from spent cotton goods is of significant concern today. Chapter 15 discusses issues related to the recycling of cotton textiles including reuse, disposal, landfill and incineration. Life cycle analyses of cotton require the examination of the environmental impact of cotton production, energy consumption in processing and disposal. The sources of cotton as well as the processing methods for recycling are detailed in this chapter. The ultimate conversion of cotton cellulose requires chemical processing or dissolution and remains a technological challenge.

Reference

1. McDill, N.R., Commercial Standardization of Instrument Testing of Cotton, *Proceedings of the EFS® Systems Conference*, 7pp., 2004

Part I

The structure and properties of cotton

1

Chemical structure and properties of cotton

Y L HSIEH, University of California, USA

1.1 Introduction

Cotton fibers are the purest form of cellulose, nature's most abundant polymer. Nearly 90% of the cotton fibers are cellulose. All plants consist of cellulose, but to varying extents. Bast fibers, such as flax, jute, ramie and kenaf, from the stalks of the plants are about three-quarters cellulose. Wood, both coniferous and deciduous, contains 40–50% cellulose, whereas other plant species or parts contain much less cellulose. The cellulose in cotton fibers is also of the highest molecular weight among all plant fibers and highest structural order, i.e., highly crystalline, oriented and fibrillar. Cotton, with this high quantity and structural order of the most abundant natural polymer, is, not surprisingly, viewed as a premier fiber and biomass.

This chapter focuses on the chemical structure of cotton fibers and its structural relationship to cellulose synthesis, fiber development and dehydration as well as other chemical and structural aspects (physical properties, dyeing and finishing) not dealt with in the following chapters. Cotton fiber cells are developed in four overlapping but distinct stages of initiation, elongation, secondary cell wall thickening and maturation and desiccation (Naithani *et al.*, 1982). Structural development and properties of cotton fibers during the primary wall formation (elongation) and secondary wall thickening (cellulose synthesis) as well as during desiccation (transition from mobile to highly hydrogen-bonded structure) are detailed.

1.2 Chemistry

1.2.1 Chemical composition

Cotton fibers are composed of mostly α-cellulose (88.0–96.5%) (Goldwaith and Guthrie, 1954). The noncellulosics are located either on the outer layers (cuticle and primary cell wall) or inside the lumens of the fibers whereas the secondary cell wall is purely cellulose. The specific chemical compositions of cotton fibers vary by their varieties, growing environments (soil, water, temperature, pest, etc.) and maturity. The noncellulosics include proteins (1.0–1.9%), waxes (0.4–1.2%), pectins (0.4–1.2%), inorganics (0.7–1.6%), and other (0.5–8.0%) substances. In less developed or immature fibers, the non-cellulosic contents are much higher.

The primary cell walls of cotton fibers contain less than 30% cellulose, noncellulosic polymers, neutral sugars, uronic acid, and various proteins (Huwyler *et al.*, 1979; Meinert and Delmer, 1977). The cellulose in the primary cell walls has lower molecular weight, with the degree of polymerization (DP) between 2,000 and 6,000 and their distributions are broader (Goring and Timell, 1962; Hessler *et al.*, 1948). The secondary wall of the cotton fiber is nearly 100% cellulose. The DP of the cellulose in the secondary wall is about 14,000, and the molecular weight distribution is more uniform (Figini, 1982). The high molecular weight cellulose characteristic of mature cotton has been detected in fibers as young as eight days old. In the later stage of elongation or 10–18 days following initiation, the higher molecular weight cellulose decreases while the lower-molecular weight cell wall components increase, possibly from hydrolysis (Timpa and Triplett, 1993). Between the ages of 30 and 45 days, the DPs estimated from intrinsic viscosities of fibers have been shown to remain constant (Nelson and Mares, 1965).

Of the non-cellulosic components in the cotton fibers, the waxes and pectins are most responsible for the hydrophobicity or low water wettability of raw cotton fibers. The term ‘cotton waxes’ has been used to encompass all lipid compounds found on cotton fiber surfaces including waxes, fats, and resins (Freytag and Donze, 1983). True waxes are esters, including gossypyl carnaubate, gossypyl gossypate, and montanyl montanate. Alcohols and higher fatty acids, hydrocarbons, aldehydes, glycerides, sterols, acyl components, resins, cutin, and suberin are also found in the wax portion of the cuticle in varying quantities. Pectins are composed primarily of poly(β-1,4-polygalacturonic acid) and rhamose to make up the rhamnogalacturonan backbone (Heredia *et al.*, 1993). The side chains are composed of arabinose, galactose, 2-*O*-methylfucose, 2-*O*-methylxylose and apiose. Eighty-five percent of the polygalacturonic acid groups are methylated leading to a highly hydrophobic substance. Proteins are located primarily in the lumen, but small amounts of hydroxyproline rich proteins are present on the fiber surface (Darvill *et al.*, 1980). The far lower extents of the non-cellulosics than cellulose make their detection in mature cotton fibers challenging. Extraction and reaction techniques are often employed to separate the non-cellulosic cell wall components for characterization. These procedures, however, tend to disrupt their organization and possibly alter their chemical compositions.

The amounts of the noncellulosic components change during fiber elongation and the transition from primary to secondary wall, but discrepancies remain in the exact quantities of these changes. Some of the protein constituents (enzymatic, structural or regulatory) are unique to cotton fiber cells and have been found to be developmentally regulated (Meinert and Delmer, 1977). The non-cellulosic constituents in developing cotton fibers through the onset of secondary cell wall synthesis can be clearly identified by analytical techniques, including FTIR/ATR, DSC, TGA, and pyrolysis-GC/MS methods (Hartzell-Lawson and Hsieh, 2000). The waxy compounds in developing fibers up to 17 days old are detected by their melting endotherms in the DSC. Pectins can be detected by FTIR in the 14-day-old as well as the mature fibers. FTIR/ATR measurements indicated the presence of proteins in developing fibers up to 16 dpa. The presence of proteins can be measured by FTIR/STR methods in up to 16-day-old fibers and by pyrolysis-GC/MS in up to 14-day-old fibers. Only pyrolysis-GC/MS could detect the presence of the non-cellulosic compounds in 27-days-old fibers. The detection of the non-cellulosics diminished as the proportion of cellulose rapidly increased at the onset of secondary cell wall synthesis. The presence of hydrophobic compounds on the surfaces of cotton fibers of all ages and their removal by alkaline scouring are easily determined by their water contact angles.

Among the inorganic substances, the presence of phosphorus in the form of organic and inorganic compounds is of importance to the scouring process used to prepare fibers for dyeing. These phosphorus compounds are soluble in hot water, but become insoluble in the presence of alkali earth metals. The use of hard water, therefore, can precipitate alkali earth metal phosphates on the fibers instead of eliminating them (Hornuff and Richter, 1964).

1.2.2 Cellulose chemistry and reactions

Cotton cellulose is highly crystalline and oriented. α-cellulose is distinct in its long and rigid molecular structure. The β-1,4-D(+)-glucopyranose building blocks in long cellulose chain are linked by 1,4-glucodic bonds. The steric effects prevent free rotation of the anhydrogluco-pyranose C-O-C link. Each anhydroglucose contains three hydroxyl groups, one primary on C-6 and two secondary on C-2 and C-3. The abundant hydroxyl groups and the chain conformation allow extensive inter-molecular and intra-molecular hydrogen bonding to further enhance the rigidity of the cellulose structure.

Chemical reactions and heating effects on cotton cellulose depends on the supermolecular structure as well as the activity of the C-2, C-3 and C-6 hydroxyl groups. Heat or reactions begin in the more accessible amorphous regions and the surfaces of crystalline domains. Chemical reactivity of the cellulose hydroxyl groups follows those of aliphatic hydroxyl groups, i.e., higher for the C-6 primary than the secondary on the C-2 and C-3. Etherification and esterification are the two main categories of reactions. Esterification reactions, such as nitration, acetylation, phosporylation, and sulfation, are usually carried out under acidic conditions. Etherification, on the other hand, is favored in an alkaline medium.

Cellulose is readily attacked by oxidizing agents, such as hypochlorites, chlorous, chloric, and perchloric acids, peroxides, dichromates, permanganates, periodic acid, periodate salts, and nitrogen tetroxide (Bikales and Segal, 1971). Most oxidizing agents are not selective in the way they react with the primary and secondary hydroxyl groups. Oxidation of cellulose can lead to two products, reducing and acidic oxycellulose. In reducing oxycellulose, the hydroxyl groups are converted to carbonyl groups or aldehydes, whereas in acidic oxycellulose, the hydroxyl groups are oxidized to carboxyl groups or acids. The oxycellulose can be further oxidized to acidic oxycellulose. Reducing oxycellulose is more sensitive to alkaline media and the chain lengths are often reduced. Periodic acid and periodate salts break the anhydroglucose ring between C-2 and C-3, converting the two secondary hydroxyl to aldehydes which can be further oxidized to carboxyl groups. Nitrogen tetraoxide reacts specifically with the primary hydroxyl groups on C-6, oxidizing it to carboxyl group directly or to polyglucuronic acid, an oxycellulose.

1.2.3 Heating effects

Heating generally causes dehydration and decomposition of cellulose. These reactions are influenced by the presence of other compounds as well as the temperature and rate of heating. Dehydration reactions are favored in the presence of acid catalysts whereas depolymerization reactions are favored by alkaline catalysis. Heating at lower temperatures favors dehydration and enhances subsequent char formation (Shafizadeh, 1975). Higher temperature heating causes rapid volatilization via the formation of laevoglucosan, forming more gaseous combustible products. Greater dehydration also reduces the yield of laevoglucosan and subsequently lowers the volatile species. Therefore, acid catalysts are of special importance to impart flame retardancy to cellulose.

Heating cotton cellulose up to 120 °C drives off moisture without affecting strength. Heating to a higher 150 °C has been shown to reduce solution viscosity, indicative of lowered molecular weight, and tensile strength (Shafizadeh, 1985). Between 200 °C and 300 °C, volatile products and liquid pyrolyzate, mainly 1,6-anhydro-β-D-glucopyranose, commonly known as levoglucosan, evolve. At 450 °C, only char remains. Of total pyrolytic products, 20% is the gaseous phase (CO, CO_2, CH_4), 65% is the liquid phase (of which 80% is levoglucosan) and 15% is the char. The heating rate can affect the amount of char formation (Shafizadeh, 1985). Heating below 250 °C affects only the amorphous regions since no change in the crystalline structure has been found. The crystalline structure of cellulose has been shown to be lower when heated at 250 °C to 270 °C, and then disappear on further heating to

300 °C. Highly crystalline cellulose has been shown to decompose at higher temperatures, for instance 380 °C (Bikales and Segal, 1971).

Blocking the primary hydroxyl groups of cellulose prevents depolymerization, thus reducing production of volatiles. The reduction of flammable gases is accompanied by more complete intra-ring and inter-ring dehydration, giving rise to keto-enol tautomers and ethermic linkages, respectively. The carbonyl groups so formed can participate in a variety of reactions, leading to cross-linking, thus increasing char formation as well as carbon dioxide. The packing density of cellulose also affects the extent of levoglucosan formation. Lowered crystallinity in cotton by either mercerization or liquid ammonia leads to a higher yield of levoglucosan formation (Shafizadeh, 1985). Mono- and difunctional radicals are formed by the cleavage of glucoside linkages, and these radicals in turn give rise to volatile products and levoglucosan.

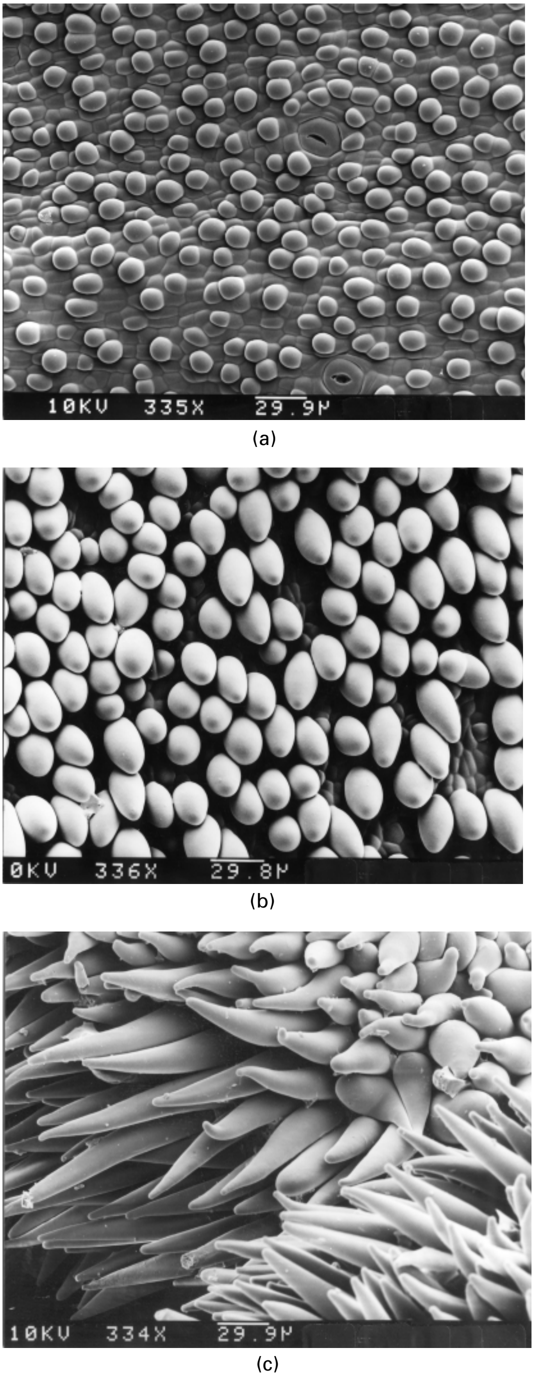
1.3 Fiber development

1.3.1 Fiber structures during cell growth

The structure of cotton fibers can be viewed along the fiber axis and across the fiber section. Current understanding of cotton fiber structure has been mainly from investigation of the matured fibers in their dried state. Although the biochemical nature of cotton cell structure, particularly during early cell growth, has been extensively studied, the development macrostructure of the main constituent of the fiber, cellulose, is not as well understood.

Cotton fibers are the largest (longest) single cells in nature. The fibers are single-celled outgrowths from individual epidermal cells on the outer integument of the ovules in the cotton fruit. About one in four epidermal cells differentiates into fiber cells beginning at one day before to two days after anthesis (flowering) (Graves and Stewart, 1988). Four overlapping but distinct stages are involved in cotton fiber development: initiation, elongation, secondary-wall thickening, and maturation (Naithani *et al.*, 1982). The initiation of fibers begins from the epidermal cells on the ovule surface (Fig. 1.1(a)) followed by the elongation and formation of the primary cell wall. Elongation of the primordial fiber cells starts on the day of anthesis by spherical expansion above the ovular surface (Figs 1.1(b) and 1.1(c)) and continues for 16 to 20 days. The cell elongation orients initially against the micropylar end of the ovule, then become spiral after two to three days. The primary cell walls continue to elongate until reaching the final fiber lengths of 22 to 35 mm in about 20 to 25 days. This primary cell wall is very thin (0.2 to 0.4 μm) and extensible.

Secondary wall synthesis starts around 15 to 22 days past anthesis (dpa) and continues for 30 to 40 days. The cellulose formation is about 130 ng/mm



1.1 Scanning electron micrographs of seed with the initiation (a) 0 dpa of fibers and the beginning of elongation (b) 1 dpa; (c) 2 dpa. Provided by J. Jernstedt, University of California, Davis.

during secondary wall formation as compared to 2 ng/mm during primary wall development (Meinert and Delmer, 1977). Fiber maturation is evident by desiccation of the fiber and collapse of the cylindrical cell into a flattened, twisted ribbon beginning 45 to 60 dpa. Most cotton fibers have aspect ratios, or length-to-width ratios, in the 1,000 to 3,000 range. However, some matured fibers can reach up to 4,000 times in length of their diameters. Both fiber length and secondary wall thickness are increased with higher potassium supply during growth (Cassman *et al.*, 1990).

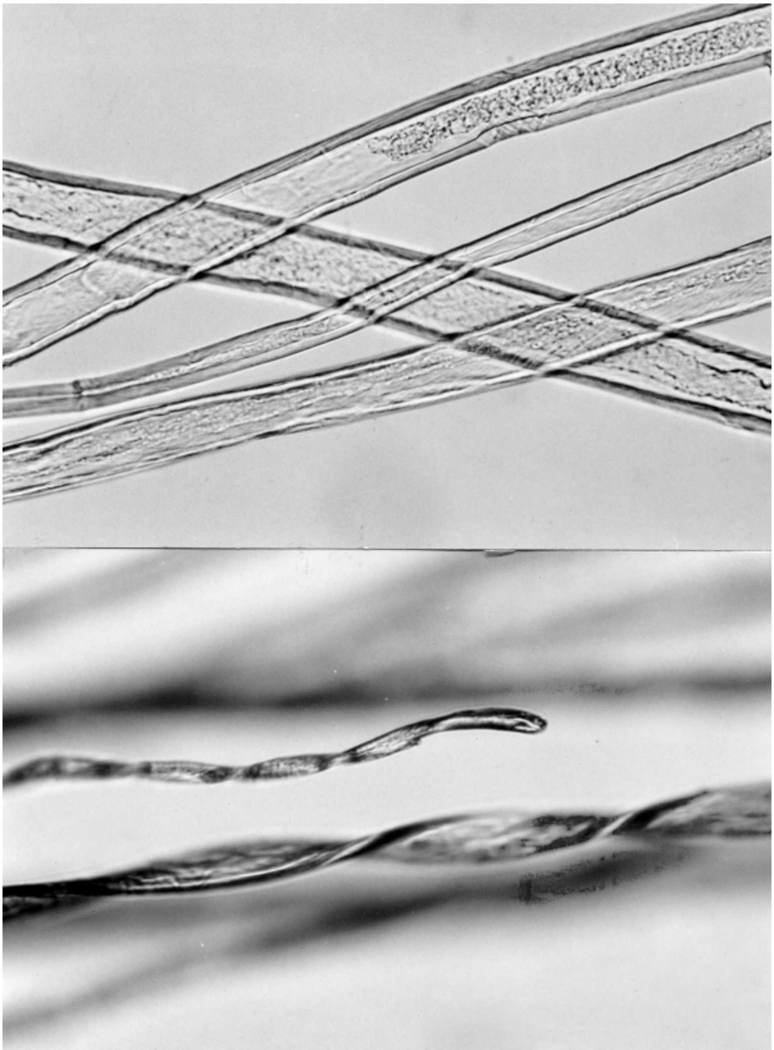
1.3.2 Desiccation and dehydration

The fully hydrated cylindrical fibers are cylindrical under light microscopy (Fig. 1.2(a)). Drying of the fibers involves the removal of fluids from the lumens and inter-molecular water in the cellulose. The fluid loss from the lumens causes the cylindrical fibers to collapse to form twists or convolutions (Fig. 1.2(b)). The loss of intermolecular water allows the cellulose chains to come closer together and form intermolecular hydrogen-bonds. Prior to ball dehiscence and fiber desiccation, matured cotton fibers have been shown to exhibit high intrinsic mobility and porosity in their structure (Ingram *et al.*, 1974). The accessibility of water in fiber structure in the hydrated state is higher than after desiccation.

The collapse of cell walls and hydrogen bond formation cause irreversible morphological changes including structural heterogeneity, decreasing porosity, and sorption capacity in the fibers (Stone and Scallan, 1965). These changes increase molecular strains and reduce chain mobility, and may have an influence on properties essential to strength and dyeing/finishing processes. As these irreversible changes determine the utility of fibers, understanding of the structural changes from desiccation is essential to fiber quality research.

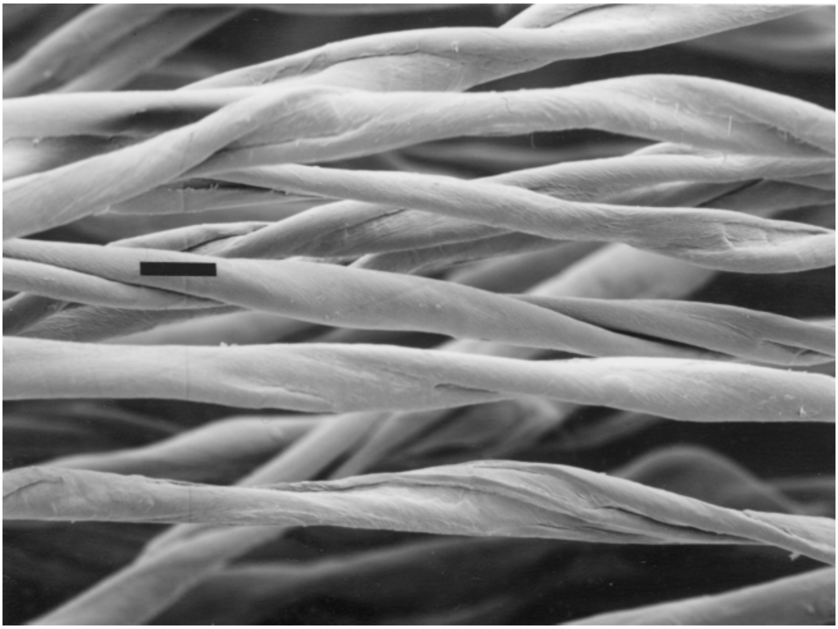
The matured fibers dry into flat twisted ribbon forms (Fig. 1.3). The twist or convolution directions reverse frequently along the fibers. The number of twists in cotton fibers varies between 3.9 and 6.5 per mm (Warwicker *et al.*, 1966) and the spiral reversal changes one to three times per mm length (Rebenfeld, 1977). The convolution angle has been shown to be variety dependent (Peterlin and Ingram, 1970). Differences in reversal frequency have been observed among different species and varieties of cotton, between lint and fuzz on the same ovule, and along a single fiber (Balls, 1928).

The reversals in cotton fibers are related to the orientation of the secondary wall microfibrils whose organization is critically important to fiber strength. The orientation angles and shifts of microfibrils along the fiber axis change with cell-development stages and have been related to the cellular organization of the cortical microtubule during cotton fiber development (Seagull, 1986, 1992; Yatsu and Jacks, 1981). At the beginning of fiber development, i.e., 1 dpa, cortical microtubules have a random orientation. During the transition



1.2 Light micrographs of fully hydrated fibers (top) and dried fibers (bottom).

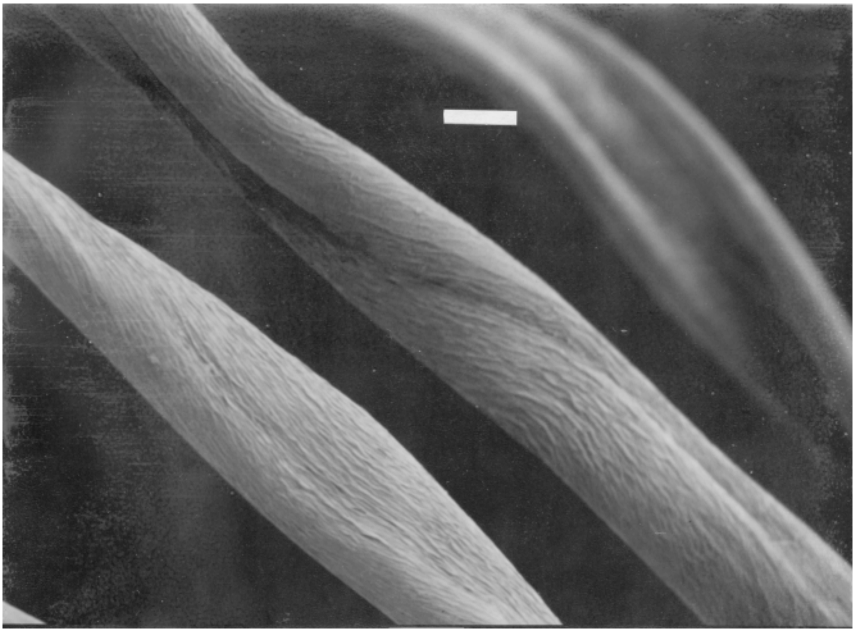
between initiation and elongation, i.e., 2–3 dpa, a shallow pitched helical orientation of 75–80° is developed. Such angles, which are nearly perpendicular to the fiber axis, are maintained throughout primary wall synthesis. An abrupt shift in orientation to a steeply pitched helical pattern occurs between the primary and secondary wall synthesis. As secondary cell walls thicken, the angles reduce further. In early secondary wall synthesis, there is a four-fold increase in the number of microtubules. The fibrillar orientation reverses along the fiber periodically. The mechanism which regulates the synchronized shifts in microtubule orientation is not yet understood.



1.3 Scanning electron micrographs of mature fibers (bar=18.9).

The concomitant shifts in orientations of microtubules and microfibrils indicate a strong relationship between the two. However, differing degrees of variability between these two populations suggest other factors may modify the order imparted by the microtubules. During secondary wall synthesis, microfibrils exhibit variability in orientation or undulations. Inter-fibril hydrogen bonding and differential rigidity of microtubules and microfibrils have been suggested as possible factors influencing the final microfibril organization.

The spiral fibrillar structure can be observed on the surface of mature fibers underneath the primary wall (Fig. 1.4). Parallel ridges and grooves are seen at 20–30° angles to the fiber axis. Scouring exposes the fibrils of the primary and secondary walls. Neither soaking in water nor slack mercerization removes surface roughness (deGruy *et al.*, 1973; Muller and Rollins, 1972; Tripp *et al.*, 1957). However, stretching a swollen fiber can smooth the surface and make residual ridges more parallel to the fiber axis secondary walls. The less developed cotton fibers have thinner secondary cell walls and contain less cellulose. They appear flattened with little or no twist as seen in the SEM of Fig. 1.5. These fibers tend to become entangled into matted fibrous clusters, called neps, causing problems in mechanical processing and dyeing of cotton products. They cannot be dyed to shades as dark as mature fibers. Their flat surfaces also reflect more light and give them a lighter color. Immature fibers can cause white specks, the light spots on a dyed

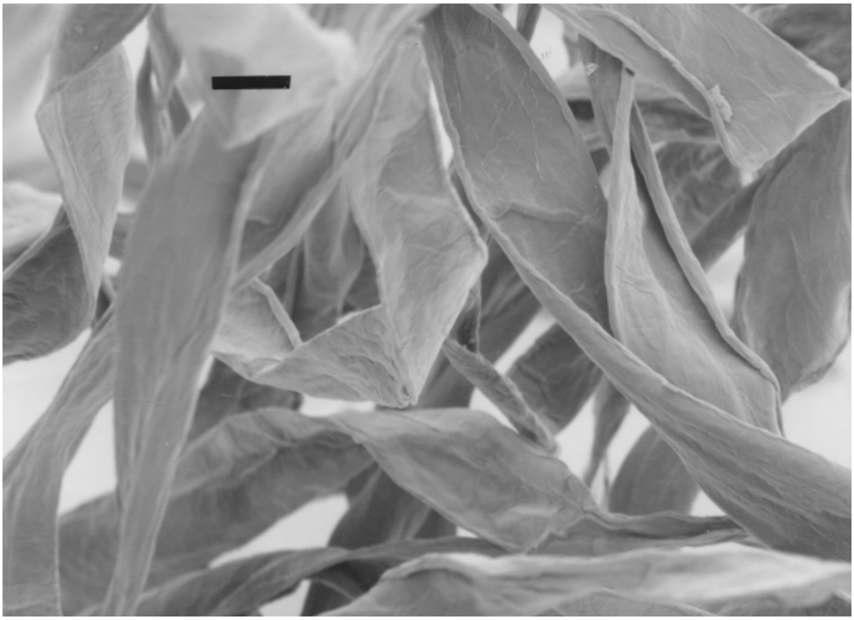


1.4 The cellulose fibrils orient at an angle to the fiber axis and spiral around the concentric layers. The fibril angle reverses every so often. The fibrillar structure and the reversal of outer most cellulose layer can be observed on the fiber surface through the primary wall on these 34-dpa fibers (bar = 10.3).

fabric that either have an absence of color or appear lighter than the rest of the fabric.

The molecular packing densities along the fiber, particularly near the spiral reversals, are believed to vary. The packing of fibrils at the reversals is denser (Patel *et al.*, 1990). The adjacent fibrillar structures are less densely packed and often have different dimensions (fineness). Therefore, these adjacent regions are believed to be the weak points on the fiber rather than the reversals themselves. It has also been suggested that the reversals may be growth points in the fibers (Raes *et al.*, 1968). However, this has not been confirmed by others.

The dried cotton fibers have a bean-shaped cross-section. The bilateral structure is thought to originate from the asymmetry of mechanical forces in the fibers during drying. Heterogeneity of molecular packing in cotton fibers has been demonstrated by ultramicrotomy, histochemical staining, and accessibility to reagents (Naithani *et al.*, 1982; Basra and Malik, 1984; Meinert and Delmer, 1977). The two highly curved ends of the bean-shaped cross-section have the highest molecular packing density and least accessibility to reagents. The structure of the convex part is less dense and more accessible.



1.5 Immature fibers have much thinner secondary cells or less cellulose. Collapse of the immature fibers leads to flattening with little or no twist as seen in this 21-dpa fiber (bar = 17.4).

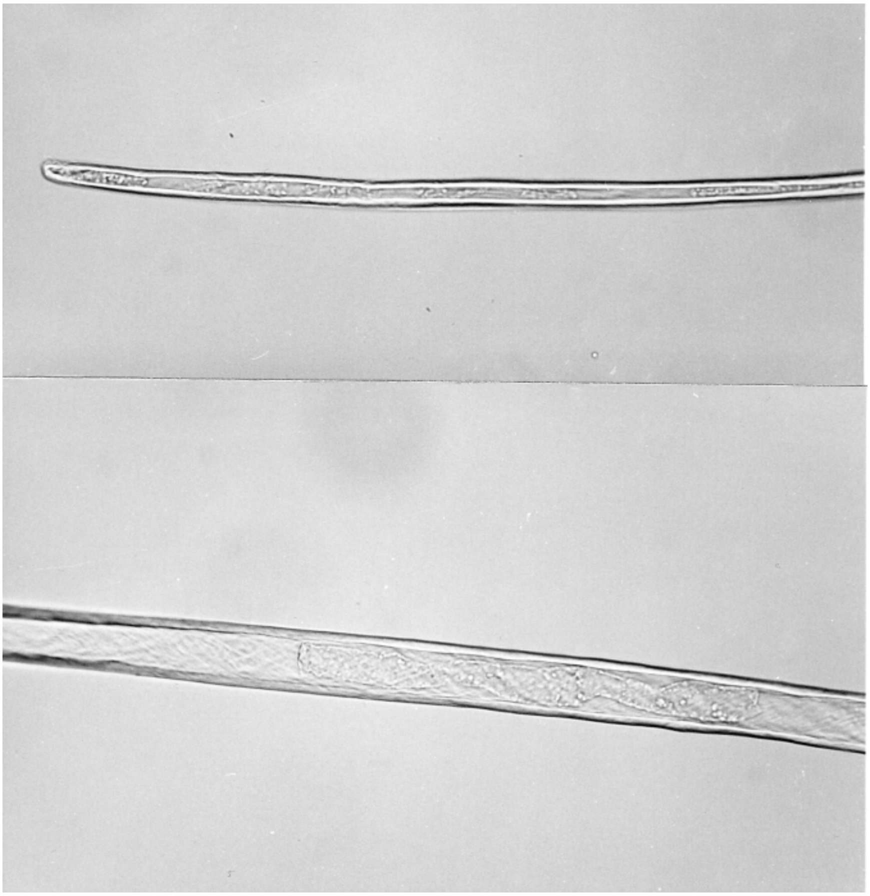
The concave section of the cross-section is the most accessible and most reactive portion of the fibers. The higher density and parallel membranes in the curved extremes and convex parts are thought to result from radial compressive forces, whereas the concave portion of the cross-section is subject to tangential compressive forces. The sections between the curved ends and concave parts are denoted as neutral zones which are by far the most accessible. These differential structures in the cotton cross-section have been confirmed by enzymatic attacks (Kassenback, 1970).

1.3.3 Structural variations

Cotton seed fibers include the long lint and short fuzz fibers, both epidermal hairs on the cotton ovules or seeds. Fuzz fibers are initiated 4 to 10 dpa in successive waves of initiation (Beasley, 1977). Fiber quality traits, i.e, length, fineness, and strength, are determined by both the genetic and environmental variables. Both fiber fineness and fiber length are genetic characteristics. Fiber fineness has been shown to be developed at the base of the fibers by about 2 dpa (Fryxell, 1963; Kulshreshtha *et al.*, 1973a). Fiber length is determined during the elongation stage, i.e., during the first 20 to 25 dpa.

Fibers on a single ovule initiate and mature at different times (Stewart, 1975) and boll development on a single plant depends on the positions on plants (Jenkins *et al.*, 1990). On an ovule, fibers initiate first near the chalazal end, then down toward the micropylar end. Seeds located near the middle of a locule have the longest fibers whereas those near the basal location have thickest secondary cell wall (Davidonis and Hinojosa, 1994). On a single ovule, fibers in the micropylar region have thicker cell walls than those in the chalazal end. Bolls located closer to the main stem are favored in the allocation of nutrients (Jenkins *et al.*, 1990). Temperatures lower than optimal reduce both fiber length and cell wall thickness (Gibson, 1986; Haigler *et al.*, 1991). Seasonal effects of secondary wall development have been demonstrated on summer-grown versus autumn-grown fibers (Goynes *et al.*, 1995).

It has been shown that fibers taper toward thinner tip ends. Using light microscopy, we have observed that about 15% of fiber length from the tip has smaller dimensions on fully developed SJ-2 fibers (Fig. 1.6). As much as



1.6 Light microscopy of a hydrated fiber showing thinner tip than the rest of the fiber.

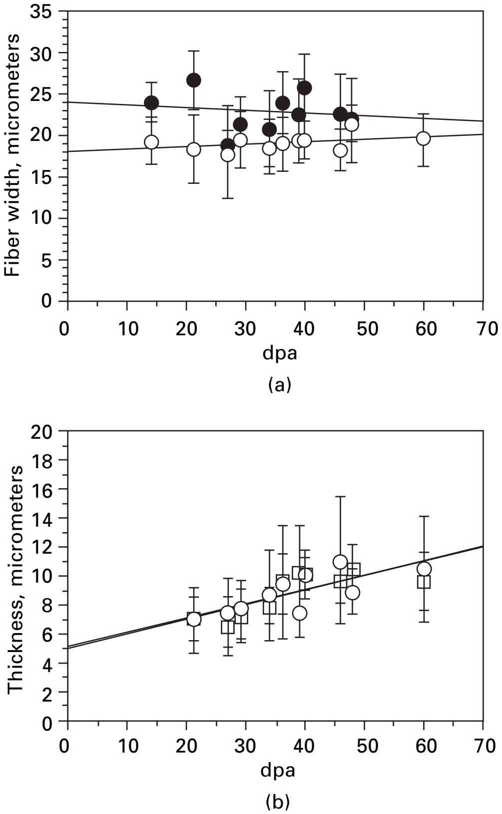
one-third of fiber length has been reported on Delta 61 fibers (Boylston *et al.*, 1993). Fibers shrink in proportion to the amount of cellulose present in the cell wall. The perimeter of less mature fibers (thinner cell wall) is larger than that of a more mature (thicker cell wall) fiber. The thinner cell wall is found nearer the fiber tip than the rest of the fiber. Fiber fineness directly determines yarn fineness. Although as few as 30 fibers can be spun into yarns in ring spinning, approximately 100 fibers in the yarn cross-section are usually the lower limit. Therefore, reduction in fiber fineness is the only way to achieve fine yarns within the limit of spinning processes.

Fiber maturity is a growth characteristic. The definition of fiber maturity is the proportion of cotton cell wall thickness compared to the maximum wall thickness when growth is completed. Therefore, maturity represents the development of the secondary cell wall and the maturity level can be complicated by both developmental and environmental factors.

1.3.4 Twist and convolution

The formation of twists or convolution occurs when the fully hydrated cylindrical fibers collapse from the loss of fluids and drying upon maturation and boll opening or as previously shown during light microscopy observation (Fig. 1.2). On developing SJ-2 fibers, typical twists were observed on 28-dpa fibers whereas 21 dpa fibers tend to roll and fold onto themselves (Fig. 1.5). The lateral dimensions of convoluted fibers are characterized by their ribbon or ‘fiber width’ (widest portion) and ‘twist thickness’ (thinnest portion). The fiber widths decrease from drying (Fig. 1.7(a)). The twist thicknesses increase with fiber development, from approximately 6.5 μm at 21 dpa to 10.5 μm at 40 dpa and maturity (Fig. 1.7(b)). The twist frequency or the lengths between twists have been found to be highly irregular along an individual fiber as well as among fibers. The lengths between twists have been grouped into ‘short’ and ‘long’. At 21 dpa, the average short and long lengths between twists are 110 μm and 240 μm, respectively. As fibers developed, long lengths reduce by nearly one-half to 130 μm. Short twist lengths, on the other hand, show only a slight decrease with fiber development to about 90 μm. Upon drying, fiber widths between the long twists are reduced slightly but not significantly than those of the hydrated fibers. Fiber widths between the long twists are slightly higher than those between the short twists, but these differences diminish with fiber development.

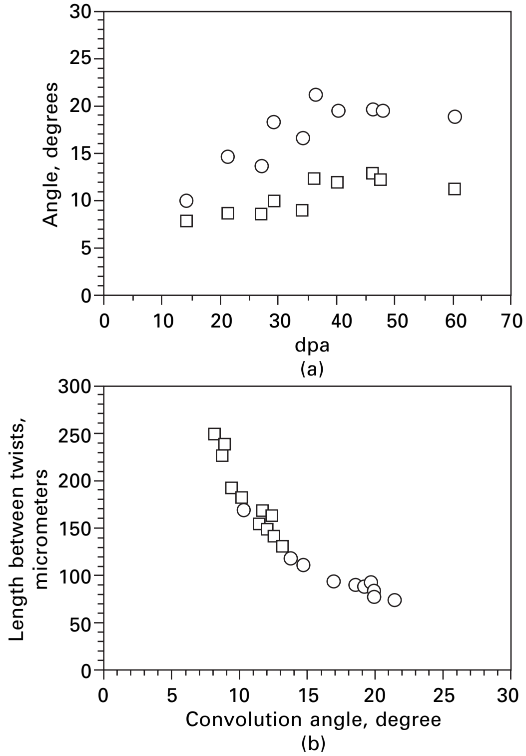
The twist thicknesses increase slightly between 20 and 36 dpa and then become level, but the twist thicknesses remain similar between the long and short twists. Using the average W and L values, the convolution angle (θ) of the twist is calculated as $\theta = \tan^{-1}(2W/L)$. A distinct increasing trend with development to about 40 dpa has been observed on the convolution angles of the long twists whereas only a slight increase is observed on the short twists



1.7 Fiber dimensions at varying developmental stages of *G. hirsutum* (SJ-2), (a) Fiber width: ● hydrated, y = 24.0 – 0.034x, r = 0.16; ○ dried short twists, y = 18.1 – 0.03x, r = 0.41. (b) Twist thickness: ☐ long twists, y = 5.0 + 0.10x, r = 0.77, ○ short twists, y = 5.1 – 0.10x, r = 0.78.

during the same period (Fig. 1.8a). This trend is expected from the fiber width and twist length data. The lengths between twists lowered with increasing convolution angles (Fig. 1.8(b)). The insignificant changes in convolution angles after 36 dpa indicate insignificant changes in both the twist length and width, coinciding with the little change in the linear density or cell wall mass. These findings show that twist characteristics are closely associated with secondary cell wall thickness and thus are excellent indicators of fiber maturity within a given variety of cotton.

As the spiral reversals occur less frequently (1 to 3 times per mm as reported by Rebenfeld, 1977) than the convolution (3.9 to 6.5 twists per mm by Warwicker *et al.*, 1966), the lateral alignment of the fibrillar reversals in the concentric cellulose layers and the ultimate twists in the dried fibers appear to be related. Twists are formed from cell collapsing and the numbers of twists increase with fiber maturity or with increasing secondary cell wall



1.8 Convolution or twist characteristics of developing *G. hirsutum* (SJ-2) fibers (□ long, ○ short): (a) angles; (b) relationship between lengths and angles.

thickness. Upon drying, lateral dimensions of the fibers reduce. The spiral reversals of the cellulose fibrils are where buckling most likely occurs in each layer. As secondary cell wall thickens, the probability of the reversals in the concentric layers overlapping at a given point across the fiber increases, leading to twists. It appears that when a threshold level of overlapped reversals is reached, stress from buckling leads to twist formation. Whether the twist or the span between two twists is where the reversals overlapped is unclear. How the reversals in the concentric layers related to the varying packing density or accessible regions in the fiber cross-section is also an important question.

1.4 Fiber strength

1.4.1 Single fiber strength

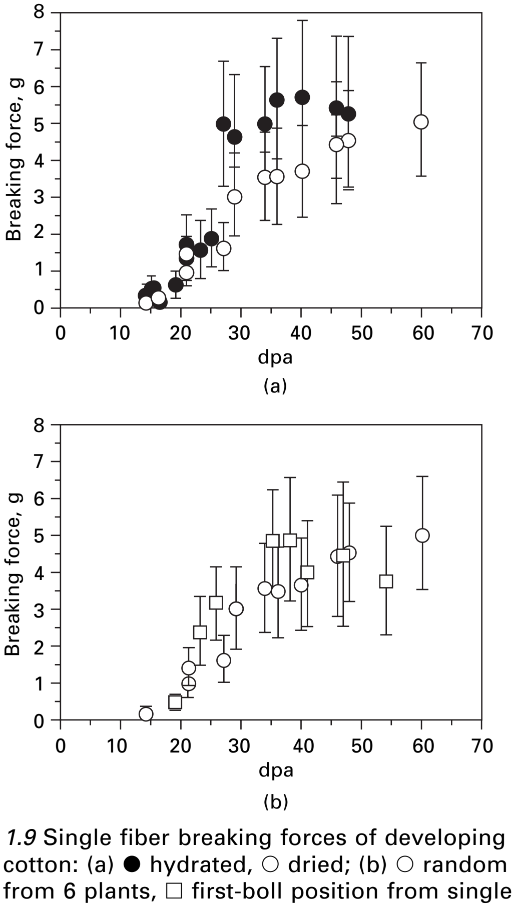
The strength of cotton fibers is attributed to the rigidity of the cellulosic chains, the highly fibrillar and crystalline structure, and the extensive intermolecular and intramolecular hydrogen-bonding. Varietal link to fiber strength has been well documented by bundle strength, such as that generated by the Stelometer and the high volume instrument (HVI) in recent years. Much less is known about the strength of developing cotton fibers. Kulshreshtha *et al.* (1973a) have shown that the Stelometer bundle strength increases gradually with fiber growth between 30 and 70 dpa. The youngest age, in that case, is about two weeks into, or about half way through, the secondary cell wall development. However, bundle strength has been shown not to be sensitive to strength variability.

How fiber strength is developed during growth and is related with genotypical traits has been confirmed by single fiber tensile measurements. The major challenges in single fiber measurements are the selection and the quantity of fibers to represent each specific population. Single fiber tensile measurements using a standard tensile tester and fiber sampling protocols were evaluated in an exploratory study (Hsieh, 1994) and subsequent extensive data collection (Hsieh *et al.*, 1995).

Tensile measurements of both hydrated (as early as 15 dpa) and dried fibers were made using either an Instron tensile tester (1122 TM) equipped with standard pneumatic and rubber-faced grips or a Mantis single fiber tester. A 3.2 mm-gauge length was used with both methods. A 50-mm/min strain rate was employed on the Instron whereas the strain rate on the Mantis was 60 mm/min. All measurements were performed at a constant temperature of 70 °F and a 65% relative humidity. The much higher rate of measurement on the Mantis instrument has enabled collections of much larger number of single fiber strength data (Hsieh *et al.*, 1995, 1997; Hsieh 1999; Hsieh and Wang 2000; Hu and Hsieh, 1996, 1997a, 1998; Liu *et al.*, 2001, 2005). As a Mantis single fiber tensile instrument is not readily available but is employed in most work cited in the following sections, it is worth mentioning the difference from the Instron measurements. The breaking forces measured by the Mantis instrument appear to be slightly higher than those by the Instron whereas the opposite is observed with the breaking elongation values (Hsieh *et al.*, 1997). On the Mantis, fibers are positioned manually. The instrument automatically straightens, clamps down, and exerts a preload on individual fibers. Single fiber measurements conducted on the Instron tensile instrument required extensive handling to prepare each fiber in a paper holder (Hsieh *et al.*, 1995). The extra fiber handling on the Instron is believed to be the cause of the lower strength. The absence of preload when preparing fibers for measurement using the Instron explains the higher breaking elongation values.

A standardized fiber selection and sampling approach for developing cotton has been established. It starts with tagging the flowers on the day of flowering (anthesis). Green bolls aged 14 days post anthesis (dpa) to 50 dpa and opened bolls can be sampled from first-position (closest to the main stem) between the fourth and the twelfth fruiting branches. Sources of fiber development variations can be minimized by using the fibers from the medial section of the ovules and the middle ovules from each boll. Furthermore, the middle sections of fibers are measured as they are stronger than the fiber sections closer to the basal or the tip ends at all stages of fiber development. The verification of this approach is briefly summarized in the following section.

The forces required to break hydrated and dried single Maxxa fibers increase with fiber development (Fig. 1.9(a)), with hydrated fibers being stronger. The breaking elongation values are higher for the dried fibers, leading to similar work to break between the hydrated and dried fibers. The breaking forces of the dried fibers appear to increase at a higher rate between 20 and 30 dpa than in the later stages. The decreasing forces and increasing strain at break from the hydrated state to the dry state may be explained by the increased convolution angles resulting from cell collapsing and dehydration. The effects between branches from branch four to twelve on single fiber strength are negligible (Fig. 1.9(b)).



(a)

(b)

1.9 Single fiber breaking forces of developing *G. hirsutum* (SJ-2) cotton: (a) ● hydrated, ○ dried; (b) ○ random first-boll position from 6 plants, □ first-boll position from single plant.

The cotton ovules or seeds are shaped like inverted teardrops, with the round and pointed ends being the chalazal and micropylar regions of the seeds, respectively. For *G. hirsutum* (Maxxa), the medial fibers and the micropylar fibers have similar breaking force and fiber widths (Table 1.1) (Hsieh *et al.*, 1997). Fibers from the chalazal ends were narrowest and had lower linear densities whereas those from the micropylar end have higher linear densities, indicating thicker secondary cell walls. Therefore, the medial fibers have the higher tenacities, while those from the chalazal and micropylar ends being lower and similar. Similar observations have been made on Texas Marker 1, another *G. hirsutum* variety and Pima S7 (*G. barbadense*) as well (Hsieh *et al.*, 2000). These findings confirmed the medial seed region fiber selection.

Fibers from five varieties representing four cultivated cotton species (*G. herbeceum*, *G. arboreum, G. hirsutum, G. barbadense*) were studied for effects of seed position on fiber strength (Liu *et al.*, 2001). With the exception of *G. arboreum*, breaking forces, toughness and linear density are highly dependent on the seed positions in the locule, and the dependence is especially high for *G. herbeceum* and *G. barbadense*. Fibers from seeds located closer to the main stem have higher breaking forces and linear density, indicating their association to the distribution of nutrition resources. These findings confirmed that the mid-ovule fibers represent the population.

The relationships between single fiber tensile properties and fiber lengths also vary among these cotton species (Liu *et al.*, 2001). The breaking forces and tenacities are independent of fiber lengths for *G. barbadense*, whereas positive fiber-length dependence is observed with *G. herbaceum*, *G. arboreum*

Table 1.1 Properties of plant-matured fibers* from three seed locations of *G. hirsutum* (Maxxa)

Properties/seed location	Chalazal	Medial	Micropylar
Force to break (g)	3.13	5.47	6.16
CV (%)	24	19	13
Breaking elongation(%)	7.4	7.6	7.6
CV (%)	16	10	10
Work to break (μJ)	4.2	6.9	7.5
CV (%)	33	23	15
Linear density (tex)	0.132	0.197	0.259
CV (%)	13	10	9
Tenacity (g/tex)	23.7	27.8	23.9
CV (%)	21	16	14
Ribbon width (μm)	13.9	15.6	16.2
CV (%)	2	3	4

* Tensile properties and ribbon widths were from a total of 750 measurements on fibers sampled from 15 ovules of five first-position plant-matured bolls. Linear density data were calculated from 45 measurements of 100-fiber bundles, nine each, from the same five bolls.

and a negative trend is found with the Maxxa variety of *G. hirsutum*. For *G. herbaceum*, *G. arboreum*, longer fibers have higher breaking forces whereas the opposite is found in Maxxa. The single fiber breaking elongation decreases with increasing fiber lengths for all except for *G. barbadense*. Overall variations of single fiber tensile properties are associated more strongly with the seed positions in the locule than with the fiber lengths. Among these five cultivars, the single fiber strength of Pima S7 is highest, with *G. hirsutum* varieties being second, *G. herbaceum* the third and *G. arboreum* the lowest (Table 1.2). The cell wall mass as indicated by the linear density (LD) follows the same order, except that *G. herbaceum* is the highest due mostly to its high fiber widths.

The distributions of breaking forces and elongation of single fibers from these five cultivated cotton varieties show significantly different range and distribution patterns and appear to be highly dependent on genotypes (Liu *et al.*, 2005). Within each cultivar, fibers of varying lengths have similar distributions in their breaking forces and elongation. This lack of relationship with fiber length suggests that these fiber tensile properties may be independent of length development, i.e., during elongation of primary cell wall through the early state of secondary cell wall synthesis. Single fiber breaking force and elongation were positively correlated (r = 0.259 to 0.443) for all five varieties, with Pima having the highest correlation coefficient.

The mass of seed fibers (fiber and seed) and fibers as in linear density have both shown to be reliable indicators for the stage of fiber development. The seed fiber weights increase linearly with fiber development. With developing fibers, the strength and seed fiber weight relationship is similar to that of the strength-dpa relationship. Therefore, it is quite conceivable that fiber strength may be projected from seed fiber weight throughout the secondary cell wall synthesis stage when such strength-seed fiber weight correlations have been established. The linear densities of the developing fibers also increase with fiber development, most significantly during the first 10–14 days of secondary cell wall synthesis. The linear density to age relationship varies with the varieties, indicating the rate of cellulose synthesis and how single fibers gain strength during the early part of secondary cell develop to be variety dependent.

Generally, the forces to break single fibers increased significantly during the fourth week of fiber development. Beyond 30 dpa, neither linear densities nor single fiber tenacities showed any changes. Data on *G. hirsutum* varieties have shown that fibers at about 21–24 dpa exhibit significant strength. This is at the onset of the secondary wall formation where fiber elongation is nearly completed. Using estimated linear densities for SJ-2 fibers at 14 to 16 dpa, the breaking tenacities of dried fibers are estimated to be 21.5 and 31.3 g/tex, respectively (Hsieh *et al.*, 1995). The primary cell wall appears to contribute toward two-thirds or more of the fiber strength. These fiber strength

Table 1.2 Tenacity (gf/tex) and linear density (mtex) of fibers from middle seeds in locule*

	G. herbaceum African-51		*G. arboreum* Asia 163		*G. hirsutum* Maxxa		TM-1		*G. barbadense* Pima S7	
	tenacity	LD	tenacity	LD	tenacity	LD	tenacity	LD	tenacity	LD
Mean	44.6	213	37.3	274	41.2	180	39.1	185	55.9	150
CV (%)	7.3	11.9	5.7	3.2	2.8	5.7	3.1	4.0	6.2	7.4
r	0.77	0.99†	–0.70	0.82	0.64	0.96†	0.43	0.89†	0.80	0.95†

* Twenty first-position plant-mature bolls from ten plants of each variety were harvested five to seven days after boll opening. Three bolls with weights closest to the average boll weight (BW) of the 20 collected were used.

† Denotes different correlation coefficients of the linear regression between fiber tensile properties and seed positions in locule at a 5% significance level.

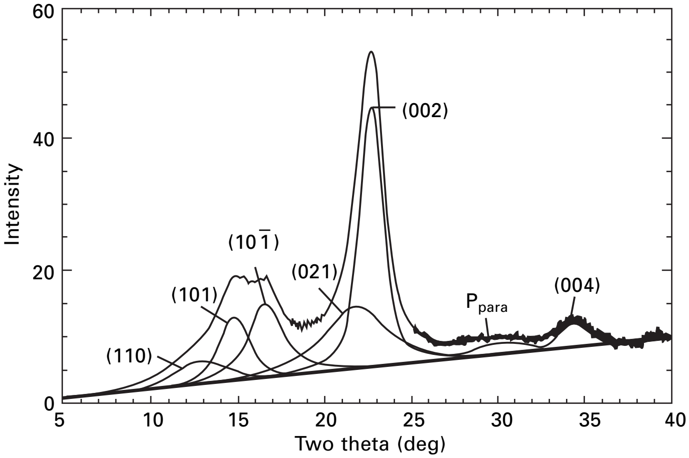
estimations are consistent with the report on 14 dpa *G. hirsutum* Delta Pine 61 fibers whose breaking tenacity was slightly more than half of the fibers that were 49 dpa (Hebert, 1993). Both the breaking forces and fiber mass or linear densities continue to increase throughout the first 36–40 days of fiber development. Therefore, the secondary wall thickening continues to contribute to the single fiber breaking force. However, the breaking tenacities of single fibers appear to reach the maximal level when the fibers are about 21 to 24 dpa.

1.4.2 Crystalline structure of cellulose

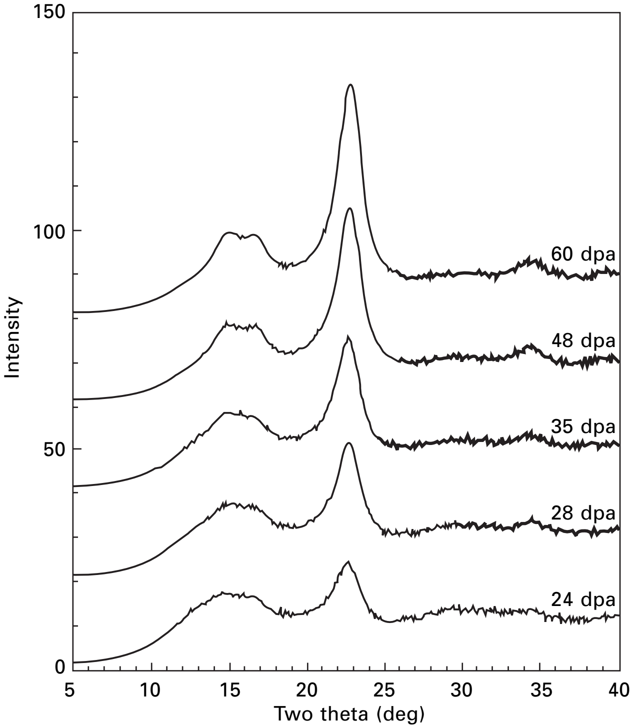
The fine structure of cotton cellulose has been most widely investigated by wide-angle X-ray diffraction, a well-developed and powerful tool for discerning structural organization of polymer solids. The structural studies of cotton cellulose have been extensively reported, mainly on field grown matured cotton and those treated in urea and sodium hydroxide (Khalifa *et al.*, 1991). The formation of primary and secondary cell walls in cotton fibers is distinct and of relatively long duration, allowing studies of crystalline structure at specific stages of fiber development. The crystalline structure of developing *G. hirsutum* cotton fibers (Hu and Hsieh, 1996, 1997a; Hsieh *et al.*, 1997) has been detailed using wide-angle X-ray diffraction and a multi-peak resolution method previously developed (Hindeleh *et al.*, 1980). In this method, the total scatter was resolved into peaks over a non-crystalline scatter background, where crystallinity is the ratio of the summation of all resolved peaks to the total scatter as detailed in our previous paper (Hu and Hsieh, 1996). Crystallite dimensions normal to the hkl planes were calculated following peak broadening corrections caused by structural broadening (δβ) and instrumental broadening. The apparent crystallite sizes of the 101, $10\bar{1}$ and 002 reflection planes was based on the Sherrer equation.

A typically resolved X-ray diffraction spectrum of 60-dap Maxxa cotton fibers is illustrated in Fig. 1.10. The multiple peak resolution method yields seven peaks from the WAXD spectrum collected between 5° and 40°. The four peaks located near 2θ angles of 14.7°, 16.6°, 22.7° and 34.4° are characteristic of the 101, $10\bar{1}$, 002 and 040 reflections of cellulose I, respectively, and are used for structural analysis and comparison.

The cellulose **I** crystalline structure is clearly evident near the onset of secondary cell wall formation, or 21 dpa (Fig. 1.11). The cellulose **I** crystalline structure has been confirmed on dried SJ-2 and Maxxa cotton fibers at varying developmental stages and remains unchanged during secondary cell wall biosynthesis and at maturity (Hsieh *et al.*, 1997). The degree of crystallinity doubled from the beginning to the end of the secondary cell wall formation, i.e., from about 30% at 21 dpa to 60% at 60 dpa. The most significant increase in crystallinity, i.e., from 30% to 55%, is observed between 21 and



1.10 Typical wide-angle X-ray diffraction pattern of matured cotton fibers.



1.11 Crystallite dimensions of developing *G. hirsutum* (Maxxa) cotton fibers.

34 dpa. The extensive data on several Acala varieties grown under well-controlled green-house conditions show that significant crystallinity is attained during the first half of the secondary cell wall development. One early report also showed increased crystallinity with fiber development of a field-grown Indian cotton variety (Kulshreshtha *et al.*, 1973b). The stage studied was in the later stages of secondary cell wall development (35 to 65 dpa).

Both *G. barbedense* and *G. hirsutum* series of developing cotton fibers show increased overall crystallinity and apparent crystallite sizes with fiber development (Table 1.3) (Hsieh *et al.*, 2000). The most significant increases in L_{101}, $L_{10\bar{1}}$, and crystallinity occur between 20 dpa and 35 dpa, corresponding to the first two weeks of cellulose synthesis or the fourth and fifth weeks of overall fiber development. Fiber development beyond five weeks does not contribute to any change in crystallite dimensions nor cyrstallinity. This is consistent with the leveling of tenacities at the later stage of fiber development. These are consistent with others' findings that the lateral apparent crystallite sizes and their orientation increase during the cellulose biosynthesis (Nelson and Mares, 1965).

Structural studies of native celluloses have also included the use of high-resolution CP/MAS ^{13}C NMR (Atalla and VanderHart, 1984; VanderHart and Atalla, 1984, 1987). Native celluloses have been classified into two families: that of algal-bacterial cellulose, where the cellulose is rich in the I_α phase, and that of cotton-ramie-wood cellulose, where the I_β phase is dominant. Infra-red spectroscopy is another solid-state technique that can be used to distinguish the structures of these two families of celluloses (Michell, 1990). The Fourier transfer infra-red spectroscopy (FTIR), another structural characterization tool, was employed to elucidate the crystalline structure of a series of highly crystalline celluloses (Sugiyama *et al.*, 1991). The absorption

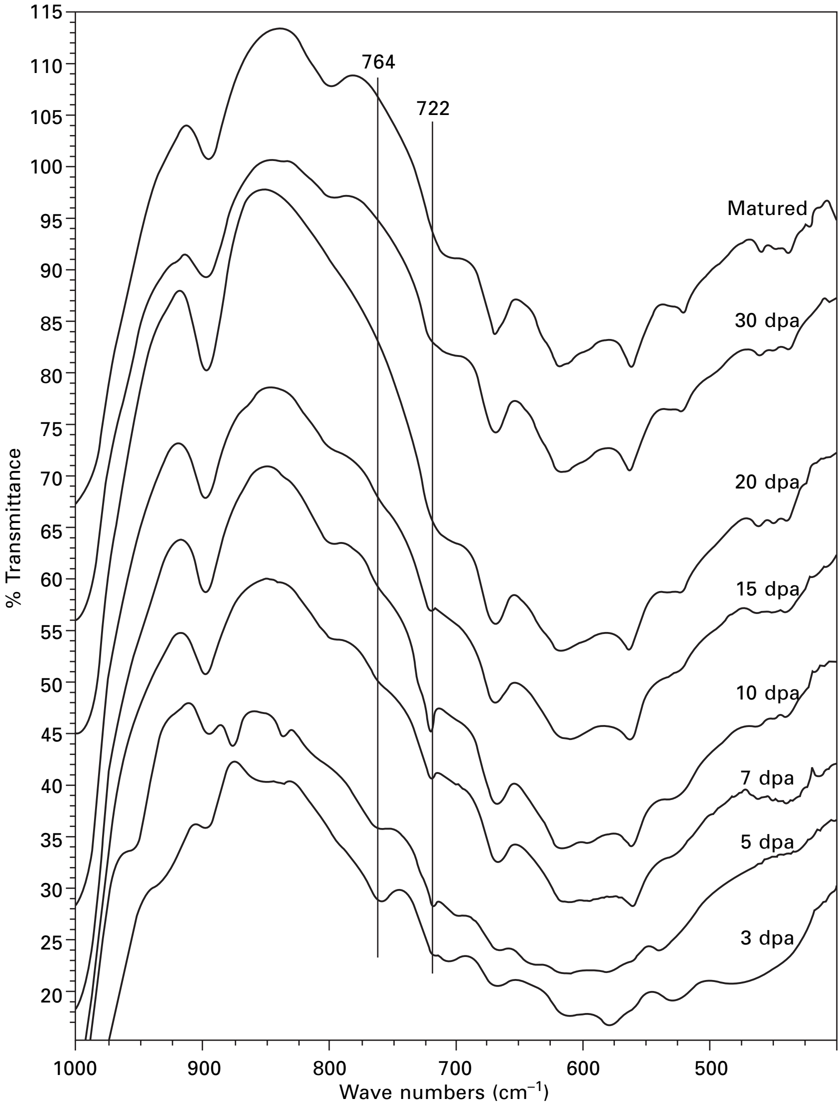
Table 1.3 Crystallite size (L, angstrom) and crystallinity (X, %) of developing *G. hirsutum* (Texas Marker 1) and *G. barbedense* (Pima S7) cotton fibers*

	20 dpa	28 dpa	35 dpa	42 dpa	Mature
G. hirsutum (Texas Marker 1)					
L_{101}	22.2	27.2	37.8	40.1	37.7
$L_{10\bar{1}}$	22.3	27.1	36.0	39.5	37.5
L_{002}	41.3	41.2	41.9	44.4	43.6
X	23	37	52	54	46
G. barbedense (Pima S7)					
L_{101}	26.9	35.2	43.6	43.9	45.7
$L_{10\bar{1}}$	22.1	30.9	34.8	34.6	35.7
L_{002}	37.7	40.7	41.4	41.2	42.3
X	23	48	55	56	60

* Fibers for each stage of development were sampled from five first-position bolls randomly sampled from nine plants.

bands at 3240 and 750 cm^{-1} corresponding to the I$_{\alpha}$ phase and those near 3270 cm^{-1} and 710 cm^{-1} corresponding to the I$_{\beta}$ phase were reported.

The FTIR spectra of developing cotton fibers exhibit absorption bands at 764 cm^{-1} and 722 cm^{-1}, characteristic of I$_{\alpha}$ and I$_{\beta}$ phases of the cellulose crystalline structure, respectively (Fig. 1.12) (Hu and Hsieh, 1997b). The 764 cm^{-1} band intensity was highest in the 3-dpa fibers, indicating rich I$_{\alpha}$ phase in fibers at the beginning of elongation. While the 764 cm^{-1} peak



1.12 FTIR of developing *G. hirsutum* (Maxxa) cotton fibers.

intensities decreased rapidly from 3 dpa to 10 dpa, the 722 cm^{-1} band, also observed in the spectrum of 3-dpa fibers, increased markedly. Only a trace of the 764 cm^{-1} band was observed in the spectrum of 15-dpa fibers. The FTIR spectra clearly showed that the I_α and I_β phases coexist at the beginning of fiber elongation. The I_β phase increases markedly from 3 dpa to 10 dpa and becomes predominant at the onset of the secondary wall synthesis, i.e., 15 dpa, the onset of secondary cell wall synthesis. These results indicate that the crystalline components in developing cotton fibers change from the coexistence of the I_α and I_β phases at 3 dpa to a predominantly I_β phase at 15 dpa.

The interesting questions brought by the FTIR results of developing fibers are the origin in the biphasic character and their conversion of cotton fibers. The I_α phase was previously thought to be from the built-in strains during cellulose biosynthesis whereas the I_β phase was from crystallization in an entirely strain-free environment. The strong relationship between I_β/I_α ratio and fiber elongation by our FTIR suggest that such a relationship may be related to the changes in turgor pressure during fiber elongation. Other factors, such as interactions among cellulose chains, the arrangement of Tcs (cellulose-synthesizing terminal enzyme complexes), and the affinity of other polysaccharides for cellulose, may also affect the biphasic character and their conversion, but their effects are not clearly understood at this point.

The IR spectra of 20-dpa, 30-dpa, and matured samples only showed the band at 722 cm^{-1}, while the band at 764 cm^{-1} disappeared, indicating the absence of the I_α phase during the secondary cell wall synthesis and in the matured cotton fibers. This is consistent with the common knowledge of cellulose structure from higher plants. The I_β phase becomes more dominant with increasing cellulose biosynthesis in the primary cell wall. Only the I_β phase was found in the secondary wall and matured cotton fibers. The question that remains to be answered is whether the formation of the I_α phase has stopped or the triclinic I_α phase is metastable and is later converted to the stable monoclinic I_β phase during the secondary cell wall synthesis.

The evidence is clear that cotton fibers exhibit only cellulose I crystalline structure during the entire fiber biosynthesis. Contrary to few reports, neither X-ray, solid-state NMR nor FTIR provides any evidence of other cellulose structure, i.e., II, III or IV. The primary cell walls of cotton fibers contain crystalline cellulose whose degree of crystallinity is lower than that of the secondary cell wall (Hsieh *et al.*, 1997). In contrast to solid-state NMR spectroscopy and X-ray diffraction, infra-red spectroscopic methods require much smaller quantities of materials, a particular advantage for studying cotton fibers at early stages of development where fiber mass is very limited. The studies of the I_α and I_β phases in the primary and secondary walls and their polymorph changes during cell wall synthesis help to discern the *in vivo* mechanism for cellulose biosynthesis and crystallization.

1.4.3 Strength and crystalline structure relationship

Positive relationships between bundle strength by the Stelometer and crystallinity (53% to 69%) have been reported on matured fibers from eight Egyptian cottons (Hindeleh, 1980). However, the relationships between strength and crystallinity may not be easily compared among studies. One reason is that the extents of crystallinity of matured cottons range from 50% to nearly 100% depending on the measurement techniques. The differences resulting from the methods of crystallinity determination are further complicated by the inevitable variations among cotton fibers due to a combination of varietal and environmental factors.

One intriguing question about the development of strength in cotton fibers is the structural contributing factors. Although positive relationship between the Stelometer bundle tenacities and crystallinity has been shown (Hindeleh, 1980), information on strength-crystallinity relationship on developing fibers is limited. Our work has shown positive relationships between single fiber breaking forces and overall crystallinity among developing fibers from the SJ-2 and Maxxa varieties (Hsieh *et al.*, 1997). With increasing crystallinity from 30% to 58%, the forces to break Maxxa fibers increase more than those for the SJ-2 fibers. In other words, single fiber breaking forces are higher for Maxxa fibers than SJ-2 fibers when compared at the same crystallinity. Crystallinity of the Maxxa fibers is lower than SJ-2 with the same amount of cellulose. The positive relationship between single fiber breaking force and crystallinity may be variety dependent.

In general, the overall crystallinity, apparent crystallite sizes, and single fiber breaking forces of fibers increase with fiber development (Hsieh *et al.*, 1997). The patterns by which these crystalline structure parameters and properties vary with age are different between these two varieties. The breaking forces of the developing Maxxa fibers increase more with crystallinity (between 30 and 50%) than those of the SJ-2 counterparts. The increasing patterns in crystallite dimensions were different between the two varieties, resulting in different breaking force-crystallite dimension relationships. The most significant differences between SJ-2 and Maxxa are in their breaking relationships with the 101- and 002 crystallite dimensions. Therefore, the dependency of single fiber breaking force on crystallite sizes is obviously different for these two varieties.

Although the overall crystallinity and apparent crystallite sizes increase with fiber development, the unit cell sizes decrease slightly and thus the crystal densities increase with fiber development. Among the crystal lattice planes, the alignment of the glucosidic rings in respect to the 002 planes improves most significantly with fiber cell development. The crystallinity and crystal density of SJ-2 fibers are higher than those of Maxxa fibers during the fifth and sixth weeks of fiber development. The 002 and 101 crystallite dimensions of Maxxa fibers, on the other hand, are larger than those of the SJ-2 fibers. These increases coincide with the largest increase in forces to break single fibers.

Within each variety, positive relationships are observed between single fiber breaking forces and the overall crystallinity as well as between single fiber breaking force and crystallite size. However, the relationships between tenacities and crystallinity are different between these two varieties. The single fiber breaking tenacities of the SJ-2 cotton fibers do not appear to vary from 21 dpa to maturity. For the Maxxa cotton fibers, however, breaking tenacities appear to be positively related to fiber development or thickening of the secondary cell wall. Additionally, negatively relationships have been observed between breaking tenacities and crystal densities for both varieties. The increased crystallinity and crystallite sizes and perfection offer only partial explanation to the strength development of cotton fibers. Although some preliminary observation regarding the tenacity-age relationships and varietal differences in tenacity-structure relationship of developing fibers have been made, additional data collection and analysis are necessary to fully establish these relationships. Furthermore, structural parameters such as fibril orientation and residual stress may play key roles in cotton fiber strength and should be considered in future work.

1.5 Conclusion

Cotton fibers are nature's purest form of cellulose, composing about 90% of α-cellulose. The non-cellulosics are located on the outer layers or inside the lumens of the fibers whereas the secondary cell wall is purely cellulose. Both the structure and compositions of the cellulose and noncellulosics depend on the variety and the growing conditions. The cellulose fibrils spiral in the concentric cell wall layers at decreasing angle toward the center of the fiber. The spirals reverse along the fiber length and cause the cylindrical cells to collapse into the twisted ribbon fibers upon drying.

Cotton cellulose consists of β-1,4-D(+)-glucopyranose that repeats thousands of times. The very long chain that is limited in rotational freedom about the anhydrogluco-pyranose C-O-C link leads to a rigid and highly crystalline structure. The abundant hydroxyl groups, one C-6 primary and two C-2 and C-3 secondary on each anhydroglucose unit, allow extensive inter-molecular and intra-molecular hydrogen bonding to further enhance the cellulose structure for strength. These hydroxyl groups are also critical chemical characteristics of cotton fibers as they bond water and are responsible for the chemical reactivity such as in chemical modification, dyeing and finishing.

All three main fiber quality parameters, i.e., length, fineness and strength, have been linked to genotypes as well as growing conditions. The length and fineness of fibers are determined in the early stages of cell growth and development. Fiber length is determined during the elongation stage, i.e., during the first 20 to 25 days past anthesis (dpa). The final thickness of fiber cells is developed at the base of the fibers by about 2 dpa. How cotton fibers gain strength has much to do with both primary wall formation (elongation) and secondary wall thickening (cellulose synthesis) as well as during desiccation (transition from mobile to highly hydrogen-bonded structure).

Ultimate fiber tensile properties were reached in the 30 dpa fibers and further fiber development contributed to thicker cell wall, thus fiber mass or lint turnout, but not the intrinsic fiber strength. For *G. hirsutum* varieties, the single fiber breaking forces increase most significantly during the fourth week of fiber development. The forces required to break single fibers are similar among varieties through the end of the fourth week of cell development. Beyond 30 dpa, both the single fiber breaking forces and tenacities differentiate among cultivars due partly to the differences in their linear densities and seed fiber weights at the same developmental stages. The cellulose **I** crystalline structure is clearly evident at 21 dpa and remains unchanged throughout fiber development. The overall crystallinity and the apparent crystallite sizes increase with fiber development for all varieties. Within each variety, the single fiber breaking forces are positively related to both the overall crystallinity and crystallite sizes. At the same developmental stages, Maxxa fibers have larger crystal sizes but lower crystallinity and lower crystal density than the SJ-2 fibers.

Although positive relationships between single fiber breaking forces and the overall crystallinity as well as between single fiber breaking force and crystallite size have been observed in both *G. hirsutum* and *G. barbedense* varieties, the relationships between tenacities and crystalline structure parameters are different between these two varieties. The tenacity-age relationships and varietal differences in tenacity-structure relationships remain to be further clarified. Additionally, experimentally determined fiber strengths are far from those predicted theoretically. Better understanding of the structural factors for cotton fiber strength will help to explain these discrepancies, and to improve strength.

1.6 Acknowledgements

Special appreciation is extended to Dr X.-P. Hu, Dr M.M. Hartzell, Professors J. Liu, A. Wang, H. Yang, E. Honik, P.T. Dong, V. Ngyen and A. Ngyen, for their contributions and assistance in research. Support from Cotton Incorporated (#93-069) is greatly appreciated.

1.7 References and further reading

Atalla, R. H. and VanderHart, D. L. (1984). Native cellulose: a composite of two distinctive crystalline forms, *Science*, **223**, 283–285.

Balls, W. L. (1928). *Studies of Quality in Cotton*, Macmillan, London.

Basra, A. S. and Malik, C. P. (1984). Development of the Cotton Fiber, *Int. Rev. Cytol.,* **89**, 65–113.

Beasley, C. A. (1977). Ovule culture: fundamental and pragmatic research for the cotton industry, in *Plant Cell, Tissue and Organ Culture*, J. R. Reinert and J. P. S. Bai, eds, 160.

Benedict, D. R., Kohel, R. J. and Jividen, G. M. (1994). Crystalline cellulose and cotton fiber strength, *Crop Science*, **34**(1), 147–151.

Berlin, J. D. (1986). The outer epidermis of the cottonseed, in Mauney, J. R. and J. McD. Stewart, eds, *Cotton Physiology*, pages 375–415, The Cotton Foundation.

Bikales, N. M. and Segal, L. Eds, (1971). *High Polymers*, Vol. V, Part V, *Cellulose and Cellulose Derivatives*, Wiley Interscience, New York, NY.

Boylston, E. K., Thibodeaux, D. P. and Evans, J. P. (1993). Applying microscopy to the development of a reference method for cotton fiber maturity, *Textile Res. J.*, **63**(2), 80–87.

Cassman, K. G., Kerby, T. A., Roberts, B. A., Bryuant, D. C. and Higashi, S. L. (1990). Potassium nutrition effects on lint yield and fiber quality of Acala cotton, *Crop Sci.*, **30**, 672–677.

Darvill, A., McNeil, M., Albersheim, P. and Delmer, D. P. *The Biochemistry of Plants, Vol. 1*, Academic Press, New York, 1980, pp. 91–161.

Davidonis, G. and Hinojosa, O. (1994). Influence of seed location on cotton fiber development *in planta* and *in vitro*, *Plant Science*, **203**, 107–113.

deGruy, I. V., Carra, J. H. and Goynes, W. R. (1973). *Fine Structure of Cotton*, *An Atlas of Cotton Microscopy*, in Fiber Science Series V.6, ed. R. T. O'Conner, Dekker, New York.

Elias, H. G. *Macromolecules: Part 2: Synthesis and materials*, Plenum Press, New York, 1977, chap. 31, p. 1081.

Figini, M. (1982). Cellulose and other natural polymer systems, *Biogenesis, structure and degradation*, 243–271, Plenum Press, New York.

Freytag, R. and Donze, J.-J. (1983). Alkali Treatment of Cellulose Fibers, in *Handbook of Fiber Science and Technology: Volume 1, Chemical Processing of Fibers and Fabrics, Fundamentals and Preparation*, Part A Marcel Dekker, NY, pp. 94–120.

Fryxell, P. A. (1963). Morphology of the base of seed hairs of *Gossypium* I. gross morphology, *Bot. Gas.*, **124**, 196–199.

Gibson, J. R. (1986). Temperature effects on growth, development, and fiber properties, in *Cotton Physiology*, J. R. Mauney and J. M. Steward, eds, The Cotton Foundation, Memphis, TN, pp. 47–56.

Goldwaith, F. G. and Guthrie, J. D. (1954). *Matthew's Textile Fibers*, H. R. Mauersberger, ed., Wiley Interscience, New York.

Goring, D. A. I. and Timell, T. E. (1962). Molecular weight of native cellulose, *TAPPI*, **45**, 454–460.

Goynes, W. R., Ingber, B. F. and Triplett, B. A. (1995). Cotton fiber secondary wall development – time versus thickness, *Textile Res. J.*, **65**(7), 400–408.

Graves, D. A. and Stewart, J. M. (1988), Chronology of the differentiation of cotton (Gossypium hirsutum L.) fiber cells, *Planta*, **175**, 254–258.

Green, C. C. and Culp, T. W. (1990). Simultaneous improvement of yield, fiber quality, and yarn strength in Upland cotton, *Crop Sci.*, **30**, 66–69.

Haigler, C. H., Rao, N. R., Roberts, E. M., Huang, J., Upchurch, D. R. and Trolinder, N. L. (1991). Cultured ovules as models for cotton fibers developed under low temperatures, *Plant Physiol.* **95**(1), 88–91.

Harig, H. (1992). Possibilities and problems in the further development of cotton as a raw material, *ITS Textile Leader*, **10**, 71.

Hartzell-Lawson, M. M. and Hsieh, Y.-L. Characteristics of noncellulosics in developing cotton fibers, *Textile Research Journal* **70**(9): 810–819 (2000).

Hebert, J. J. (1993). Strength of the primary wall of cotton fibers, *Textile Res. J.* 63(11), 695.

Hebert, J. J., Boylston, E. K. and Thibodeaux, D. P. (1987). Orientation Measurements in Developing Cotton Fibers*, Text. Res. J.*, **57**(12), 742–743.

Heredia, A., Guillen, R., Jimenez, A. and Fernandez-Bolanos, J. Review: Plant Cell Wall Structure. *Revista Espanola de Ciencia y Technologia de Alimentos*, **33**, 113–131 (1993).

Hermans, P. H. and Weidinger, A. (1949). X-Ray Studies on the Crystallinity of Cellulose, *J. Polym. Sci.*, **4**, 135–144.

Hermans, P. H. and Weidinger, A. (1950). Quantitative Investigation of X-Ray Diffraction by 'amorphous' Polymers and Some Other Noncrystalline Substances, *J. Polym. Sci.*, **5**, 269–281.

Hessler, L. E., Merola, G. V. and Berkley, E. E. (1948). Degree of polymerization of cellulose in cotton fibers, *Textile. Res. J.*, **18**, 628–634.

Hindeleh, A. M. (1980). Crystallinity, crystallite size, and physical properties of native Egyptian cotton, *Textile Res. J.*, **50**(11), 667–674.

Hindeleh, A. M., Johnson, D. J. and Montague, P. E. (1980). Computational Methods for Profile Resolution and Crystallite Size Evaluation in Fibrous Polymers, in *Fiber Diffraction Methods* (eds, A. D. French and K. H. Gardner), *ACS Symposium*, **No. 141**, 149–182.

Hornuff, G. V. and Richter, H. (1964). Chemical Composition of Cotton Fibers Originating From Various Areas, *Faserforsch. Textiltechn.*, **15**, 115–126.

Hsieh, Y.-L. (1994). Single fiber strength: greenhouse grown SJ-2 Acala cotton. *Biochemistry of Cotton* 109–114.

Hsieh, Y.-L. (1999). Structural development of cotton fibers and linkages to fiber quality, *Cotton Fibers*, ed. A. S. Basra, Food Products Press, New York, 137–165.

Hsieh, Y.-L. and Wang, A. (2000). Single fiber strength variations of developing cotton fibers – among ovule locations and along fiber length, *Textile Research Journal* **70**(6): 495–501.

Hsieh, Y.-L, Honic, E. and Hartzell, M. M. (1995). A developmental study of single fiber strength: greenhouse grown SJ-2 Acala cotton, *Textile Research Journal*, **65**(2): 101–112.

Hsieh, Y.-L., Hu, X. P. and Nguyen, A. (1997). Strength and crystalline structure of developing Acala cotton, *Textile Research Journal* **67**(7): 529–536.

Hsieh, Y.-L., Hu, X.-P. and Wang, A. (2000). Single fiber strength variations of developing Cotton gibers – strength and structure of *G. hirsutum* and *G. barbedense*, *Textile Research Journal* 70(8): 682–690.

Hu, X. P. and Hsieh, Y.-L. Distribution of single cotton fiber tensile properties, *Textile Research Journal* (submitted).

Hu, X. P. and Hsieh, Y.-L. (1996). Crystalline structure of developing cotton fibers, *Journal of Polymer Science*, Polymer Physics Edition, **34**, 1451–1459.

Hu, X. P. and Hsieh, Y.-L. (1997a). Breaking elongation distributions of single fibers, *Journal of Materials Science* **32**: 3905–3912.

Hu, X.-P. and Hsieh, Y.-L. (1997b) Crystalline phases in developing cotton fibers by FTIR, *Recent Research Developments in Polymer Science*, 1: 249–254.

Hu, X.-P. and Hsieh, Y.-L. (1998). Distribution of single-fiber toughness, *The Journal of Textile Institute*, **89**, 457–467.

Hu, X.-P. and Hsieh, Y.-L. (2001). Effects of dehydration effects on the structure and tensile properties of developing Acala cotton fibers, *Textile Research Journal* **71**(3): 231–239.

Huwyler, H. R., Franz, G. and Meier, H. (1979). Changes in the composition of cotton fiber cell walls during development. *Planta* **146**, 635–642.

Ingram, P., Woods, D. K., Peterlin, A. and Williams, J. L. (1974). Never-dried cotton, part I: morphology and transport properties, *Textile Res. J.*, **44**, 96–106.

Jacobsen, K. R., Grossman, Y. L., Hsieh, Y.-L., Plant, R. E., Larlor, W. F. and Jernstedt, J. A. (2001). Neps, seed-coat fragment and non-seed impurities in processed cotton, dyeing characteristics of processed fibers, *Journal of Cotton Science* **5**(1): 53–67.

Jenkins, J. N., McCarthy, J. C. and Parrot, W. L. (1990). Fruiting efficiency in cotton: boll size and boll set percentage, *Crop Science*, **30**, 857–860.

John, M. E. and Stewart, J. McD. (1992). *Trends in Biotechnology*, **10**(5), 165–170.

Joshi, P. C., Wadhwani, A. M. and Johri, B. M. (1967). Morphological and embryological studies of Gossypium L. *Proc. Natl. Inst. Sci. India*, B(**33**), 37–93.

Kassenback, P. (1970). Bilateral structure of cotton fibers as revealed by enzymatic degradation, *Textile Res. J.*, **40**, 330–334.

Khalifa, B. A., Abdel-Zaher, N. and Shoukr, F. S. (1991). Crystalline character of native and chemically treated Saudi Arabian cotton fibers, *Textile Res. J.*, **61**(10): 602–608.

Kulshreshtha, A. K., Patel, K. F., Patel, A. R., Patel, M. M. and Baddi, N. T. (1973a). The fine structure and mechanical properties of cotton fibres at various stages of growth, *Cellulose Chemistry and Technology*, **7**: 307–314.

Kulshreshtha, A. K., Patel, K. F., Patel, A. R., Patel, M. M. and Baddi, N. T. (1973b). A study of equatorial X-ray diffraction from fresh, undried cotton fibre at various stages of its growth, *Cellulose Chemistry and Technology*, **7**: 343–349.

Liu, J.-H., Yang, H. and Hsieh, Y.-L. (2001). Variations of mature cotton fiber tensile properties – association with seed positions and fiber lengths, *Textile Research Journal* **71**(12): 1079–1086.

Liu, J.-H., Yang, H. and Hsieh, Y.-L. (2005). Distribution of Single Fiber Tensile Properties of Four Cotton Genotypes, *Textile Research Journal* **75**(1): 117–122.

Mark, H. (1940). Intermicellar Hole and Tube System in Fiber Structure, *J. Phys. Chem.*, **44**, 764–788.

Meinert, M. C. and Delmer, D. P. (1977). Changes in biochemical composition of the cell wall of the cotton fiber during development, *Plant Physiol.*, **59**: 1088–1097.

Michell, A. J. (1990). *Carbohydr. Res.* **197**, 53.

Muller, M. (1991). Precise measurement of important fiber properties in cotton, *International Textile Bulletin*, 73–88.

Muller, L. L. and Rollins, M. L. (1972). Electron microscopical study of cotton fiber surfaces after purification treatment, *Microscope*, **20**, 143–152.

Naithani, S. C., Rama Rao, N. and Singh, Y. D. (1982). Physiological and biochemical changes associated with cotton fiber development, *Physiol. Plant*, **54**, 225–229.

Nelson, M. L. and Mares, T. (1965). Accessibility and lateral order distribution of the cellulose in the developing cotton fiber, *Textile Res. J.*, **35**, 592–603.

Patel, G. S., Bhama Iyer, P., Sreenivasan, S. and Krishna Iyer, K. R. (1990). Reversals in cotton: a study with scanning electron microscopy, *Textile Res. J.*, **60**, 771–774.

Peterlin, A. and Ingram, P. (1970). Morphology of secondary wall fibrils in cotton, *Textile Res. J.*, **40**, 345–354.

Raes, G., Fransen, T. and Verschraege, L. (1968). Study of the reversal phenomenon in the fibrillar structure of cotton fiber: reversal distance distribution as origin of an extended hypothesis in the cotton fiber development, *Textile Res. J.*, **38**, 182–195.

Rebenfeld, L. (1977). Mechanical properties of native fibrous materials, *Proc. 1st Cleveland Symp. Macromol.* A. G. Walton, ed., Elsevier, Amsterdam, 177–201.

Seagull, R. W. (1986). Changes in microtubule organization and wall microfibril orientation during *in vitro* cotton fiber development: an immunofluorescent study, *Can. J. Bot.*, **64**, 1373–1381.

Seagull, R. W. (1992). A quantitative electron microscopic study of changes in microtubles arrays and wall microfibril orientation during *in vitro* cotton fiber development, *J. Cell Sci.*, **101**, 561–577.

Shafizadeh, F. (1975). *Appl. Poly. Symp.*, **28**, 153.

Shafizadeh, F. (1985). Thermal Degradation of Cellulose, in *Cellulose Chemistry and Its Applications*, T. P. Nevell and S. H. Zeronia, eds; Ellis Horwood Ltd., Chichester.

Stewart, J. M. (1975). Fiber initiation on the cotton ovule, *Am. J. Bot.*, **62**, 723–730.

Stone, J. E. and Scallan, A. M. (1965). *Consolidation of the paper web*, Technical Section of the British Paper and Board Makers' Assoc., London, 145–174.

Sugiyama, J., Persson, J. and Chanzy, H. (1991). Combined infrared and electron diffraction study of the polymorphism of native celluloses *Macromolecules*, **24**, 2461–2466.

Timpa, J. D., Ramey, Jr. H. H. (1994). Relationship between cotton fiber strength and cellulose molecular weight distribution: HVI calibration stardards, *Textile Res. J.*, **64**(10): 557–562.

Timpa, J. D. and Triplett, B. A. (1993). Analysis of cell wall polymers during cotton fiber development, *Planta*, **189**(1), 101–108.

Tripp, V. W., Moore, A. T. and Rollins, M. L. (1957). The surface of cotton fibers, Part II: Modified fibers, *Text. Res. J.*, **27**, 427–436.

VanderHart, D. L. and Atalla, R. H. (1984). Studies of microstructure in native celluloses using solid-state 13C NMR, *Macromolecules*, **17**, 1465–1472.

VanderHart, D. L. and Atalla, R. H. (1987). In Atalla, R. H. (editor), *The Structure of Celluloses*, page 88, ACS Symposium Series 340, American Chemical Society, Washington, DC.

Vigil, E. L., Anthony, W. S., Columbus, E., Erbe, E. and Wergin, W. P. (1996). Fine structure aspects of cotton fiber attachment to the seed coat: morphological factors affecting saw ginning of lint cotton, *Int. J. Plant Sci.*, **157**(1): 92–102.

Warwicker, J. O., Jeffries, R., Colbran, R. L. and Robinson, R. N. (1996). Shirley Institute Pamphlet, No. 93, Manchester, U.K., December.

Yatsu, L. Y. and Jacks, T. J. (1981). An ultrastructural study of the relationship between microtubules and microfibrils in cotton cell wall reversals, *Am. J. Bot.*, **68**, 771–777.

Zeronian, S. H. (1991). The mechanical properties of cotton fibers, *J. Appl. Polym. Sci., Appl. Polym Symp.*, **47**, 445–461.

2

Physical structure and properties of cotton

J W S HEARLE, University of Manchester
UK

2.1 Introduction

Cotton was the dominant fibre of the 20th century. Now it is only exceeded in volume by polyester – and this position is achieved without the diversity of form and physical properties of polyester fibres. Partly the dominance of cotton textiles is due to the economics of production, distribution and manufacture, but it also results from the combination of structure and physical properties that is the subject of this chapter. Cotton first entered Western markets in the form of expensive fine fabrics, such as muslin and lawn, but by the end of the 19th century its properties made it a material of universal usage, sometimes as the best fibre for the purpose and sometimes as a cheaper alternative. Now cotton needs the properties that give a market for high quality, since polyester has captured much of the cheaper end of the market, as well as providing premium types for higher quality fabrics.

Section 2.2 will describe the structure and dimensions from the molecular to the whole-fibre level, which give rise to the physical properties. The absorption of moisture (section 2.3) has a major effect on properties as well as swelling the fibre. The mechanical properties (section 2.4) are the most important of the physical properties and are determined by structural features at all levels. Other properties, electrical, optical, thermal and frictional, are covered in section 2.5. Finally, the relevance of the extensive research in the middle of the 20th century will be mentioned, followed by a consideration of the future role of cotton and the effect of genetic engineering.

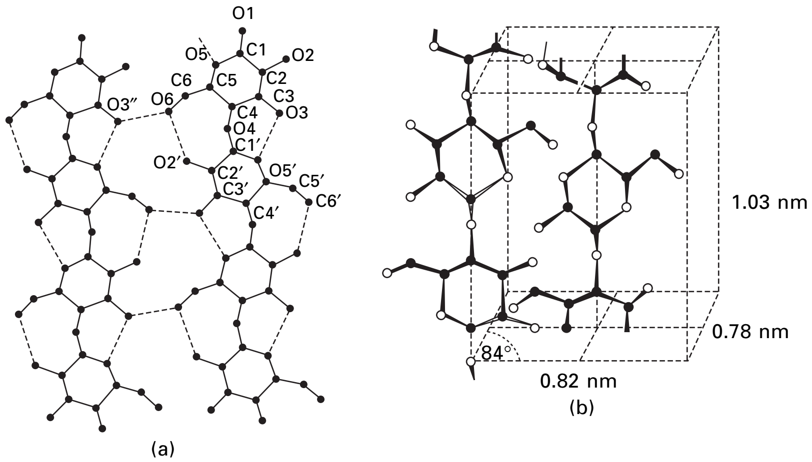
2.2 Cotton morphology

2.2.1 The cellulose molecule and crystalline fibrils

There is an abundant and sometimes contradictory literature on the formation of cellulose and its crystallisation. The following account summarises the features that are important to understand physical properties, but the numerical values, although certainly close to the real values, should not be taken as explicitly authoritative.

From a physical viewpoint the cellulose molecule, described in Chapter 1, is a ribbon-like structure of linked six-membered rings with hydroxyl groups projecting out in the plane of the ribbon. The covalently bonded chain-molecule is further stiffened by internal hydrogen bonds, which, as shown in Fig. 2.1(a), parallel the oxygen bridges between the rings. In tension, the molecule has high modulus and high strength, and it has high rigidity for bending in the plane; but it can easily twist or bend out of the plane. As discussed by Rouselle (2002), exact determination of molecular weight (MW) is difficult, because of the problems of dissolving cellulose. The use of a new solvent after a pre-(mercerisation) swelling treatment of cotton print cloth shows a distribution of molecular weights with a peak at 2×10^5 and most values between 10^4 and 5×10^6; the peak value corresponds to a chain length of about 0.5 μm with a molecular aspect ratio of about 1000:1. Timpa and Ramey (1994) report higher values of MW.

Cellulose crystallises with lattices in which hydrogen bonds between hydroxyl groups link the molecules into sheets, Fig. 2.1(a); between the sheets, there are weaker van der Waals forces. Natural cellulose fibres, including cotton, have a crystal lattice known as cellulose I, which differs from cellulose II in cellulose regenerated from solution or treated with a strong swelling



2.1 (a) Assembly of cellulose molecules in a sheet. C1, O1, etc., are positions of carbon and oxygen atoms; hydrogen atoms complete the valencies; hydrogen bonds are shown by dotted lines. From French (1985). (b) A schematic view of the crystal lattice of cellulose I, adapted from the drawing by Meyer and Misch (1937), which had anti-parallel chains. Hydrogen bonded sheets are in the plane of the paper. The sheets in the middle of the cell are staggered with respect to those on the front and back faces.

agent. The classical X-ray diffraction studies of Meyer and Misch (1937) proposed a unit cell for cellulose I, with 1.03 nm for two repeats along the chain axis, 0.835 nm for spacing between neighbouring chains in the sheets, and 0.79 nm between two equivalent sheets, which are separated by a staggered sheet of anti-parallel chains. Only small variations in the size of the unit cells have been proposed by other workers. However, the question of whether the chains were parallel or anti-parallel was controversial. Sarko and Muggli (1974) made a more detailed study of *Valonia* cellulose. They found that the chains were all aligned in the same direction in the cellulose I lattice. Since there were no differences from the pattern for cotton and ramie, except those attributable to the larger crystallite size in *Valonia*, they inferred that the cotton crystal lattice had the same cellulose I lattice, containing staggered sheets of parallel chains. There are minor differences in unit cells proposed around the same time by other studies (French, 1985). Figure 2.1(b), which is a modification of the Meyer and Misch lattice, shows the features essential to an understanding of the role of crystalline cellulose in cotton. Unlike the monomeric glucose molecules, the crystals do not dissolve in water, but can be disrupted by caustic soda and some solvents.

In growing cells, cellulose is synthesised by the condensation of glucose molecules at enzyme complexes, each of which generates 30 cellulose molecules. These naturally lie in the same direction and crystallise into long microfibrils, which are about 7 nm in width. In this sense, natural cellulose can be regarded as virtually 100% crystalline. The evidence, from moisture absorption, density, X-ray diffraction and other techniques, that cotton is about 2/3 crystalline can be explained by the imperfect packing of the microfibrils, which are normally separated by absorbed water. X-ray diffraction of ground cotton fibres gives crystallinity values of 92.6 to 94.7% (Timpa and Ramey, 1994).

2.2.2 Multi-wall helical assembly

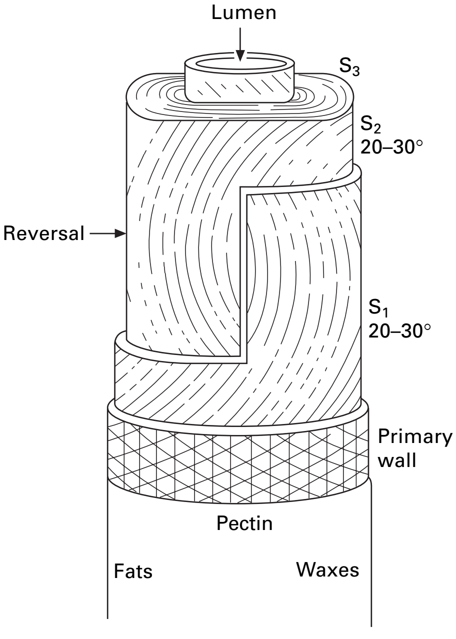
Large numbers of cotton fibres grow from each seed within the cotton boll. Each fibre is a single plant cell, which first grows to its full length and diameter by forming a primary wall. The primary wall is reported to have a 'basket-weave orientation or alignment of the fibrils' (Hebert, 1993). X-ray diffraction of fibres removed at two weeks post-anthesis (after flowering), which consist solely of the primary wall, have a crystalline index of 30%, and a calculated fibril diameter of 2.98 nm, contrasted with 70% and 4.22 nm for mature fibres at seven weeks post-anthesis (Boylston and Hebert, 1995). Studies of changes in crystalline structure during fiber development are reported by Hsieh *et al.* (1997) and Hu and Hsieh (2001).

Then a secondary wall is formed in daily growth rings inside the tube, leaving a small lumen at the centre when the cotton is mature and the boll opens. Goynes *et al.* (1995) report SEM and TEM studies of the development of the secondary wall in field and greenhouse grown cotton at different numbers of days post-anthesis. In mature fibres, the secondary wall comprises about 94% of the fibre material and thus dominates the mechanical properties. Immature cottons, resulting from premature opening of the boll, due to frost disease or application of plant hormone, are thin-walled tubes. The fibre surface consists of a waxy cuticle, which is removed by wet processing. Studies of changes in crystalline structure during fibre development are reported by Hsieh *et al.* (1997) and Hu and Hsieh (2001).

An impression of the overall structure of the cotton fibre is shown in Fig. 2.2. In the secondary wall the microfibrils are laid down in helical layers on the inside of the tube, with helix angles changing from around 35° in the outer layers to 20° in the inner layers (Hebert *et al.*, 1970; Morosoff and Ingram, 1970). At intervals along the cell walls, there are reversals between left-handed to right-handed helices. In a scanning electron micrograph, the reversals can be seen on the fibre surface.

2.2.3 Collapse and convolutions

When the fibre dries, the hollow tube collapses a characteristic shape Kassenbeck (1970) pointed out that different parts of the collapsed fibre,

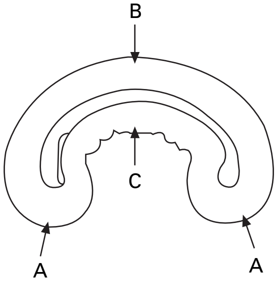


2.2 Representation of the structure of a cotton fibre. From Jeffries *et al.* (1969).

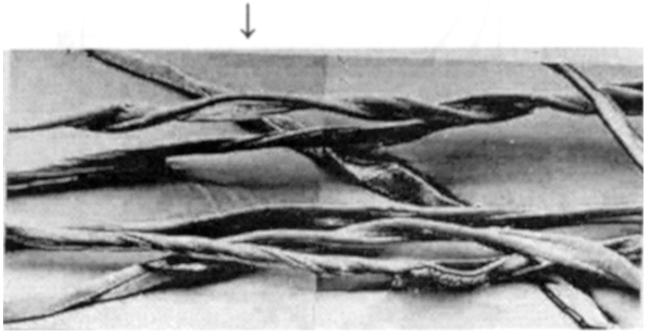
shown in Fig. 2.3, differed in structure. This can be demonstrated by collapsing a roll of adhesive tape. In regions C and N, the structure opens up and is more easily susceptible to chemical attack. In region A, the structure is tightened and, in B, there is little change.

The collapsed fibre is convoluted, as shown in Fig. 2.4. By comparison with the collapse of a twisted rubber tube, Hearle and Sparrow (1979a) showed that this was a natural consequence of the collapse of a helical structure. At intervals along the fibre, there are changes between left-handed and right-handed convolutions. Hearle and Sparrow (1979a) also showed that a cotton fibre without convolutions could be produced by tensioning a wet fibre and then allowing it to dry under tension.

The changes in structure on drying cause cotton fibres to develop crimp, a periodic kinkiness or waviness along the length of the fibre. Foulk and McAlister (2002), in an extensive study of dimensions and properties of three American upland cottons with different finenesses, each divided into seven length groups, used an opto-electrical sensor to measure crimp and report values from 11 to 13 crimps/cm.



2.3 Cotton fibre cross-section. Diagrammatic representation by Kassenbeck (1970) showing regions with differences in structure.



2.4 Convolutions of a cotton fibre. Note reversal of twisting of convolution at ↓. From Hearle and Sparrow (1979a).

2.2.4 Fibre dimensions and density

> Linear density equals mass per unit length, expressed in g/km, which is termed tex.

Cotton fibres range in dimensions from superfine Sea Island cottons with a length of 5 cm and a linear density of 1 dtex to coarse Asiatic cottons of 1.5 cm and 3 dtex. This corresponds to mean linear thicknesses of 10 to 20 μm. Most of the world's crop will be in the middle of the range. The maturity can be defined as the ratio of the area of the cell wall to the area of a circle with the same perimeter, which is equivalent to an uncollapsed fibre, and typically has values around 0.85 for mature fibres. An excess of immature fibres with values less than 0.5 is undesirable. Length, fineness and maturity and their variabilities are important measures of fibre quality, which is covered in Chapter 3. The density of the cell wall of cotton is 1.55 g/cm^3 when dry, 1.52 g/cm^3 at 65% rh and 1.38 g/cm^3 when wet. The effective density will be lower when the lumen is taken into account.

2.2.5 Mercerised and resin-treated cottons

In mercerising treatments in caustic soda or other reagents, the cotton fibre swells and de-swells. The resulting fibres are more nearly circular in cross-section and more lustrous in appearance. During mercerisation, the crystalline structure is disrupted, without complete loss of fibre integrity, to a degree sufficient for recrystallisation to occur in the form of cellulose II with anti-parallel chains. The cellulose II lattice is also found if cotton, or other sources of cellulose, is dissolved and regenerated. The degree of disorder in mercerised cotton as indicated by X-ray diffraction is 49% compared with 29% for unmercerised cotton (Warwicker *et al.*, 1966). The fibrillar structure is probably less well defined and there may be substantial regions of amorphous structure, in contrast to the wholly crystalline fibrillar structure of unmercerised cotton. In resin-treated cottons, the hydroxyl groups on neighbouring fibrils are permanently joined by the covalent groups of the resin.

2.3 Moisture absorption

2.3.1 RH-regain relations

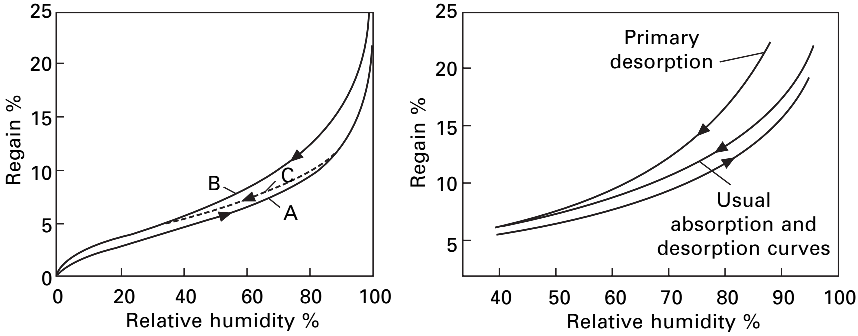
> In the recommended terminology regain – or moisture regain – is the ratio of mass of absorbed water to oven-dry mass of fibre. Moisture content is the ratio of mass of absorbed water to the total fibre mass. Both quantities are usually quoted as percentages (Denton and Daniels, 2002).
>
> As cotton fibres grow, the plant cells have a high concentration of water.

When the boll opens, the fibres lose water to equilibrate with the ambient humidity. The amount of absorbed water then rises and falls with changes in humidity. The maximum absorption at 100% rh or in water never reaches the original value, so that some studies are carried out on never-dried fibres.

The rate of absorption and desorption of water with change of humidity is very fast for an isolated fibre. For fibre assemblies, the changes are much slower and involve interaction between the rate of diffusion of water molecules and the evolution and transmission of heat of sorption. Experimental and theoretical studies by Henry (1939) and others are summarised by Morton and Hearle (1993). Changes are carried on two waves with a final exponential approach to equilibrium. A standard half-change period of 12 hours applies to a slab of cotton fibres 2.5 cm thick, with a density of 0.5 g/cm^3 when dry, at a regain of 7% and a temperature of 18 °C. Ninety-nine per cent of the total change is completed in 14 times the half-change value (one week). The time increases linearly with (volume/ surface area)^2; it increases with package density from 1/6 of standard value at 0.09 g/cm^3 to 1.33 times at 0.7 g/cm^3; it falls from six times the standard value for zero regain, to a minimum of 2/3 at 4% and then rises to five times at 14% regain; it falls from 2.4 times the standard value at 5 °C to 0.4 times at 30 °C. Due to hysteresis, the equilibrium regain is higher when humidity is increased than when humidity is decreased.

Figure 2.5(a) shows a typical rh-regain curve (Urquhart and Eckersall, 1930). Enough time was allowed for equilibrium to be reached at each humidity. The lower curve is for absorption from the dry state; the upper curve is for desorption from 100% rh; the dotted line shows desorption from an intermediate value. As Ashpole (1952) showed for viscose rayon, there are difficulties in making measurements close to 100% rh and the true saturation values may be higher than shown in Fig. 2.5(a). Preston and Nimkar (1952) found that suction of a wet cotton yarn to minus 30 cm of mercury gave a retained regain of 52%, and of 48% after centrifuging at 1000 g for five minutes; however, there is a question of how much water is held by capillary forces and how much is absorbed within the fibre. Figure 2.5(b) shows how the primary desorption curve of cotton from the boll is at a higher regain level down to 40% rh.

Urquhart and Williams (1924) showed that up to about 85% rh, the regain of cotton at a given humidity decreases with rise of temperature from 50 to 110 °C. The reduction increases from 0.9% at 20% rh to 1.8% at 70% rh. At 85% rh, the curves cross over and there is a higher regain at higher temperatures. In a standard atmosphere of 65% rh and 20 °C, the absorption regain of cotton is 7–8%. Hysteresis increases the desorption value by 0.9%. The recommended allowance for calculating the mass of fibre in commercial transactions is 8.5%.



(a) (b)

2.5 (a) Typical regain-rh curve for cotton (soda-boiled). *A*: absorption. *B*: desorption. *C*: intermediate. (b) Primary desorption curve for cotton taken from the boll. From Urquhart and Eckersall (1930).

2.3.2 Heat of sorption

> The [differential] heat of sorption is the heat evolved when one gram of water is absorbed by an infinite mass of material at a given humidity. The heat of wetting [integral heat of sorption] is the heat evolved when a specimen of material, which has a mass of one gram when dry, is completely wetted out.

Table 2.1 gives values of the heat of sorption of cotton, which decreases rapidly from a high value for dry cotton as the starting humidity increases. The upper row are measured values for absorption of liquid water; the lower row is corrected by adding the latent heat of vaporisation of water, 2.45 kJ/g. Values of heat of sorption from the dry state ranging from 1.19 to 1.33 kJ/g have been reported for three different types of cotton (Morton and Hearle, 1993). The corresponding heats of wetting from the dry state ranged from 46.1 to 47.3 kJ/g; other data for various types and methods ranged from 41 to 54 kJ/g (Morton and Hearle, 1993).

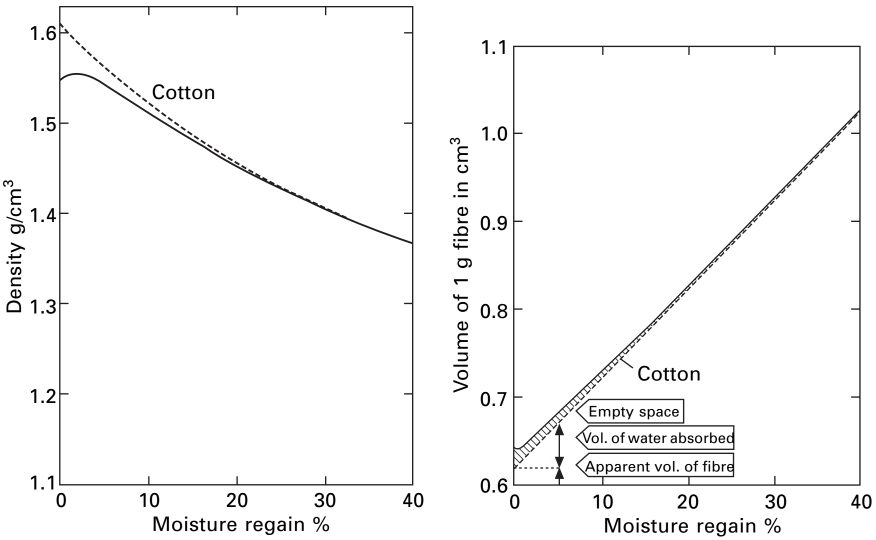
Table 2.1 Variation of heat of sorption of Sea Island cotton with humidity. From Guthrie (1949)

	Relative humidity %				
	0	15	30	45	60
Heat of sorption from liquid water kJ/g	1.24	0.50	0.39	0.32	0.29
Heat of sorption from water vapour kJ/g	3.69	2.95	2.84	2.77	2.74

2.3.3 Swelling

Figure 2.6(a) shows the change of density of cotton with change of regain; in Fig. 2.6(b), this is converted into change in specific volume. Initially from the dry state, there is an increase of density due to water molecules occupying ‘empty space’ within the fibre. The density is a maximum at about 2% regain, and then decreases since the density of water is less than that of fibre. Above 20% regain, the volume increase equals the equivalent volume of liquid water.

The swelling of cotton fibres is predominantly in the transverse direction. Meredith (1953) states that, in going from the dry to the wet state, the increase in length is 1.2% but the increase in diameter is 14%. However, these quantities are difficult to measure because of the lumen, the cross-sectional shape of cotton fibres, and changes in helix angles and twist angle of convolutions as a result of swelling. Preston and Nimkar (1949) checked values from different sources and found values for diameter swelling from dry to wet of 23, 20 and 7%, with area swellings of 42, 41 and 21%. Ibbett and Hsieh (2001) report a diameter swelling of 10–15% with a length contraction of 0–0.5%. The data in Fig. 2.6(b) would give a maximum volume swelling of 63%. This is compatible with a regain of 40%, but implies that the increase of area or length of the fibre material, excluding the lumen, must be greater than indicated by the above values.



(a) (b)

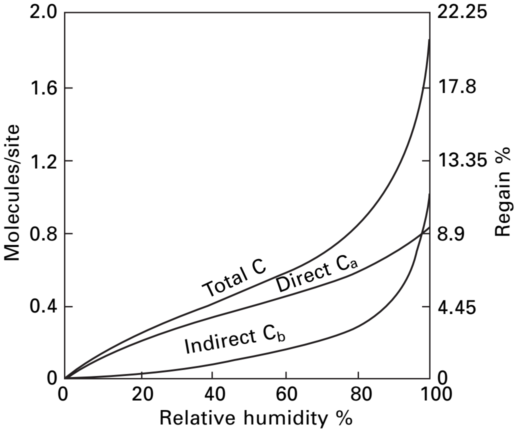
2.6 (a) Change of cotton fibre density with regain. Dotted line is density from mixture law for fibre and water based on high regain values. (b) Recalculated as change of volume. From Meredith (1953).

2.3.4 Structural changes and theoretical models

In the completely dry state, hydrogen bonds will form between those hydroxyl groups that are not already linked within crystalline regions. With the view of the structure described in section 2.2.1, the available hydroxyl groups will be on the surface of the crystalline fibrils. As humidity is increased, water will be attracted to accessible hydroxyl groups. There will be an equilibrium between the free energy of the cellulose/water mixture and the free energy of the water vapour in the atmosphere.

The first water molecules to be absorbed will be directly attached to hydroxyl groups. Later absorption may be on remaining available hydroxyl groups or form secondary layers attached to already absorbed water molecules. As indicated in section 2.3.3, the direct absorption results in more efficient molecular packing and gives an initial increase in density. The later absorption just adds the same volume as that of liquid water. The heat of sorption, as noted in section 2.3.2, is also higher for the initial absorption. At very high humidities, some water will be held by capillary forces. Experimental results suggest that this is significant only above 99% rh, which would correspond to a pore size of 110 nm (Morton and Hearle, 1993).

There have been a number of theories that explain the shape of the regain-rh curve in terms of multilayer absorption. Peirce (1929) presented a simple mechanistic argument. He assumed that there was an equal probability of an added water molecule being absorbed by unoccupied sites and already occupied sites. The experimental regain-rh curve then divides between directly and indirectly absorbed water as shown in Fig. 2.7. If C is the total number of absorbed water molecules per absorption site, which is divided into C_a directly absorbed and C_b indirectly absorbed, the resulting partition is:



2.7 Division between directly and indirectly absorbed water according to Peirce (1929).

$$C_a = 1 - \exp(-C) \quad C_b = C - 1 + \exp(-C) \qquad 2.1$$

He then showed that the torsional rigidity of cotton fibres decreased linearly with C_a, the amount of directly absorbed water.

Peirce postulated that the directly absorbed water, which is more firmly bonded, will make only a small contribution to the vapour pressure p. The indirectly absorbed water is the main controlling factor, with a vapour pressure given by (saturation vapour pressure p_0 × fraction of sites occupied by indirectly absorbed water). In order to fit experimental data, it was necessary to introduce an arbitrary factor ($1/\beta$), which represented the fraction of sites that were accessible to secondary absorption. Peirce justified this by suggesting that one indirectly absorbed water molecule blocks off a number of sites. This leads to the expression:

$$p/p_0 = 1 - \exp(-\beta\, C_b) \qquad 2.2$$

With the addition of a contribution from directly absorbed water reduced by a factor K, the assumption that only a fraction γ of hydroxyl groups are effective in absorption, substitution of the fractional regain r, and taking account of the molecular weights of water and cellulose per hydroxyl group, this gives the following dependence of rh on regain:

$$p/p_0 = 1 - [1 - K(1 - \exp(-3\gamma\, r)]$$
$$\exp\{-\beta\, [\exp(-3\gamma\, r) - 1 + 3\gamma\, r)]\} \qquad 2.3$$

Peirce found a good agreement with an experimental rh-regain relation with $\gamma = 1/3$, $K = 0.4$ and $(1/\beta) = 0.185$.

In several other theoretical treatments, which are discussed by Morton and Hearle (1993), corrections are needed at low or high humidities. Good agreement with experiment is found by Hailwood and Horrobin (1946), who treat the directly absorbed water molecule as a hydrate attached to particular units of the cellulose molecule and the indirectly absorbed water as forming an ideal solid solution.

A different approach to moisture absorption, which was developed by Barkas (1949) in relation to wood, is also relevant to cotton. Barkas, based on the analogy with osmotic pressure, considers that water is absorbed until the stresses generated by swelling prevent more water flowing into the fibres. He used a thermodynamic cycle to derive a differential equation relating directional swelling to directional stresses and moisture absorption. An alternative derivation, which includes a relation between absorption and fibre tension, is given by Hearle (1957); the prediction agreed with absorption by regenerated cellulose fibres under tension as measured by Treloar (1953).

On a purely molecular approach, hysteresis in moisture absorption is explained as a tendency for the structure to resist change in absorption and desorption:

cross-links breaking; water attaching
dry structure with →→→→→→→→→→→→ wet structure with
many cross-links ←←←←←←←←←←← few cross-links
water coming off; cross-links forming

In terms of swelling stresses, hysteresis in moisture absorption results from mechanical hysteresis, which is covered in section 2.4.1.

2.4 Mechanical properties

2.4.1 Tensile stress-strain relations

> For fibres, tensions are best normalised on a mass basis. Specific stress is given in N/tex. On an area basis, conventional stress in GPa equals (specific stress in N/tex × density in g/cm^3). Tenacity is specific stress at break. Modulus is the slope of the specific stress vs. strain curve.

Meredith (1945a) made an extensive study of the tensile properties of cottons available in the middle of the 20th century, which showed the wide range of values in different cottons. Table 2.2 gives data for the strongest, weakest and intermediate strength types. The weaker cottons, such as those grown in India, will now have been replaced by improved varieties. Tensile properties of modern cottons are included in the chapter on fibre quality. Cotton falls in the category of weaker and less extensible general textile fibres. The toughness (work of rupture) values are low, in comparison with many other textile fibres. Generally longer and finer fibres show greater tenacity, which is a measure of strength, and modulus, which is a measure of stiffness. Within a given sample of cotton, Morlier *et al.* (1951) found a rise in tenacity for fibres in increasing length array groups. Timpa and Ramey (1994) found an increase of strength, measured in four laboratories according to HVI standards, from 0.2 to 0.3 N/tex with increasing length from 21.2 mm

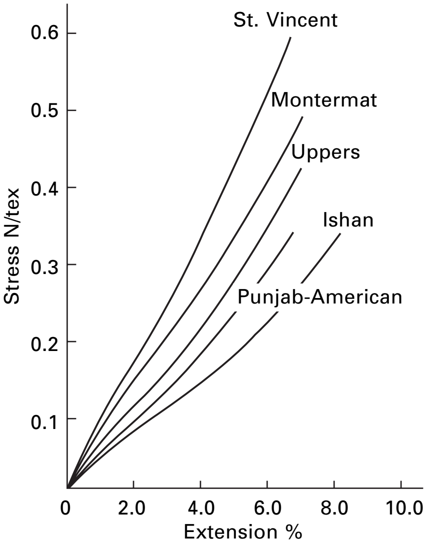
Table 2.2 Tensile properties of cotton at 65% rh, 20 °C. From Meredith's (1945a) set of tests (1 cm test length; 0.9 (N/tex)/min; 50 tests per sample)

	Fineness dtex	Initial modulus N/tex	Tenacity N/tex	Work of rupture mN/tex	Breaking extension %
St Vincent, Sea Island	1.00	7.3	0.452	15.0	6.80
Uppers, American	1.84	5.0	0.323	10.7	7.10
Bengals, Indian	3.24	3.9	0.185	5.0	5.60

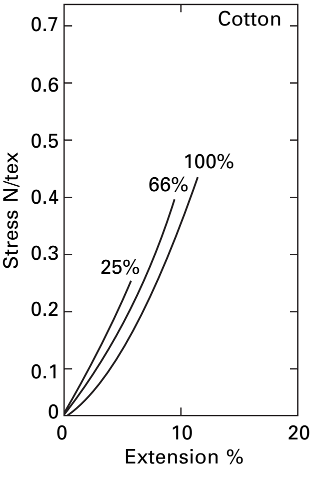
(staple length code: 26) to 32 mm (code: 40); they also found a significant increase of strength with molecular weight, albeit with considerable scatter. Foulk and McAlister (2002) report an extensive study of the tensile properties of cottons with three micronaire values, each subdivided into seven length groups. Meredith (1946) found a correlation between tenacity and birefringence with an increase from 0.2 N/tex at a birefringence of 0.04 to 0.37 N/tex at 0.05. In a later paper Meredith (1951) showed correlation with X-ray orientation angle, which correlates with convolution angle.

Figure 2.8 shows stress-strain curves for various cottons as measured by Sparrow (1973). Stress-strain curves of cotton at increasing humidities, Fig. 2.9, show a reduction of stiffness, but, unlike most fibres, an increase of strength. A technical bulletin from Du Pont (1958) shows stress-strain curves of cotton, both in air and wet, decreasing in stiffness and strength with increase of temperature.

Within a given sample of cotton, there is considerable variability in test results. Liu *et al.* (2005) give histograms of break force and break elongation for five cottons; coefficients of variation are from 37 to 45% for break force and 30 to 44% for break elongation. Hu and Hsieh (1998) give histograms for cotton fibre toughness (work of rupture) with coefficients of variation of 51 to 56% in skewed distribution with a long tail of high values. Variability between fibres leads to lower values of bundle strength than the average of single-fibre strengths. Variability along the test length has a major effect on measured strengths due to the weak-link effect. Table 2.3 shows values



2.8 Stress-strain curves for various cottons, from Sparrow (1973).



2.9 Effect of humidity on stress-strain curves of cotton at 20 °C. From Meredith (1953).

Table 2.3 Effect of test length and variability on tenacity in N/tex tests by Meredith (1946)

	Tenacity 1 cm	Standard deviation 1 cm	Coefficient of variation %	Tenacity 1 mm	Tenacity ratio % (1 cm/1 mm)
St Vincent	0.473	0.136	28.7	0.609	78
Sakel	0.405	0.180	44.4	0.535	76
Uppers	0.288	0.136	47.2	0.477	60
Ishan	0.324	0.093	28.7	0.446	73

obtained by Meredith (1946) for lengths of 1 cm and 1 mm in single-fibre tests. Although the result for Sakel cotton is anomalous, the general trend is for the loss in strength from 1 mm to 1 cm test length to increase with the coefficient of variation of the tenacity test. Data on the reduction of bundle strength with test length for various cottons is given by Brown (1954) and Taylor (1994).

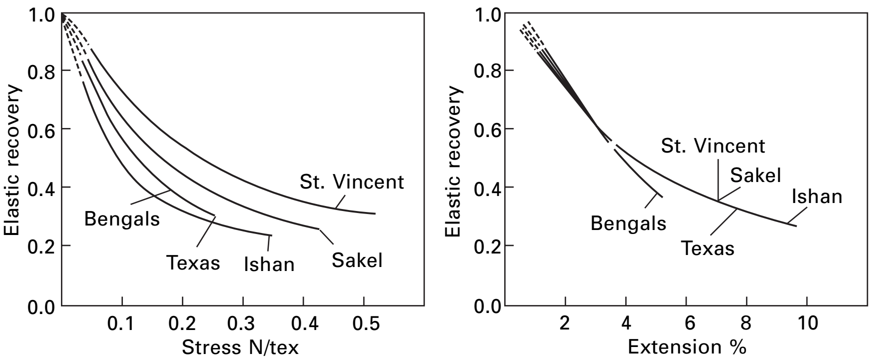
Research at University of California, Davis, has studied the change of strength and structure during fibre development in greenhouse-grown Acala cottons (Hsieh *et al.*, 1995, 1997), *G. hirsutum* and *G. barbadense* (Hsieh *et al.*, 2000), among ovule locations and along fibre lengths (Hsieh and Wang, 2000), and effects of dehydration (Hu and Hsieh, 2001). A study on mature fibres examined the association with seed position and fibre length (Liu *et al.*, 2001).

Hebert (1993) reported that the strength of an immature fibre with only primary wall was one-sixth that of a mature fibre, which is dominated by the thicker secondary wall. The tenacity was just over half that of the mature fibre, reflecting the basket-weave orientation of fibrils in the secondary wall.

2.4.2 Elastic recovery

Even under constant test conditions for a particular cotton fibre, there is not a single-valued relation between stress and strain. In tests to successively higher strains, the recovery curve falls below the elongation curve and the unrecovered extension at zero stress increases with the increase in maximum stress and strain. Figure 2.10 shows the dependence of elastic recovery, which is the ratio of recovered to total extension, as functions of imposed strain and stress respectively. Cyclic tests between strains will show a characteristic hysteresis loop.

The 'permanent' extension left after elongation when dry is reduced or eliminated when the fibre is wetted out due to swelling recovery. This effect is related to the glass transition temperature discussed in section 2.5.3. The increased stiffness and strength and reduced break extension after cotton has

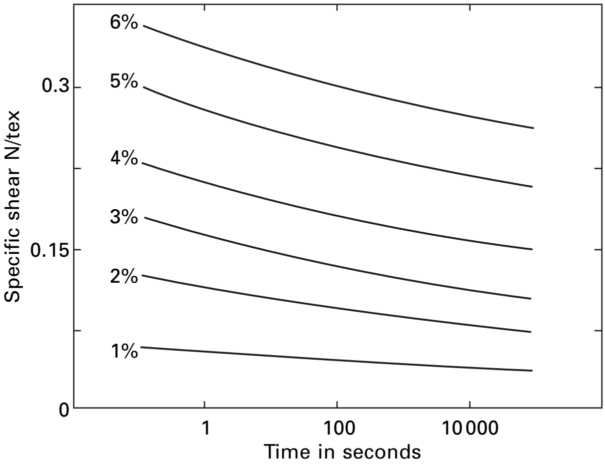


2.10 Elastic recovery of cottons plotted against stress and strain. From Meredith (1945b).

been wetted and dried under tension is discussed in connection with the influence of convolutions in section 2.4.4 (see Table 2.3).

2.4.3 Time effects

Time also affects the behaviour. Figure 2.11 shows the stress relaxation of cotton held at constant length. Roughly the stress decreases by 7% for every tenfold increase in time. Creep in fibres held under tension is the complementary effect. Tests by Collins (1924) and Steinberger (1936) showed that parts of extension-time plots were linear with log(time) though the slope changed somewhat irregularly. In tensile tests, stress levels at given strains rise with



2.11 Stress relaxation of cotton from different extensions at 65% rh, 20 °C, from Meredith (1954).

rate of extension. Meredith (1953) reports that strength of cotton decreases with time according to the equation:

$$F_1 - F_2 = 0.088 \log_{10}(t_2/t_1) \qquad 2.4$$

where F_1 and F_2 are breaking loads after times t_1 and t_2 under load.

2.4.4 Directional effects

There is only limited published data on the twisting and bending properties of cotton. For a linear-elastic rod, the flexural rigidity (bending moment per unit curvature) is proportional to the fourth power of the radius and, in terms of linear density T, specific modulus E and density ρ in consistent units, equals $(\eta ET^2/4\pi\rho)$ where η is a shape factor, which is dependent on distance from the neutral plane and is 1 for a circle. In order to eliminate the direct effect of linear density, a specific flexural rigidity in units of tex and g/cm^3 as $[(\eta E/4\pi\rho) \times 10^{-3}]$ N mm^2/tex^2 is used. Owen (1965), using a double-pendulum method, found a specific flexural rigidity for cotton of 0.53 mN mm^2/tex^2. There are complications:

- It is difficult to determine η for cotton, because of the irregular shape of the fibre.
- Due to the ribbon-like form, cotton fibres will tend to twist in such a way as to bend perpendicularly to the greater width.
- Although there is no specific information for cotton, oriented molecular structures yield more easily in compression than in tension. Consequently the neutral plane moves towards the inside of a bend and, when this yielding occurs, the bending stiffness falls below that given by the linear-elastic case.

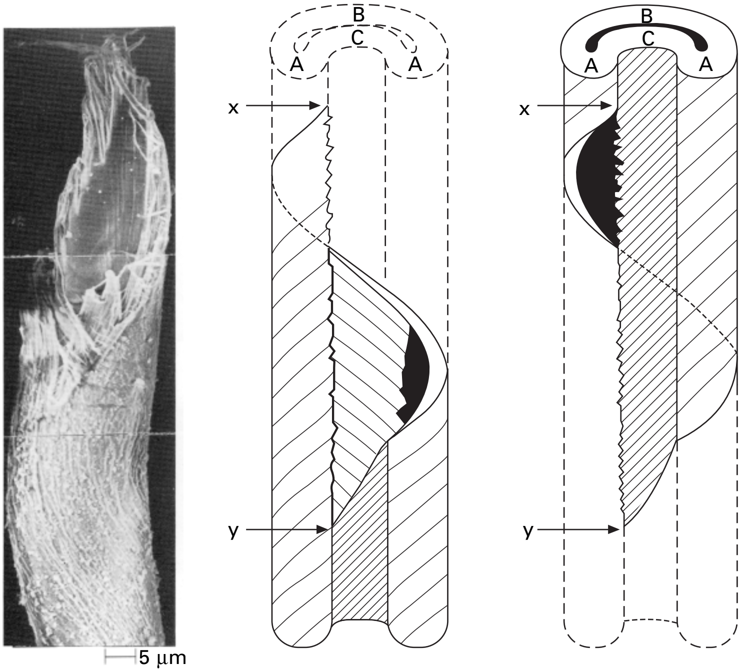
Another effect of bending is that loop and knot strengths are less than those for straight fibres. Bohringer and Schieber (1948) found that knot strength of cotton was 91% of tensile strength.

At low twist levels, torsional rigidity follows similar relations to flexural rigidity, except that shear modulus replaces tensile modulus and the shape factor ε is dependent on distance from the centre of the fibre. Owen (1965), using a double-pendulum method, found a specific torsional rigidity of 0.16 mN mm^2/tex^2 for cotton. The ratio of shear modulus to tensile modulus is given by Morton and Hearle (1993) as 0.27. At high twist levels, the increase in length of the outer levels of the fibre means that there is a large influence of tensile modulus on torsional rigidity. The breaking twist angle for cotton was found by Koch (1949) to be 34 to 37°. Dent and Hearle (1960) found that the strength of cotton fibres twisted at constant length fell from 0.34 N/tex at zero twist to near zero at a twist factor of 110 tex$^{1/2}$/cm. There was a corresponding contraction in fibre length and reduction in breaking extension.

By testing fibre bundles in shear, Finlayson (1947) estimated that the shear strength of cotton was 35% of the tensile strength. Maxwell *et al.* (2003) used atomic force microscopy to determine the hardness of the secondary wall of cotton. Penetration into a cross-section increased markedly above 70% r.h. They interpreted the reduction in hardness as being due to a glass transition.

2.4.5 Fracture and fatigue

The form of tensile fracture of cotton fibres depends on the state of the fibre (Hearle and Sparrow, 1971, 1979d). At 65% rh, the form is shown in Fig. 2.12(a), which is diagrammatically drawn in Fig. 2.12(b). Similar forms are found in mercerised cotton. Some reports have suggested that the reversal is a point of weakness, where break occurs. A closer study indicates that breaks are adjacent to reversals. The form of break is a consequence of the changes due to collapse of the fibre on drying, which were discussed in section 2.2.3 and illustrated in Fig. 2.4. There is a line of weakness at the boundary between zones A and C, which is where break starts. Under tension, there is an untwisting at reversal points, as further discussed in section 2.4.6, which



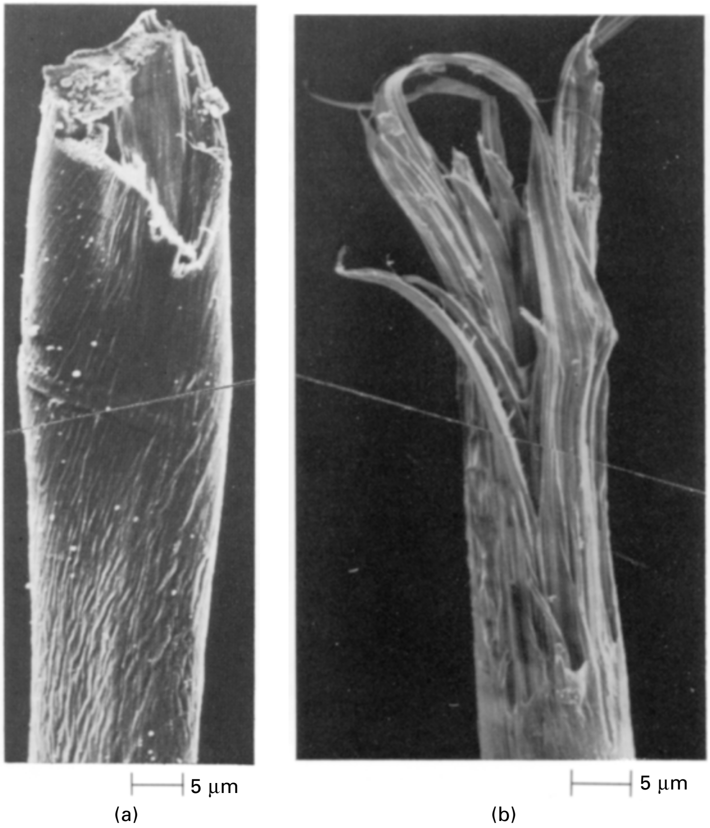
(a) (b)

2.12 (a) Scanning electron micrograph of break of cotton. (b) Schematic of form of break of cotton. From Hearle *et al.* (1998).

gives rise to shear stresses. A crack develops and runs round the fibre following the lower bonding between fibrils until it reaches the line of weakness and tears across zone C.

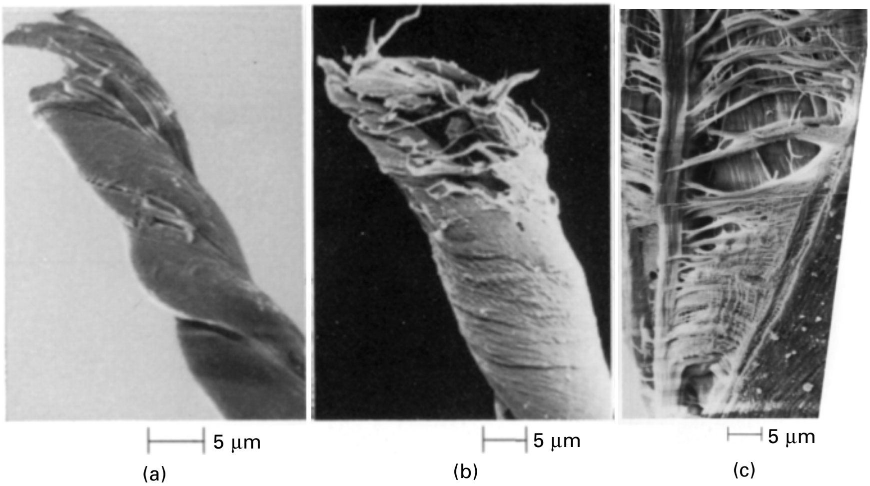
In resin-treated cotton at 65% rh, Fig. 2.13(a), and in raw cotton at zero humidity, there is a granular break, which is typical of fibres with a fibrillar structure. The axial splitting of Fig. 2.12 is resisted due to the stronger interfibrillar bonding between fibrils by covalent bonds in the treated fibre and hydrogen bonds in the dry fibre. The boding is weaker in wet resin-treated cotton, which shows breaks similar to Fig. 2.12. For wet raw cotton, the links between fibrils are weaker still. There is no cooperative effect and the fibrils break individually, Fig. 2.13(b).

Twist breaks of cotton show axial splitting with a sharp tear-off at the end, Fig. 2.14(a), (b). Tensile fatigue (Hearle and Sparrow, 1979c) results in extensive splitting between fibrils before failure, Fig. 2.14(c). Biaxial rotation fatigue gave failure with considerable splitting, but tests give a large scatter



(a) (b)

2.13 (a) Break of resin-treated cotton at 65% rh. (b) Break of wet mercerised cotton. From Hearle *et al.* (1998).



2.14 (a) Twist break of raw cotton. (b) Twist break of mercerised cotton. (c) Axial splitting due to tensile fatigue. From Hearle *et al.* (1998).

of lifetimes due to the concentration of the test on a short fibre length and complications from the shape of cotton fibres and the reversals along their length. Chauhan *et al.* (1980) report distributions for lifetimes in flex fatigue in bending over a bar. SEM views of wear for a range of products (Hearle *et al.* 1998) show that the common form of damage is multiple splitting. The cause of the splitting is twisting and bending as a result of the forces exerted on fabrics in use or in laundering. It eventually leads to wearing of holes in the fabric or to weakness that allows the fabric to be easily torn.

2.4.6 Structural mechanics

The moderately high strength and extensibility of cotton, which make it a good textile fibre, is a result of a number of structural features. The treatment in this section follows a model by Hearle and Sparrow (1979b). The easiest mode of extension of a cotton fibre results from untwisting of the convolutions. Timoshenko (1957) gives an expression for the contraction of a thin rectangular strip on twisting. The converse of this, which was confirmed by Hearle and Sparrow (1979a) with tests of a nylon strip heat-set in a twisted form, is that a ribbon of width b and twist φ would extend by ε_c, equal to $(\varphi^2 b^2/24)$, when fully untwisted. In terms of convolution angle ω_0, the extension is $(\tan^2 \omega_0)/6$. Cotton fibres have varying ω_0 along their length, unequal lengths of S and Z twist, some fibres more circular than others, and some fibres in a wrapped-ribbon instead of twisted form. The ideal expression is replaced by ε_c equals $(X \tan^2 \omega_0)$, where X takes account of the anomalies. Although there is considerable scatter in extensions, values of X between 0.5 and 1 give agreement with experiment.

The role of convolutions is supported by two observations (Hearle and Sparrow, 1979a). First, when a cotton fibre was extended in a scanning electron microscope, the convolutions are gradually removed. The ribbon was partially untwisted at 3.8% extension and fully untwisted at 6.8%; break was at 7.4%. Second, when wet cotton fibres were tensioned at two grams for five minutes and then held while being allowed to dry, optical microscopy showed that the convolutions had been removed; they are set in an extended state, which would be released on wetting. The stress-strain curves of these fibres showed less curvature, with a mean modulus about three times higher. Table 2.4 compares mean properties before and after the treatment.

The above discussion does not introduce the effect of stress in pulling out convolutions. When the convolution angle is reduced from ω_0 to ω, the strain ε is $X(\tan^2 \omega_0 - \tan^2 \omega)$. An approximate energy analysis by Hearle and Sparrow (1979b) then gives the following expression for stress f at increasing values of extension ε:

$$f = K\{[\tan \omega_0/(\tan^2 \omega_0 - \varepsilon/X)^{1/2}] - 1\} \qquad 2.5$$

where $K = (g\, A\, S/\pi\, b^2\, X)$ and g is a shape factor, A is area of cross-section, and S is shear modulus. Data on fibre dimensions and torsional properties indicate a value for K of 180 MPa, but values can be expected to vary widely for different cottons. Plots of stress against deconvolution strain with K = 200 and $\omega = 14°$ are markedly concave upwards. The curves become more concave with decreasing values of K and increasing values of ω.

The second influence on the extensibility of cotton is the basic helical arrangement of the fibrils. The simplest approximation indicates that the helix angle reduces the strain in fibrils by $\cos^2 \theta$ and the contribution to stress by $\cos^2 \theta$. Stiffness and strength would be proportional to the mean value of $\cos^4 \theta$. In cotton, the helix angle changes little from a value of 22° with distance from the centre of the fibre; this would give a reduction of 0.74 compared to a fibre with axially oriented fibrils.

Table 2.4 Properties of three fibre types before and after wetting and drying under tension. From Sparrow (1973)

Fibre type	Permanent extension %	Break extension %		Break load g	
		Before	After	Before	After
Deltapine	11.4	11.1	3.6	4.7	6.8
Menoufi	7.0	8.2	4.9	5.7	8.4
Acala 1517	5.8	7.0	3.5	4.6	7.4

A more exact analysis follows the mechanics of twisted yarn mechanics (Hearle, 1980; Thwaites, 1980). For small strains, geometrical analysis shows that fibril extension ε_f is given in terms of fibre extension ε by:

$$\varepsilon_f = \varepsilon\ (\cos^2\theta - \sigma \sin^2\theta) \tag{2.6}$$

Lateral contraction reduces the extension and consequently the Poisson's ratio σ, which is probably close to 0.5, is introduced in eqn 2.6. Furthermore, the change in helix angle leads to shear. (In twisted yarn mechanics, this is ignored because it is assumed that fibres can slide past one another, but within a cotton fibre the fibrils are hydrogen-bonded together.) The shear strain β is given by:

$$\beta = -\varepsilon\ (1 + \sigma)\ (\sin\theta \cos\theta) \tag{2.7}$$

Hence the total strain energy U per unit volume (or mass if specific quantities are used) is given by:

$$U = {}^1/_2\ \varepsilon^2\ [E_f\ (\cos^2\theta - \sigma \sin^2\theta)^2 + S_f\,(1 + \sigma)^2\ (\sin\theta \cos\theta)^2] \tag{2.8}$$

Differentiation gives stress f as a function of strain ε.

However, there is another important difference from treatments of yarn mechanics. Rotation at the reversal points will reduce the helix angle and cause extension. The system is thus equivalent to a twisted yarn that is free to untwist under tension. The fractional rotation is put equal to $(-\gamma\varepsilon)$. This leads to changes in the expression for tensile and shear strains. The full energy expression is given by[1]:

$$\begin{aligned} U = {}^1/_2\ \varepsilon^2\ \{&E_f\ [\cos^2\theta - (\gamma + \sigma)\sin^2\theta]^2 \\ &+ S_f\,(1 + \gamma + \sigma)^2\ (\sin\theta \cos\theta)^2\} \end{aligned} \tag{2.9}$$

The value of γ, determined by energy minimisation, $[\mathrm{d}U/\mathrm{d}\gamma = 0]$, is given by:

$$\gamma = [(E_f - S_f)\cos^2\theta/(E_f \sin^2\theta + S_f \cos^2\theta)] - {}^1/_2 \tag{2.10}$$

Substitution shows that the fibre modulus E, which is the term in { } in eqn 2.9, is given by:

$$E = E_f\ S_f \cos^2\theta/(E_f \sin^2\theta + S_f \cos^2\theta) \tag{2.11}$$

The final input to the prediction of the stress-strain curve of cotton consists of the values of the tensile modulus, E_f, of the fibrils, which will depend on covalent bonding along cellulose crystals, and the shear modulus S_f, which will depend on intermolecular bonding. Treloar (1960) calculated E_f to be

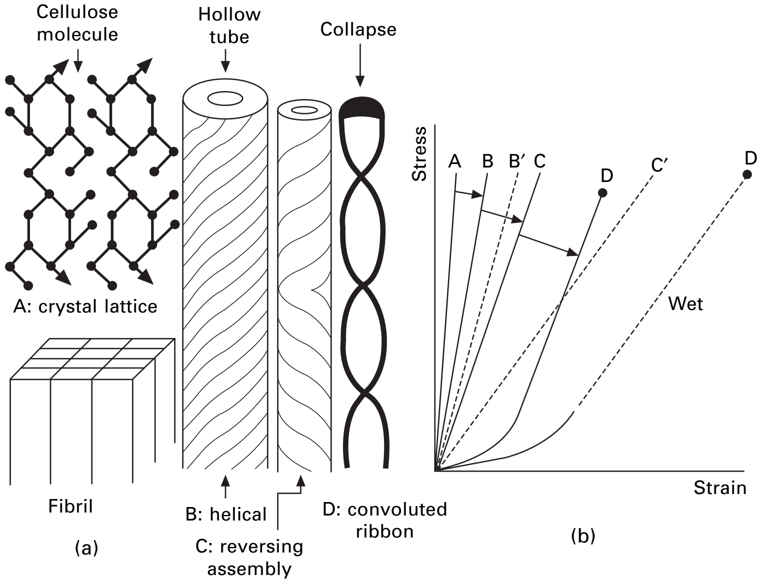
---

[1] The full analysis by Hearle and Sparrow (1979b) includes a volume energy term, but energy minimisation shows surprisingly that the extension is at constant volume with $\sigma = {}^1/_2$.

57 GPa, and Jawson *et al.* (1968) calculated values between 36 and 67.2 MPa for S_f. Taking the higher value for S_f, eqn 2.11 gives a modulus of 24 GPa for an unconvoluted fibre with a helix angle of 22°. This agrees well with extrapolation of Meredith's (1946) experimental data to zero convolution angle. If we take a typical value of 5 N/tex, which is equivalent to 7.5 GPa, and multiply it by the threefold increase from untreated cotton to cotton tensioned wet and dried, we have a value of 22.5 GPa.

The above discussion relates to dry fibres in which there will be fairly strong hydrogen-bonding between fibrils. In wet cotton, absorbed water will lower the shear modulus. This reduces the resistance to untwisting of convolutions and lowers the shear modulus acting in both the extension of the helical structure and the rotation at reversals.

There are many uncertainties resulting from the complexity of variability, shape and internal structure of cotton, but the treatment outlined here explains the mechanisms involved in the extension of cotton fibres in terms of a reasonable quantitative model. This is summarised in Fig. 2.15 in the reverse order to the above presentation. The modulus of the crystal lattice in the fibrils (A) gives the line A, which is then lowered due to the helical structure (B) and the reversals (C). The convolutions (D) bring in the nonlinearity. For wet fibres the lower shear modulus shifts the lines to B′, C′, D′.



2.15 (a) Structural features of cotton, which determine the tensile properties. (b) Stress-strain plots. Line A is for extension of crystal lattice, lowered to B due to helical structure, to C by untwisting of reversals and to D by pulling out convolutions. The dotted lines are for wet cotton. From Hearle (1991).

The increase in strength with increase of moisture content is due to the release of internal stresses as the hydrogen-bonding is weakened and to the ability to pull the structure into a more highly oriented form without generating stress concentrations. The existence of internal stresses is confirmed by Perel (1990), who found that the apparent crystallite size in the (0,0,1) direction increased from measurements at 20% rh to those at 90% rh.

2.5 Other physical properties

2.5.1 Electrical properties

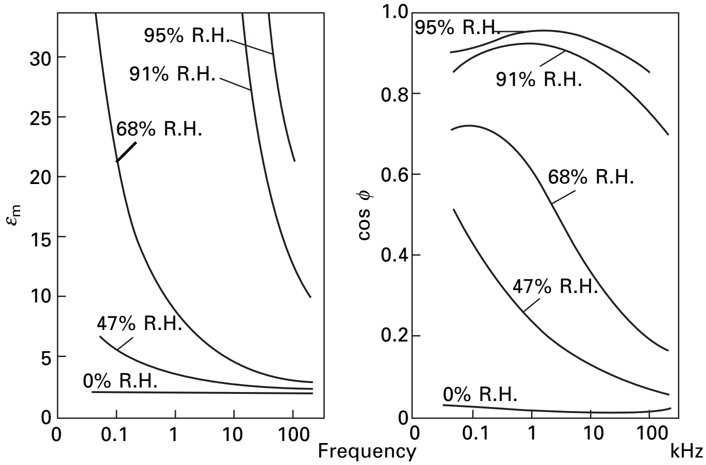
For many fibres, static electrification is the electrical property of most concern but, as shown below, the electrical conductivity of cotton is high enough to dissipate the charge rapidly except at extremely low humidities. Static electricity is not a problem for cotton. For moisture-absorbing fibres such as cotton, conductivity is by movement of charged ions. Salts, which are naturally present in the fibre, increase their degree of dissociation with increase in dielectric constant, thus increasing the number of ions available to transport electric charges. Hearle (1953d) showed that this led to the following relation between electric resistance R and dielectric constant (permittivity) κ:

$$\log R = a/\kappa + b \qquad 2.12$$

where a is proportional to the energy of dissociation with $\kappa = 1$ and inversely proportional to temperature, and b depends on the concentration and valency of available ions.

The above relation fits experimental data well except at very high humidities, when dissociation is complete. Interestingly, salts with bivalent ions do not dissociate so easily and consequently replacement by calcium sulphate increases the resistance. A more detailed account of experimental and theoretical aspects of dielectric properties, resistance and static electrification of fibres is given in Morton and Hearle (1993).

In practice, it is only possible to measure the dielectric properties of an assembly of fibres, which is a mixture with air. Hearle (1954) made measurements on cotton yarns wound on a cone. An outer cone was pressed on to give a packing factor of about 45%. Figure 2.16 shows values of the dielectric constant ε_m and power factor cos φ of the air-cotton mixture. At the lower frequencies, there is a rapid rise in dielectric constant, which is alternatively termed *relative permittivity*, and power factor with humidity. The changes are not as great at lower frequencies. The dielectric constant decreases with frequency and this trend continues in other experiments at frequencies in the megacycle range (Hearle, 1956). Except for some data at low humidity and low frequency, power factor decreases with increase of frequency. When plotted against moisture content M, dielectric constant



2.16 Dielectric properties of cotton yarns between cones at a packing factor of 45%. From Hearle (1954).

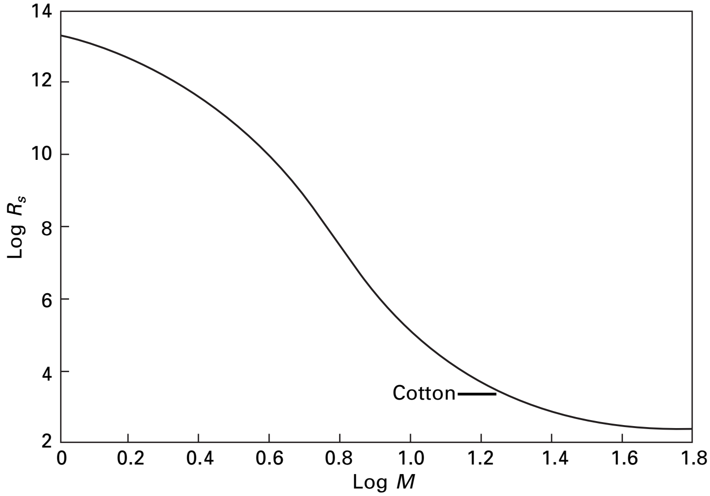
rises rapidly above $M = 4\%$ and power factor shows a sigmoidal relation similar to that found for electrical conductivity.

Electrical conductivity was measured by Hearle (1953a) on multiple ends of yarn held between bulldog clips. The results were presented in terms of 'mass specific resistance', which in consistent units equals the conventional specific resistance in (ohm m) multiplied by density in kg/m^3. In practice, values of R_s are expressed in ohm g/cm^2. Figure 2.17 shows the change of resistance with moisture content. The use of a log-log scale is partly because of the many orders of magnitude of change of resistance and partly because, over the important middle range between 30% and 90% rh, there is a linear relation between log R_s and log M. With constants n and K, this gives the equation:

$$\log R_s = -n \log M + \log K \quad \text{or} \quad R_s M^n = K \tag{2.13}$$

If M is expressed as a percentage, the values for cotton are $n = 11.4$ and log $K = 16.7$. The high value of the index n reflects the great effect of moisture on electrical resistance, as dissociation of ions increases exponentially in its dependence on dielectric constant.

Cotton shows a linear decrease in log R_s with relative humidity from a specific resistance of 10^{11} ohm g/cm^2 at 10% rh to 10^6 ohm g/cm^2 at 80% rh. Static electrification becomes a serious problem only for values > 10^{10} ohm g/cm^2 (about 30% rh for cotton), so, in this context of high voltages and low charges, cotton is a 'good conductor'. However, the resistance is high enough for cotton to be an effective insulator. Until the middle of the 20th century, when better plastic insulators became available, electric wires were commonly wrapped in cotton, though steps were taken to increase resistance by reducing ion content.



2.17 Change of mass specific resistance Rs of cotton with moisture content M%. Note that M = 7% (65% rh) is at log M = 0.85, close to the middle of the graph. The maximum value of 1.8 is at M = 63%: a high moisture content with water molecules effectively free. From Hearle (1953a).

Purification of cotton can increase resistance by five times; addition of salts lowers resistance, for example by 180 times for 10% of added potassium chloride (Hearle, 1953a). The electrical resistance of cotton decreases about 100 times between 20 °C and 80 °C (Hearle, 1953b). The electrical conductivity of cotton is non-linear, increasing rapidly for voltages below 50 V; this and other complicating factors are reported by Hearle (1953c).

2.5.2 Optical properties

Fundamentally, optical properties are electrical properties at very high frequencies. Refractive index is a measure of polarisability and depends on the orientation of polarisable groups, mainly the –OH groups, in the cellulose molecules. Birefringence is the difference between axial refractive index n_1 and transverse refractive index n_2. The calculated isotropic refractive index is n_{iso}. Table 2.5 gives values of refractive indices measured by Meredith (1946). The calculated isotropic refractive index is n_{iso}. The birefringence decreases with increase in spiral angle, but as discussed in section 2.2.3 this is an average value of the fibril helix angles increased by the effect of convolutions, which cause the main difference between cotton fibre types. The increase in birefringence is due to decreases in n_1. The small scatter of values of n_2 and n_{iso} is probably due to experimental error.

Measurements of regenerated cellulose by Hermans (1949) showed that, after a small increase from 0 to 5% regain, n_2 decreased from 1.534 to 1.508

Table 2.5 Refractive indices and birefringence of cotton related to spiral angle (Meredith, 1946)

Cotton type	Refractive indices			Birefringence	Spiral angle θ
	n_1	n_2	n_{iso}		
St Vincent	1.581	1.530	1.556	0.052	27°
Giza	1.579	1.530	1.554	0.049	29°
Sakel	1.580	1.532	1.556	0.048	29°
Montserrat	1.578	1.529	1.553	0.049	30°
Punj-Amer	1.577	1.530	1.553	0.047	31°
Uppers	1.576	1.530	1.554	0.046	32°
Uganda	1.576	1.532	1.554	0.044	32°
Memphis	1.575	1.532	1.554	0.044	33°
Texas	1.575	1.532	1.554	0.044	33°
Tanguis	1.575	1.530	1.554	0.044	34°
Brazilian	1.574	1.531	1.552	0.044	34°
Oomras	1.574	1.532	1.552	0.043	34°
Bengals	1.574	1.531	1.551	0.043	34°

at 20% regain with little change in birefringence. A similar reduction in n_2 with increased moisture absorption would be expected in cotton, but the birefringence will be affected by the change in helical structure and convolutions due to swelling.

The lustre of cotton fibres is strongly influenced by their ellipticity, *a/b* where *a* and *b* represent equatorial and polar fibre x-section radii respectively Adderley (1924) examined ten cotton types and found that the lustre in arbitrary units ranged from 5.7 for an American cotton with $a/b = 3.07$ to 10.7 for a Sea Island cotton with $a/b = 1.91$. The correlation was not perfect for intermediate values and this may be due to differences in convolutions. A rounder mercerised cotton with $a/b = 1.47$ gave a lustre of 13.9.

2.5.3 Thermal properties

Values for various thermal properties of cotton are reported in the literature. The specific heat of dry cotton is 1.21 J g^{-1} K^{-1} (Magee *et al.*, 1947). However, as discussed in section 2.3.2, the effective specific heat of cotton will be dominated by the heat of absorption as the moisture content changes with temperature. The thermal conductivity of a pad of cotton with a bulk density of 0.5 g/cm^3, i.e., a packing factor of 1/3, is 71 mW m^{-1} K^{-1} (Rees, 1946), which is 2.8 times that of still air. The coefficient of expansion of cotton is 4×10^{-4} K^{-1} (Morton and Hearle, 1993). Cotton does not melt, but decomposes by charring with loss of water at about 200 °C with increased burning to carbon dioxide at higher temperatures. Illingworth (1953) reported that at 100 °C cotton lost 8% of its strength after 20 days and 32% after 80 days; at 130 °C, the losses were 62% and 90%.

As in all polymers, there are secondary transitions, which may be called glass-to-rubber transitions, at temperatures below the notional melting-point when thermal vibrations would disrupt the crystals if decomposition had not intervened. Increase of temperature causes a drop in elastic modulus and a peak in the dissipation factor tan δ. For dry cotton, Meredith (1969) found that tan δ in dynamic bending tests on mercerised cotton was a minimum at about 40 °C. Tan δ was increasing towards one peak at less than –50 °C, which would be due to the loss of rotational and flexural mobility in some covalent bonds, most likely the oxygen bridges, in amorphous regions of mercerised cotton. The effect may not be present in more perfectly crystalline, unmercerised cotton. Going to higher temperatures, there is a small shoulder at about 125 °C and continuing rise to what would be a peak above 170 °C. This change is ascribed to increased mobility at hydrogen bonds. A similar effect was found by van der Meer (1970, 1974) for viscose rayon, who also observed that the peak fell below 0 °C when the fibre was wet. Increased mobility and a low transition temperature would also be expected in wet cotton. The change from above to below the transition temperature when cotton dries is a cause of creasing and wrinkling after laundering.

2.5.4 Friction

The frictional properties of fibres are determined by the state of the fibre surface. In raw cotton there are natural waxes on the surface that may be removed by washing and bleaching. Other finishes may be added to improve processing or to enhance performance in use. Furthermore, the simple laws of friction are not obeyed; the coefficient of friction varies with normal load, form and area of contact, and speed and direction of rubbing. Reported values of coefficient of friction thus vary widely. Table 2.6 gives typical values for the coefficient of friction μ of cotton.

Buckle and Pollitt (1948) measured friction for a coarse grey (unbleached) cotton yarn over stainless steel of radius 0.75 in (19 mm) at standard conditions of 79 yd/min (72 m/min), 25 g initial tension, 70 °F (21 °C) and 65% rh.

Table 2.6 Values for coefficient of friction μ of cotton

System	μ	Reference
Cotton on cotton		
Crossed fibres	0.29, 0.57	Mercer and Makinson (1947)
Parallel fibres	0.22	Morton and Hearle (1993)
Cotton passing over guides		
Hard steel	0.29	Buckle and Pollitt (1948)
Porcelain	0.32	Buckle and Pollitt (1948)
Fibre pulley	0.23	Buckle and Pollitt (1948)
Ceramic	0.24	Buckle and Pollitt (1948)

Increasing speed increased the coefficient of friction from 0.159 at 1.9 yd/min (1.7 m/min) to 0.279 at 120 yd/min (110 m/min). On a finer cotton yarn at 67 yd/min (61 m/min), the coefficient of friction fell from 0.30 at 25 g initial tension to 0.245 at 250 g.

Morrow (1931) found that the coefficient of friction of cotton on steel increases from 0.24 at 0% regain to 0.36 at 11% regain. This can be explained by the increased softening of the fibre, which leads to more intimate contact. Theory indicates that frictional force is proportional to shear strength × area of contact. If contact results from plastic yielding this leads to proportionality to (normal load)^n, where n is between 0.5 and 0.75 depending on the contact geometry. El Mogahzy and Broughton (1993) describe experimental and theoretical studies of the effect of number of contacts in fibre/fibre and fibre/metal contacts. In general, one can say that the coefficient of friction of cotton is highly dependent on the state of the fibre and the test conditions.

2.6 Sources of further information

The great period for the study of cotton structure and properties started around 1920 with the formation of the British Cotton Industry Research Association, which grew to several hundred staff. Later the Textile Research Institute was founded in the USA and the United States Department of Agriculture did a great deal of work on cotton in their New Orleans laboratory. Other laboratories in Europe and India were also active. The National Cotton Council in USA and the International Institute for Cotton in Europe supported research. This period of major research activity ended by about 1980.

Consequently, the major source of information on physical structure and properties of cotton is found in research papers from this early period, particularly those in the *Journal of The Textile Institute* and the *Textile Research Journal*. Books from the same period are another source of information, notably *Matthews' Textile Fibers* (Mauersberger, 1954), Meredith's (1956) *The Mechanical Properties of Textile Fibres* and the chapter by Bailey *et al.* (1963) in *Fibre Structure*. More specialised books are *Moisture in Textiles* (Hearle and Peters, 1960) and *Friction in Textiles* (Howell *et al.*, 1959). More general aspects of physical structure and properties are covered in *Physical Properties of Textile Fibres* (Morton and Hearle, 1993). The review by Warwicker *et al.* (1966), of which about a quarter is directly relevant to this chapter, contains 1484 references.

Finally, one should mention a pioneer in the field, the botanist, W. L. Balls who, after working on cotton growing in Egypt, became research director of a UK spinning company; his *Studies of Quality in Cotton* (1928) still provides valuable insights and information.

2.7 Future trends

The physical structure and properties of cotton have been thoroughly researched. Experimental studies will continue to characterise the properties of particular cottons depending on their type and growth location and conditions. The major new feature is the advent of genetic engineering. To date, this has been used to improve yields and resistance to pests. It has not been used, so far as I know, to modify fibre properties – and conventional breeding has been limited to the more obvious characteristics of length, fineness, colour and strength.

Genetic engineering gives the opportunity to design cottons with properties optimised for particular markets, including new features with special market opportunities. However, if molecular biologists are not to introduce genes at random, it will be necessary to develop a thorough understanding of the sequence: genes → growth of fibre → fibre structure → fibre properties → performance in processing and use. In the context of this chapter, the need is to convert the generic analysis described in section 2.4.6 into a model that can input the structural differences between different cottons. The model would be validated by measurements on current cottons and then used to explore new variants. The model would also need to be developed to include other properties that influence performance, particularly bending and twisting of fibres. The effects of moisture absorption and chemical treatments on structure and properties would also have to be covered. This is a challenging research opportunity, but should be possible with current computer power.

2.8 References

Adderley A (1924), 'The physical causes of the luster in cotton', *J Textile Inst*, **15**, T195–206.

Ashpole D K (1952), 'The moisture relations of textile fibres at high humidity', *Proc Roy Soc*, **A212**, 112–123.

Bailey T L W, Tripp V M and Moore A T (1963), Cotton and other vegetable fibres, in Hearle J W S and Peters R H, *Fibre structure*, Manchester, The Textile Institute, 422–454.

Balls W L (1928), *Studies of quality in cotton,* London, Macmillan.

Barkas W W (1949), *The swelling of wood under stress*, London, HMSO.

Bohringer H and Schieber W (1948), cited by Schiefer H F, Fourt L and Kropf R, 'Textile testing in Germany. Part II. Serviceability evaluation of textiles', *Textile Res J*, **18**, 18–38.

Boylston E K and Hebert J J (1995), 'The primary wall of cotton fibres', *Textile Res J*, **65**, 429–431.

Brown H M (1954), 'Correlation of yarn strength with fiber strength measured at different gauge lengths', *Textile Res J*, **24**, 251–260.

Buckle H and Pollitt J (1948), 'An instrument for measuring the coefficient of friction of yarns against other materials', *J Textile Inst*, **39**, T199–210.

Chauhan R S, Shah N M and Dweltz N E (1980). 'The flexural bending fatigue of single cotton fibres', *J Textile Inst*, **71**, 18–29.

Collins G E (1924), 'The stress-strain relations of cotton hairs', *J Textile Inst*, **15**, T519–528.

Dent R W and Hearle J W S (1960), 'The tensile properties of twisted single fibres', *Textile Res J*, **30**, 805–826.

Denton M J and Daniels P N (2002), *Textile terms and definitions*, 11th edition, Manchester, The Textile Institute.

Du Pont (1958), *Technical Bulletin X-82,* Wilmington, Delaware, E I du Pont de Nemours & Co Inc.

El Mogahzy Y E and Broughton R M (1993), 'A new approach for evaluating the frictional behaviour of cotton fibers', *Textile Res J*, **63**, 465–475.

Finlayson D (1947), 'The shear strength of fibres and filaments', *J Textile Inst*, **38**, T50–53.

Foulk J A and McAlister D D (2002), 'Single cotton fibre properties of low, ideal and high micronaire values', *Textile Res J*, **72**, 885–891.

French A D (1985) 'Physical and theoretical methods for determining the supramolecular structure of cellulose', in Nevell T P and Zeronian S H, *Cellulose chemistry and its applications*, Chichester, Ellis Horwood Ltd.

Goynes W R, Ingber B F and Triplett B A (1995), 'Cotton fibre secondary wall development – time versus thickness', *Textile Res J*, **65**, 400–408.

Guthrie J C (1949) 'The integral and differential heats of sorption of water by cellulose', *J Textile Inst*, **40**, T489–504.

Hailwood A J and Horrobin S (1946), 'Absorption of water by polymers: analysis in terms of a simple model', *Trans Faraday Soc*, **42B**, 84–102.

Hearle J W S (1953a), 'The electrical resistance of textile materials. Part I. The influence of moisture content', *J Textile Inst*, **44**, T117–143.

Hearle J W S (1953b), 'The electrical resistance of textile materials. Part II. The effect of temperature', *J Textile Inst*, **44**, T144–154.

Hearle J W S (1953c), 'The electrical resistance of textile materials. Part III. Miscellaneous effects', *J Textile Inst*, **44**, T155–176.

Hearle J W S (1953d), 'The electrical resistance of textile materials. Part IV. Theory', *J Textile Inst*, **44**, T177–198.

Hearle J W S (1954), 'Capacity, dielectric constant and power factor of fiber assemblies', *Textile Res J*, **24**, 307–321.

Hearle J W S (1956), 'The dielectric properties of fiber assemblies', *Textile Res J*, **26**, 108–111.

Hearle J W S (1957), Thermodynamic relations among stresses, deformation and moisture absorption, *Textile Res J*, **27**, 940–945.

Hearle J W S (1980), 'The mechanics of dense fibre assemblies', in Hearle J W S, Thwaites J J and Amirbayat J, editors, *Mechanics of flexible fibre assemblies*, Alphen aan den Rijn, Sijthoff & Noordhoff, 51–86.

Hearle J W S (1991), 'Understanding and control of textile fibre structure', *J Appl Polymer Science*: *Appl Polymer Symp*, **47**, 1–31.

Hearle J W S and Peters R H (1960), editors, *Moisture in textiles*, Manchester, the Textile Institute.

Hearle J W S and Sparrow J T (1971), 'The fractography of cotton', *Textile Res J*, **41**, 736–749.

Hearle J W S and Sparrow J T (1979a), 'Mechanics of the extension of cotton fibres. I. Experimental studies of the effect of convolutions', *J Appl Polymer Sci*, **24**, 1465–1477.

Hearle J W S and Sparrow J T (1979b), 'Mechanics of the extension of cotton fibres. II. Theoretical modelling', *J Appl Polymer Sci*, **24**, 1857–1874.

Hearle J W S and Sparrow J T (1979c), 'Tensile fatigue of cotton fibers', *Textile Res J*, **49**, 242–243.

Hearle J W S and Sparrow J T (1979d), 'Further studies of the fractography of cotton', *Textile Res J*, **49**, 268–282.

Hearle J W S, Lomas B and Cooke W D (1998), *Atlas of fibre fracture and damage to textiles,* Cambridge, Woodhead Publishing.

Hebert J J (1993), 'Strength of the primary wall of cotton', *Textile Res J*, **63**, 695.

Hebert J J, Geardina R, Mitcham D and Rollins M L (1970), 'The effect of convolutions in orientation measurement of cotton fibres', *Textile Res J*, **40**, 126–129.

Henry P S H (1939), 'Cotton bales: uptake of water', *Proc Roy Soc*, **A171**, 215–241.

Hermans P H (1949), *Physics and chemistry of cellulose fibres,* Amsterdam, Elsevier, pages 214 *et seq*.

Howell H G, Miezkis K W and Tabor D (1959), *Friction in textiles*, Manchester, The Textile Institute.

Hsieh Y-L and Wang A (2000), 'Single fiber strength variations of developing cotton fibers: among ovule locations and along the fiber length', *Textile Res J*, **70**, 495–501.

Hsieh Y-L, Honik E and Hartzell M M (1995), 'A developmental study of single fiber strength: greenhouse grown SJ-2 Acala cotton', *Textile Res J*, **65**, 101–112.

Hsieh Y-L, Hu X-P and Nguyen A (1997), 'Strength and crystalline structure of developing Acala cotton', *Textile Res J*, **67**, 529–536.

Hsieh Y-L, Hu X-P and Wang A (2000), 'Single fiber strength variations of developing cotton fibers – strength and structure of *G. hirsutum* and *G. barbadense*', *Textile Res J*, **70**, 682–690.

Hu X-P and Hsieh Y-L (1998), 'Distributions of single-fiber toughness', *J Textile Inst*, **39**, Part 1, 457–467.

Hu X-P and Hsieh Y-L (2001), 'Effects of dehydration on the crystalline structure and strength of developing cotton fibres', *Textile Res J*, **71**, 231–239.

Ibbett R N and Hsieh Y-L (2001), 'Effect of swelling on the structure of Lyocell fabrics', *Textile Res J*, **71**, 164–173.

Illingworth J W (1953), 'Yarns and fabrics in the rubber industry', *J Textile Inst*, **44**, P328–346.

Jawson M A, Giles P P and Mark R E (1968), 'The elastic constants of crystalline native cellulose', *Proc Roy Soc,* **A306**, 389–412.

Jeffries R, Jones D M, Roberts J G, Selby K, Simmens S C and Warwicker J O (1969), 'Current ideas on the structure of cotton', *Cellulose Chem Technol*, **3**, 255–274.

Kassenbeck P (1970), 'Bilateral structure of cotton fibers as revealed by enzymatic degradation', *Textile Res J*, **40**, 330–354.

Koch P-A (1949), 'Textile fibres: angle of twist to rupture', *Textil-Rundschau*, **4**, 199–211.

Liu J, Yang H and Hsieh Y-L (2001), 'Variations of mature cotton fiber tensile properties: association with seed position and fibre length', *Textile Res J*, **71**, 1079–1086.

Liu J, Yang H and Hsieh Y-L (2005), 'Distribution of single fibre tensile properties of four cotton genotypes', *Textile Res J*, **75**, 117–122.

Magee F C, Portas H J and Wakeham H (1947), 'Moisture in textile fibres: calorimetric investigations', *J Amer Chem Soc*, **69**, 1896–1902.

Mauersberger H R editor (1954), *Matthews' Textile Fibers*, 6th edition, New York, John Wiley.

Maxwell J M, Gordon S G and Huson M G (2003), 'Internal structure of mature and immature cotton fibers revealed by scanning probe microscopy', *Textile Res J*, **73**, 1005–1012.

Mercer E H and Makinson K R (1947), 'The frictional properties of wool and other textile fibres', *J Textile Inst*, **38**, T227–240.

Meredith R (1945a), 'The tensile behaviour of raw cotton and other textile fibres', *J Textile Inst*, **36**, T107–130.

Meredith R (1945b), 'A comparison of the tensile elasticity of some textile fibres', *J Textile Inst*, **36**, T147–164.

Meredith R (1946), 'Molecular orientation and the tensile properties of cotton fibres', *J Textile Inst*, **37**, T205–218.

Meredith R (1951), 'Cotton fibre tensile strength and X-ray orientation', *J Textile Inst*, **42**, T291–299.

Meredith R (1953), 'Properties depending on the amorphous regions of fibres', in Preston J M, editor, *Fibre Science,* 2nd edition, The Textile Institute, Manchester, 236–262.

Meredith R (1954), 'Relaxation of stress in stretched cellulose fibres', *J Textile Inst*, **45**, T438–461.

Meredith R editor (1956), *The Mechanical Properties of Textile Fibres*, Amsterdam, North-Holland Publishing Company.

Meredith R (1969), 'Dynamic mechanical properties of textile fibres' *Proc Fifth Int Congress in Rheology,* Tokyo, University of Tokyo Press, Vol **1**, 43–60.

Meyer K H and Misch L (1937), 'Cellulose: crystal structure', *Helv Chim Acta*, **20**, 232–244.

Morlier O W, Orr R S and Grant J N (1951), 'The relation of length to other physical properties of cotton fibres', *Textile Res J*, **21**, 6–13.

Morosoff M and Ingram P (1970), 'The spiral angle of cotton', *Textile Res J*, **40**, 250–255.

Morrow J A (1931), 'The frictional properties of cotton materials', *J Textile Inst*, **22**, T425–440.

Morton W E and Hearle J W S (1993), *Physical Properties of Textile Fibres*, Manchester, The Textile Institute.

Owen J D (1965) 'The application of Searle's single and double pendulum methods to single fibre rigidity measurements', *J Textile Inst*, **56**, T329–339.

Peirce F T (1929), 'A two-phase theory of the absorption of water vapour by cellulose', *J Textile Inst*, **20**, T133–150.

Perel J (1990), 'An X-ray study of regain-dependent deformation in cotton crystallites', *J Textile Inst*, **81**, 241–244.

Preston J M and Nimkar M V (1949), 'Measuring the swelling of fibres in water', *J Textile Inst*, **40**, P674–688.

Preston J M and Nimkar M V (1952), 'Capillary phenomena in assemblies of fibres', *J Textile Inst*, **43**, T402–422.

Price J B, Cui X, Calamari T A and McDaniel R G (2001), 'Assessing the quality of four naturally colored cottons', *Textile Res J*, **71**, 993–999.

Rees W H (1946), 'The protective value of clothing', *J Textile Inst*, **37**, P132–153.

Rouselle M-A (2002), 'Determining the molecular weight distribution of cotton cellulose: a new GPC solvent', *Textile Res J*, **72**, 131–134.

Sarko A and Muggli R (1974), 'Packing analysis of carbohydrates and polysaccharides. III *Valonia* cellulose and cellulose II', *Macromolecules*, **7**, 486–494.

Sparrow J T (1973), *The fracture of cotton*, PhD thesis, University of Manchester.

Steinberger R L (1936), 'Cotton hair: creep under load; effect of humidity', *Textile Res J*, **6**, 325–330.

Taylor R A (1994), *The true strength of HVI bundles. Part B: Stelometer and reference measurements*, ITMF HVI Working Group Meeting, Bremen.

Thwaites J J (1980), 'A continuum model for yarn mechanics', in Hearle J W S, Thwaites J J and Amirbayat J, editors, *Mechanics of flexible fibre assemblies*, Alphen aan den Rijn, Sijthoff & Noordhoff, 87–98.

Timoshenko S (1957), S*trength of materials*, Part II, New York, Van Nostrand, page 259.

Timpa J D and Ramey H H (1994), 'Relationship between cotton fibre strength and cellulose molecular weight distribution: HVI standards', *Textile Res J*, **64**, 537–562.

Treloar L R G (1953), 'The absorption of water by cellulose and its dependence on applied stress', *Trans Faraday Soc*, **49**, 816–823.

Treloar L R G (1960), 'Calculations of elastic moduli of polymer crystals. III. Cellulose', *Polymer*, **1**, 290–303.

Urquhart A R and Eckersall N (1930), 'The moisture relations of cotton. vii – A study of hysteresis', *J Textile Inst*, **21**, T499–510.

Urquhart A R and Williams A M (1924), 'The moisture relations of cotton. The taking up of water by raw and soda-boiled cotton at 20 °C', *J Textile Inst*, **15**, T138–143.

van der Meer S J (1970), *The dynamic mechanical properties of fibres*, Doctoral thesis, Delft University of Technology.

van der Meer S J (1974), 'The dynamic mechanical properties of yarns in water and the critical washing temperature of fabrics', *J Textile Inst*, **65**, 288–292.

Warwicker J G, Jeffries R, Colbran R L and Robinson R N (1966), *A review of the literature on the effect of caustic soda and other swelling agents on the fine structure of cotton*, Manchester, The Cotton Silk and Man-Made Fibres Research Association.

3

Cotton fibre quality

S GORDON, CSIRO Textile and Fibre Technology, Australia

3.1 Introduction

Measures of cotton fibre quality may be described by any of, or in relation to, the chemical and/or physical properties described in Chapters 1 and 2. The reason for attributing value to cotton is to gain premiums (or discounts) from the market on the basis of that cotton's suitability for particular end-uses. In fact it can be said that cotton fibre quality is the utility particular cotton achieves in the textile processes involved in its conversion to the final product. Traditionally, the most desirable cotton (*Gossypium spp.*) is said to be as white as snow, as strong as steel, as fine as silk and as long as wool.[1] As well as this, spinners also demand that the fibre be inexpensive.[2] This chapter discusses the fibre properties defined and valued by the textile industry; how these properties are currently measured, and the limitations of the test methods applied to measure each property. For the most part the fibre properties discussed in this chapter are closely linked to the physical and chemical properties already discussed in Chapters 1 and 2, however each of the parameters discussed in this chapter has a large effect on yarn and fabric quality and processing efficiency, and as such, are be used routinely in combination with other parameters to predict the expected quality of the yarn or fabric and the efficiency with which it is produced.

Fibre quality properties, e.g. length, strength, fineness and colour have always been important in determining the value of cotton fibre. These properties and others are measured soon after the cotton is ginned to determine the market value of the cotton, and to reward (or discount) growers for the quality they have grown. Until 50 years ago a sample of cotton taken from the ginned bale was classed against physical cotton standards by a human cotton classer. Comparison with physical standards, whether those of the United States Department of Agriculture (USDA) Agricultural Marketing Service (AMS), to which there are over 20 signatory cotton associations from around the world, or other national country standards, is still the predominant method for measuring the value of cotton fibre. However, there is currently active organization from within the international cotton industry to promote objective test measurement of important fibre parameters.[3]

The stimulus to determine cotton fibre quality by more accurate and precise objective means is not only based on technical considerations of predicting spinning efficiency and product quality from measured fibre properties more accurately; it is also based on the cost and risk of using cotton as a natural raw material. Raw material costs in a spinning mill comprise up to 65% of mill operating costs. Further, the advocacy for objective testing is also about competition in the world short-staple fibre market and keeping cotton competitive with synthetic fibres such as polyester, which are less variable in nature and more predictable in terms of processing behavior.

For the three short-staple spinning systems used by the cotton textile industry today, i.e. ring-spinning, rotor (or open-end) spinning and air-jet spinning, the fibre properties listed in Table 3.1 are considered especially important. In combination, the listed parameters describe fibres that are sufficiently flexible to accommodate the continuous arrangement and bending of fibers during drafting and consolidation; and which also have optimum surface adhesion to allow smooth drafting.

3.1.1 Cotton classing

Subjective classing by hand and eye with the help of physical reference standards has been the predominant method of grading cotton fibre quality since cotton trading began. Establishment of formal cotton classification standards occurred in the United States after the 1907 International Cotton Congress at a time when the commercial trade of raw cotton and fabrics made from cotton yarns reached significant volumes.[4] Even at the time it was recognized that cotton destined for the manufacture of textiles for household and clothing products, demanded the development of measurements for predicting yarn and fabric attributes. The first cotton classification standards for fibre colour and length grades were established in 1909 by the USDA. The standards for colour were, at first, based on physical samples that exhibited a range of colour. Cotton fibre length was judged by a human cotton classer using a manual technique that involved pulling fibres away from small bundles into a spread of fibres from which the fibre length, or staple length as it is still known, could be determined.

Table 3.1 Major fibre parameters of importance in short-staple spinning systems

Importance rank	Ring	Rotor (open-end)	Air-jet (inc. MVS)
1	Length	Strength	Length
2	Strength	Fineness	Trash
3	Fineness	Length	Fineness
4		Trash	Strength

A Universal Cotton Standards Agreement was established in 1923 between the USDA and 23 other cotton associations from 21 countries.[4] Since this time other cotton nations have developed their own official cotton standards and descriptions, e.g. the Tanzanian Cotton Board (TCB) has developed physical standards based on colour, trash and preparation, good preparation of which is essentially the smooth appearance of the fibre after combing in the lint cleaning process. The USDA Universal Cotton Standards now cover strength, length, uniformity index, micronaire, colour grade, and procedures used to achieve agreement.

3.1.2 Development of instrument test methods

Anderson[5] defined three distinct phases in the development of fibre measurement methods; the first being subjectively based hand and eye perceptions, the second phase from 1920 to 1948, which utilized direct, more objective tests, e.g. microscopes, scales and comb sorters, and the third phase from 1950 to 1970, which arose from industry demand for quicker objective test methods. The high volume instrument (HVI) lines used today (Fig. 3.1) evolved during this period as textile mills installed high-speed manufacturing equipment that places additional stresses on the raw fibres. These instrument-based methods, which except for strength measurements made using a strain gauge, measured fibre properties indirectly via light meters, air-flow meters, pressure gauges and capacitors.

The second and third phases defined by Anderson[5] are actually less distinct as the Fibrograph and Micronaire, two instruments still used today to assess fibre quality, were developed during the 1940s. After 1980, increases in computing power and the development of digital sensors and robotic systems enabled a cotton sample to be measured for multiple properties in less than a minute. Today, one HVI line measures 825 samples for length, length uniformity, short fibre content (SFC), strength, extension, micronaire and colour in a seven-hour, 20-minute shift.[6] Since 1980 there has also been the development of test instruments to measure other important fibre properties such as stickiness, fineness and maturity, and the distribution of fibre properties such as length and trash.

3.2 Length properties

Cotton fibre length is probably the most significant fibre property because it directly affects irregularity of fibre assemblies and longer lengths contribute to the tenacity of yarn via increased frictional forces with adjacent fibres. The presence of short fibre in cotton causes appreciable increases in processing wastes, excessively uneven fibre assemblies, less efficient spinning, and weaker yarns. Cotton is the shortest commercial textile fibre and as such a

3.1 Modern high volume instrument (HVI) lines (photo courtesy of Australian Classing Services, Wee Waa, Australia).

premium is typically paid for long fibre. However, no premium is paid for cotton with good uniformity of length, but nor is a discount applied to cotton with high SFC.

Fibre length is a genetic trait and varies considerably across different cotton species and varieties. Length and length distribution are also affected by agronomic and environmental factors during fibre development, and mechanical processes at and after harvest. Gin damage to fibre length is known to be dependent upon variety, seed moisture, temperature (applied in the gin) and field exposure.[7–9] The distribution pattern of length in hand-harvested and hand-ginned samples is markedly different from samples that have been mechanically harvested and ginned; two processes that result in the breakage of fibres. Cotton that is mechanically harvested and ginned is likely to have an extended tail of shorter fibres or even an additional peak, bi-modal distribution, at shorter lengths.

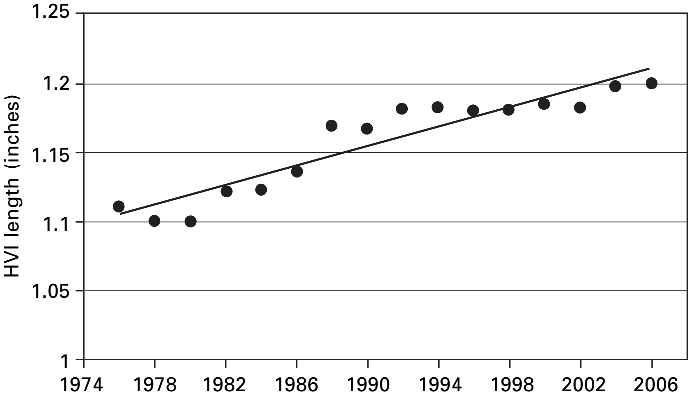
Fibres from a single seed reveal different distribution patterns depending on the region of the cotton-seed that the fibre is taken from. Delanghe[10] found markedly different patterns in fibres taken from the micropylar (upper pointed end), middle and chalazal (bottom rounded end) regions of the cotton-seed, whilst Vincke *et al.*[11] found mean fibre lengths were shortest in the micropylar region of *Gossipyium hirsutum*, *G. barbadense* and *G. arboreum* cottons. Bradow and Davidonis[1] and May[12] reviewed the environmental and genetic factors respectively that effect length and other fibre parameters.

The selected studies they reviewed showed length to be affected by temperature,[13–16] water supply[17,18] and light.[19] Selective plant breeding has resulted in increases in 'staple' length[20] (Fig. 3.2).

Upland cotton varieties (*G. hirsutum*), which represent 90% of the world's cotton production have staple lengths typically ranging from 1 (25.4 mm) to $1^1/_8$ inches (28.6 mm). Fibre lengths of Upland cotton have increased over the last 20 to 30 years with new Upland varieties extending this range currently to $1^1/_4$ inches (32 mm). Pima-type cotton (*G. barbadense*), which includes 'Sea Island' and 'Egyptian' long staple (LS) and extra-long staple (ELS) type cotton and represents around 8% of the world's production, are longer and finer than Upland cotton. The staple length of *G. barbadense* cottons typically ranges from $1^1/_4$ (32 mm) to 2 inches (50.8 mm). Fibre from other cotton plant species such as *G. Arboreum* and *G. Herbaceum* is produced in small quantities (< 2%), and typically have very short, coarse fibre with staple lengths ranging only to 1 inch (25.4 mm).

3.2.1 Measuring fibre length

Fibre length is defined usually as the upper-half mean length (UHML) or 2.5% span length (2.5%SL) from a Fibrogram beard. Both measures coincide in a roundabout way with the classer's staple. Historically, fibre length is measured in inches (in 1/32-inch divisions) although conversion into millimetres is now common. There are various methods of measuring fibre length. Length can be measured simply by aligning the end length of a fibre against a ruler and noting its length. However, this approach is tedious and cotton fibres in any sample vary considerably in their length such that measuring a representative sample in this way is impractical. In the past cotton classers were trained to evaluate 'staple' length by measuring the length of a paralleled bunch of fibres



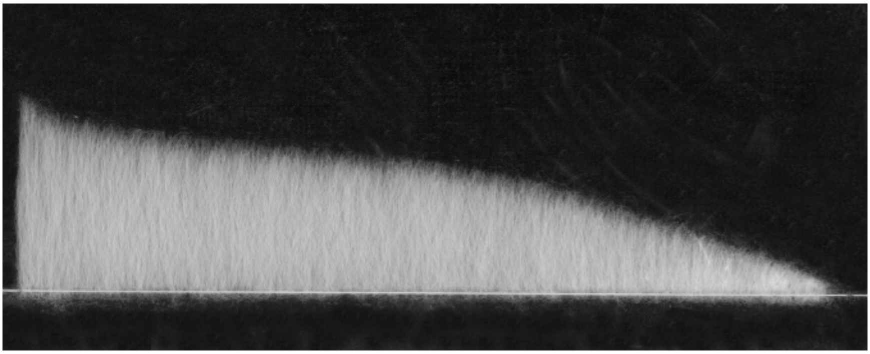
3.2 Improvement in Upland HVI staple length (UHML) [20].

against one of their digits. The Textile Institute definition of staple length noted that 'the staple length corresponds very closely to the modal or most frequent length of the fibres when measured in a straightened condition'.[21]

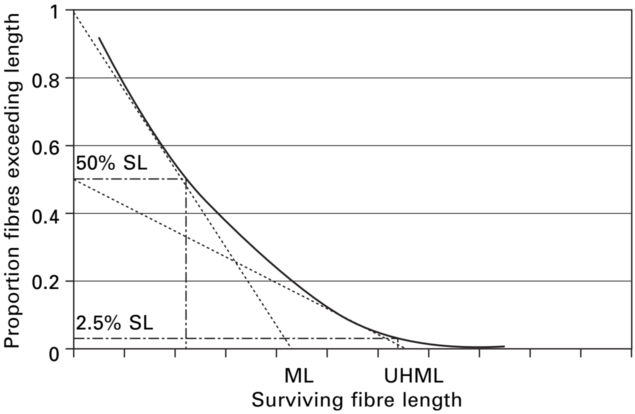
Accurate determination of fibre length can be achieved using fibre arrays or staple diagrams (Fig. 3.3) produced using a comb-sorter apparatus. The diagrams can be used to define upper staple lengths such as the upper-quartile length (UQL), which is the length of the shortest fibre in the upper quarter of the length distribution by weight, and other length parameters such as mean length, 'effective' length and SFC.[22,23] Comb-sorter apparatus uses a series of hinged combs separated at 1/8-inch intervals, to align, separate and allow the withdrawal and description of weight-length or number-length groups from a sample.

Whilst comb-sorter methods are accurate they are unacceptably expensive in terms of operator cost, too slow and too imprecise for routine testing for commercial trading purposes. To this end the Fibrograph Tester instrument was developed in the early 1940s by Hertel.[24] Initially used as a stand-alone instrument it was later incorporated into HVI lines. Test specimens are fibre beards prepared either manually for stand-alone and older HVI instruments, or automatically from a bale sample by newer HVI units. The fibre beard is held in a comb that is inserted into the instrument and scanned by a light source. The variation in density (light intensity) of the different lengths of fibre is recorded and reproduced in the form of a length-frequency curve called a Fibrogram (Fig. 3.4). Interpretation of the Fibrogram takes into account the comb gauge length, i.e., the depth of the comb at which fibres are held (0.25 inch).

Two different kinds of fibre length measurement can be generated from a Fibrogram; mean lengths and span lengths. Mean lengths, e.g. UHML, which is the mean length by numbers of the longer half (50%) of the fibre by weight,[25] and the mean length (ML) are more commonly used since they



3.3 Comb-sorter staple array of ginned cotton (CSIRO Textile and Fibre Technology, Belmont, Australia).



3.4 Fibrogram showing position of mean (ML and UHML) and span length (2.5% SL and 50% SL) measurements.

relate the mean of percentages of fibres represented in the Fibrogram. Span lengths, which came about as a result of a technical shortcoming in the ability of the first digital Fibrograph to graphically run a tangent to the Fibrogram, represent fibre extension distances, e.g. the 2.5%SL represents the distance the longest 2.5% of fibres extend from the comb.

Proponents of the Fibrograph make the point that the fibre beard scanned to produce the Fibrogram expresses a fibre length distribution comparable to the situation, during the processing of fibre into yarn, at any instant of time, of fibres caught and protruding from draft rollers or aprons. It is this relationship, some say, which makes the Fibrogram information superior to comb-sorter arrays. However, others note that fibres held in the Fibrograph comb are less parallel in arrangement than fibres found in sliver and yarn assemblies. Further, fibres in the comb are caught randomly along their length and there is a high probability, dependent upon fibre length, that the ends protruding from the comb represent the same fibre curled around one or two teeth of the comb. Much work has been undertaken in the past to relate comb-sorter measurements to Fibrogram measurements in order to provide calibration material for the Fibrograph. However, although significant correlations have been obtained on some data sets,[26] the relationships between the two are never perfect since the fibre assemblies are never the same and each measures or senses different parameters.[5] Further, specimen selection for Fibrograph analysis tends to be length and weight biased, i.e. longer fibres tend to be selected by the Fibrosampler comb and in describing length on weight basis the heavier longer fibres are accentuated in the distribution.

Other currently used methods for measuring fibre length include the Uster Advanced Fibre Information System (AFIS) length and diameter module, which yields information on single fibre length and is able to build and report length by number and by weight distributions. The AFIS is also calibrated to measure fineness and maturity, neps and trash and dust. Measurement is based on detecting the amount of light that is scattered and occluded by a fibre or particle as it is transported by air through a beam of near-infra-red light. When the fibre or particle impinges on the beam the electro-optical sensor records two signals, i.e. scattered and occluded light. A computer program analyzes the signals and presents mean and distribution data on the particular parameter. The AFIS takes a 0.5 gram sample of fibre hand-drawn into a 25 cm sliver. Test time is around three minutes including sample preparation, which limits the test to laboratory analyses rather than commercial testing. Further, results are influenced by operator technique in preparing samples.

Cotton length measurements using the Peyer Almeter AL-101 system are less frequently reported. This instrument, a version of which is widely used to test wool fibre length, is less common in cotton testing because of speed and sample preparation issues. The measurement is based on a scanning light measurement like the Fibrograph but is able to return a staple diagram by number on the basis that the fibre ends of the sample are aligned during the test. Using an estimate of the sample weight allows the AL-101 to calculate length characteristics according to three length distribution types; unbiased distributions by number, weight-biased and a length-weight span length distribution.[27] The Premier aQura is a new cotton test instrument that automates sample preparation and measures length from an end aligned sample in the same way as the AL-101.

3.2.2 Length uniformity

Length uniformity is generally defined as either the uniformity index[27] (UNI), which is the ratio between the ML and the UHML expressed as a percentage, or the uniformity ratio (UNR), which is the ratio generally between the 2.5%SL and the 50%SL.[28] Table 3.2 lists the descriptive designations given to HVI generated values of uniformity index by the USDA AMS.[29] Inter-laboratory coefficients of variation (CV) for UNI are good; across a range of different cottons tested as part of the Bremen Round Trials between 2003 and 2005, inter-lab CVs ranged between 0.67% and 1.09%.[30]

3.2.3 Short fibre content

The most common definition of short fibre content (SFC) is the proportion by weight of fibre shorter than one half inch (12.7 mm). The value is of concern to textile manufacturers because it relates directly to the amount of waste extracted in combing and cotton with high values has a detrimental effect on the quality of yarn and fabric.[31–33] Short fibre content measured by

Table 3.2 USDA descriptive designation for HVI uniformity index values

Descriptive designation	HVI uniformity index
Very high	Above 85
High	83 to 85
Average	80 to 82
Low	77 to 79
Very low	Below 77

the HVI is referred to as short fibre index (SFI) and is the most widely used value to describe SFC in a sample, even though short fibres are not actually measured directly by the HVI Fibrograph, nor can the instrument be calibrated. Typical SFI values vary from 4–12% in ginned lint and are much lower in un-ginned lint. Precision is generally poor by comparison with test methods for other properties. Inter-laboratory CVs for SFI across a range of different cottons tested as part of the Bremen Round Trials between 2003 and 2005 ranged between 15.8% and 24%.[30]

Accuracy of the measure of HVI SFI is debatable. Calibration and selection of appropriate predictors are the main issues. In the past, SFI has been calculated from Fibrogram data using first-order algorithms that used measures such as 2.5%SL and 50%SL and the 2.5%SL and the uniformity index[34] as independent variables. More recently SFI in HVI lines has been predicted using second-order algorithms containing HVI length and uniformity index[35] (see eqn 3.1). The author notes that because these length measures are functions of the fibre-length distribution they will work well only for cotton exposed to similar picking and gin practices. Currently, a SFI value determined by an algorithm, which calculates the fibre array curve from the Fibrogram, is being tested. From this a weight-based length distribution is derived from which the percentage of short fibres at one-half inch is calculated. The mathematical basis for the conversion algorithms is described in reviews by Woo[36] and Zeidman and Batra.[37] The relationship between SFI measured this way and SFC measured by the AFIS is reasonable with a correlation of 0.96 quoted for a series of standard cottons with different staple lengths.[38]

$$Z = a + bX + cX + dX^2 + eY^2 + fXY \qquad 3.1$$

where
Z = predicted short fibre index,
X = HVI length,
Y = Uniformity Index,
$a = 384.3966$, $b = -120.3791$, $c = -6.7003$, $d = 12.4901$, $e = 0.02957$ and $f = 1.0306$

As well as the issue of repeatability in the SFC measurement, much debate is currently centred on the definition of SFC; the view held is that the one-half inch definition is inadequate given that spinning machinery is largely adjusted to accommodate the proportion of longer fibres, synonymous with the standard measures of staple length. The argument for changing the one-half inch benchmark is that for a given amount of fibre damage short-staple cotton will show a higher percentage of short fibres than longer staple cotton. One inch staple fibre is not necessarily unfortunate if processing equipment, i.e. draft zones have been set up for this length fibre. Short fibre content is therefore a relative number that should be minimized as a proportion of the measured long or effective length so that problems associated with uncontrolled fibres can be avoided. Heap[39] proposed a measure of relative SFC, defined as the percentage of fibres by weight shorter than one-half of the staple length (or UHML).

Kearny-Robert *et al.*[40] proposed and illustrated the concept of the broken fibre content (BFC), which they propose would be a more accurate measure of SFC, since the term allows for separation of inherent SFC from 'phenotypic' SFC. El-Moghazy and Krifa[41] define the length utilization efficiency (LUE) expressed as the ratio between the percentage of fibres longer than an upper threshold, of nominally one inch, and those shorter than a lower threshold, nominally a half inch, although its value at these thresholds had yet to be determined.

3.3 Transverse properties

Cotton fibres are single elongated plant cells and their growth from the cotton seed epidermis is determined largely by the environmental conditions. A mature fibre is defined as one that has achieved an acceptable degree of cell wall thickening relative to the perimeter of its cross-section. Conversely, an immature cotton fibre is one that has little or no cell wall thickening. The perimeter by itself, and which is largely genetically determined, defines the intrinsic or biological fineness of a cotton fibre, although cotton fibre fineness is nearly always expressed in terms of linear density, defined as the mass per unit length. Units are usually given in tex (grams per km) or more usually for fibres, millitex (milligrams per km). The average linear density depends on both perimeter and the degree of wall thickening (maturity). Intrinsically fine cottons of small perimeter can give lower values or mass per unit length than coarse cottons of large perimeter. For a constant perimeter mature fibres have a higher degree of wall thickening.

Both properties are regarded as important; both define the number of fibres required in a yarn cross-section, a number which has significant effects on yarn quality and processing efficiency. Both also have significant effects on fibre lustre and degree of dye uptake. Immature fibres are associated with the formation of small fibre entanglements called neps, irregularities in processed fibre assemblies including finished yarns, non-uniform dyeing of fabrics and decreased processing efficiency. Good reviews on test methods to the 1980s, which remain largely relevant today, and the importance of fineness and maturity to the spinner include those by Ramey[42] and Lord and Heap.[44]

3.3.1 Measurement of fibre maturity

Whilst it is easy to define fibre maturity, measurement is more difficult. Limitations of the test methods currently available are slow test times making large numbers of measurements impractical and/or the test methods measure fibre parameters not solely related to fibre maturity, e.g. Micronaire measures specific surface area by the air pressure differential across a weighed plug of randomly distributed fibres. Maturity can also be expressed as the absolute wall thickness or wall area measured directly from microscope images of transverse sections (Fig. 3.5). However, because average wall thickness tends to increase with increasing perimeter, it is an unsuitable measure for comparing levels of maturity between different cottons. Moreover, the process of sectioning cotton fibres and measuring their cross-sectional area is a process fraught with experimental and sampling type errors.

3.5 Cross-sections of cotton fibres embedded in methyl-butyl methacrylate resin showing cell wall and lumen (CSIRO Textile and Fibre Technology, Belmont, Australia).

It is proposed[43,44] that the most satisfactory expression of maturity is one that measures maturity independently of differences in intrinsic fineness. Thus the degree of thickening (notated θ) is defined as the ratio of the cross-section area of the fibre wall (A_w) to the area of a circle of the same perimeter (P) as the fibre cross-section (see eqn 3.2).

$$\theta = 4\pi A_w/P^2 \tag{3.2}$$

The ratio is equal to unity for a completely solid circular fibre and becomes smaller for fibres with less wall development. Mature cottons have average θ in excess of 0.60 whilst particularly immature cottons have average θ values of less than 0.30. In all cottons there will be a wide distribution of θ values, e.g. a sample of mature cotton will contain fibres with θ values ranging from 0.15 through to 0.96.[45] Ratios of other cross-sectional and longitudinal geometric measurements have also been used to express maturity although θ remains the preferred and most used measure.

3.3.2 Measurement of fibre fineness

The Micronaire is the most widely used test method for obtaining estimates of cotton fibre fineness. The test measures the resistance offered by a weighed plug of fibres to a metered airflow. The change in the rate of airflow or pressure is correlated with measurements of linear density although it is now understood that the change in airflow is dependent upon specific surface area. The test was incorporated into HVI lines from the beginning of their development and has been changed to improve test time and precision from the earlier laboratory bench-top instrument of the late 1940s, which took a couple of minutes to measure a well blended and conditioned sample of 50 grains (3.24 grams) in weight. The HVI version now takes a 10 gram sample of raw, unblended but conditioned fibre from the bale sample and completes the test in seconds. The scale on the Micronaire is marked in micrograms per inch, which is based on an observed linear relationship between air permeability and linear density for a range of cotton samples of similar maturity. Subsequent testing of immature cotton produced results that varied significantly from actual weight per unit inch determinations. Further studies showed the relationship between Micronaire and fibre weight was curvilinear and that changes in fibre maturity produced concomitant variations in Micronaire readings.[46] Equation 3.3 shows the relationship between Micronaire (X) and the linear density (H) and maturity (M), measured as maturity ratio,[56] determined in ref. 46:

$$MH = 3.86X^2 + 18.16X + 13 \tag{3.3}$$

Despite these shortcomings the Micronaire test is still widely accepted on the basis that the usefulness of other expressions for cotton fibre fineness, including perimeter, diameter or ribbon width, cross-sectional area and standard fibre weight, is also hindered by inter-relationships that exist between them and other parameters such as maturity and the density of the fibre. Inter-laboratory CVs for Micronaire across a range of different cottons tested as part of the Bremen Round Trials between 2003 and 2005 ranged between 1.7% and 3.2%.[30] Table 3.3 lists the typical range of Micronaire values found in Upland cotton together with comments on the type of cotton they represent from a market viewpoint and the range of premiums and discounts applied to particular values. The Micronaire scale is nominally calibrated from 2.3 μg/inch to 8.0 g/inch,[47] and suffers from significant error at either end of the scale. An alternative scale exists for Pima-style cotton.[48]

3.3.3 Methods for separating fibre maturity and fineness

The need to separate the widely used Micronaire into its fineness and maturity components is of particular importance to producers of fine, mature cotton which can be wrongfully discounted because low Micronaire values are taken as indicating immaturity. For example, there is cotton grown in the 3.3 to 3.7 range in Table 3.3 that is actually fine and mature and therefore should have a premium rather than a discount applied.

The International Textile Manufacturers Federation (ITMF) Working Group on Fineness and Maturity advocates that any instrument measure of fibre maturity should give results that vary directly with θ.[44] However, whilst theoretically more accurate, this direct method suffers from significant experimental error due to the fine detail involved in preparing fibres for measurement and the limited number of fibres that can be practically measured. The same issue applies to Standard Methods for determining fibre linear density.[51] These issues have limited the measurement and application of reference method values to only a few laboratories around the world and left fineness and maturity measurement to indirect methods such as Micronaire, the Uster AFIS and the 'Shirley' Fineness and Maturity Tester (FMT), a

Table 3.3 Micronaire values for Upland Cotton

Micronaire (μg/inch)	Comments	Discounts applied (points* per pound [49, 50])
< 3.2	Significantly immature	400 to 1400 pts off
3.3–3.7	Immature	200 to 500 pts off
3.8–4.5	Fine and mature fibre for fine to medium count yarn	50 pts on for 3.8 to 4.2 range
4.6–4.9	Coarse fibre for coarse count yarn	
> 5.0	Significantly coarse	250 to 700 pts off

* 100 points = 1 US cent.

double compression airflow instrument that relates the pressure differential for air metered at two flow rates between a plug of fibres compressed to two volumes.[52]

Over the last twenty years a number of methods different from those already discussed have been investigated for their potential to measure fibre fineness and maturity separately. Near-infra-red reflectance (NIR) spectroscopy was investigated extensively for measuring fibre fineness and maturity because the speeds that can be applied in measurement and sample preparation suit inclusion in HVI lines. However, the method largely measures the physical scattering of light from the specimen, a response that correlates very well with Micronaire and other descriptions of surface area. A thorough review of published work on its application to measuring cotton fineness and maturity has been written by Montalvo and Von Hoven.[53] Other more recent and promising investigations have focused on automating already standard direct methods utilizing high-speed digital cameras and image analysis to measure fineness and maturity. Two such methods are the Commonwealth Scientific Industrial Research Organisation (CSIRO) SiroMat,[54,55] which measures maturity based on the interference colours transmitted by fibres under crossed polars,[56] and the CSIRO Cottonscan,[55,57] which measures the length of a weighed bundle of fibre snippets suspended in a liquid as they pass through an optical cell.

3.4 Tensile properties

The ability of cotton to withstand tensile force is fundamentally important in the processing of cotton. Yarn strength correlates highly with fibre strength, and good tensile strength specific to fibre fineness, is an important factor in resisting damage through the gin, particularly through the lint cleaner.[58] A minimum tensile strength exists for base grade cotton with large discounts for fibre with values below this level. Table 3.4 lists the descriptive designations given to HVI measured values of tenacity by the USDA AMS.[29] Much of the world's exported cotton exceeds these tenacity values. However, no premiums are paid for high tenacity values although improved tensile properties remain a primary objective for cotton plant breeders.

3.4.1 Tensile measurement

The fundamental aspects of tensile strength testing are explained in depth in Chapter 2. To recap, the maximum resistance to stretching forces developed during a tensile test in which the fibre or fibre bundle is broken is called the breaking load, and is measured in terms of grams (or pounds) weight. In order to compare cotton fibres of different fineness the breaking load is normalized by dividing it by the fineness of the fibre measured in terms of

Table 3.4 USDA descriptive designation for HVI tenacity values

Descriptive designation	HVI tenacity (grams per tex)
Very weak	< 20
Weak	21 to 23
Average	24 to 26
Strong	27 to 29
Very strong	> 30

linear density. Tenacity is a useful parameter for describing fibre quality because different cotton varieties and growths can be compared directly with each other and with values for the subsequent yarn or fabric.

Rapid measurement of fibre tenacity and breaking extension is currently realized through HVI measurement of these properties. The current HVI instrument that measures tensile properties evolved from laboratory bench fibre bundle test method instruments like the Pressley Tester and later the Stelometer. In both, a flat bundle of fibres is prepared and the ends fixed between two clamps. A controlled rate of load is applied; in the Pressley Tester by the application of a beam-lever mechanism, and later in the Stelometer by a dashpot controlled pendulum assembly, which improved reproducibility over the Pressley Tester and added the measurement of breaking extension. The broken fibre bundle is weighed using a micro-balance and the result expressed as the average tenacity of that bundle. Average single fibre test results correlate reasonably well with bundle test results, with differences attributable to fibre interaction within the fibre bundle and subsequent effects on the 'weak-link' theory, particularly at small to zero gauge lengths.[59] Table 3.5 from ref. 59 lists the tenacity measured on a Pima cotton tested in single fibre and fibre bundle forms over a series of gauge lengths. The drop in tenacity values is attributed to a 'weak-link' effect in both situations.

Bundle tests measure the tensile properties of the weakest and least extensible fibres included in the bundle. Suh *et al.*[60] pointed out that a typical bundle strength test measures only 1/25,000,000th of the fibres in a bale. The use of small, flat bundles of aligned cotton fibres expedites accurate measurement that could be obtained only through exhaustive sampling and testing of thousands of single fibres. However, the methods of bundle preparation and the gauge length at which they are broken have significant effects on the end result. Residual crimp adversely affects the bundle force measurement in HVI lines. If a bundle is not flat then not all fibres will contribute directly to the load applied. The same is true if fibres are not 100% extended between the jaws by brushing.[61] Fibre specimens prepared by automatic samplers were more representative of cotton lint than specimens prepared for strength tests by conventional methods.[62] Further, the gauge length at which fibres

Table 3.5 Pima cotton stress properties at different gauge lengths using different tensile tests

Nominal gauge length	Tenacity (gf/tex)	
	Single fibre	Flat bundle
0-inch	52.23	40.67
1/8-inch	42.92	27.9
3/16-inch	39.61	25.26
$^1/_4$-inch	37.65	23.41

are broken introduces an inverse length bias on the test, particularly if a sample has a high SFC.

Use of laboratory bench bundle testers is diminishing and most tensile values reported today are generated using HVI lines. Inter-laboratory CV results for fibre strength across a range of different cottons tested as part of the Bremen Round Trials between 2003 and 2005 ranged between 3.6 and 5.1%.[30] Aside from increased speed, due to faster equilibrating strain gauges and the development of high-speed measurements of specimen linear density using light, the success of the HVI strength measurement has arisen from the change in specimen loading to a constant rate of extension rather than a constant rate, which eliminated force measuring errors caused by hardware accelerations.[63] Godbey *et al.*[64] varied the extension rate of the clamping jaws in an HVI over a wide range, and showed tensile strength increased with rates of extension at moderately high speeds and then declined at near-ballistic speeds of load. Since the measurements of specimen linear density do not provide sufficient accuracy, strength calibrations are performed by testing calibration cottons whose bundle strength value has been established. The strength values of calibration cottons are established by testing them on other HVI systems, calibrated with calibration test cottons.

3.4.2 Extension

As well as average tenacity, breaking extension, which is also termed extensibility and elongation is also measured, although the value of this parameter in the market is less understood. No premium or discount is paid on the basis of this property and only a small number of high-end spinning mills appear to pay attention to this property.[2] Little or no attention is paid also to the continuous record of load versus extension although it is likely that plant breeders will take an interest in new varieties that withstand higher breaking loads but which reportedly have lower breaking extensions.

3.5 Colour

Objective measurements of cotton fibre colour are defined in terms of the Nickerson-Hunter colour diagram, which describes colour in three planes; reflectance (Rd), red/green (a) and yellow/blue (+b). The red/green plane is not used because the range of values across physical cotton standards is relatively small and its exclusion simplified the colour classification. The Nickerson-Hunter diagram scale runs from 40 to 85 for Rd values, although the calibrated range of the two photo-sensors in the colorimeter of HVI lines, using physical colour tiles, is from 60 to 90 and from 5 to 15 for yellowness values, with a calibrated range of 7 to 11. The colour of cotton lint has always played a major part in assessing fibre value although for much of the base grade export cotton, e.g. USDA colour grade 31 traded each year, colour becomes largely irrelevant after blending in the spinning mill where cotton of colour grades 31 and higher are very similar to each other in terms of processing ability.

The USA and many other cotton-producing nations use USDA classing colour grade to describe the colour of cotton. Under this system colour is related to physical 'universal' cotton standards, which have names and a number identity. In the 1960s the 'Universal' standards were overlaid by a XY plot of Rd versus +b values to enable comparison between objective measurements using a colorimeter and subjective assessment of colour. The USDA colour grades are listed in Table 3.6[29] with typical ranges of Rd and +b values applicable to each grade. These colour grades refer only to Upland (*G. hirsutum*) cottons, which represent the bulk of the world crop. *Gossypium barbadense* have a creamier yellow appearance and are distinctly different in terms of Rd and +b ranges. Discolorations due to dust, contamination, rain damage, ultraviolet radiation, insect secretions, heat and microbial blooms attract different descriptions, e.g. colour grade 32 relates to a middling grade cotton with light spot. More recently, in the name of objectivity, the USDA AMS have required that colour grade be assessed entirely by objective measurement using the colorimeter operated within the standard HVI line.

Table 3.6 USDA Colour grades and corresponding Rd and +b values

Classer USDA grade		Colorimeter	
		Rd	+b
Good middling	11	80–82	8.2–11.2
Strict middling	21	78–81	7.8–10.2
Middling	31	75–79	7.0–9.8
Strict low middling	41	71–78	5.8–9.0
Low middling	51	66–74	5.2–8.4
Strict good ordinary	61	60–67	5.0–8.6
Good ordinary	71	54–62	5.0–8.0

3.6 Impurities in cotton

3.6.1 Trash

Trash particles or visible foreign matter (VFM) in cotton are typically plant parts that are incorporated into the seed-cotton during harvest and then broken down into smaller pieces during mechanical ginning. Chief components are pieces of stem, bract, bark, seed-coat fragments, motes (whole immature seeds) and leaf. Trash accounts for 1–5% by weight of baled cotton with the amount and type of trash reflected in the leaf and colour classing grade of particular cotton.

The need to determine the amount and type of trash in a particular cotton fibre is based on the effort required to clean it, the adverse effects on yarn quality and process efficiency and the realized yield of fibre, in particular raw cotton. Whilst larger particles of cotton fruit and leaf trash affect the classer's leaf grade they are easier to remove during processes in the spinning mill. The presence of bark and grass is a more serious problem because their fibrous nature makes these contaminants difficult to separate from the cotton fibre. Bark or grass spun into yarn and then knitted or woven into fabric, results in costly claims to the seller of the yarn or fabric. As a result the presence of bark and grass in the classer's sample attracts heavy discounts at classing. Pepper trash, which comprises very small particles of plant matter and dust, is more difficult to 'see' and even though by weight represents a small proportion of the bale, creates large problems in rotor spinning. The sensitivity to rotor spinning of small trash and dust particles has led to the development of instruments that measure the different aspects of trash content; the Uster AFIS Trash and Dust module separates and measures the amount of trash and dust by number and by weight; the Micro-Dust and Trash Analyzer (MDTA3), which has had several manufacturers, separates trash and dust particle fractions via a series of filters, allowing expression of a weight-based measure.

Trash content in a particular cotton is still largely determined by subjective assessment against physical and descriptive grades. Determination by instrument is either too slow, e.g. gravimetric based methods, or too imprecise, e.g. optical (scanner) methods utilized in current HVI lines. The USDA ARS has been investigating the latter methods since the late 1970s when Barker and Lyons[65] used a TV monitor to capture images to measure trash. Research over the last 20 years on the application of scanning devices (TV and video cameras were followed by digital cameras and scanners) for measuring trash has focused on the spectral contribution of colour and trash particles, gaining consistent illumination and contrast in samples to ensure accurate thresholding of scanned images, measuring the effects of pixel resolution and thus trash particle edge definition and calibration of image shape to define the type of trash 'seen' by the analysis.[66]

In 1992 USDA cotton grades were separated into colour and leaf grades. Table 3.7 lists the percentage area of trash, i.e. the percentage area of sample scanned covered by leaf particles, in USDA physical standards scanned by the HVI Trashmeter (of 1992)[66] with the USDA Classer's Leaf Grade scale. A new set of six glass-covered physical samples covering a similar range of trash areas is currently in use in 2006, however, inter-laboratory CVs for the HVI Trashmeter units are still too high[30] and are outside USDA prescribed performance specifications.

3.6.2 Neps

Neps occur in all ginned cotton but hardly at all in unpicked seed-cotton. Neps are fibre entanglements that have a hard central knot that is detectable. Harvesting, ginning (particularly lint cleaning), opening, cleaning, carding and combing in the mill are mechanical processes that affect the amount of nep found in cotton. The propensity for cotton to nep is dependent upon its fibre properties, particularly its fineness and maturity, and the level of biological contamination, e.g. seed coat fragments, bark and stickness. Numerous articles have been published on the conditions for the formation of neps and their deleterious effects on yarn and fabric appearance. Notable among these is the early defining work by Pearson,[67–69] the review of research by Mangialardi[70] and the more recent review of the subject at large by Van der Sluijs and Hunter.[71]

The formation of a nep usually centres around some sort of catching device around which fibres collect and become entangled. Three types of nep are defined throughout the literature; mechanical neps, biological or shiny neps and seed-coat fragment neps. In mechanical neps, the nep nucleus comprises folded immature or fine fibre, although mature fibres are also found. Similarly, trash particles including seed-coat fragments and stick, leaf and bark pieces may contribute to the formation of a nep. In some cases the contents of the fibre lumen (the fibre cell protoplasm) can escape causing fibres to stick together with the cohering fibres becoming the nucleus to

Table 3.7 HVI trashmeter area versus USDA leaf grade

Percent area	Classer's leaf grade
0.08	1
0.12	2
0.18	3
0.34	4
0.55	5
0.86	6
1.56	7

form a biological nep. Other naturally occurring ‘cements’ such as the exudates from insects (see stickiness) or the cotton flower can also act to coalesce fibres and create neps. Mechanical processes involved in taking fibre to the yarn stage also influence the extent to which neps are formed although neps formed from overly aggressive processing are not necessarily correlated with the above fibre properties.

Mechanical neps

The formation of mechanical neps is dependent on two factors; the properties of the fibre that enable it to resist collapse and buckling when frictional and direct forces are applied and the type and degree of mechanical processing exerting force on the fibre. Properties that affect the degree of nep formation include fibre immaturity, fineness (micronaire), low strength, length (in relation to the aspect ratio), high and low wax content and resistance to bending and twisting. Dever *et al.*[58] found nep formation was influenced and inversely related to fibre maturity and directly related to the trash content of cotton. The combination of long-staple length and fibre fineness was conducive to nep formation during mechanical manipulation. Together with non-lint content, these fibre properties predicted nep formation better than any single fibre property. Alon and Alexander[72] suggested that processing fibres produces neps through a stress build-up and sudden realease mechanism, which induces buckling along the fibre length. The propensity for a fibre to buckle is strongly correlated with fibre properties such as maturity, fineness and length. Marth *et al.*[73] found an inverse logarithmic relationship between neps in card sliver and Micronaire values. Fibre with micronaire values less than 3 had more than four times the number of neps greater than fibre with Micronaire values greater than 3.5.

The number of mechanical neps found in cotton has been surveyed many times by workers through each stage of processing from the boll through ginning to the spinning mill.[71] Typical nep numbers found at each stage of mechanically harvested and ginned cotton through to the mill are listed in Table 3.8. Although there is no discount applied to cotton on the basis of its measured nep content most spinning mills prefer fibre with low nep numbers. A value of 250 neps per gram, as measured by the AFIS nep instrument, is often nominated as a maximum value.

Biological neps

Unlike mechanical neps, the nuclei of biological or shiny neps are not formed as a result of a mechanical process. They are found in the opened cotton boll and are thought to form when sticky fluid from the cell protoplasm leaks onto fibres causing them to stick together. It has been noted that the fibres in

Table 3.8 Mechanical neps found through each stage of production and processing

Process	AFIS neps per gram
Field	
Boll	30
Harvest	90
Gin	
Pre-clean	115
Pre-gin	140
Pre-lint cleaner no. 1	210
Pre-lint cleaner no. 2	290
Bale	300
Pre-card	400
Card sliver	90
1st Draw passage	80
Comber lap	60
Comber sliver	20

these neps are usually dead or very immature and are stuck together in a parallel arrangement.[74,75] This suggests that these neps are formed when the boll ripening process is interrupted by insect attack, extreme weather or the premature application of a harvest aid. When these fibres are processed they do not separate from the cemented clump, although the clump may be broken into smaller particles. The clumps tend to be larger prior to ginning and are broken down into smaller particles during ginning and other mechanical processes. The concern for weavers and knitters is that these neps survive processing and show up as white and light-coloured un-dyed specks on finished fabric.[76]

Measurement of neps

When cotton was assessed largely by hand and eye, high levels of nep in the bale or classing sample would indicate that the cotton was likely to be immature. However, subjective assessment of nep levels is unable to be any more than an indicator of potential problems in later processing. There are several methods for measuring the number of neps in loose fibre or mechanically prepared fibre webs. Some involve counting neps directly while more recent methods utilize electro-optical signals and/or digital cameras to measure the number and also the size and shape of neps in a sample. Methods for measuring neps in loose fibre can be divided into four general groups.

1. Manual assessment, where neps in cotton are counted in thin webs prepared by a carding machine or by hand; such methods have become less practical as speeds of other fibre test methods have increased. Further, there is

always difficulty in obtaining reproducible results when the counting is conducted by different operators.

2. Gravimetric assessment, where dust, trash and neps are mechanically separated in a trash separator and weighed; the difficulty with this approach is that neps are not separated from other trash and non-lint particles. There is also the question of whether the opening process in the separator also contributes to the formation of neps.
3. Electro-optical assessment is used in the AFIS Nep Module to assess the number, size and shape profile of neps that pass through a beam of near infra-red light. The voltage/time wave forms produced are proportional to the amount of light scattered and occluded by the object. Individual neps produce a characteristic spike wave form, which is much greater in amplitude and period than the wave forms for individual fibres. A series of threshold voltage levels indicate the size and shape of the nep, which allows neps to be categorized into two categories, fibre (or mechanical) neps and seed-coat fragments.[77,78]
4. Digital cameras are currently used in two commercial instruments that measure neps via analysis of web images. The Truetzschler Nep Control (NCT) uses a digital camera to record the condition of the fibre web being doffed in a cotton card. It continuously records the number and type of neps; fibrous and seed-coat fragment neps, in the fibre web. Good correlations (r = 0.98) have been observed between NCT results and the AFIS nep results.[79] The recently developed Lintronic Fibre Contamination Tester (FCT) works in a similar manner to the NCT. The instrument automatically prepares a web from a sample of raw fibre, which is then photographed by a digital camera. The image is then analysed for neps.

Measurement of biological or shiny neps using any of the above methods is difficult because of their small size. Conversion of fibre into woven and dyed sateen fabric is required for accurate counts of these neps. Against moderately dark, dyed backgrounds these neps contrast as white specks and can be counted manually or by image analysis. Knitted fabric can be used also although nep counts are lower as a proportion of the neps are hidden in the knit structure.

3.6.3 Stickiness

Sticky cotton is a major concern for spinning mills. Physiological plant sugars in immature fibres, contaminants from crushed seed and seed coat fragments, grease, oil and pesticide residues are all potential sources of stickiness. However, these are insignificant compared with contamination of cotton from the exudates of the silverleaf whitefly (*Bemisia tabaci*) and the cotton aphid (*Aphis gossypii*).[80] The sugar exudates from these insects lead to significant problems in the spinning mill including a build-up of residues on textile machinery, which results in irregularities and stoppages in sliver and yarn production. Even at low to moderately contaminated levels, sugar residues build up, decreasing productivity and quality, and forcing the spinner to increase the frequency of cleaning schedules.[81] A reputation for stickiness has a negative impact on sales, exports and price for cotton from regions suspected of having stickiness. Reductions in the market value of lint due to stickiness are applied regionally and indiscriminately. In Arizona, perceptions regarding stickiness lead to 563-point (5.63 US cents)/lb discounts relative to Californian cotton.[82]

The major sugars excreted by *A. gossypii* are melezitose, sucrose, glucose and fructose while for *B. tabaci*, there is the additional sugar, trehalulose. Analysis by Hendrix *et al.*[83] of cotton aphid and silverleaf whitefly exudates showed that around 40% of the total sugar exuded by the aphid was melezitose, while the silverleaf whitefly exudate consisted of around 40% trehalulose plus about 17% melezitose. The two sugars that contribute most to cotton stickiness problems in spinning mills are trehalulose (a disaccharide) and melezitose (a trisaccharide).

Measurement of stickiness

There are a range of test methods currently used to assess stickiness in cotton. Test methods can be divided into two types: either counting methods whereby sticky spots that arise from heating a thin card web of the suspected cotton compressed against a heated plate for a certain time are counted, or chemical analyses whereby the sugars are extracted and identified according to colour changes, spectroscopy or chromatography. The main limitations of these are speed and, except for high-performance liquid chromatography (HPLC) and forms of spectroscopy, which are not widely used in routine analyses, the inability of the test methods to distinguish between types of sugar, particularly with regards to concentrations of the sugar trehalulose, which is difficult to collect because of its low melting point and high hygroscopicity. Recent work has shown that whitefly exudate caused more trouble in the mill than the cotton aphid exudate.[81]

Specific test methods for measuring cotton stickiness (spots) include the Sticky Cotton Thermodetector (SCT) developed by the Center de Co-operation Internationale Recherché Agronomique pour le Development (CIRAD), the High Speed Stickiness Detector (H2SD), which is a high speed version of the original SCT developed also by CIRAD and the Lintronics Fiber Contamination Tester (FCT) developed by Lintronics. Agreement between test method results, and between laboratories for the same test method are typically poor[84] although the methods are reasonable at ranking sticky cotton samples consistently.

3.6.4 Contamination

Contamination, even from a single foreign fibre, can lead to the downgrading of yarn, fabric or garments or even the total rejection of an entire batch. In 2002 the ITMF reported[85] that claims due to contamination amounted to between 1.4 and 3.2% of total sales of cotton and blended yarns. Most contamination arises from impurities being incorporated into the bale as a result of human interaction during harvesting, ginning and baling. The ITMF Cotton Contamination Survey of 2005[86] again showed a rise in the level of contamination in raw cotton from the last several surveys, which are sent to spinning mills every two years. Fibrous contamination from plants, e.g. bark and grass, human hair and materials such woven polypropylene, woven polyethylene, dyed cotton yarn and jute constitute the worse type of contamination for spinners because of the difficulties in removing them from cotton fibre. As a result of the increased incidence of contamination spinning mills are forced to use detection sensors and clearing devices throughout the mill, although there are limitations to what these sensors can 'see' with small contaminants incorporated into yarn or fabric, that are still objectionable to the human eye, e.g. < 1 mm, being difficult to see and remove. One mill currently employs the unique option of manually removing contamination from every bale purchased for contamination-sensitive products, i.e. light coloured weaves and yarn sales.[87] In doing this they are able to provide objective data on the level of contamination found in the growths they use. Table 3.9 lists the percentage of bales delivered from selected countries that contained extraneous (non-plant) contamination. In these data a single foreign fibre found in a bale establishes the bale as being contaminated.

Table 3.9 Percentage of bales from selected growths with extraneous contamination measured manually

Origin	1999/2000	2004/2005	
	Average	Average	Range
Australia	14	20	10 to 30
China	20	23	15 to 30
Brazil	35	27	15 to 35
USA SJV	28	28	20 to 45
USA Memphis	23	32	30 to 60
West Africa	58	66	62 to 80
Uzbekistan	84	86	80 to 95
India	94	92	87 to100
Zimbabwe	–	93	75 to 100
Pakistan	100	97	95 to 100
Syria	100	100	100

3.7 Moisture

Regain and moisture content are terms used interchangeably to refer to the mass of water as a percentage of the fibre mass. The correct terminology is defined in Chapter 2. The commercial regain of cotton is 8.5% although this level is practically unachievable in new cotton under normal ambient conditions. As per descriptions given in Chapter 2 regains in excess of 7.5% indicates wet cotton. The rate of diffusion between absorption and desorption is relatively quick and cotton will readily equilibrate to ambient conditions dependent upon temperature and packing density of the cotton sample. Under ambient conditions in temperate climes moisture levels in bales of cotton typically range from 3.5% to 6.5% moisture.

Moisture is important in fibre testing because of its effect on the physical properties of cotton particularly tensile properties and other expressions normalized for weight. Fibre crimp, compressability and torsional rotation are also affected by high humidity. The fibre strength (tenacity) of cotton conditioned at 55% relative humidity (RH) was 25.8 g/tex and this increased to 29.1 g/tex after conditioning at 75% RH.[88] Moisture content increases with trash content and fibre yellowness.[89] Much work has been aimed at adjusting HVI tensile measurements for conditions in the laboratory at the time of testing.[90] Under ideal standard laboratory conditions and conditioning fibre samples passively for 48 hours, or by following prescribed rapid conditioning protocols, these adjustments do not need to be made. However, maintaining and exposing cotton to standard conditions is a large cost and so new methods that adjust measurements to allow or correct for moisture are attractive. Taylor[90] investigated four methods for measuring moisture in HVI systems including capacitance, two conductivity methods and NIR. All were compared to weight loss by oven drying, which remains the standard test for determining moisture.[91] Near infra-red reflectance spectroscopy was the most accurate method of the four tested.

3.8 Wax content

Cotton wax is essential for the efficient processing of cotton fibre into spun yarn. It provides a lubricating layer that reduces fibre-to-metal friction and therefore fibre breakage during mechanical processing. The downside is that this layer also acts as an impermeable barrier to the entry of water and dye molecules into the fibre. For successful even dyeing this barrier must be removed by scouring and/or bleaching.

Cotton wax is the lipid material extracted from cotton by an organic solvent. Sugars are co-extracted with most solvents and it is necessary to separate the wax lipids from these sugars for quantitative wax analysis. The most common method for determination of the wax content of cotton was developed by Conrad in 1944.[92] This method involves extraction of the fibre with hot ethanol, which is claimed to extract more wax, more quickly than other solvents, followed by a back extraction with chloroform and water. The sugars and non-waxy constituents remain dissolved in the water fraction while the wax passes into the chloroform layer, which is separated and then evaporated off to leave the wax component. Generally between 0.6% and 1% wax by weight of fibre is obtained by the Conrad method. The chemical composition of the wax is complex and contains a number of lipid classes including wax alkanes, fatty acids, fatty alcohols, plant steroids and mono, di and triglycerides.[93–96]

Only a limited amount of work in establishing the quantitative and qualitative differences in wax content among different cotton samples to the varietal and/or environmental background of the plant has been published. Most of these studies[97–99] found that the chemical components of wax from different varieties and species were very similar. However, in two circumstances Marsh *et al.*[98] and Gordon *et al.*[99] cottons with waxes that were significantly different in content were found. Marsh *et al.*[98] found wax from cotton exposed to weathering had a lower melting point, and higher wax content as measured by the Conrad method, whilst Gordon *et al.*[99] found some low Micronaire cotton in the set examined had much higher concentrations of hydrocarbon or alkane waxes. High concentrations of this wax were not found on all low-Micronaire cotton samples tested and the tentative conclusion was made that the relationship became manifest after the particular cotton had suffered heat and water stress during growth. The strong relationship between the amount of wax extracted from the fibre and the surface area per unit weight of fibre, determined by airflow methods such as the Micronaire is also revealed in these and other studies.[100,101] Table 3.10 lists the correlations for the relationships between the wax extracted and the surface area per unit weight of the fibre as quoted in the literature.

Table 3.10 Relationship between percentage wax (%EW) by the Conrad method and specific surface area by various test methods

Reference	Surface area measurement	Micronaire range	%EW range	No. of samples	Correlation coefficient
98	Arealometer	2.17–3.92[2]	0.19–0.95	74	0.94
100	Micronaire	3.62–4.95	0.52–0.72	36	–0.79
101	Micronaire[1]	3.62–4.95	0.52–0.72	33	–0.82
99	Micronaire	3.8–4.8	0.29–1.05	29	–0.42

1. Micronaire values calculated from AFIS fineness and maturity ratio measurements.
2. Specific surface area values measured using the Arealometer (cm^2/mg).

3.9 Microbial attack

The term 'cavitoma' was coined in the 1950s to describe cotton damaged by micro-organisms such as cellulolytic bacteria and fungi. All cotton contains populations of micro-organisms that increase if the right conditions for their growth are applied. The condition was noted in the 1950s in the mid-south and eastern growth areas of the USA during some wet years. Moisture and warmth are the chief criteria required to propel micro-organism populations. Moisture levels in excess of 9% are the minimum required for growth of the micro-organisms.[102]

Perkins and Brushwood[103] provide the most recent review of the conditions and fibre effects associated with micro-organisms and test methods to identify their presence. Acute infection by cellulolytic micro-organisms results in alkaline pH, low sugar content, colour change, poor appearance, low strength and increased wet-out. The tests for cavitomic infection tend to be qualitative tests based around pH indicator tests, and exposure of the sample to UV light to view any fluorescent spots associated with growth of some fungi. Spinning mills using a pH indicator spray will sometimes rate the degree of staining that occurs after spraying the cavitomic cotton. Infected fibres can also be examined under a microscope. Examination of cavitomic fibres under a light microscope can reveal fungal hyphae and fractures in the surface of the fibre. Swelling cavitomic fibres in concentrated sodium hydroxide will cause differential swelling at fracture points along the length of the fibre. Allen *et al.*[104] found good agreements between laboratories examining cavitomic cotton, induced in the field, on the basis of pH determinations and reasonable agreements between laboratories using a method involving microscopic analysis of fibres in sodium hydroxide.

3.10 Future trends

Cotton fibre quality is dependent upon progress in understanding and modifying the genetic and environmental influences on the cotton plant, particularly at the point of fibre development. In the future fibre quality will be defined by the expression of fibre properties in transgenic cotton varieties (see Chapter 4) and through better control of agronomic, water and nutritional variables. The fibre from these plants will likely be longer, finer and stronger, and may have new attributes such as colour or increased extension.

Measurement of fibre quality in industrial countries, e.g. the USA, will occur in the gin rather than at classing laboratories. According to Ghorashi,[6] the future fibre testing system will be implemented in the gin (see Chapter 6). The testing will be fully automated and installed in line with the process flow of the gin. The system of the future will have remote monitoring, calibration and will measure all pertinent fibre qualities a multiplicity of times. For agricultural based countries the proportion of cotton classed by HVI lines will increase.

3.11 Sources of further information

Steadman, R. G., Cotton Testing, *Textile Progress*, **27(1)**, 66 pp., 1997.

USDA Agricultural Marketing Service (AMS), http://www.ams.usda.gov/Cotton/

Hunter, L., *Textiles: Some Technical Information and Data, V: Cotton*, SAWTRI Special Publication, Port Elizabeth, South Africa, 174 pp., 1980.

Lord, E., *Manual of Cotton Spinning, Vol. 2, Part I, Physical Properties of Cotton Fibre*, Butterworths, London, UK, 245 pp., 1965.

3.12 References

1. Bradow, J. M. and Davidonis, G. H., Quantitation of Fibre Quality and the Cotton Production-Processing interface: A Physiologist's Perspective, *J. Cotton Sci.,* **4**, 34–64, 2000.
2. Gordon, S. G., Van Der Sluijs, M. H. J. and Prins, M. W., Quality Issues for Australian Cotton from a Mill Perspective, *Report to the Australian Cotton Industry*, Australian Cotton CRC (pub.), 54pp, July 2004.
3. International Cotton Advisory Committee, *A Summary of Decisions to Date of the Task Force on CSITC*, ICAC, 3 pp., Mar. 2006.
4. Knowlton, J. L., Cotton Classing and the Need for a Universal Cotton Quality Evaluation System, *Proceed. Cotton Council International Cotton Symposium* Turkey, 24–26 April 2005.
5. Anderson, S. L., The Measurement of Fibre Fineness and Length: The Present Position, *J. Textile Inst.*, **68**, 175–180, 1976.
6. Ghorashi, H., *The Universal Transition from Manual to Instrument Cotton Classing*, report to ITMF HVI Working Group Meeting, Bremen, 2006.
7. Van der Sluijs, M. H. J., Gordon, S. G. and Naylor, G. R. N., Australian Fibre Quality and International Feedback, *Proceed. Australian Cotton Grower Research Conf.*, Gold Coast QLD, August 2004.
8. Anthony, W. S. and Bragg, C. K., Response of Cotton Fiber Length Distribution to Production and Ginning Practices, *Trans. American Society of Agricultural Engineers*, 30, 290–296, 1987.
9. Anthony W. S., 'Postharvest management of fiber quality', in Basra, A. S. (ed.), *Cotton Fibers,* Food Products Press, Inc., New York, London, Oxford, 293–337, 1999.
10. Delanghe, E. A. L., Lint Development, in Mauney, J. R. and Stewart, J. McD. (eds), *Cotton Physiology*, The Cotton Foundation, Memphis TN, 325–349, 1986.
11. Vincke, H., DeLanghe, E., Fransen, T. and Verschreage, L., Cotton Fibres are Uniform in Length Under Natural Conditions, in *Cotton Fibres: Their Development and Properties*, Inst. of Cotton, Manchester UK, 2–4, 1985.
12. May, O. L., Quality Improvement of Upland Cotton, in Basra, S. A. and Randhawa,

L. S., (eds), *Quality Improvements in Field Crops*, The Haworth Press Inc., 371–394, 2002.

13. Hanson, R. G., Ewing, E. C. and Ewing Jr., E. C., Effect of Environmental Factors on Fiber Properties and Yield of Deltapine Cottons, *Agron. J.*, **48**, 546–581, 1956.
14. Gipson, J. R. and Ray, L. L., Fiber Elongation Results in Different Varieties of Cotton, *Proc. Beltwide Cotton Conferences*, 212–217, 1968.
15. Gipson, J. R. and Ray, L. L., Influence of Night Temperature on Boll Development and Properties of Five Varieties of Cotton, *Proc. Beltwide Cotton Conferences*, 117–118, 1969.
16. Bradow, J. M., Bauer, P. J., Hinojosa, O. and Sassaranth-Cole, G. F., Quantitation of Cotton Fibre-Quality Variations Arising from Boll and Plant Growth Environments, *Eur. J. Agron.*, **6**, 191–204, 1997.
17. Grimes, D. W. and Yamada, H., Relation of Cotton Growth and Yield to Minimum Leaf Water Potential, *Crop Sci.*, 22, 134–139, 1982.
18. Hearn, A. B., The Principles of Cotton Water Relations and Their Application to Management, *Proc. World Cotton Conf. I*, Brisbane Australia, Feb. 1994.
19. Bradow J. M., Bauer, P. J., Sassaranth-Cole, G. F. and Johnson, R. M., Modulations of Fiber Properties by Growth Environment that Persist as Variations of Fiber and Yarn Quality, *Beltwide Cotton Conferences*, 1351–1360, 1997.
20. Constable, G. A., Australian Cotton Research Institute (ACRI) Fibre Quality Data, 1976 to 2006.
21. *Textile Terms and Definitions*, The Textile Institute, Manchester, 5th edition, 1963.
22. ASTM D1440, Standard Test Method for Length and Length Distribution of Cotton Fibers (Array Method).
23. Shirley Institute Test Leaflet 1961.
24. Hertel, K. L., A Method of Fiber Length Analysis Using the Fibrogram, *Textile Res. J.*, **10**, 510–524, 1940.
25. ASTM D4604, Standard Test Method for Measurement of Cotton Fibers by High Volume Instruments (HVI).
26. Zeidman, M. I., Suh, M. W., Batra, S. K. and Sasser, P. E., *Determining HVI-Specific Fibre Length Measures from Array Data*, Paper presented to the 7th Ann. Cotton Inc. EFS Res. Forum, Raleigh NC, 177–189, Nov 1994.
27. Behery, H. M., *Short Fibre Content and Uniformity Index in Cotton*, ICAC Review Articles on Cotton Production Research No. 4, 35pp., 1993.
28. ASTM D1445, Standard Test Method for Breaking Strength and Elongation of Cotton Fibers (Flat Bundle Method).
29. USDA AMS, *Explanation of HVI Fiber Measurements on the Class Card for Classing Offices Equipped with Video Trashmeters*, USDA (pub.), July 1990.
30. Drieling, A., *Comparison Between Bremen Round Trial Results for Uster and Premier High Volume Instruments*, Present. To ITMF HVI Working Group, Bremen, Mar. 2006.
31. Tallant, J. D., Fiori, L. A. and Landstreet, C. B., The Effect of Short Fibers in Cotton on its Processing Efficiency and Product Quality Part II: Yarns Made by Miniature Spinning Techniques from Differentially Ginned Cotton, *Text. Res. J.*, **30**, 792–795, 1960.
32. Pillay, K. P. R., A Study of the Hairiness of Cotton Yarns – Part I: Effect of Fiber and Yarn Factors, *Text. Res. J.*, **34**, 663–674, 1964.
33. Hequet, E. and Ethridge, D. A., ‘Effect of Cotton Fibre Length Distribution on Yarn Quality’, *Proceed. Beltwide Cotton Conf.*, 1507–1514, 2000.

34. Zeidman, M. I. and Batra, S. K., Determining Short Fiber in Cotton Part II: Measures of Short Fibre Content from HVI – Statistical Models, *Textile Res. J.*, **61**, 103–113, 1991.
35. Knowlton, J. L., *New Measures of HVI SFI*, Proceed. Beltwide Cotton Conf., 1093–1098, 2001.
36. Woo, J. L., An Appraisal of the Length Measures Used For Cotton Fibres, *J. Textile Inst.*, **59**, 557–572, 1967.
37. Zeidman, M. I. and Batra, S. K., Determining Short Fiber in Cotton Part I: Some Theoretical Fundamentals, *Textile Res. J.*, **61**, 21–31, 1991.
38. Schleth, A., *A New Measure of HVI SFI*, Present. to ITMF Length Working Group, ITMF (pub.) Bremen, Mar. 2006.
39. Heap, A. S., *Relative Short Fibre Content*, Present. To ITMF Length Working Group, ITMF (pub.), Bremen, 2004.
40. Robert, K. Q., Dunn, M. C., Cui, X. L. and Price, J. B., *Method for Determining Broken Fibre Content in Ring Yarn*, Proceed. Beltwide Cotton Conf., 3068–3074, 2005.
41. El-Moghazy, Y. E. and Krifa, M., *Fiber Length Utilization Efficiency – A New Approach to Utilizing Fibre Length*, Proceed. Beltwide Cotton Conf., 3056–3066, 2005.
42. Ramey Jr., H. H., *The Meaning and Assessment of Cotton Fibre Fineness*, International Institute for Cotton, 30 pp., 1982.
43. Pierce, F. T. and Lord, E., The Fineness and Maturity of Cotton, *J. Textile Inst.*, **30**, T173–T210, 1939.
44. Lord, E. and Heap, S. A., *The Origin and Assessment of Cotton Fibre Maturity*, International Institute for Cotton, 40 pp., 1988 and in ITMF Working Group Meetings on Cotton Fibre Fineness and Maturity, Bremen, ITMF (pub.) 1990 to 2006.
45. Gordon, S. G., Cotton Fibre Maturity: Its Measurement and Effects on Processing, *Doctoral dissertation*, Latrobe University, Melbourne, Australia, 1994.
46. Lord, E., Air Through Plugs of Textile Fibres, Part II. The Micronaire Test for Cotton, *J. Textile Inst.*, **47**, T17–T47, 1956.
47. USDA Production and Marketing Administration Cotton Branch, Revised Micronaire Fiber-Fineness Scale for Use in Testing American Upland Cottons, Washington, Oct. 1950.
48. USDA Production and Marketing Administration Cotton Branch, Micronaire Fiber-Fineness Scale for Use in Testing American Egyptian Cotton, Washington, Jan. 1952.
49. Adams, G., Managing Lint quality, Making a Profit: An Economic Perspective, *Proceed. Beltwide Cotton Conf.*, 3091–3092, 2005.
50. Australian Cotton Industry, Average Premiums and Discounts Applied to Grower Cotton, Collected Merchant P&D Sheets from 2004–2005.
51. ASTM D1769, Standard Test Method for Linear Density of Cotton Fibers (Array Method).
52. ASTM D3818, Standard Test Method for Linear Density and Maturity Index of Cotton Fibers (IIC Shirley Fineness/Maturity Tester).
53. Montalvo Jr., J. M. and Von Hoven, T., Cotton Fiber Quality, Chapter in *Near Infrared Spectroscopy in Agriculture*, Roberts, C.A., Workman, Jr., J. and Reeves III, J.B. (eds), Crop Science Society of America (pub.), 822 pp., 2004.
54. Gordon, S. G. and Phair, N. L., An Investigation of the Interference Colours Transmitted by Mature and Immature Fibre Under Polarized Light Microscopy, *Proceed. Beltwide Cotton Conf.*, 2566–2573, 2005.

55. Gordon, S. G., Naylor, G. R. N. and Van Der Sluijs, M. H. J., *New Developments in Cotton Quality Assessment: The Australian Direction*, Proceed. Bremen International Cotton Conference, Mar. 2004.
56. ASTM D1442, Standard Test Method for Maturity of Cotton Fibers (Sodium Hydroxide Swelling and Polarized Light Procedures).
57. Naylor, G. R. N. and Purmalis, M., *Update on Cottonscan: An Instrument for Rapid and Direct Determination of Fiber Maturity and Fineness*, Proceed Beltwide Cotton Conf., 2302–2307, 2005.
58. Dever, J. K., Gannaway, J. R. and Baker, R. V., Influence of Cotton Fiber Strength and Fiber Fineness on Fiber Damage During Lint Cleaning, *Textile Res. J.*, **58**, 433–438, 1988.
59. Duckett, K. E., Krowicki, R. S. and Cheng, C. C., Some Observations on Single Fiber and Flat-Bundle Tensile Tests, and on the Application of Weak-link Theory to the Determination of True Zero-gauge Tensile-Test Length of Single Cotton Fibers, *Applied Polymer Symposium*, **27**, 359–368, 1975.
60. Suh, M. W., Cui, X. and Sasser, P. E., *New Understanding of HVI Tensile Data Based on Mantis Single Fiber Test Results*, Proceed. Beltwide Cotton Conf., 1400–1403, 1994.
61. Taylor, R. A. and Godbey, L. C., *A Control on Specimen Brushing will Improve HVI Strength Measurements*, Proceed. Beltwide Cotton Conf., 1083–1084, 1993.
62. Taylor, R. A., Cotton Tenacity Measurements with High Speed Instruments, *Text. Res. J.*, **56**, 92–101, 1986.
63. Taylor, R. A., *The True Strength of HVI Bundles Part B: Stelometer and Reference Measurements*, Present. to ITMF HVI Working Group Meeting, Bremen, Germany, 1994.
64. Godbey, L. C., Taylor, R. A. and Brown, R. S., Development of a Computerized Method to Measure Cotton Tenacity at Different Extension Rates, *Text. Res. J.*, **61**, 452–460, 1991.
65. Barker, R. L. and Lyons, D. W., Instrumental Procedures for Analysis of Non-Lint Particles in Cotton, *ASME Trans. J. Engr. For Industry*, **98**, No. 7, 1976.
66. Taylor, R. A., *An Update on HVI Technology: Its Use in Optimizing Cotton Fiber Performance and Utilization*, Present. to ITMF HVI Working Group, Bremen, Mar. 1992.
67. Pearson, N. L., Neps and Similar Imperfections in Cotton, *USDA Technical Bulletin*, No. 396, Nov. 1933.
68. Pearson, N. L., Naps, Neps, Motes and Seed Coat Fragments, *US Agricultural Market Service Report*, Mar. 1937.
69. Pearson, N. L., Neps in Cotton Yarns as Related to Variety, Location and Season of Growth, *USDA Technical Bulletin*, No. 878, Dec. 1944.
70. Mangialardi, G. J., *Neps in Ginned Lint: A Review of Research*, Proc. Beltwide Cotton Conf., 358–368, 1985.
71. Van Der Sluijs, M. H. J. and Hunter, L., Neps in Cotton Lint, *Textile Prog.*, **28 (4)**, 51 pp., 1999.
72. Alon, G. and Alexander, E., Mechanism of Nep Formation, *Melliand Textilber.*, **59**, 792–795, 1978.
73. Marth, C. T., Arthur, H. E. and Berkley, E. E., Fiber fineness (Micronaire), Neps in Card Web, and Yarn Appearance Grades, *Textile Res. J.*, **22**, 561, 1952.
74. Hebert, J. J., Boyleston, E. K. and Thibodeaux, D. P., Anatomy of a Nep, *Textile Res. J.*, **58**, 380–382, 1988.

75. Watson, M., Mechanical and Biological Neps and Their Influence on Quality, Internal Report, Cotton Inc., Raleigh NC, 1991.
76. Bel-Berger, P. D., Vinyard, B.T., Thibodeaux, D.T., Von Hoven, T.M. and Columbus, E.P., *The Effect of Harvesting Times on White Specks: A Study of Field to Fabric Properties*, Proceed. Beltwide Cotton Conf., 1440–1444, 1995.
77. Douglas, K. (ed.), Measurement of the Quality Characteristics of Cotton Fibers, *Uster News Bulletin, No. 38*, July, 1991.
78. Jones, P. C. and Baldwin, J. C., The influence of seed-coat neps in yarn manufacturing, *Uster Solutions, No. 3*, Sep. 1995.
79. Schlicter, S. and Lösbrock, P., *On-line Test of Neps and Trash Particles at High Performance Cards*, Proceed. Bremen Int. Cotton Conf., Bremen, 1996.
80. Hequet, E. and Wyatt, B., *Evidence of the Origins of Sugar Causing Stickiness in Cotton*, Proceed. Beltwide Cotton Conf., 698–700, 1999.
81. Hequet, E. and Abidi, N., Processing Sticky Cotton, Implication of Trehalulose in Residue Build-up, *J. Cotton Sci.*, **6**, 77–90, 2002.
82. Ellsworth, P. C., Tonstrad, Leser, J., Goodell, P. B., Godfrey, L. D., Hennebury, T. J., Hendrix, D., Brushwood, D., Naranjo, S. E., Castle, S. and Nichols, R. L., *Sticky cotton resources and solutions*, IPM Series No. 13, Uni. of Arizona, Tucson AZ, 4 pp., 1999.
83. Hendrix, D. L., Wei, Y. and Leggett, J. E., Homopteran Honeydew Composition is Determined by Both the Insect and Plant Species, *Comparative Biochemistry Physiology*, **101B**, 23–27, 1992.
84. Goze, E., Frydrych, R. and Gourlot, J. P., *The H2SD: Inter-laboratory Test Results*, Proceed. Beltwide Cotton Conf., 2590–2595, 2005.
85. Strolz, H. M., *ITMF Cotton Contamination Survey 2001*, Proceed. Bremen Int. Cotton Conf., 40–44, 2002.
86. Schindler, C., *The ITMF Cotton Contamination of 2005*, Proceed. Bremen, Int. Cotton Conf., 57–60, 2006.
87. Vijayshankar, *Extraneous Contamination in Raw Cotton Bales: A Spinners Nightmare*, Proceed. Bremen, Int. Cotton Conf., 61–76, 2006.
88. Taylor, R. A. and Godbey, L. C., *A Reference Method for HVI Strength*, Proceed. Beltwide Cotton Conf., 1076–1079, 1993.
89. Taylor, R. A., Moisture Analysis for HVI Testing of Cotton, *Textile Res. J.*, **60**, 94–102, 1990.
90. Taylor, R. A. and Godbey, L. C., *Evaluation of High Speed Methods to Measure Cotton Moisture for HVI Testing*, Proceed. Beltwide Cotton Conf., 1418–1421, 1994.
91. ASTM D2495, Oven Method of Moisture Measurement.
92. Conrad, C. M., Determination of Wax in Cotton Fibre, A New Alcohol Extraction Method, *Ind. Eng. Chem. Anal. Ed.,***16**, 745–748, 1944.
93. Fargher, R. G., Cotton Wax, *Brit. Assoc. Adv. Sci. Rept.,* 436, 1923.
94. Fargher, R. G. and Probert, M. E., Alcohols Present in the Wax of American Cotton, *J. Textile Instit.,* **15**, 337–346T, 1924.
95. Hornoff, Gunther v. and Richter, H., Chemical Composition of Cotton Fibres Originating from various Areas, *Faserforsch. Textiltech.,* **15**, 165–177, 1964.
96. Kling, A., and Hofstetter, H. H., Lipids in Cotton, *Seifen-Oele-Fette-Wachse,* **92**, 323–329, 1966.
97. Heyn, A. N. J., Relationship of Wax Content to Maturity of Cotton, Letters to the Editor, *Text. Res. J.*, **19**, 711–714, 1949.
98. Marsh, P. B., Barker, T. K., Kerr, T. and Butler, M. L., Wax Content as Related to Surface Area of Cotton Fibers, *Text. Res. J.*, **20**, 288–297, 1950.

99. Gordon, S. G., Evans, D., Church J., Petersen, P., Thom, S. L. and Woodhead, A., A Survey of Cotton Wax Contents in Australian Cotton, *Report to the Australian CRDC*, 34 pp., Nov. 2002.
100. Cui, X. L., Price, J. B., Calamari, T. A., Hemstreet J. M. and Meredith, W., Cotton Wax and its Relationship with Fibre and Yarn Properties, Part I: Wax Content and Fibre Properties, *Text. Res. J.*, **72**, 399–404, 2002.
101. Price, J. B., Cui, X. L. and Calamari, T. A., Cotton Wax and its Relationship with Fibre and Yarn Properties, Part II: Wax Content and Yarn Properties, *Text. Res. J.*, **72**, 631–637, 2002.
102. Heyn, A. N. J., Causes and Detection of Damage in Raw Cotton, *Textile Ind.*, **120**, 137–145, 1956.
103. Perkins, H. H. and Brushwood, D. E., *Cavitoma – A Modern Assessment*, Proceed. Beltwide Cotton Conf., 1654–1657, 1997.
104. Allen, S., Auer, P. D. and Pailthorpe, M. T., Microbial Damage to Cotton, *Textile Res. J.*, **65**, 379–385, 1995.

Part II

Production processes for cotton

4

The genetic modification of cotton

S ORFORD, S DELANEY and J TIMMIS,
The University of Adelaide, Australia

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/

4.10 References

Adams K L and Wendel J F (2004), 'Exploring the genomic mysteries of polyploidy in cotton', *Biol J Linn Soc*, 82, 573–581.

Arpat A B, Waugh M, Sullivan J P, Gonzales M, Frisch D, Main D, Wood T, Leslie A, Wing R A and Wilkins T A (2004), 'Functional genomics of cell elongation in developing cotton fibers', *Plant Mol Biol*, 54, 911–929.

Bates S L, Zhao J Z, Roush R T and Shelton A M (2005), 'Insect resistance management in GM crops: past, present and future', *Nat Biotechnol*, 23, 57–62.

Brookes G and Barfoot P (2005) 'GM crops: the global socioeconomic and environmental impact – the first nine years 1996–2004', PG Economics Ltd, UK.

Castillo A R, Gallardo M R, Maciel M, Giordano J M, Conti G A, Gaggiotti M C, Quaino O, Gianni C and Hartnell G F (2004), 'Effects of feeding rations with genetically modified whole cottonseed to lactating Holstein cows', *J Dairy Sci*, 87, 1778–1785.

CottonAustralia (2005), http://www.cottonaustralia.com.au/factSheets/resources/Biotechnology.pdf, 2/9/05

CSIRO (2003), http://www.csiro.au/proprietarydocuments/pi_info_bollgard.pdf, 18/10/05

Cui X, Shin H, Song C, Laosinchai W, Amano Y and Brown R M, Jr. (2001), 'A putative plant homolog of the yeast beta-1,3-glucan synthase subunit FKS1 from cotton (*Gossypium hirsutum* L.) fibers', *Planta*, 213, 223–230.

Dale P J, Clarke B and Fontes E M (2002), 'Potential for the environmental impact of transgenic crops', *Nat Biotechnol*, 20, 567–574.

Daniell H (2002), 'Molecular strategies for gene containment in transgenic crops', *Nat Biotechnol*, 20, 581–586.

Dixon D C, Seagull R W and Triplett B A (1994), 'Changes in the accumulation of α- and β-tubulin isotypes during cotton fibre development', *Plant Physiol*, 105, 1347–1353.

Dixon D C, Meredith Jr W R and Triplett B A (2000), 'An assessment of alpha-tubulin isotype modification in developing cotton fiber', *Int J Plant Sci*, 161, 63–67.

Endrizzi J E, Turcotte E L and Kohel R J (1985), 'Genetics, cytology and evolution of *Gossypium*', *Adv Genet*, 23, 271–375.

Ferguson D L, Turley R B and Kloth R H (1997), 'Identification of a delta-TIP cDNA clone and determination of related A and D genome subfamilies in *Gossypium* species', *Plant Mol Biol*, 34, 111–118.

Fernandez-Corneio J (2005), http://www.ers.usda.gov/Data/BiotechCrops/adoption.html, 19/10/05

Firoozabady E, DeBoer D L, Merlo D J, Halk E L, Amerson L N, Rashka K E and Murray E E (1987), 'Transformation of cotton (*Gossypium hirsutum* L.) by *Agrobacterium tumefaciens* and regeneration of transgenic plants', *Plant Mol Biol*, 10, 105–116.

Fitt, G P (2003) 'Implementation and impact of transgenic Bt cottons in Australia'. In *Cotton Production for the New Millenium. Proceedings of the third World Cotton Research Conference*, Cape Town, South Africa, Agricultural Research Council, 371–381.

Fryxell P A (1969), 'A classification of *Gossypium*', *Taxon*, 18, 585–591.

Giesy J P, Dobson S and Solomon K R (2000), 'Ecotoxicological risk assessment for Roundup (R) herbicide', *Rev Env Contam Toxicol*, 167, 35–120.

Haigler C H, Zhang D and Wilkerson C G (2005), 'Biotechnological improvement of cotton fibre maturity', *Physiol Plant*, 124, 285–294.

Harmer S E, Orford S J and Timmis J N (2002), 'Characterisation of six alpha-expansin genes in *Gossypium hirsutum* (upland cotton)', *Mol Genet Genomics*, 268, 1–9.

Hasenfratz M P, Tsou C L and Wilkins T A (1995), 'Expression of two related vacoular H+-ATPase 16-kilodalton proteolipid genes is differentially regulated in a tissue-specific manner', *Plant Physiol*, 108, 1395–1404.

He C, Yan J, Shen G, Fu L, Holaday A S, Auld D, Blumwald E and Zhang H (2005), 'Expression of an *Arabidopsis* vacuolar sodium/proton antiporter gene in cotton improves photosynthetic performance under salt conditions and increases fibre yield in the field', *Plant Cell Physiol*, 46, 1848–1854.

Head G, Surber J B, Watson J A, Martin J W and Duan J J (2002), 'No detection of Cry1Ac protein in soil after multiple years of transgenic *Bt* cotton (Bollgard) use', *Env Entomol*, 31, 30–36.

Hsu C Y, Creech R G, Jenkins J N and Ma D P (1999), 'Analysis of promoter activity of cotton lipid transfer protein gene LTP6 in transgenic tobacco plants', *Plant Sci*, 143, 63–70.

Huang C-Y, Ayliffe M A and Timmis J N (2003), 'Direct measurement of the transfer rate of chloroplast DNA into the nucleus', *Nature*, 422, 72–76.

Janmaat A F and Myers J (2003), 'Rapid evolution and the cost of resistance to *Bacillus thuringiensis* in greenhouse populations of cabbage loopers, *Trichoplusia ni*', *Proc Royal Soc London B*, 270, 2263–2270.

Ji S J, Lu Y C, Feng J X, Wei G, Li J, Shi Y H, Fu Q, Liu D, Luo J C and Zhu Y X (2003), 'Isolation and analyses of genes preferentially expressed during early cotton fiber development by subtractive PCR and cDNA array', *Nucl Acids Res*, 31, 2534–2543.

Jiang C, Wright R J, El-Zik K M and Paterson A H (1998), 'Polyploid formation created unique avenues for response to selection in *Gossypium'*, *Proc Natl Acad Sci USA*, 95, 4419–4424.

Jingen J (1999), http://www.people.com.cn/english/199906/11/chnmedia.html, 2/11/05

John M E (1999), 'Genetic engineering strategies for cotton fiber modification'. In Basra A S, *Cotton Fibers: Developmental Biology, Quality Improvement and Textile Processing*, New York, Haworth Press, 271–292.

John M E and Crow L J (1992), 'Gene expression in cotton (*Gossypium hirsutum* L.) fibre: cloning of the mRNAs', *Proc Natl Acad Sci USA*, 89, 5769–5773.

John M E and Keller G (1995), 'Characterisation of mRNA for a proline-rich protein of cotton fiber', *Plant Physiol*, 108, 669–676.

John M E and Keller G (1996), 'Metabolic pathway engineering in cotton: biosynthesis of polyhydroxybutyrate in fiber cells', *Proc Natl Acad Sci USA*, 93, 12768–12773.

Kim H J, Williams M Y and Triplett B A (2002), 'A novel expression assay system for fibre-specific promoters in developing cotton fibres', *Plant Mol Biol Rep*, 20, 7–18.

Kishore G M and Shah D M (1988), 'Amino acid biosynthesis inhibitors as herbicides', *Ann Rev Biochem*, 57, 627–663.

Kumar S, Dhingra A and Daniell H (2004), 'Stable inheritance of the cotton plastid genome and maternal inheritance of transgenes', *Plant Mol Biol*, 56, 203–216.

Lawrence S (2005), 'Agbio keeps on growing', *Nat Biotechnol*, 23, 281.

Lee J A (1980), 'Cotton'. In Fehr W R and Hadley H, *Hybridisation of crop plants*, Madison, Wisconsin, American Society of Agronomy.

Leelavathi S, Sunnichan V G, Kumria R, Vijaykanth G P, Bhatnagar R K and Reddy V S (2004), 'A simple and rapid *Agrobacterium*-mediated transformation protocol for cotton (*Gossypium hirsutum* L.): embryogenic calli as a source to generate large numbers of transgenic plants', *Plant Cell Rep*, 22, 465–470.

Li X B, Cai L, Cheng N H and Liu J W (2002), 'Molecular characterisation of the cotton GhTUB1 gene that is preferentially expressed in fiber', *Plant Physiol*, 130, 666–674.

Li X, Wang X D, Zhao X and Dutt Y (2004), 'Improvement of cotton fiber quality by transforming the acsA and acsB genes into *Gossypium hirsutum* L. by means of vacuum infiltration', *Plant Cell Rep*, 22, 691–697.

Li X B, Fan X P, Wang X L, Cai L and Yang W C (2005), 'The cotton actin1 gene is functionally expressed in fibres and participates in fiber elongation', *Plant Cell*, 17, 859–875.

Light G G, Mahan J R, Roxas V P and Allen R D (2005), 'Transgenic cotton (*Gossypium hirsutum* L.) seedlings expressing a tobacco glutathione S-transferase fail to provide improved stress tolerance', *Planta*, 222, 346–354.

Liu H C, Creech R G, Jenkins J N and Ma D P (2000), 'Cloning and promoter analysis of the cotton lipid transfer protein gene Ltp3', *Biochim Biophys Acta*, 1487, 106–111.

Liu Q, Singh S and Green A (2002a), 'High-oleic and high-stearic cottonseed oils: nutritionally improved cooking oils developed using gene silencing', *J Am Coll Nutr*, 21, 205S-211S.

Liu Q, Singh S P, Green A G, Singh S and Green A (2002b), 'High-stearic and high-oleic cottonseed oils produced by hairpin RNA-mediated post-transcriptional gene silencing', *Plant Physiol*, 129, 1732–1743.

Loguercio L L and Wilkins T A (1998), 'Structural analysis of a hmg-coA-reductase pseudogene: insights into evolutionary processes affecting the hmgr gene family in allotetraploid cotton (*Gossypium hirsutum* L.)', *Curr Genet*, 34, 241–249.

Ma D P, Tan H, Si Y, Creech R G and Jenkins J N (1995), 'Differential expression of a lipid transfer protein gene in cotton fibre', *Biochim Biophys Acta*, 1257, 81–84.

Ma D P, Liu H C, Tan H, Creech R G, Jenkins J N and Chang Y F (1997), 'Cloning and characterisation of a cotton lipid transfer protein gene specifically expressed in fibre cells', *Biochim Biophys Acta*, 1344, 111–114.

Martin G S, Liu J, Benedict C R, Stipanovic R D and Magill C W (2003), 'Reduced levels of cadinane sesquiterpenoids in cotton plants expressing antisense (+)-delta-cadinene synthase', *Phytochem*, 62, 31–38.

May O L (1999), 'Genetic variation in fibre quality'. In Basra A S, *Cotton Fibers: Developmental Biology, Quality Improvement and Textile Processing*, New York, Haworth Press, 183–230.

Mei M, Syed N H, Gao W, Thaxton P M, Smith C W, Stelly D M and Chen Z J (2004), 'Genetic mapping and QTL analysis of fiber-related traits in cotton (*Gossypium*)', *Theor Appl Genet*, 108, 280–291.

Meredith Jr W R (2000), 'Continued progress for breeding for yield in the USA'. In Kechagia U, *World cotton research conference II*, Athens, Greece, 97–101.

Mishra R, Wang H-Y, Yadav N R and Wilkins T A (2003), 'Development of a highly regenerable elite Acala cotton (*Gossypium hirsutum* cv. Maxxa) – a step towards genotype-independent regeneration', *Plant Cell, Tissue and Organ Culture*, 73, 21–35.

Orford S J and Timmis J M (1997), 'Abundant mRNA's specific to the developing cotton fibre', *Theor Appl Genet*, 94, 909–918.

Orford S J and Timmis J N (2000), 'Expression of a lipid transfer protein gene family during cotton fibre development', *Biochim Biophys Acta*, 1483, 275–284.

Paterson A H, Saranga Y, Menz M, Jiang C X and Wright R J (2003), 'QTL analysis of genotype x environment interactions affecting cotton fiber quality', *Theor Appl Genet*, 106, 384–396.

Pear J R, Kawagoe Y, Schreckengost W E, Delmer D P and Stalker D M (1996), 'Higher plants contain homologs of the bacterial celA genes encoding the catalytic subunit of cellulose synthase', *Proc Natl Acad Sci USA*, 93, 12637–12642.

Peeters M-C, Willems K and Swennen R (1994), 'Protoplast-to-plant regeneration in cotton (*Gossypium hirsutum* L. cv. Coker 312) using feeder layers', *Plant Cell Reports*, 13, 208–211.

Peng L, Kawagoe Y, Hogan P and Delmer D P (2002), 'Sitosterol-beta-glucoside as primer for cellulose synthesis in plants.' *Science*, 295, 147–50.

Perlak F J, Deaton R W, Armstrong T A, Fuchs R L, Sims S R, Greenplate J T and Fischhoff (1990), 'Insect resistant cotton plants', *Biotech*, 8, 939–943.

Poon S, Clarke A and Heath R (2004), 'Improving the efficiency of embryogenesis in elite cotton cultivars'. In *Proceedings 11th Australian Cotton Conference,* Broadbeach, Australia, ACGRA, 733–737.

Rinehart J A, Petersen M W and John M E (1996), 'Tissue-specific and developmental regulation of cotton gene *FbL2A*. Demonstration of promoter activity in transgenic plants', *Plant Physiol*, 112, 1331–1341.

Rong J K, Abbey C, Bowers J E, Brubaker C L, Chang C, Chee P W, Delmonte T A, Ding X L, Garza J J, Marler B S, Park C H, Pierce G J, Rainey K M, Rastogi V K, Schulze S R, Trolinder N L, Wendel J F, Wilkins T A, Williams-Coplin T D, Wing R A, Wright R J, Zhao X P, Zhu L H and Paterson A H (2004), 'A 3347-locus genetic recombination map of sequence-tagged sites reveals features of genome organisation, transmission and evolution of cotton (*Gossypium*)', *Genetics*, 166, 389–417.

Ruan Y L, Chourey P S, Delmer D P and Perez-Grau L (1997), 'The differential expression of sucrose synthase in relation to diverse patterns of carbon partitioning in developing cotton seed', *Plant Physiol*, 115, 375–385.

Ruan Y L, Llewellyn D J and Furbank R T (2001), 'The control of single-celled cotton fiber elongation by developmentally reversible gating of plasmodesmata and coordinated expression of sucrose and K+ transporters and expansin', *Plant Cell*, 13, 47–60.

Ruan Y L, Llewellyn D J and Furbank R T (2003), 'Suppression of sucrose synthase gene expression represses cotton fiber cell initiation, elongation, and seed development', *Plant Cell*, 15, 952–964.

Sakhanokho H F, Zipf A, Rajasekaran K, Saha S and Sharma G C (2001), 'Induction of highly embryogenic calli and plant regeneration in Upland (*Gossypium hirsutum* L.) and Pima (*Gossypium barbadense* L.) cottons', *Crop Sci*, 41, 1235–1240.

Sanjaya, Satyavathi V V, Prasad V, Kirthi N, Maiya S P, Savithri H S and Sita G L (2005), 'Development of cotton transgenics with antisense AV2 gene for resistance against cotton leaf curl virus (CLCuD) via *Agrobacterium tumefaciens*', *Plant Cell Tissue and Organ Culture*, 81, 55–63.

Saranga Y, Menz M, Jiang C X, Wright R J, Yakir D and Paterson A H (2001), 'Genomic dissection of genotype x environment interactions conferring adaptation of cotton to arid conditions', *Genome Res*, 11, 1988–1995.

Shelton A M, Robertson J L, Tang J D, Perez C, Eigenbrode S D, Preisler H K, Wilsey W T and Cooley R J (1993), 'Resistance of Diamondback Moth (Lepidoptera, Plutellidae) to *Bacillus-thuringiensis* subspecies in the field', *J Econ Entomol*, 86, 697–705.

Shin H and Brown R M, Jr (1999), 'GTPase activity and biochemical characterisation of a recombinant cotton fiber annexin', *Plant Physiol*, 119, 925–934.

Sims S R, Berberich S A, Nida D L, Segalini L L, Leach J N, Ebert C C and Fuchs R L (1996), 'Analysis of expressed proteins in fibre fractions from insect-protected and glyphosate-tolerant cotton varieties', *Crop Sci*, 36, 1212–1216.

Singh P K, Kumar M, Chaturvedi C P, Yadav D and Tuli R (2004), 'Development of a hybrid delta-endotoxin and its expression in tobacco and cotton for control of a polyphagous pest *Spodoptera litura*', *Transgenic Res*, 13, 397–410.

Smart L B, Vojdani F, Maeshima M and Wilkins T A (1998), 'Genes involved in osmoregulation during turgor-driven cell expansion of developing cotton fibers are differentially regulated', *Plant Physiol*, 116, 1539–1549.

Smyth S, Khachatourians G G and Phillips P W B (2002), 'Liabilities and economics of transgenic crops', *Nature Biotech*, 20, 537–541.

Song P and Allen R D (1997), 'Identification of a cotton fiber-specific acyl carrier protein cDNA by differential display', *Biochim Biophys Acta*, 1351, 305–312.

Squire G R, Brooks D R, Bohan D A, Champion G T, Daniels R E, Haughton A J, Hawes C, Heard M S, Hill M O, May M J, Osborne J L, Perry J N, Roy D B, Woiwod I P and Firbank L G (2003), 'On the rationale and interpretation of the farm scale evaluations of genetically modified herbicide-tolerant crops', *Phil Trans Royal Soc London B*, 358, 1779–1799.

Stotzky G (2000), 'Persistence and biological activity in soil of insecticidal proteins from *Bacillus thuringiensis* and of bacterial DNA bound on clays and humic acids', *J Environl Qual*, 29, 691–705.

Stotzky G (2004), 'Persistence and biological activity in soil of the insecticidal proteins from *Bacillus thuringiensis*, especially from transgenic plants', *Plant and Soil*, 266, 77–89.

Sun Y, Fokar M, Asami T, Yoshida S and Allen R D (2004a), 'Characterisation of the Brassinosteroid insensitive 1 genes of cotton', *Plant Mol Biol*, 54, 221–232.

Sun Y, Zhang X, Nie Y, Guo X, Jin S and Liang S (2004b), 'Production and characterisation of somatic hybrids between upland cotton (*Gossypium hirsutum*) and wild cotton (*G. klotzschianum* Anderss) via electrofusion', *Theor Appl Genet*, 109, 472–479.

Sunilkumar G, Connell J P, Smith C W, Reddy A S and Rathore K S (2002a), 'Cotton alpha-globulin promoter: isolation and functional characterisation in transgenic cotton, *Arabidopsis*, and tobacco', *Transgenic Res*, 11, 347–359.

Sunilkumar G, Mohr L, Lopata-Finch E, Emani C, Rathore K S, Connell J P, Smith C W and Reddy A S (2002b), 'Developmental and tissue-specific expression of CaMV 35S promoter in cotton as revealed by GFP', *Plant Mol Biol*, 50, 463–474.

Suo J, Liang X, Pu L, Zhang Y and Xue Y (2003), 'Identification of *GhMYB109* encoding a R2R3 MYB transcription factor that expressed specifically in fiber initials and elongating fibers of cotton (*Gossypium hirsutum* L.)', *Biochim Biophys Acta*, 1630, 25–34.

Tabashnik B E, Cushing N L, Finson N and Johnson M W (1990), 'Field development of resistance to *Bacillus-thuringiensis* in Diamondback Moth (Lepidoptera, Plutellidae)', *J Econ Entomol*, 83, 1671–1676.

Tabashnik B E, Carriere Y, Dennehy T J, Morin S, Sisterson M S, Roush R T, Shelton A M and Zhao J Z (2003), 'Insect resistance to transgenic *Bt* crops: lessons from the laboratory and field', *J Econ Entomol*, 96, 1031–1038.

Tan H, Creech R G, Jenkins J N, Chang Y F and Ma D P (2001), 'Cloning and expression analysis of two cotton (*Gossypium hirsutum* L.) genes encoding cell wall proline-rich proteins', *DNA Seq*, 12, 367–380.

Umbeck P, Johnson G, Barton K and Swain W (1987), 'Genetically transformed cotton (*Gossypium hirsutum* L.) plants', *Biotech*, 5, 263–266.

University of Richmond (2004), http://pewagbiotech.org/resources/factsheets/display.php3?FactsheetID=2, 5/10/05

Vysotski K A (1958), 'Cotton-mallow and cotton-hybiscus hybrids', *Bot Genet Select*, 31, 151–161.

Wang S, Wang J W, Yu N, Li C H, Luo B, Gou J Y, Wang L J and Chen X Y (2004), 'Control of plant trichome development by a cotton fiber MYB gene', *Plant Cell*, 16, 2323–2334.

Wendel J F (1989), 'New World tetraploid cottons contain Old World cytoplasm', *Proc Natl Acad Sci USA*, 86, 4132–4136.

Whittaker D J and Triplett B A (1999), 'Gene-specific changes in alpha-tubulin transcript accumulation in developing cotton fibers', *Plant Physiol*, 121, 181–188.

Wilkins T A and Jernstedt J A (1999), 'Molecular genetics of developing cotton fibres'. In Basra A S, *Cotton Fibers: Developmental Biology, Quality Improvement and Textile Processing*, New York, Haworth Press, 231–263.

Wilkins T A, Rajasekaran K and Anderson D M (2000), 'Cotton biotechnology', *Crit Rev Plant Sci*, 19, 511–550.

Williams G M, Kroes R and Munro I C (2000), 'Safety evaluation and risk assessment of the herbicide Roundup and its active ingredient, glyphosate, for humans', *Reg Toxicol Pharmacol*, 31, 117–165.

Willmitzer L (1999), 'Plant biotechnology: output traits – the second generation of plant biotechnology products is gaining momentum', *Curr Opin Biotech*, 10, 161–162.

Xu Y H, Wang J W, Wang S, Wang J Y and Chen X Y (2004), 'Characterisation of GaWRKY1, a cotton transcription factor that regulates the sesquiterpene synthase gene (+)-delta-cadinene synthase-A', *Plant Physiol*, 135, 507–515.

Yan J, He C, Wang J, Mao Z, Holaday S A, Allen R D and Zhang H (2004), 'Overexpression of the *Arabidopsis* 14-3-3 protein GF14 lambda in cotton leads to a "stay-green" phenotype and improves stress tolerance under moderate drought conditions', *Plant Cell Physiol*, 45, 1007–1014.

Zhang B-H, Feng R, Liu F and Wang Q (2001), 'High frequency somatic embryogenesis and plant regeneration of an elite Chinese cotton variety', *Bot Bull Acad Sin*, 42, 9–16.

Zhang T Z, Yuan Y L, Yu J, Guo W Z and Kohel R J (2003a), 'Molecular tagging of a major QTL for fiber strength in Upland cotton and its marker-assisted selection', *Theor Appl Genet*, 106, 262–268.

Zhang X D, Jenkins J N, Callahan F E, Creech R G, Si Y, McCarty J C, Saha S and Ma D P (2003b), 'Molecular cloning, differential expression, and functional characterization of a family of class I ubiquitin-conjugating enzyme (E2) genes in cotton (*Gossypium*)', *Biochim Biophys Acta*, 1625, 269–279.

Zhang D, Hrmova M, Wan C H, Wu C, Balzen J, Cai W, Wang J, Densmore L D, Fincher G B, Zhang H and Haigler C H (2004), 'Members of a new group of chitinase-like genes are expressed preferentially in cotton cells with secondary walls', *Plant Mol Biol*, 54, 353–372.

Zhao G R and Liu J Y (2001), 'Isolation of a cotton RGP gene: a homolog of reversibly glycosylated polypeptide highly expressed during fibre development', *Biochim Biophys Acta*, 1574, 370–374.

Zhao J Z, Cao J, Collins H L, Bates S L, Roush R T, Earle E D and Shelton A M (2005), 'Concurrent use of transgenic plants expressing a single and two *Bacillus thuringiensis* genes speeds insect adaptation to pyramided plants', *Proc Natl Acad Sci USA*, 102, 8426–8430.

Zhu Y Q, Xu K X, Luo B, Wang J W and Chen X Y (2003), 'An ATP-binding cassette transporter GhWBC1 from elongating cotton fibres', *Plant Physiol*, 133, 580–588.

5

Organic cotton

P J WAKELYN, National Cotton Council, USA and
M R CHAUDHRY, International Cotton Advisory
Committee, USA

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 biohazards 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.

5.11 References

Agronomy Facts 55 (1997), *Estimating Manure Application Rates*, Pennsylvania State University, College of Agricultural Sciences, Cooperative Extension (http://cropsoil.psu.edu/extension/facts/agfact55.pdf).

Alabama Cooperative Extension System (2006), *Broiler Litter as a Source of N for Cotton, Timely Information, Agriculture and Natural Resources*, Agronomy Series, Department of Agronomy and Soils, Auburn University (http://hubcap.clemson.edu/~blppt/chick/html).

Anonymous (2004), 'Kyrgyzstan: organic cotton tested in the South, Reuters Alert Net', Dec 28, 2004 (http://www.alertnet.org/).

Anonymous (2004a), 'US organic cotton production drops despite increasing sales of organic cotton products', Organic Trade Association, news release, Dec 28, 2004 (http://www.ota.com). Organic Exchange, http://organicexchange.org, 2005.

Anonymous (2006), 'US organic cotton production trends: US Acreage of organic cotton gains ground', Organic Trade Association, news release, Jan 4, 2006 (http://www.ota.com/news/press/185.html).

Anonymous (2006a), '2004 US organic cotton acreage increases by 37 percent', *Textile World, Textile News*, Feb 24, 2006 (http://www.textileworld.com/News.htm?CD=5&ID=10644).

Anthony WS and Mayfield WD, eds, (1994), *Cotton Ginners Handbook*, US Dept. of Agriculture, Agricultural Handbook 503, Washington, DC.

Australian Cotton Industry (2005), *BMP Cotton, Best Management Practices.*

Bremen Cotton Report (Feb. 5, 1993), special edition, *Investigation of Chemical Residues on Cotton* http://www.baumwollboerse.de/cotton/investig.htm.

Chaudhry MR (1993), 'Suitable varieties for organic cotton production', presented at the *International Conference on Organic Cotton, Cairo, Egypt, September 23–25, 1993.* The conference was held under the auspices of the International Federation of Organic Agriculture Movements, Germany, and the Bio Foundation and IMO Institute of Market Ecology, Switzerland.

Chaudhry MR (1998), 'Organic cotton production IV', *The ICAC Recorder*, vol. XVI, No. 4, December 1998.

Chaudhry MR (2003), 'Limitations on organic cotton production', *The ICAC Recorder*, vol. XXI, No. 1, March 2003.

Cotton Incorporated (1996), *Cotton Dyeing and Finishing: Technical Guide*, Cotton Incorporated, Cary, NC, 1996.

CropLife International (2005), *Crop Protection Stewardship Activities of the Plant Science Industry: A Stocktaking Report*, p. 15 (http://www.croplife.org/librarypublications.aspx.)

Cropnosis (2005), *Outlook*, September 2005, Croposis Ltd., Edinburgh, UK.

Demeritt L (2006), 'Behind the buzz: what consumers think of organic labeling', *Organic Processing* 3(1), 14–17.

Dickerson WA, Brashear AL, Brumley JT, Carter FL, Grefenstelle WJ and Harris FA, eds, (2001), *Boll weevil eradication in the United States through 1999*, Number Six, The Cotton Foundation Reference Book Series, The Cotton Foundation, Memphis, TN, USA.

Diehl R (2004), 'Weaving preparation yesterday, today, tomorrow', *International Textile Bulletin* 3, 46–48.

Dimitri C and Oberholtzer L (2005), 'Market-Led Growth vs. Government-Facilitated Growth: Development of the US and EU Organic Agricultural Sectors', WRS-05-05, USDA, Economic Research Service, Aug 2005. http://www.ers.usda.gov/publications/WRS0505/wrs0505.pdf.

Dimitri C and Oberholtzer L (2006), 'EU and US Organic Markets Face Strong Demand Under Different Policies', *Amber Waves*, USDA, Economic Research Service, Feb 2006. http://www.ers.usda.gov/AmberWaves/February06/Features/feature1.htm.

EEC (2006), 'Commission Regulation (EC) No. 780/2006, amending Annex VI to Council Regulation (EEC) No. 2092/91 on organic production of agricultural products', *Official J European Union* 25.5.2006, L137/9-L137/14 (http://eur-lex.europa.eu/LexUriServ/site/en/oj/2006/1_137/1_13720060525en00090014.pdf).

El-Lissy O and Grefensette W (2002), 'Boll Weevil Eradication in the US 2001', in *Proc. 2002 Beltwide Cotton Conf.*, National Cotton Council, Memphis, TN, 2002.

ETAD (1997), *Handling Dyes Safely* ETAD, Washington, DC.

EU Directive 2002/61/EC of the European Parliament and of the Council of 19 July 2002, 'amending for the 19th time Council Directive 78/769/EEC relating to restrictions on the marketing and use of certain dangerous substances and preparations (azocolourants) (2002), *Off J European Communities* 11.9, L243/15-L243/18.

European Union (EU) (1991), 'Regulations for organic production of agricultural products', http://europa.eu.int/eur-lex/en/consleg/main/1991/en_1991R2092_index.html

EU (2000), 'The organic logo', (http://europa.eu.int/comm/agriculture/qual/organic/logo/index_en.htm)

EU (2002), Ecolabel for Textiles, (http://europa.eu.int/eur-lex/pri/en/oj/dat/2002/l_133/l_13320020518en00290041)

Farm Bill (1990), Food, Agriculture, Conservation, and Trade Act of 1990 (FACTA), Public Law 101-624, Title XVI, Subtitle A, Section 1603.

Fitt GP, Wakelyn PJ, Stewart JM, Roupakias D, Pages J, Giband M, Zafar Y, Hake K and James C (2004), *Report of the Second Expert Panel on Biotechnology in Cotton,* International Cotton Advisory Committee (ICAC), Washington, DC, USA, Nov. 2004.

Fox SV (1994), 'Organic Cotton', in *Proc. Int. Cotton Conf. Bremen, 1994,* pp. 317–19.

Garrott B (2006), Paul Reinhart AG, personal communication. Paul Reinhart AG is a cotton merchant that sells organic cotton worldwide.

Green Cotton Thailand Co., Ltd. (2006), www.greencotton.co.th.

Greenfeet.com (2006), 'The Truth About Cotton', http://www.greenfeet.net/newsletter/truthaboutcotton.shtml.

Guerena M and Sullivan P (2003), 'Organic Cotton Production', ATTRA Current Topic, July 2003 (http://www.attra.ncat.org/attra-pub/PDF/cotton.pdf).

Hae Now, Organic Cotton Clothing (2006), 'Why Choose Organic', http://www.haenow.com/whyorganic.php.

Hake SJ, Kerby TA and Hake KD, eds, (1996), *Cotton Production Manual*, Pub. 3352, University of California, Division of Agriculture and Natural Resources, Oakland, CA.

Hardy, ML (1998), 'Ecolabels and their effect on flame retardants and fire safety', paper presented at the *Fire Retardant Chemical Association Meeting: Fire Safety and Technology* March 22–25, 1998.

Howard A (1940), *An Agricultural Testament.* Oxford University Press, New York and London.

International Cotton Advisory Committee (ICAC) (1996), *Growing Organic Cotton*, International Cotton Advisory Committee, 1629 K Street, Suite 702, Washington DC 20006, USA. October 1996.

ICAC (1998), 'The Cost of Producing Cotton. 1998', *The ICAC Recorder*, Vol. XVI, No. 4.

ICAC (2003), 'Irrigation of cotton', *The ICAC Recorder*, Vol. XXI, No. 4, pp. 4–9.

ICAC (2005), 'COTMAN: a growth monitoring system', *The ICAC Recorder*, Vol. XXIII, No. 3

International Federation of Organic Agriculture Movements (IFOAM) (2005), http://www.ifoam.org/ and http://www.ifoam.org/about_ifoam/standards/norms/ibsrevision/ibsrevision.html.

International Textile Manufacturers Federation (ITMF) (2005), *Cotton Contamination Surveys* 1999, 2001, 2003, 2005.

Kimmel LB and Day MP (2001), 'New life for an old fiber: attributes and advantages of naturally colored cotton', *AATCC Rev.*, 1(10), 32.

King EG, Phillips JR and Coleman, RJ, eds, (1996), *Cotton Insects and Mites: Characterization and Management*, The Cotton Foundation Book Series Number 3, The Cotton Foundation, Memphis, TN, USA.

Kuepper G and Gegner L (2004), *Organic crop production overview*, ATTRA, National Center for Appropriate Technology (NCAT), Fayetteville, AR, USA.

Kuster B (1994), 'Determination of Fibre Impurities and Contaminants in the Cotton Finishing Process', in *Int. Cotton Conf Bremen, 1994,* pp. 159–69.

Lee JA (1984), 'Cotton as a World Crop', Chapter 1, in *Cotton*, Kohel RJ and Lewis CF, eds, Agronomy Monograph No. 24, American Society of Agronomy, Crop Sciences Society of America and Soil Science Society of America, Madison, WI, 1984, pp.1–25.

Le Guillou G and Scharpé A (2000), *Organic Farming – Guide to Community Rules*, Directorate General for Agriculture, European Commission, ISBN 92-894-0363-2.

Marquardt S (2003), 'Organic Cotton: Production and Market Trends in the United States and Canada – 2001 and 2003', in *Proc. 2003 Beltwide Cotton Conf. National Cotton Council,* Memphis, TN, pp. 362–366.

McWorter CG and Abernathy JR, eds, (1992), *Weeds of Cotton: Characterization and Control*, The Cotton Foundation Book Series Number 2, The Cotton Foundation, Memphis, TN, USA.

Murray P and Coody LS (2003), 'American Organic Standards, Fiber: Post Harvest Handling, Processing, Record Keeping, & Labeling', Version 6.14: Dec 2003 (Approved by OTA Board, Jan 2004) (*Organic Trade Association's Fiber Processing Standards*, Organic Trade Association, Greenfield, MA, USA, 2004).

Myers D (1999), ‘The Problems with conventional cotton’, Chapter 2, Myers D and Stolton S, eds, 1999, *Organic Cotton – From Field to Final Product,* Intermediate Technology Publications, Intermediate Technology Development Group, 103/105 Southampton Row, London, WC1B 4HH, UK. pp. 8–20.

Myers D and Stolton S., eds, (1999), *Organic Cotton – From Field to Final Product,* Intermediate Technology Publications, Intermediate Technology Development Group, 103/105 Southampton Row, London, WC1B 4HH, UK.

National Cotton Council (2006a), ‘Boll Weevil Eradication Update, 2004’, http://www.cotton.org/tech/pest/bollweevil/index.cfm.

National Cotton Council (2006b), ‘Nematode Management Practice’, http://www.cotton.org/tech/pest/nematode/practice.cfm?renderforprint=1.

National Organic Program (NOP) (2002), US Department of Agriculture (USDA), Agricultural Marketing Service. http://www.ams.usda.gov/nop/indexIE.htm.

National Organic Program (NOP) (2005), ‘Certification of agricultural products that meet NOP standards’, http://www.ams.usda.gov/nop/NOPPolicyMemo08_23_05.pdf.

Öktem T, Gürel A and Akdemir H (2003), ‘The characteristic attributes and performance of naturally colored cotton’, *AATCC Review* 3(5), 24–27.

Organic Exchange (2006), http://organicexchange.org ; http://www.organicexchange.org/Documents/ocsymbiosis.pdf

Organic Exchange Blended Standard version 2/2005 (2005), http://www.organicexchange.org/ (click OE Blended Standard).

Organic Exchange Guidelines, ‘Tracking and Documenting the Purchase, Handling and Use of Organic Cotton Fiber’ (2004), http://www.organicexchange.org/Documents/guidelines0605.doc.

Organic Essentials (2006), http://www.aboutorganiccotton.org/PDFs/OrganicCotton_legal.pdf.

Organic Trade Association (OTA) (2005), ‘Global Approaches to Organic Textiles’, in *Proc. 4th International Conference on Organic Textiles – INTERCOT, May 1–3, 2005.* Organic Trade Association, PO Box 547, Greenfield, MA 01302, USA.

Organic Trade Association (OTA) (2005a), ‘American Organic Standards for Fiber: Post-Harvest Handling, Processing, Record Keeping & Labeling’ (Organic Fiber Processing Standards), http://www.ota.com/standards.fiberstandards.html.

Orgaz F, Mateos L and Fereres E (1992) Season length and cultivar determine the optimum evapotranspiration deficit in cotton, *Agron. J.*, 84(4): 700–706.

Patagonia (2006), http://www.patagonia.com/enviro/organic_cotton.shtml.

Paul Reinhart AG (2006), http://reinhart.com (click on organic cotton).

Pick S and Givens H (2004), *Organic Cotton Survey – 2003 US Organic Cotton Production & the Impact of the National Organic Program on Organic Cotton Farming*, Organic Trade Association, Available at http://www.ota.com/2004_cotton_survey.html.

Ratter SG (2004), ‘Organic and Fair Trade Cotton in Africa’, EU Africa Cotton Forum: July 2004. Available at http://www.cotton-forum.org/docs/presentations/6.3-en.pdf

Ryser U (1999), ‘Cotton fiber initiation and histodifferentiation’, in *Cotton Fibers, Developmental Biology, Quality Improvement, and Textile Processing*, Basra, AS, Ed., The Haworth Press, Inc. Binghamton, NY, chap. 1, pp. 21–29.

Ryser U, Meier H and Holloway PJ (1983), ‘Identification and localization of suberin in the cell walls of green cotton fibres (*Gossypium hirsutium L.*, var. green lint)’, *Protoplasma*, 117, 196–205.

Schmidt M and Rehm G (2002), *Fertilizing Cropland with Poultry Manure*, University of Minnesota Extension Service (http://www.extension.umn.edu/distribution/cropsystems/DC5881.html).

Schmutz A, Jenny T, Amrhein N and Ryser U (1993), 'Caffeic acid and glycerol are constituents of the suberin layers in green cotton fibers', *Planta*, 189, 453–460.

Smith WF (1996), 'Precision farming overview', *Proc Beltwide Cotton Conf*, Vol 1, 179–180.

Swezey SL (2002), 'Cotton yields, quality, insect abundance, and cost of production of organic cotton in northern San Joaquin Valley, California', in *Proc 14th IFOAM Organic World Congress*, Canadian Organic Growers, Ottawa, Ontario, Canada.

Swezey SL and Goldman PH (1999), 'Organic Cotton in California: Technical aspects of production', Myers, D and Stolton, S, eds, in *Organic Cotton – From Field to Final Product,* Intermediate Technology Publications, Intermediate Technology Development Group, 103/105 Southampton Row, London, WC1B 4HH, UK, pp. 125–132.

Traoré D (2005), 'Promotion of organic cotton cultivation in Mali', in *Proc. 4th International Conference on Organic Textiles – INTERCOT, May 1–3, 2005*. Organic Trade Association, PO Box 547, Greenfield, MA 01302, USA.

Tripathi KS (2005), 'Textile processing of the future: The state of the art', in *Proc. 4th International Conference on Organic Textiles – INTERCOT, May 1-3, 2005*. Organic Trade Association, PO Box 547, Greenfield, MA 01302, USA.

US Department of Agriculture – NASS (2001), *Agricultural Chemical Usage*, 2000, *Field Crop Summary*.

US Department of Agriculture – NASS (2004), *Agricultural Chemical Usage: 2003 Field Crop Summary*, p. 93.

US Environmental Protection Agency (EPA) (1999), Assessing Health Risks from Pesticides, US EPA 735-F-99-002, http://www.epa.gov/cgi-bin/epaprintonly.cgi.

US EPA (2006), Worker Protection Standard, 40 Code of Federal Regulations Part 170.

US EPA (2006a), Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), 7 US Code 136; Federal, Food, Drug and Cosmetic Act (FFDCA) (1996) as amended by the Food Quality Protection Act (FQPA).

US EPA (2006b), Data Requirements for Registration, 40 CFR 158.

US EPA (2006c), Pesticide Management and Disposal: Standards for Pesticide Containers and Containment; Final Rule (40 CFR Parts 9, 156, 165), 71 Federal Register pages 47329–47437, August 16 and Pesticides: Regulating Pesticides, Storage and Disposal (http://www.epa.gov/pesticides/regulating/storage.htm).

US EPA (2006d), 'Sustainability'. http://www.epa.gov/sustainability/basicinfo.htm.

US EPA (2006e), US Pesticides Safety Highest in World (http://epa.gov/cgi-bin/epaprintonly.cgi)

Van Elzakker, B and Caldas, T (1999), 'Organic cotton production', Myers, D and Stolton, S, eds, in *Organic Cotton – From Field to Final Product,* Intermediate Technology Publications, Intermediate Technology Development Group, 103/105 Southampton Row, London, WC1B 4HH, UK, pp. 21–35.

Vreeland JM, Jr (1993), 'Naturally colored and organically grown cottons: anthropological and historical perspectives', in *Proc. Beltwide Cotton Conf.*, National Cotton Council, Memphis, TN, pp. 1533–36.

Vreeland JM Jr (1999), 'The revival of colored cotton', *Sci. Am.*, 280, 112, 1999.

Wakelyn PJ (1994), 'Cotton: environmental concerns and product safety', in *Proc. 22nd Int. Cotton Conf., Bremen*, Harig H and Heap SA, eds, Faserinstitut Bremen e.V., Bremen, Germany, pp. 287–305.

Wakelyn PJ (1997), Cotton yarn manufacturing, in *ILO Encyclopaedia of Occupational Health and Safety,* 4th end, Chapter 89, 'Textile Goods Industry', AL Ivester and JD Neefus, eds, International Labour Office, Geneva, Switzerland, pp. 89.9–89.11.

Wakelyn PJ and Gordon MB (1995), ‘Cotton, naturally’, *Textile Horizons*, 15(1), 36–38.

Wakelyn PJ, Bertoniere NR, French AD, Thibodeaux DP, Triplett BA, Rousselle MA, Goynes Jr. JR, Edwards JV, Hunter L, McAlister DD and Gamble GR (2006), ‘Cotton Fibers’, Chapter 9, in *Handbook of Fiber Chemistry* (3rd edition, revised and expanded). M Lewin and EM Pearce, eds, CRC Press, New York. 2006, in press.

Wakelyn PJ, May OL and Menchey EK (2004), ‘Cotton and biotechnology’, in *Handbook of Plant Biotechnology*, Christou P and Klee H, eds, John Wiley and Sons, Ltd., Chichester, West Sussex, UK, chap. 57, pp. 1117–1131.

Wakelyn PJ, Menchey K and Jordan AG (2000), ‘Cotton and environmental issues’, in *Cotton – Global challenges and the Future*, papers presented at a Technical Seminar at the 59th Plenary Meeting of the International Cotton Advisory Committee (ICAC), Cairns, Australia, Nov. 9, pp. 3–11.

Wakelyn PJ, Thompson DW, Norman BM, Nevius CB and Findley DS (2005), ‘Why Cotton Ginning is Considered Agriculture’, *Cotton Gin and Oil Mill Press* 106(8), 5–9.

Yafa S (2005), *Big Cotton: how a humble fiber created fortunes, wrecked civilizations and put America on the map*, Viking Penguin, a member of Penguin Group (USA) Inc. pp. 290–301.

Zarb J, Ghorbani R, Koccheki A and Leifert C (2005), ‘The importance of microorganisms in organic production’, *Outlooks Pest Manag.*, 16, 52–55.

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,

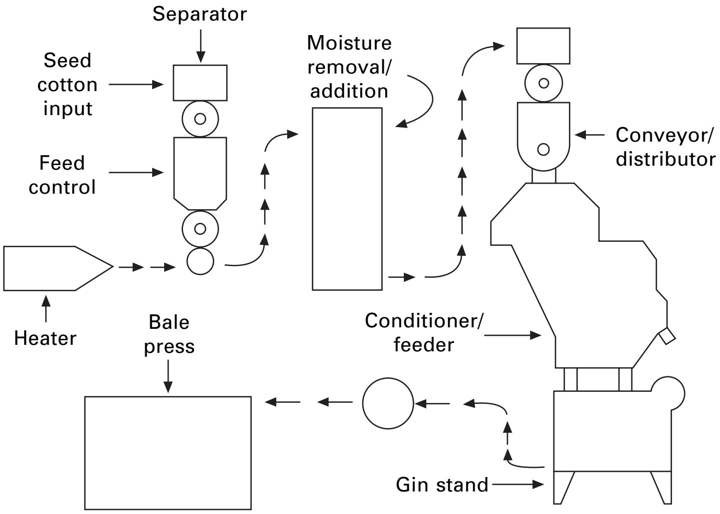
---

*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.

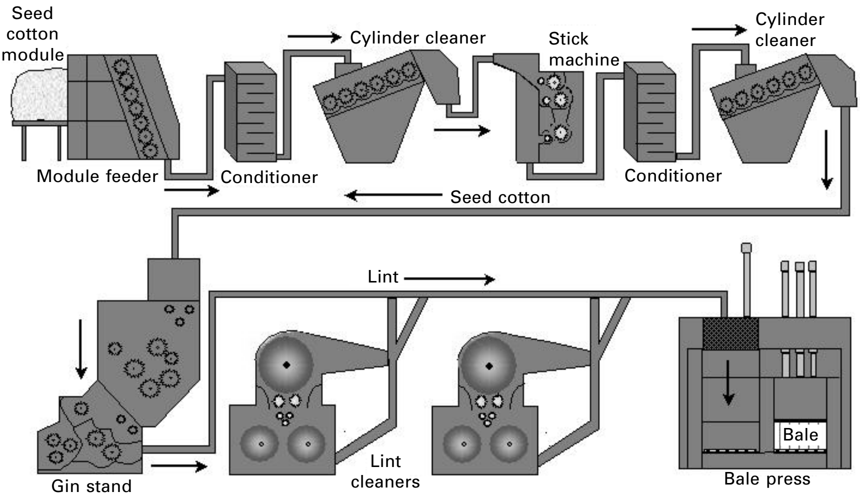
1982, 1990a, b, c, d, 1994a, b, 1996, 1999; Anthony and Calhoun, 1997). Cotton gins are responsible for converting a raw agricultural product, seed cotton, into commodities such as bales of lint, cottonseed, motes, compost, etc. Gins are a focal point of the cotton community and their location, resources,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

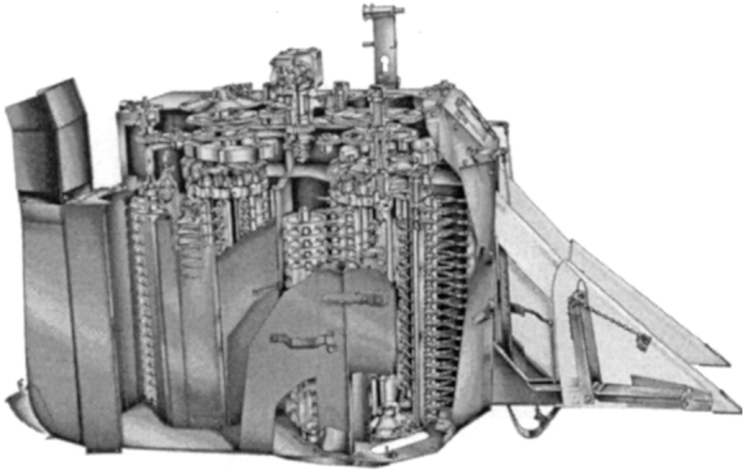
6.3 Typical spindle-type mechanical harvester for cotton.

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

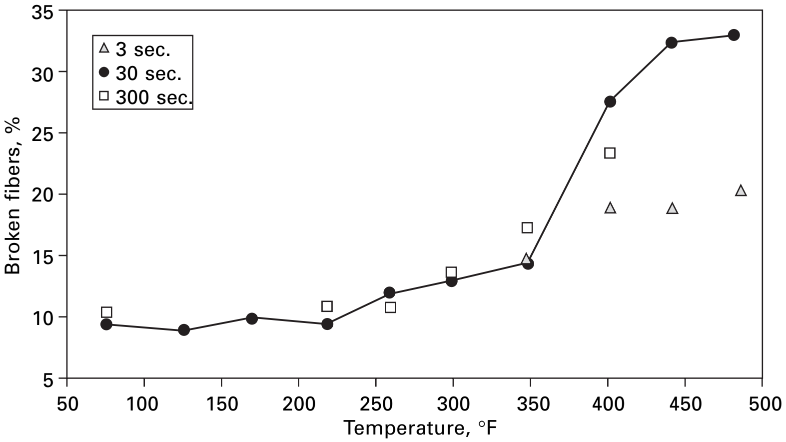
The moisture content of seed cotton is very important in the ginning process. When seed cotton enters the gin plant with high moisture content, it should be exposed to as little machinery as possible (especially extractors) before entering the drying system. Seed cotton having too high a moisture content 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



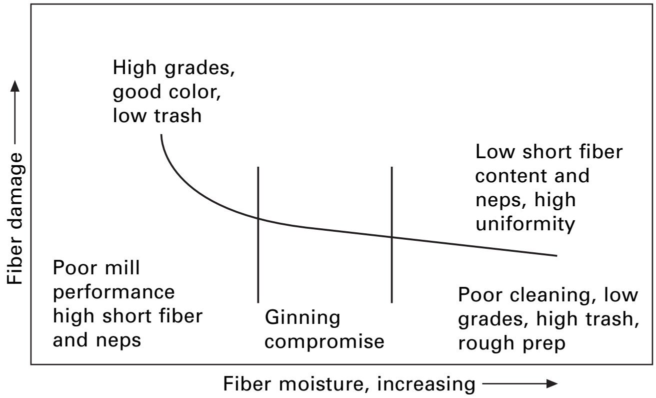
6.8 When drying temperatures exceed 220 °F, the percentages of broken fibers increase.

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.

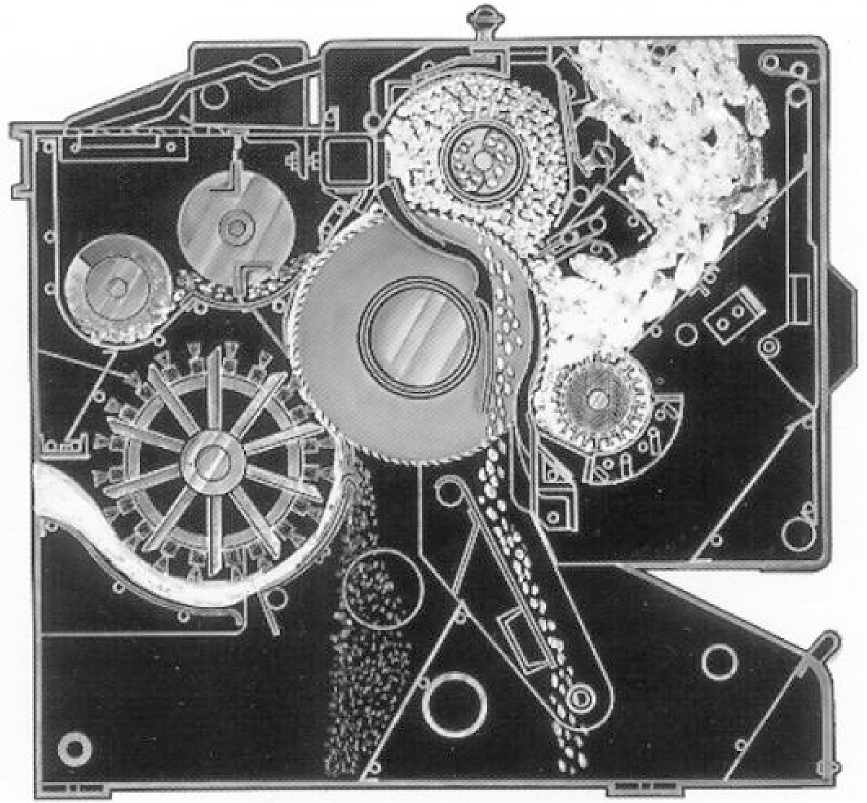
Extractor-feeders are efficient cleaners. Seed cotton is usually well dispersed when it enters an extractor-feeder, and the feed rate through this machine is often lower than the feed rate of other seed cotton cleaning machinery. Studies wherein all seed cotton cleaners prior to the extractor-feeder 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.

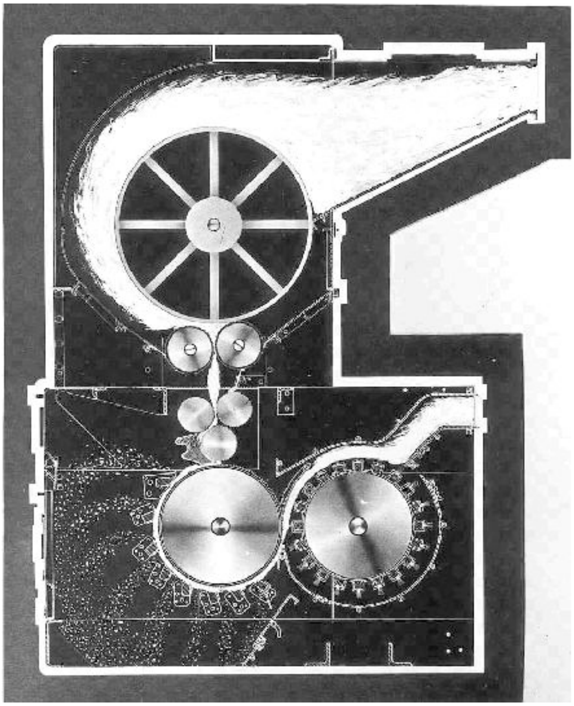
Flow-through air lint cleaner

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.

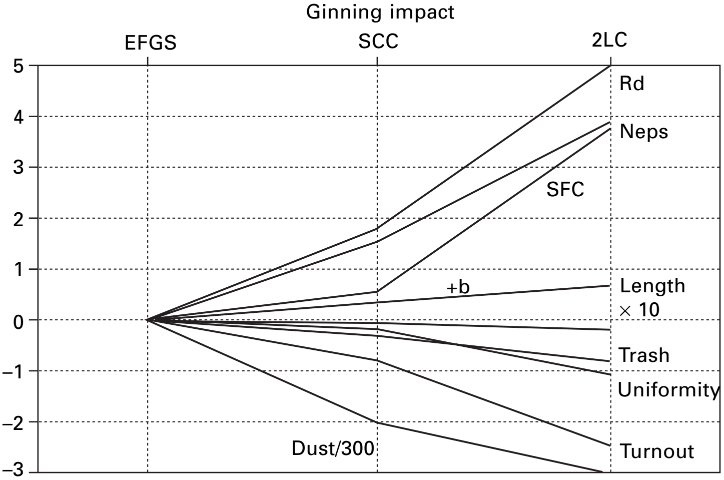
Bales should be fully covered (including openings caused by sampling), and all bale covering material should be clean, in sound condition, and of sufficient strength to adequately protect the cotton. Bales are covered in natural fibers such as cotton (preferably), burlap, and jute, and synthetics such 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.

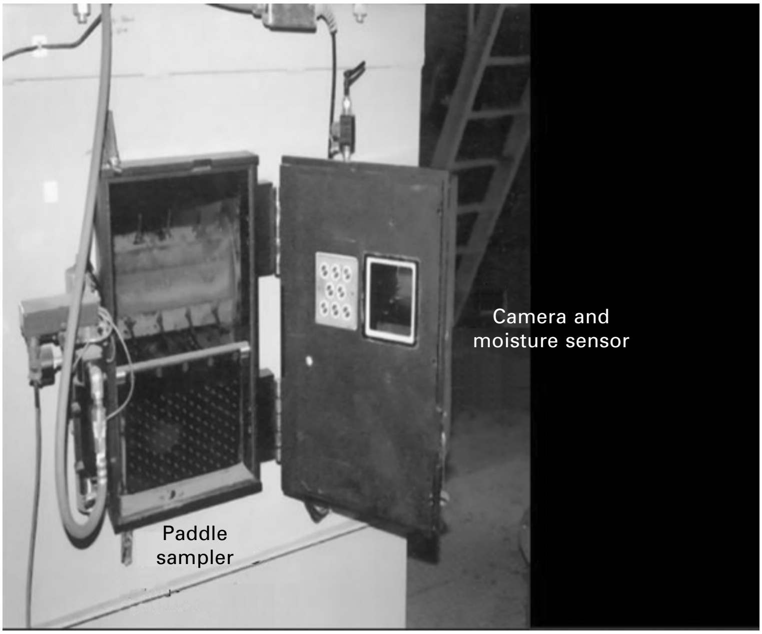
For long storage periods, moistures should be below 12%. The temperature of cotton harvested at safe storage moisture will generally not increase more than 8 °C (15 °F) during the initial five to seven days and will then level off and even cool down as storage continues. Foreign-matter levels in seed 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.

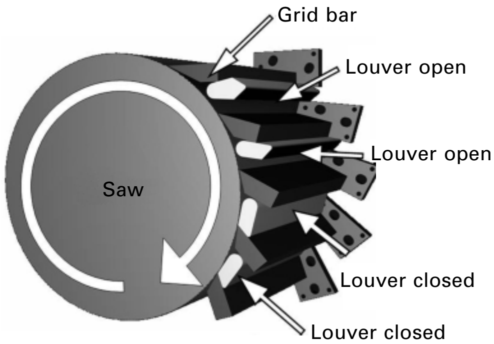
Ginners must determine the needs of their customers and select the drying and cleaning processes that meet their needs. They must ensure that farmers are aware of the impact of varieties and cultural practices on the quality of the seed cotton brought to the gin, and thus, the amount of gin processing 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.

6.8 References

Anthony W S (1982), 'Response of fiber properties to gin machinery and moisture during ginning as measured by HVI', *The Cotton Gin and Oil Mill Press*, 83 (24), 16–20.

Anthony W S (1990a), 'A good bale of cotton: Interaction of variety, harvesting and ginning', *The Cotton Gin and Oil Mill Press*, 91 (20), 8–14.

Anthony W S (1990b), 'Computerized gin process control', *Applied Engineering in Agriculture*, American Society of Agricultural Engineers, 6 (1), 12–18.

Anthony W S (1990c), 'Gin cleanability of selected cotton cultivars', *Transactions of the ASAE*, 33 (3), 749–756.

Anthony W S (1990d), 'Performance characteristics of cotton ginning machinery', *Transactions of the ASAE*, 33 (4), 1089–1098.

Anthony W S (1994a), 'Response of cotton color to gin machinery', *The Cotton Ginning Journal*, 33–39.

Anthony W S (1994b), 'The effect of gin machinery on measurement of high volume instrument color and trash of cotton', *Transactions of the ASAE*, 37 (2), 373–380.

Anthony W S (1996), 'Impact of cotton gin machinery sequences on fiber value and quality', *Applied Engineering in Agriculture*, American Society of Agricultural Engineers, 12 (3), 351–363.

Anthony W S (1999), 'Postharvest management of fiber quality', in Basra A S (editor), *Cotton Fibers,* Food Products Press, Inc., New York, London, Oxford, 293–337.

Anthony W S and Calhoun S (1997), 'Processing cotton cultivars with conventional gin machinery', *Applied Engineering in Agriculture*, American Society of Agricultural Engineers, 13 (5), 565–576.

Anthony W S and A C Griffin, Jr. (2001), 'Fiber breakage at gins: Causes and solutions', *Proc Beltwide Cotton Conf, National Cotton Council*, Memphis, TN, 1347–1358.

Anthony W S and Mayfield W D (editors) (1994), *Agricultural Handbook 503*, United States Department of Agriculture 377 pp.

Mangialardi G J, Jr. (1990), 'Performance of air-type lint cleaners in reducing motes and seed-coat fragments', *Proc Beltwide Cotton Conf, National Cotton Council*, Memphis, TN, 669–674.

Mangialardi G J, Jr. (1993), 'Effect of lint cleaning at gins on market value and quality', *Applied Engineering in Agriculture*, American Society of Agricultural Engineers, 9(4), 365–371.

Mangialardi G J, Jr. (1996), 'Lint cleaning options to preserve fiber quality', *Applied Engineering in Agriculture*, American Society of Agricultural Engineers, 12(5), 555–562.

Mangialardi G J, Jr. and Anthony W S (1998), 'Field evaluation of air and saw lint cleaning systems', *Journal of Cotton Science*, 2 (1), 53–61.

Disclaimer

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture and does not imply approval of the product to the exclusion of others that may be available.

7

The opening, blending, cleaning, and carding of cotton

C LAWRENCE, University of Leeds, UK

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.

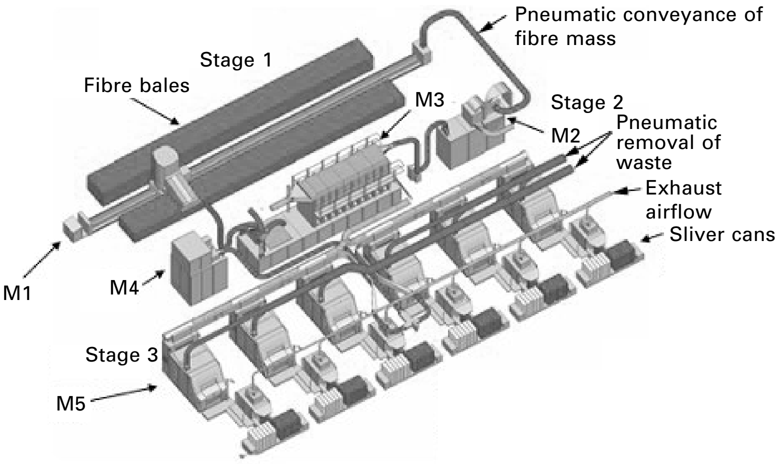
The action of breaking the baled fibre mass down into initially large and then smaller size tufts (tuflets) is termed opening (fibre opening) and the converting of small size tufts into individual fibres is called carding. With natural fibres such as cotton, the baled fibre mass will contain impurities, 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.

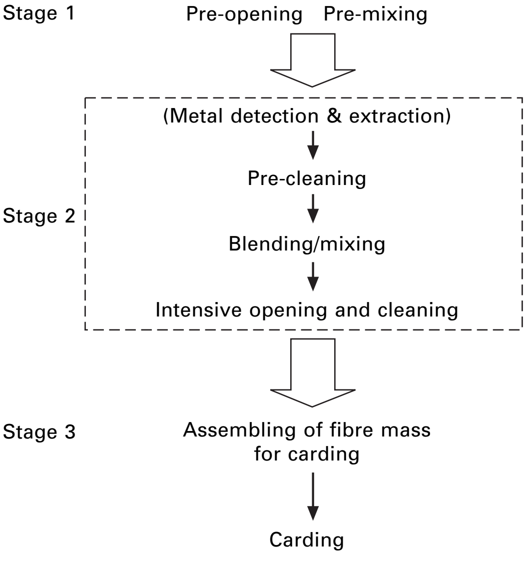
When the baled fibre mass is to be opened into small tufts a sequence of machines is used to perform this task and as they can also carry out cleaning of the tufts, the machine sequence is called an opening and cleaning line; machines making up such a line are generally referred to as opening and cleaning 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.



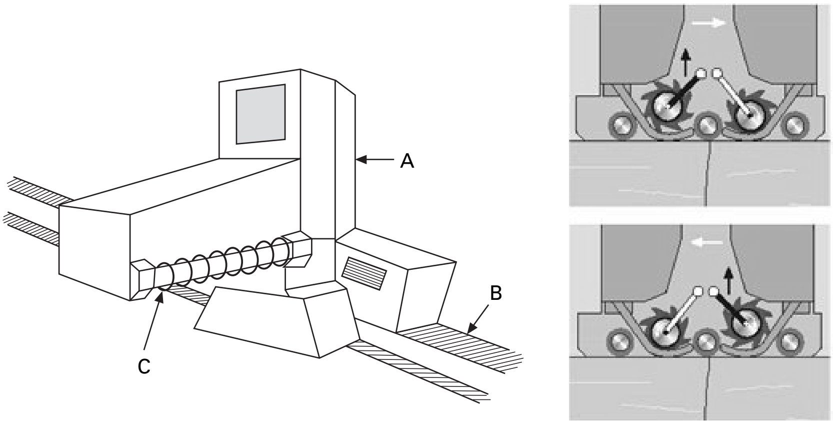
7.2 Basic sequence of blowroom operations.

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



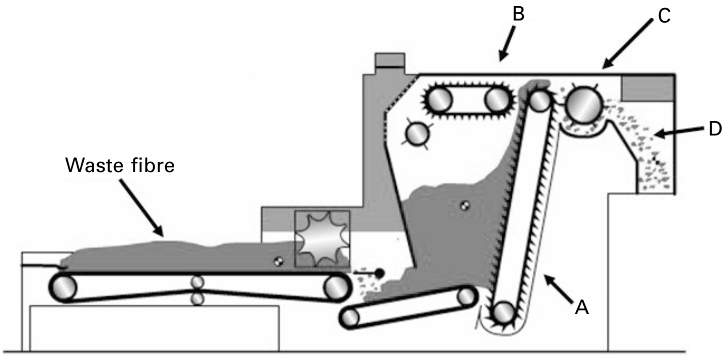
7.3 Automatic bale opener: Trutzschler Baleomat.

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}.

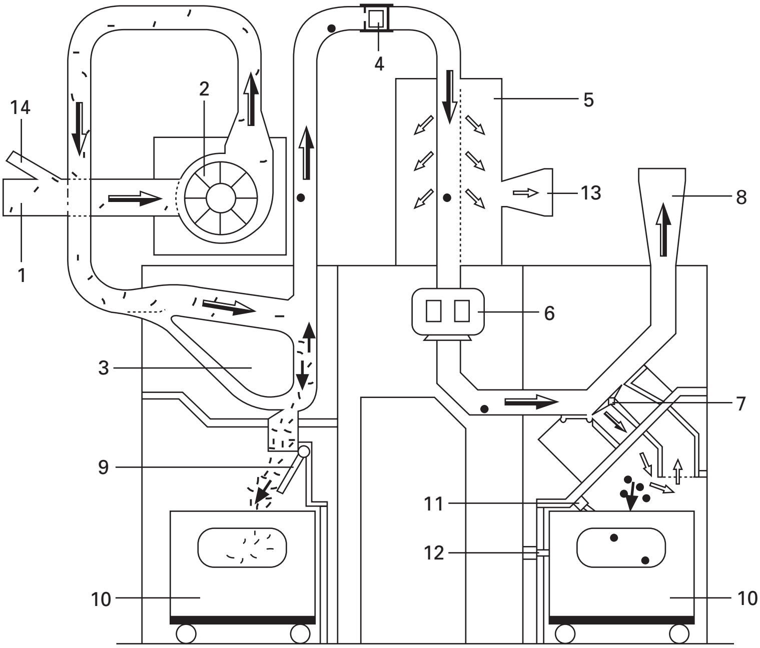
It should be evident that bales of different cotton grades or fibre types (cotton + viscose or cotton + polyester) could be positioned to make up the lines and in so doing, get a useful pre-mixing for the eventual production of ‘blended yarns’. Process waste with high fibre content (usually from the 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.

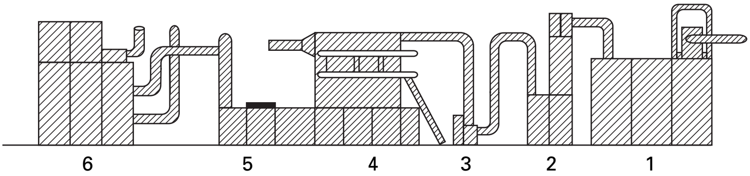
With combustible materials, there is always the possibility of tufts being ignited from sparks caused by metal particles impacting on the sides of the air trunking. Burning or smouldering tufts will need to be removed before reaching the opening/pre-cleaning stage. A detector (4) signals the diverter (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.

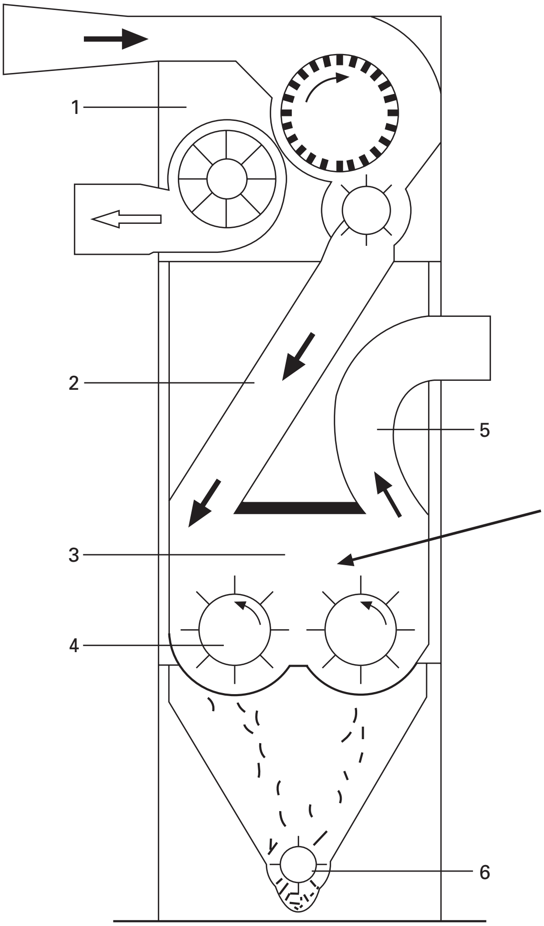
The condenser fulfils two functions. It removes dust particles in the air stream and from the surface of the tufts as they are 'condensed' onto it. Second, its rotation transports the tufts into the feed trunk, which is positioned to ensure tangential feeding to the left beater or cleaning roll. The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

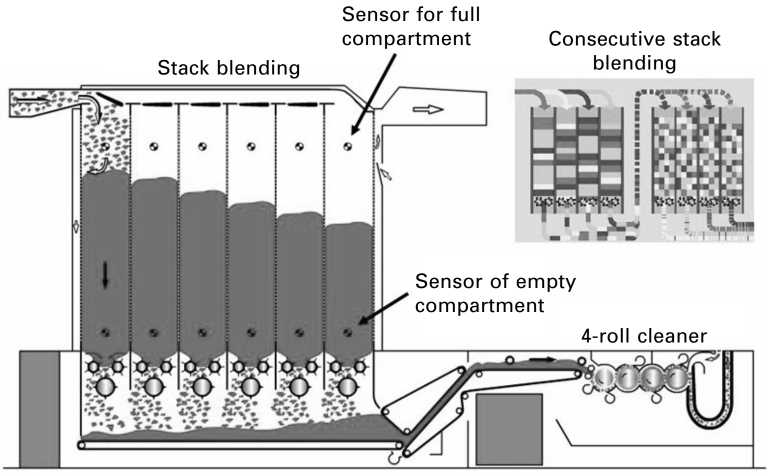


7.7 Opener/pre-cleaner.

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:

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

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

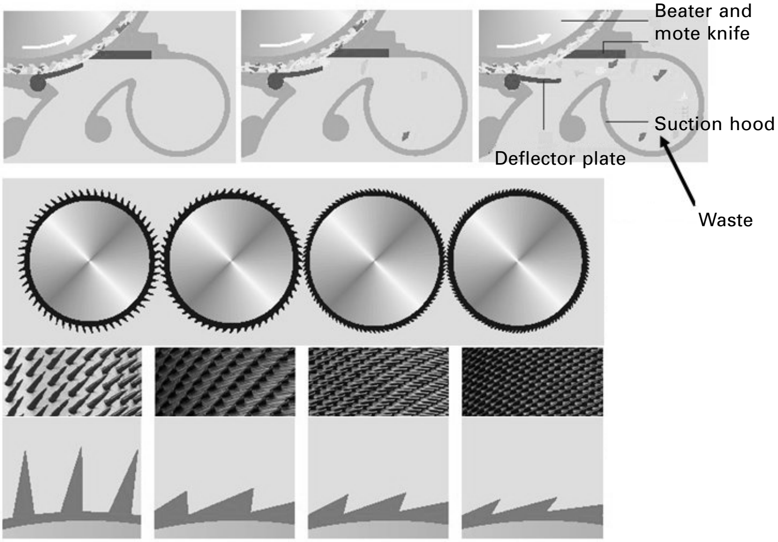
where W_b is the total mass, and w_i and p_i are the individual mass contributions and blend fractions of the fibre components for $i = 1$ to n components. In preparing to blend different cotton grades, or mmf/cotton blend, it is useful to estimate the average fibre characteristics of the blend that 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)	$d_m^2 = \sum p_i d_i^2$ 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)	$f_m = 100/[\sum q_i / f_i]$ 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	$L_m = \sum p_i L_i$ 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	$S_m = \sum p_i S_i$ 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

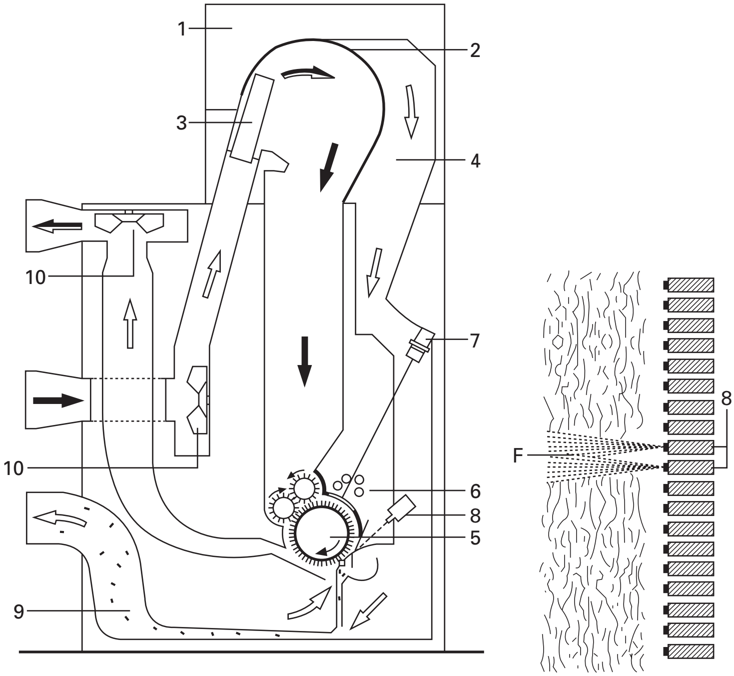


7.9 Intensive cleaning action.

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,

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

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.

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

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.

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

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,

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

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

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

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

7.4 Stage 3: carding

7.4.1 Basic principle of carding

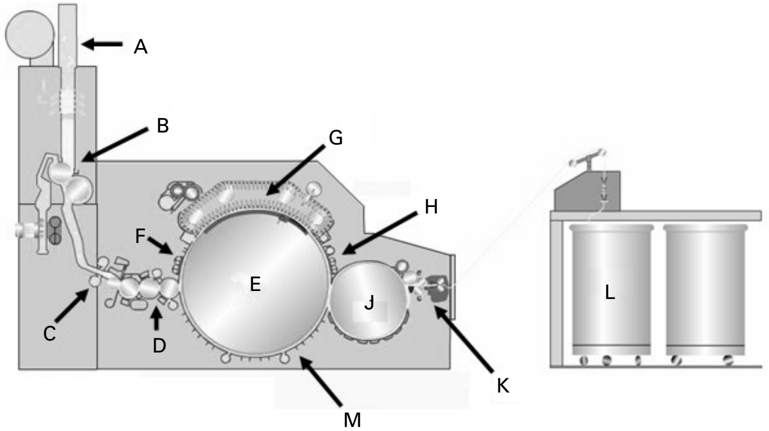
Carding involves:

- 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.

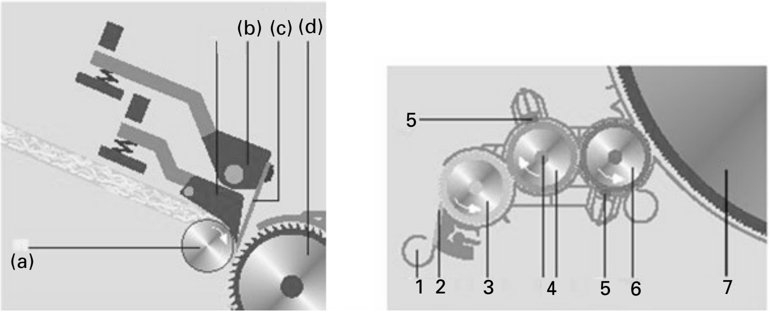
- Zone IV: the fibre mass transfer, the card web formation and consolidation; this includes a second fixed-flats cleaning system, H; a second cylinder, J, called a doffer, clothed with saw-tooth wire; a web doffing unit, K, and a sliver delivery and automatic sliver-can changing system, L. The angle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



Feed roller and feed plates

Triple taker-in system

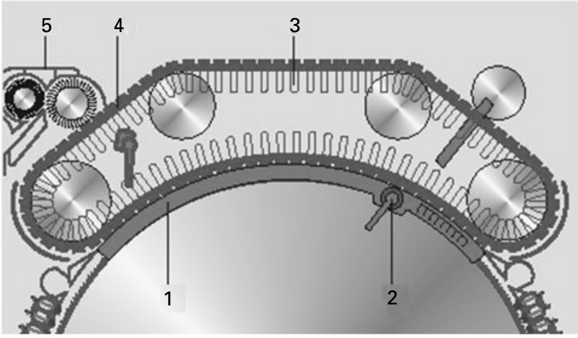
7.12 Main components of Zone II.

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 rmin^{-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.

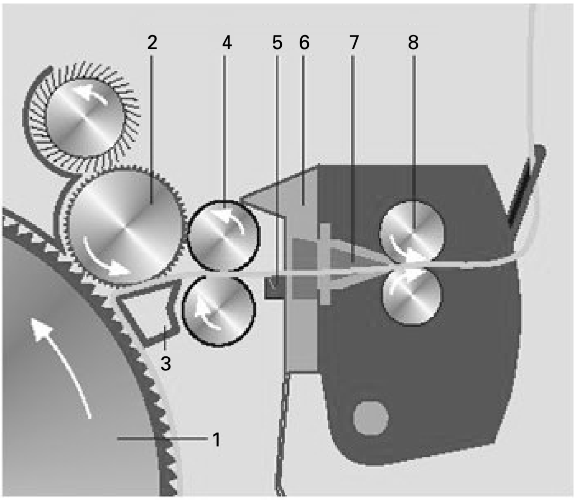
During carding, the motion of the cylinder clothing generates air turbulence that, along with mechanical forces, causes the trailing ends of fibres attached to the teeth of the cylinder clothing to vibrate rapidly and shake loose dust, trash particles and neps still remaining among the fibres. The fibre 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



1 – Doffer
2 – Web stripping rollers
3 – Web guide
4 – Crush rollers
5 – Card web
6 – Sliver forming unit
7 – Funnel
8 – Calender rollers

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

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

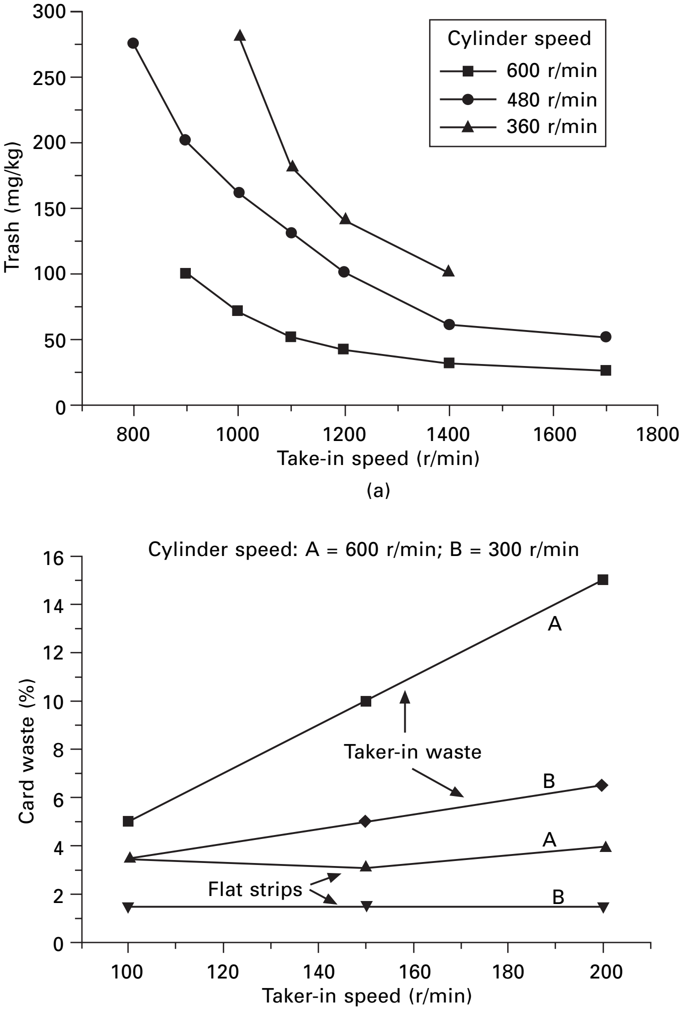
This is usually much lower than the fibre mass flow from Stage 2. For example, in processing a cotton with not too high a trash content, on average the production rate for the opening and cleaning line would be 500 kgh^{-1}, whilst the production rate of the card would be below 100 kgh^{-1}. In certain 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



(a)

(b)

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

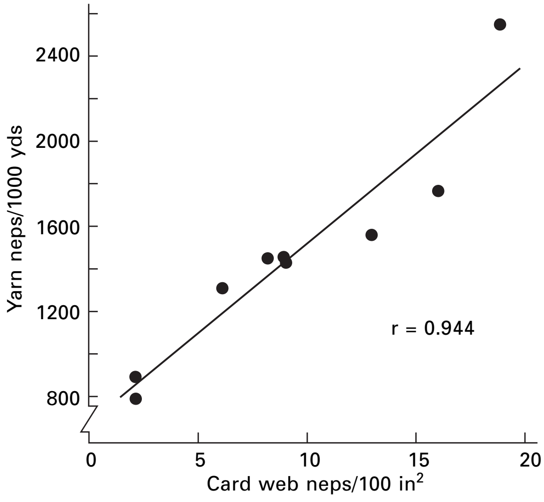
above 1500 r/min gives negligible improvement on sliver cleanliness but can lead to fibre breakage and increased waste.

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 prerequisite 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.

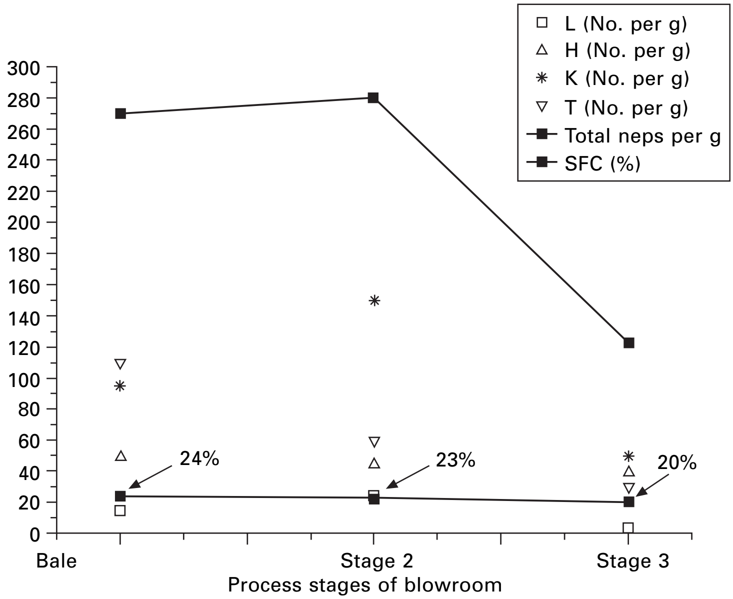
7.5.3 Short fibre content (SFC)

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'.



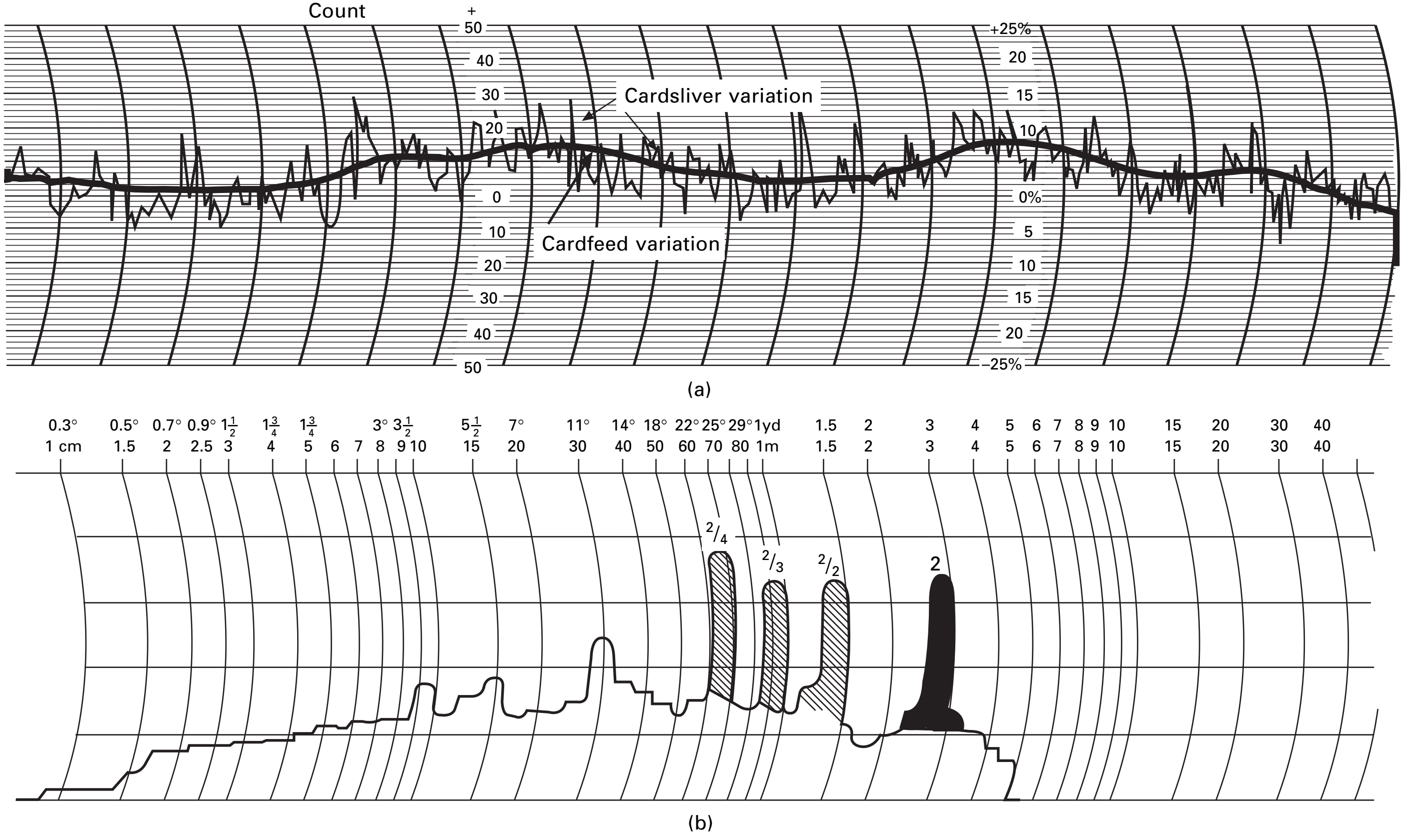
7.17 Changes in nep and SFC cotton fibre processing.

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

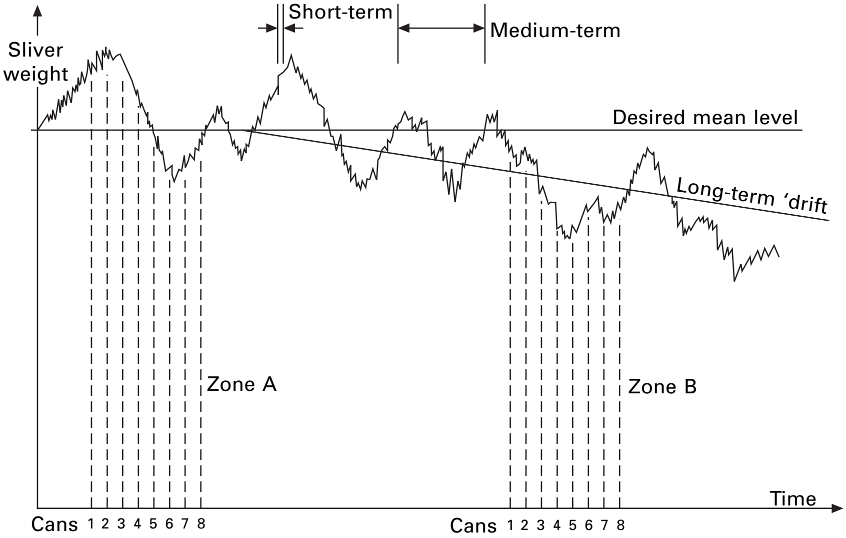
The Uster CV% of a sliver is a measure of the short-term irregularity of the sliver and is not therefore a useful predictive indicator for the Uster CV% of the yarn[28] This is because the short-term irregularity for a yarn is more dependent on the short-term variations introduced during post-carding 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

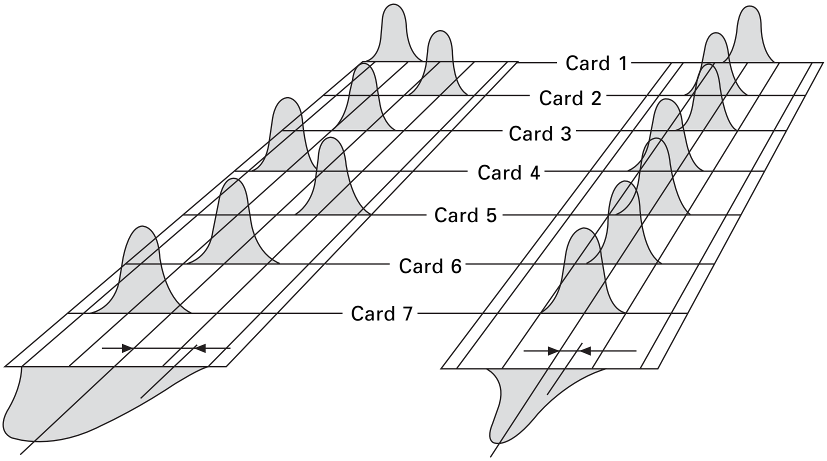
Figure 7.19 illustrates the medium- to longer-term variability of a sliver, that is to say the irregularity of a sliver length that comprises a full can of sliver and the variation between cans of sliver. The Uster CV% is not a measure of this variability. The CV% of sliver count measurements, made at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

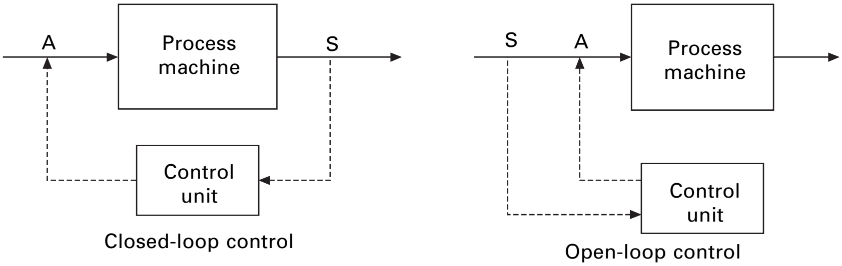


7.20 Count variations within and between cards.

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.

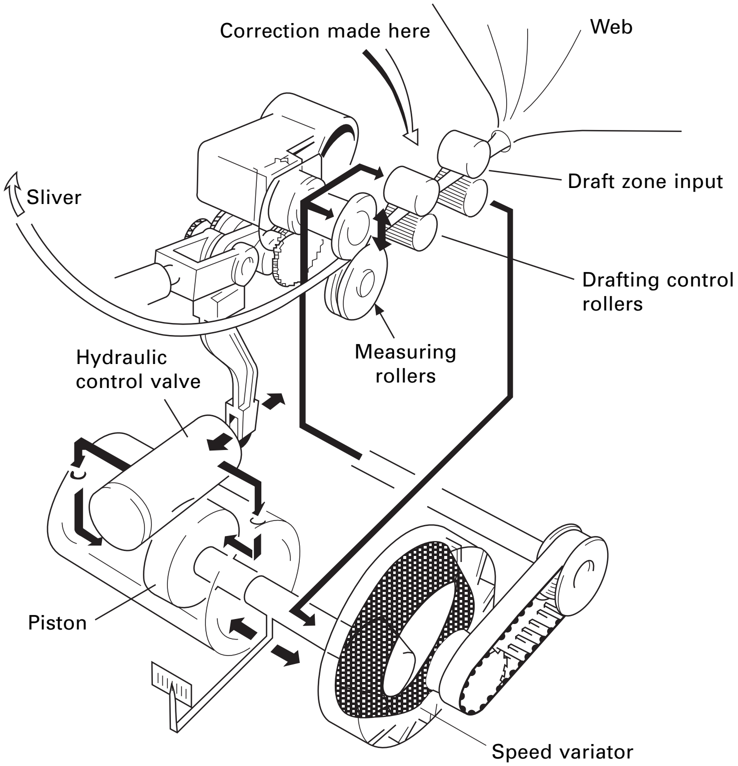


7.21 Closed-loop and open-loop control systems.

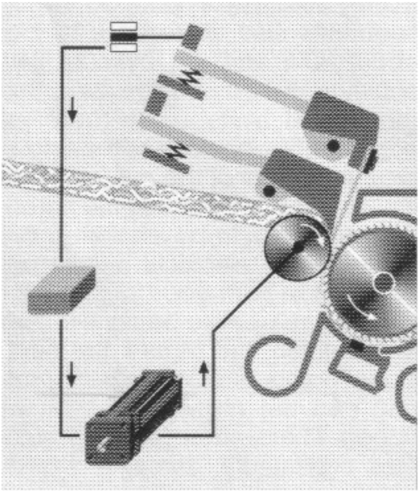
The open-loop system results in a quicker response time to the deliberate changes since the lag time of the carding process is avoided. However, there is no feedback from the output to ensure that corrections made achieve minimum variation of the output characteristics. Most autolevelling systems on 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.

7.6 References

1. Lee, J. K. and Kin, Y. S., Linear Programming for Cotton Mixing: *Computers in the World of Textiles*, The Textile Institute, Manchester, (1984) 90.
2. Szaloki, S. Z., *Opening, Cleaning and Picking*, Vol. I, The Institute of Textile Technology, Charlottesville, Virginia, USA, 1976, p 126.
3. Dehghani, A., Lawrence, C. A., Mahmoudi, M., Greenwood, B. and Iype, C., Fibre Dynamics in a Revolving-Flats Card: An Assessment of Changes in the State of the Fibre Mass During the Early Stages of the Carding Process., *J. Text. Inst*, 91, 359, 2000.
4. Feil, R. W., Fibre Separation and Cleaning on Cotton Card, *Melliand Textilberichte* (eng. edn) September, (1980), 1207–1213.
5. Saville, B. P., *Physical Testing of Textiles*, The Textile Institute and Woodhead Publishing Ltd, Chapter 2, 26–43, 1999.
6. Lawrence, C. A., *Fundamentals of Spun Yarn Technology*, Chap. 4, CRC Press, 2003.
7. Leifeld, F., Meeting the challenge of the future: the holistic approach, *International Textile Bulletin*, 4, 34–38, 1997.
8. Van Alphen, W. F, The Card as Dedusting Machine, *Melliand Textilberichte*, (Eng. edn) 12/80, 1523–1528, 1980.
9. The Textile Institute, *Textile Terms and Definitions*, 10th Edition.
10. Frey, M. and Schleth, A., (Zellweger Uster AG), *Examples of Data Acquisition for Fibres and the Application in the Spinning Mill*, 22nd International Cotton Conference Bremen, 2–5 March, 1–30, 1994.
11. Liefield, F., The Importance of Card Sliver Quality for the Running Behaviour and Yarn Quality in Unconventional Spinning Methods, *International Textile Bulletin, Yarn Forming*, 4, 1988.
12. Perkins, H. H. and Bargeron, J. D., Nep Forming on a Cotton Card – Honeydrew – Additives as a Means to Reduce Air-Borne Dust., *Melliand Textilberichte*, 2, 129–131, 1981.
13. Schleth, A., *Uster AFIS Nep Measurement on the way to Standardization, ITMF International Committee on Cotton Testing Methods*, Meeting of Working Group on Dust/Trash, March, 1–11, 1994.
14. Frey, Manfred, *(Rieter Spinning Systems) Practical Experience with New Cotton Measuring Methods*, 20th International Cotton Conference, Bremen, March 15–17, 1–16, 1990.
15. Leifeld, F., Meeting the challenge of the future: the holistic approach, *International Textile Bulletin*, 4, 34–38, 1997.
16. Uster News Bulletin, The Analysis of Faults in Yarns, No. 6, 1-7, August 1965.
17. Liefield, F., The Importance of Card Sliver Quality for the Running Behaviour and Yarn Quality in Unconventional Spinning Methods, *International Textile Bulletin, Yarn Forming*, 4, 1988.
18. Faufmann, D., Neps and Carding, *Textil Praxis* (English edn), 4, November, 151–156, 1957.

19. Harrison, R. E. and Bargeron, J. D., Comparison of Several Nep Determination Methods, *Textile Research Journal*, February, 77–79, 1986.
20. Ashdown, T. W. G. and Townend, P. P., The Effect of the Density of Card Clothing on the Carding Process, *Journal of Textile Institute*, 52, T171, 1961.
21. Wyatt, B. G. and Ethridge, M. D., Combining the Use of Overspray and Blending for Succesful Processing of Very Sticky Cotton, *Textile Topics, International Textile Centre*, Texas Tech. University, 2–4, 1996.
22. Booth, J. E., *Principles of Textile Testing*, Temple Press Books Ltd, London, 1964.
23. Futer, R., (Zellweger Uster AG), *Manual of Textile Technology, Evenness Testing in Yarn Production Part I*, The Textile Institute, (1982), ISBN 0 900739 48 7.
24. Futer, R., (Zellweger Uster AG), *Manual of Textile Technology, Evenness Testing in Yarn Production Part II*, The Textile Institute, (1982), ISBN 0 900739 49 5.
25. Dyson, E., Some Observations on Yarn Irregularity, *Journal of Textile Institute*, (1973), 215–217.
26. Felix, E., Analysing the Irregularity of Yarns, Rovings and Slivers by means of the Wave Length Spectrum, *The Textile Manufacturer*, August, (1955), 415–421.
27. Uster News Bulletin, *The Uster System of Evenness Testing*, No. 28, July (1980), 1–27.
28. Crosrol Technical Bulletin, Ref. T 80/02.
29. Catling, H. and Davis, I., Conservation of Mean Level in Autolevelling, *Shirley Institute Memoirs*, Vol, XXXIX, (1966), 27–47.
30. Szaloki, S. Z., *High-Speed Carding and Continuous Card Feeding*, The Institute of Textile Technology, Charlottesville, Virgina, USA, Vol. II, (1977) 152–175.

8

Cotton spinning technology

L HUNTER, CSIR and Nelson Mandela Metropolitan University, South Africa

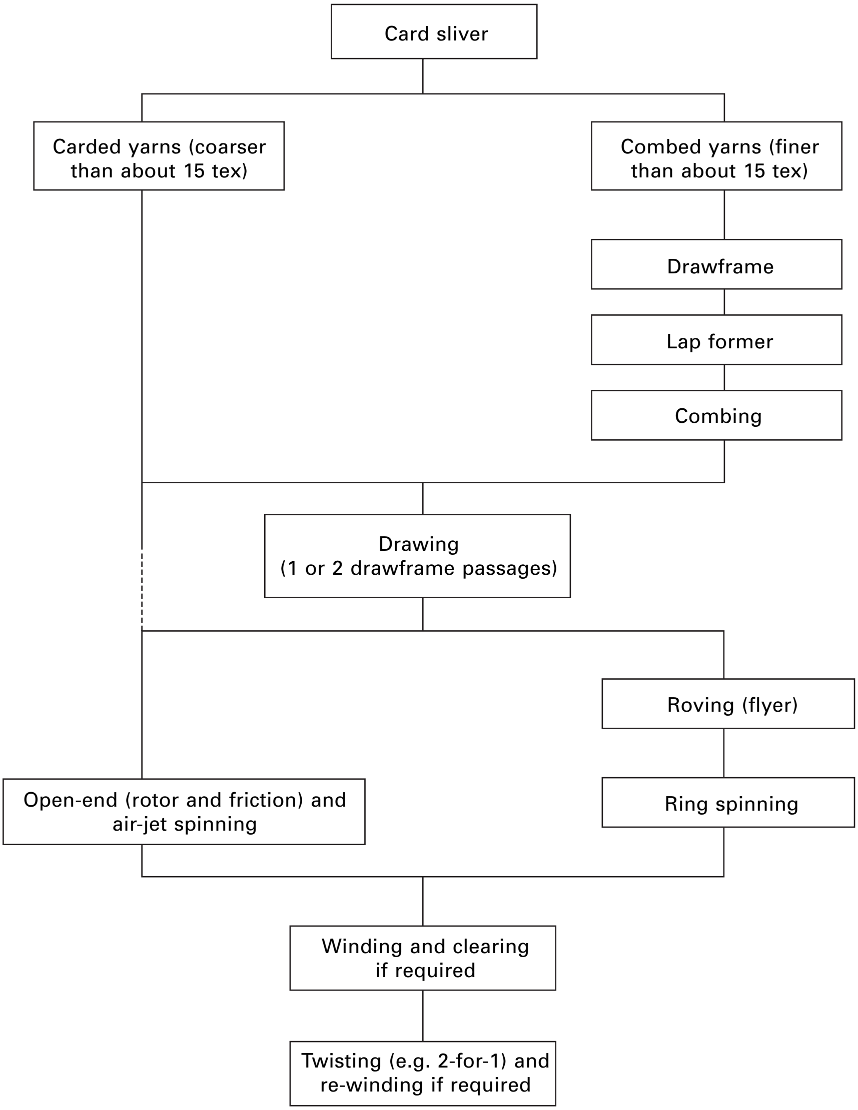
8.1 Introduction

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).

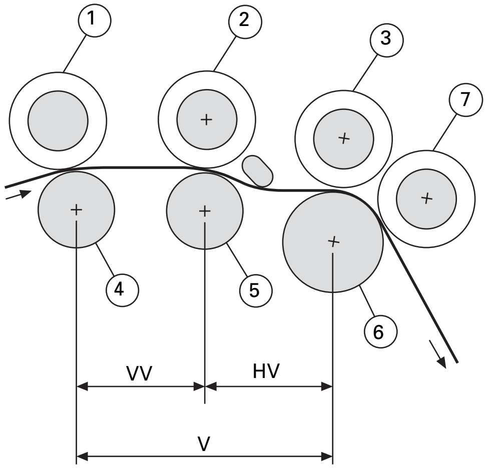
The latter effects the greatest change in sliver linear density.

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



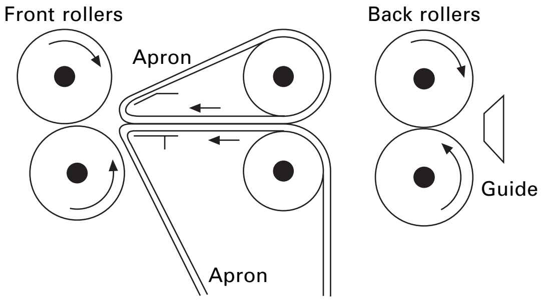
8.2 Roller drafting arrangement in the drawframe (source: Maschinenfabrik Rieter AG).

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:

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

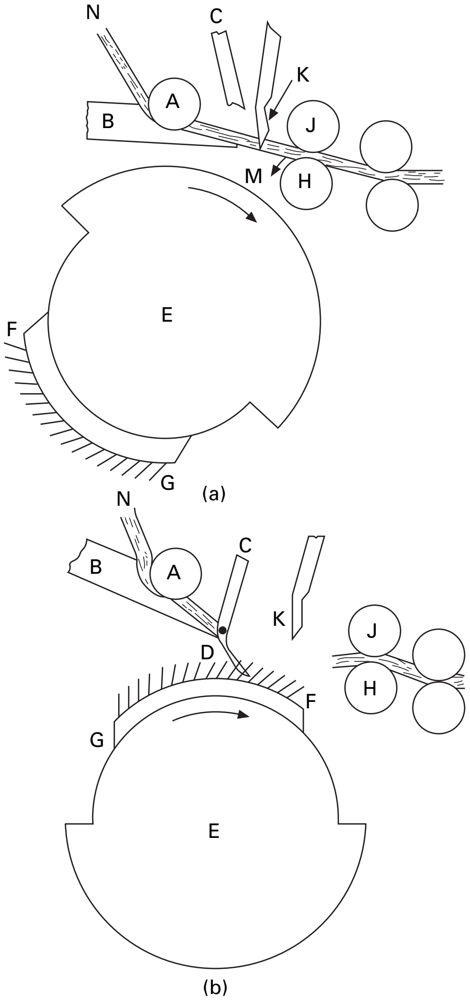
In preparation for combing, a number of drawframe slivers, are combined in a 'lap winder' to produce a comber lap consisting of a closely spaced sheet of slivers wound onto a cylindrical holder. The speed of the lap winder exceeds 100 m/min, with a draft of between two and four, the high doubling combined 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.

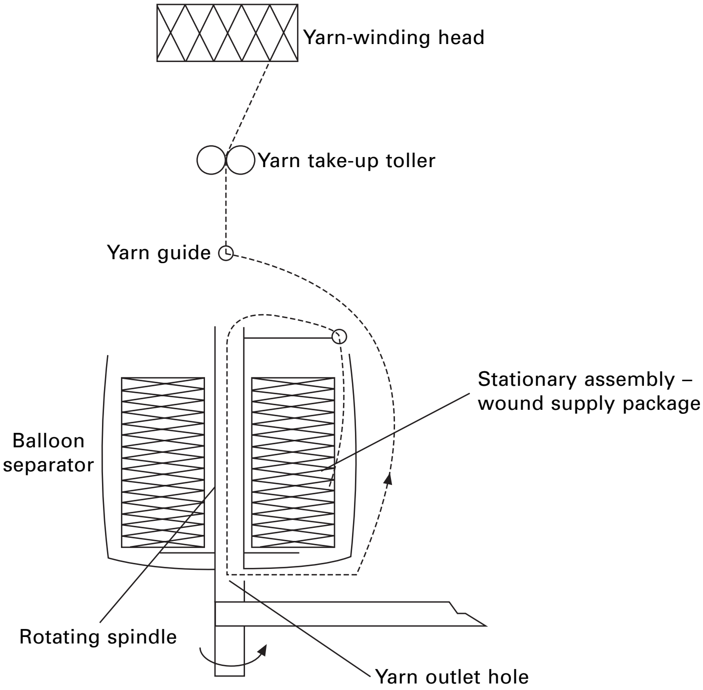


8.4 Cotton comb cycle of operations (side elevations) (a) feeding, final combing, and drawing-off (b) initial combing. A, feed roller; B, feed plate and lower nipper; C, upper nipper; D, fibre fringe initially combed ; E, cylinder; F, first row of pins; G, last row of pins; H, bottom detaching roller; 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:

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

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*

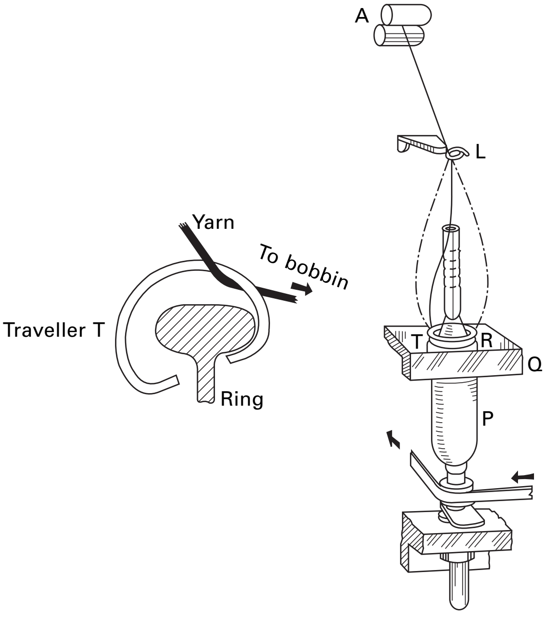
Property	Ring-spun yarn	Rotor-spun yarn	Friction-spun yarn	Air-jet-spun yarn
Tensile strength	Good	Lower than ring-spun yarn	Lower than ring- and rotor-spun yarn	Good
Evenness	Good	Very good to good	Satisfactory	Good
Imperfections	–	–	Fairly high	–
Hairiness	High	–	High	–
Snarling tendency	High	Low	Hign	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]

* $\alpha_{tex} = \text{turns/m}\sqrt{\text{tex}}$

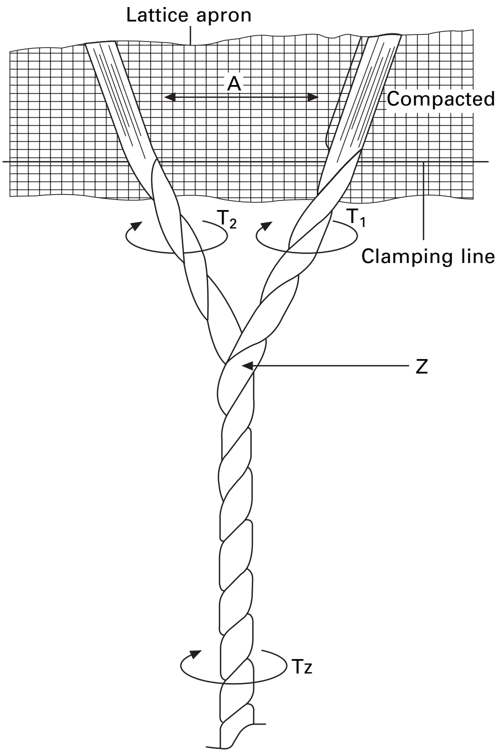
$$\alpha_e = \frac{\alpha_{tex}}{958}$$

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.

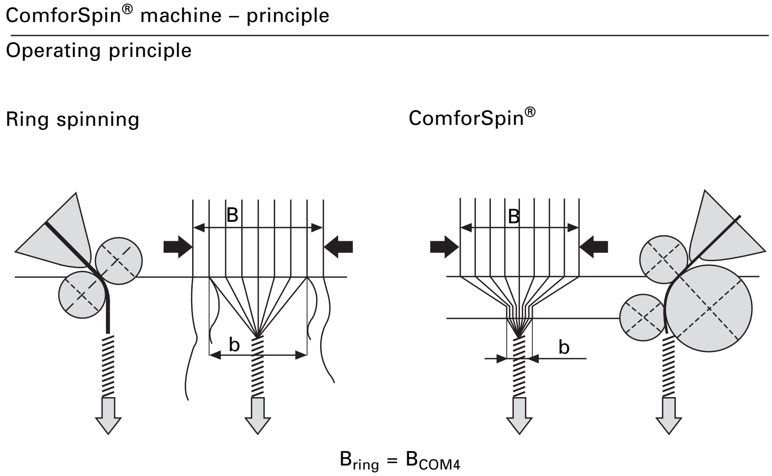


8.7 Two-strand spinning EliTwist (source: Ramasubbu, Spindelfabrik Suessen GmbH).

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.

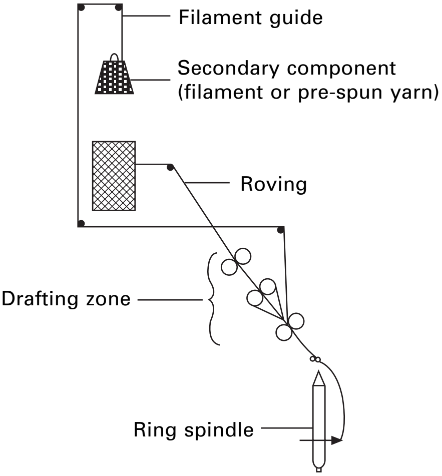


8.8 Compact spinning (Maschinenfabrik Rieter AG).[27]

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:

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

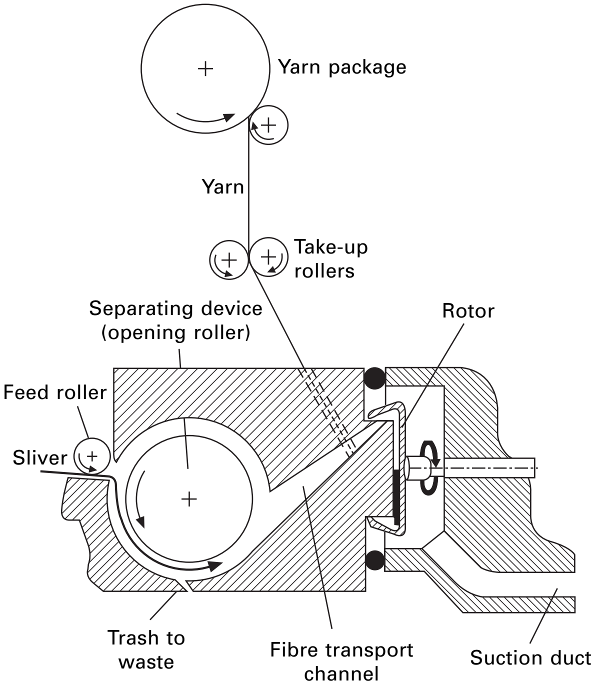
where D = rotor diameter (m). Assuming the following typical values: D = 0.04 m, B = 12 km (or gf/tex), and S = 1.5, we have $n_{\max}$ = 190,000 rev/min.

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.

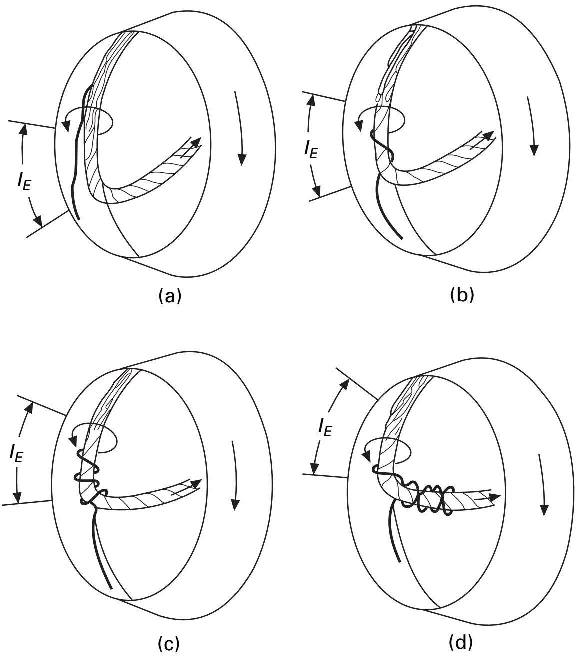
The yarn formed rotates around its own axis and is withdrawn through a specially designed navel (doffing tube) one turn of twist being inserted per rotor revolution, twist running from the rotating yarn to the fibres lying in the rotor groove (Fig. 8.10). The twist inserted can be calculated as follows:

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

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.

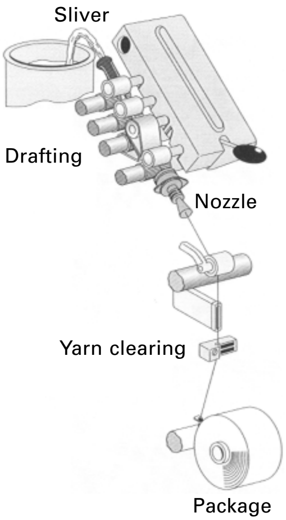
Automation (rotor cleaning, piecing and doffing) has reached high levels in rotor spinning, with on-line yarn quality monitoring (including long-term yarn linear density variations) and fault classifying and clearing, using optical or capacitance systems, as well as waxing taking place during spinning. 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.

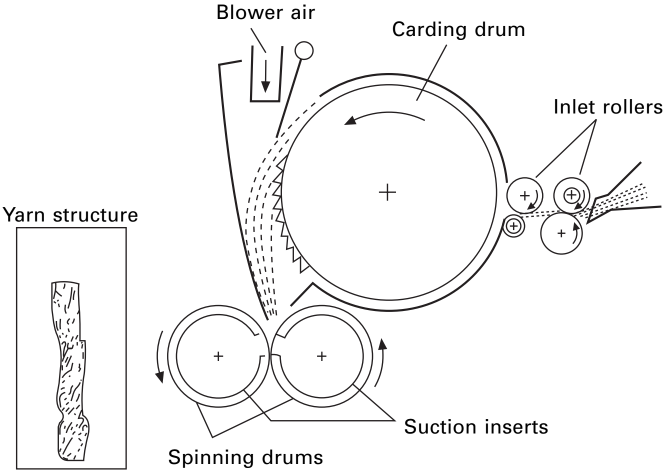
In friction spinning, twist is inserted into the yarn by a rolling action due to frictional forces generated between, for example, two perforated rollers and the yarn surface, it being relatively easy to produce core-spun yarns by introducing a filament yarn which is then wrapped by a sheath of staple 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]

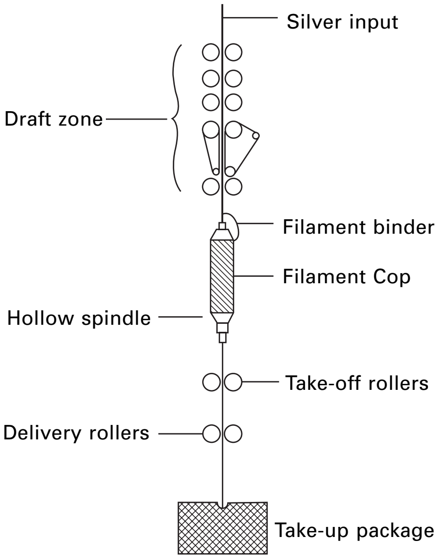
8.5.10 Wrap (hollow spindle) spinning

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 ($\mathrm{CV_L}$), assuming completely random distribution of fibres, can be calculated as follows:

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

where $\mathrm{CV_D}$ 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:

$$I = \frac{\mathrm{CV}(\%)}{\mathrm{CV}_\mathrm{L}} \qquad 8.10$$

For cotton this becomes:

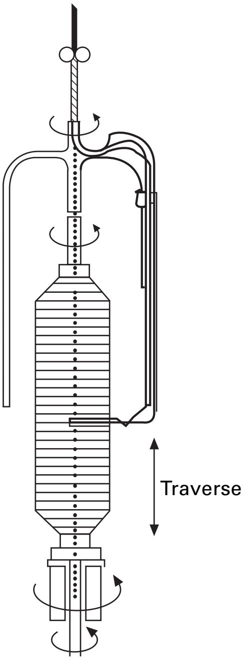
$$I = \frac{\mathrm{CV}(\%)\sqrt{n}}{106} \qquad 8.11$$

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.



Flyer spinning

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

1. Grosberg, P. and Iype, C., *Yarn Production: Theoretical Aspects*, The Textile Institute, Manchester UK, 1999.
2. Lord, P.R., *Handbook of Yarn Production: Technology, Science and Economics*, The Textile Institute, CRC Press and Woodhead Publishing Ltd, 2003.

3. Klein, W., *Manual of Textile Technology: Short-staple Spinning Series*, Vol 1 (2nd edn), *The Technology of Short-staple Spinning*, The Textile Institute, Manchester 1998.
4. Oxtoby, E., *Spun Yarn Technology*, Butterworths & Co., London, 1987.
5. Ishtiaque, K.R., Salhotra, K.K. and Gowda, R.V.M., Friction Spinning, *Text. Progr.*, 2003, **33** (2).
6. Klein, W., *Manual of Textile Technology: Short-staple Spinning Series*, Vol 5, *New Spinning Systems*, The Textile Institute, Manchester 1993.
7. Artzt, P., Short Staple Spinning: Quality Assurance and Increased Productivity, *ITB Int. Text Bull*, 2003, **49** (6), 10.
8. Lord, P.R. and Grover, G., Roller Drafting, *Text. Progr.*, 1993, **23** (4).
9. Hunter, L., *Wool*: *Science and Technology*, (Simpson, W.S. and Crawshaw, G.H. (eds)), The Textile Institute and Woodhead Publishing Ltd, 2002, Chapter 6, 160.
10. Basu, A., Progress in Air-Jet Spinning, *Text. Progr.*, 1997, **29** (3).
11. Shaw, J., Short-staple Ring-spinning, *Text. Progr.*, 1980, **12** (2).
12. Lawrence, C.A. and Chen, K.Z., Rotor Spinning, *Text. Progr.*, 1981, **13** (4).
13. Hunter, L., The Production and Properties of Staple-fibre yarns made by Recently Developed Techniques, *Text. Progr.*, 1978, **10** (1/2).
14. Barella, A. and Manich, A.M., Yarn Hairiness: A Further Update, *Text. Progr.*, 2001, **31** (4).
15. Rowe, T. (ed.), Busby, K.P., Halfpenny, J.R. and Holmes, D.A., *An Introduction to Textiles Volume II – Yarns*, (Comett, Eurotex), School of Textile Studies, Bolton Institute, UK.
16. Klein, W., *Manual of Textile Technology: Short-staple Spinning Series: Vol 4, A Practical Guide to Ring Spinning*, The Textile Institute, Manchester.
17. Das, A., Ishtiaque, S.M. and Kumar, R., Study on Drafting Force of Rovings: Part I – Effect of Process Variables, *Indian J. Fibre & Text. Res.*, 2004, **29** (2), 173 Part II – Effect of Material Variables, 2004, **29** (2), 179.
18. Stalder, H., Short Staple Spinning Systems: Possibilities and Limitations, *Text Month*, 1984 Sept, 12.
19. Deussen, H., Cotton's Role in the New Technologies, *Text Month,* 1984 Nov, 41.
20. Booth, J.E., *Textile Mathematics*, Vol II, The Textile Institute, Manchester, UK, 1975, 350.
21. Tang, Z-X, and Wang, X., Distribution of Power Requirements during Yarn Winding in Ring Spinning, *Text. Res. J.*, 2004, **74** (8), 735.
22. Stalder, H., High Performance Ring Spinning, *Mell. Textilber.,* 1991, **72** (8), E245, 585.
23. Anon., The Long and the Short of it: Continuing the Search for 'New' Spinning Systems, *ITS Textile Leader*, 1994, 15/94, 51.
24. Krifa, M. and Ethridge, M., Dean, A Qualitative Approach to Estimating Cotton Spinnability Limits, *Text. Res. J.*, 2004, **74** (7), 611.
25. Ramasubbu, S., EliTe® Compact Spinning System – A User's View, *Spinnovation*, 03/2005, No. 21, 17.
26. Stalder, H., ComforSpin® – A New Spinning Process, *African Text.*, 2000 April/ May, 16.
27. Anon., ComforSpin® Machine K44, Competence in Compacting, *Rieter Brochure*, 2005.
28. Anon., IWS Wool Profiles, Training Programme, 1988.
29. Brandis, C., Physical Limits to Spinning, *Int. Text. Bull. Spinning*, 1975, (2), 257.
30. Ishida, T., Manual of Textile Technology (Series 2), *JTN Monthly*, 1996 Feb., No. 495, 108.

31. Lünenschloss, J. and Kampen, E., Einfluss von Zahl und Formierung der 'Bauchbinden' auf die Eigenschaften rotorgesponnerer Garne, *Text. Praxis Int.*, 1976 Nov., **31** (11), 1274.
32. Egbers, G., The Future of Spinning and Weaving, *Mell. Int.*, 1999, **5** (1), 8.
33. Kadoglu, H., Influence of Different Rotor Types on Rotor Yarn Properties, *Mell. Textilber.* (English), 1999, **80** (3), E36, 130.
34. Murata (Muratec) *Air-jet Spinning Brochure*.
35. Zeng, Y.C., Wan, Yu-Qin and Yu, C.W., Controlling the Air Vortex Twist in Air-Jet Spinning, *Text. Res. J.*, 2005, **75** (2), 175.
36. Zeng, Y.C., Wang, K.F. and Yu, C.W., Predicting the Tensile Properties of Air-Jet Spun Yarn, *Text Res. J.*, 2004, **74**(8), 689.
37. Wulfhorst, B., Future Development of Textile Processes, *Mell. Textilber*. (English), 2000, **81** (11-12), E218, 923.
38. Nierhaus, W., Theory and Practice of Modern Spinning Methods, *Text Month*, 1986 Dec., 18.
39. Martindale, J.G., A New Method of Measuring the Irregularity of Yarns with Some Observations of the Origins of Irregularities in Worsted Slivers and Yarns, *J, Text. Inst.*, 1945, **36**, T35.
40. Lorenz, R.R.C., Yarn-twisting, *Text. Progr.*, 1984, **16** (1/2).

9

Cotton knitting technology

N UÇAR, Istanbul Technical University, Turkey

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]

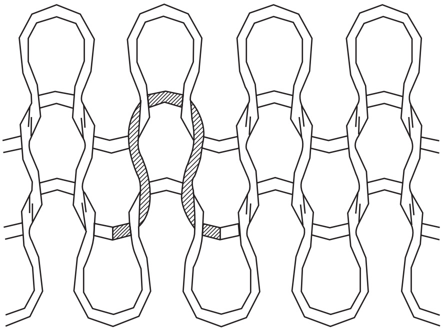
9.2 Terms used in knitting technology

9.2.1 Terms used in weft knitting technology

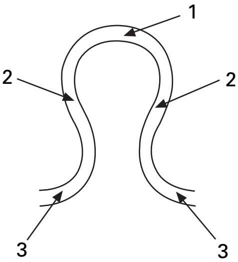
Stitch: stitch is the smallest unit in knitted fabric. A knitted fabric surface is formed by repeating it, side to side and one on top of the other (see Fig. 9.1). It consists of loop head, loop leg and loop feet (see Fig. 9.2).

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).

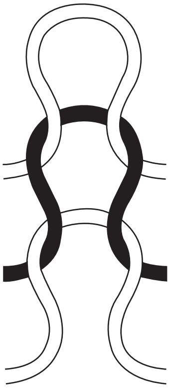
Purl stitch (reverse stitch): this is the technical reverse of the stitch where loop legs are below the neighbour stitch and the loop head is above the neighbour stitch (see Fig. 9.4). The reverse of a plain stitch (see Fig. 9.3) is the purl sititch (see Fig. 9.4).



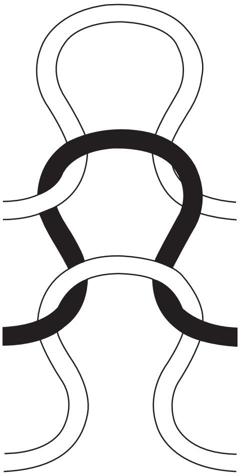
9.1 Knitted fabric surface.



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



9.3 Plain stitch.

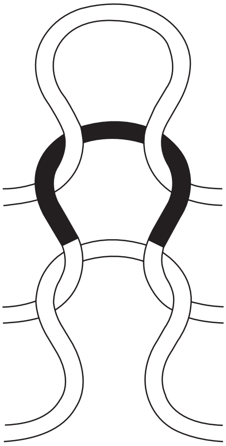


9.4 Purl stitch.

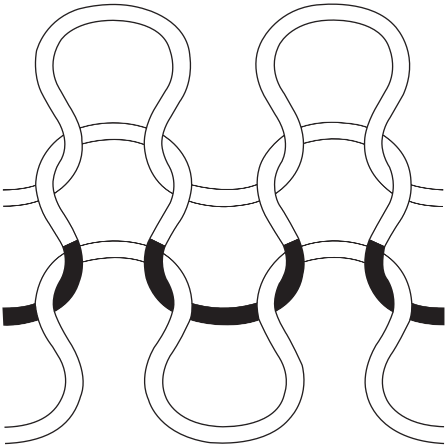
Needle loop: this is the part of the stitch which is composed of loop head and loop leg (see Fig. 9.5).

Sinker loop: this is the part of the stitch which is composed of loop feet belonging to neighbouring stitches (see Fig. 9.6).

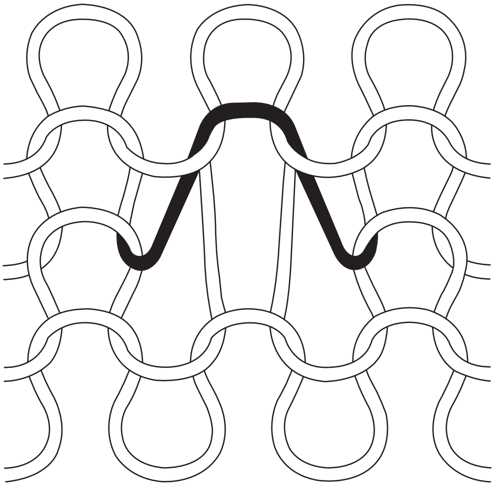
Tuck stitch: this is the stitch which has the reverse V shape. The loop head of a tuck stitch together with the previous loop head are held by the feet of the following stitch (see Fig. 9.7). Normally, a tuck stitch with more than four successive tucks on the same needle should not be used due to high 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.

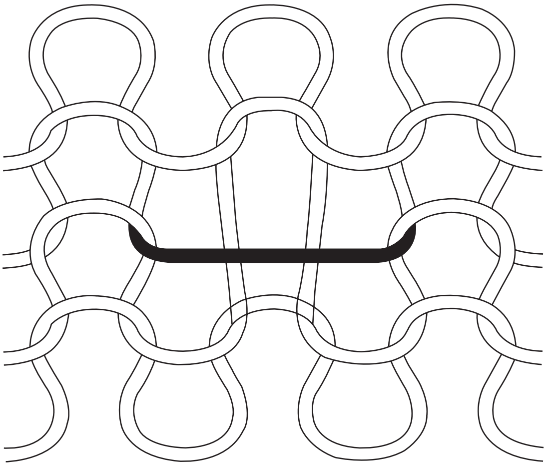


9.7 Tuck stitch.

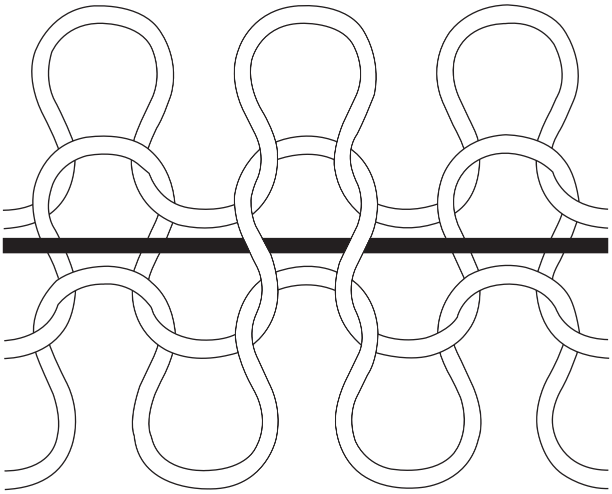
widthwise elasticity and width of the fabric. It also increases the fabric thickness and needs theoretically less yarn.

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.



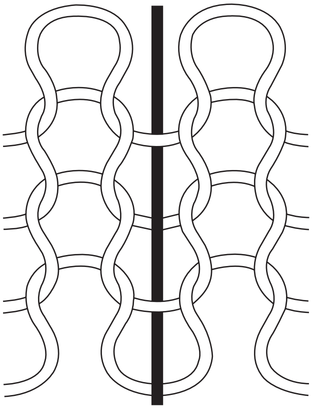
9.9 Weft.

Filler: this is the yarn length which lies between successive sinker loops in the vertical direction (see Fig. 9.10).

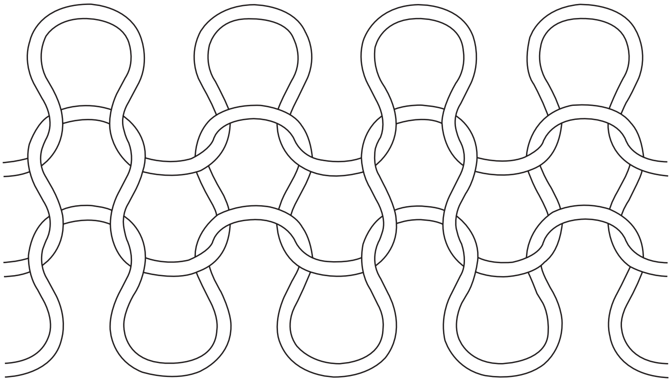
Single jersey fabric: this is a fabric structure produced using a single needle bed. It can contain knit, tuck and float stitch structures in the fabric. One side of the fabric displays only plain stitch, while the other side of the fabric displays only purl (reverse) stitch (see Figs 9.1, 9.7, 9.8).

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).

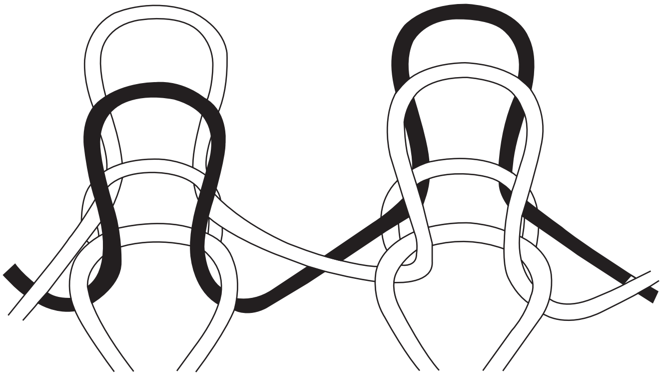
Course: this is a horizontal row of stitches produced by adjacent needles during the same knitting cycle (see Fig. 9.14).



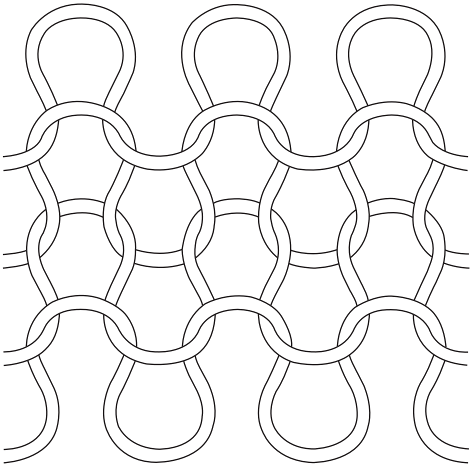
9.10 Filler.



9.11 Rib fabric 1 × 1.



9.12 Interlock fabric 1 × 1.



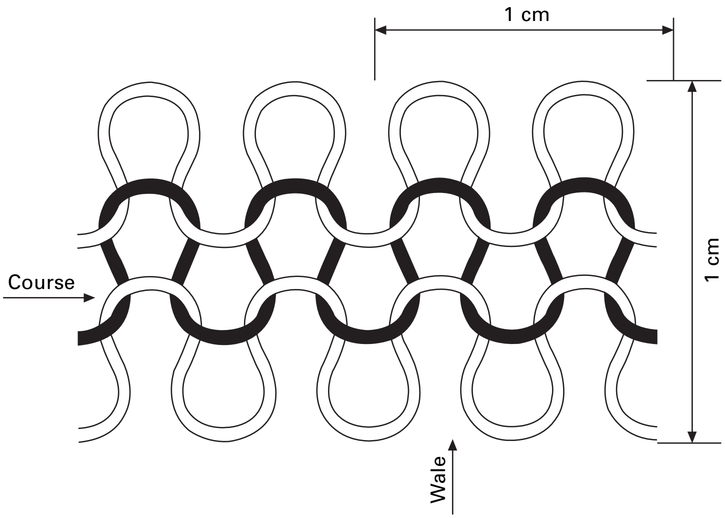
9.13 Purl fabric 1 × 1.

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.

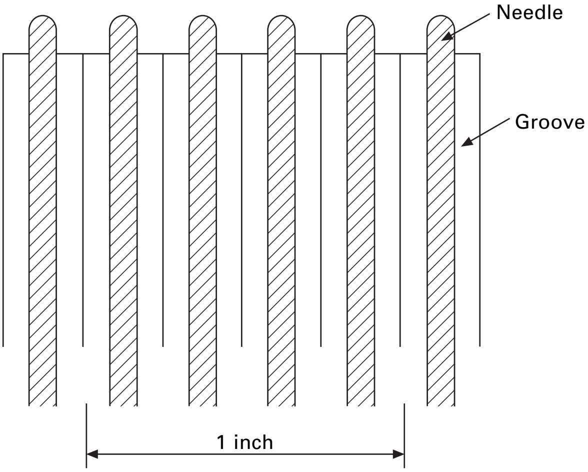
Stitch density: this is a product of course density and wale density. It gives a total number of stitches in a square area of fabric. Stitch density tends to give more accurate measurement for fabric dimensions compared



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.

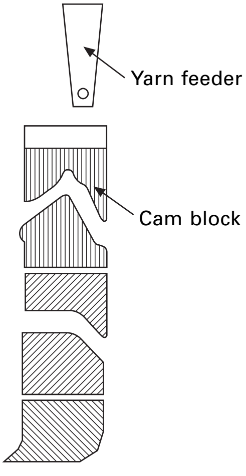
Machine pitch: This is the distance between two neighbouring needles.

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).

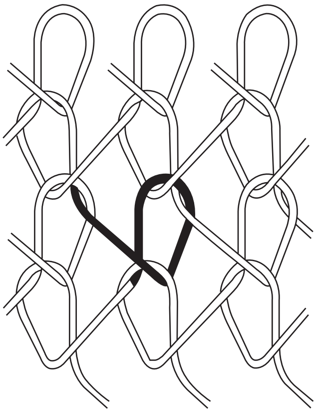
9.2.2 Terms used in warp knitting technology

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.

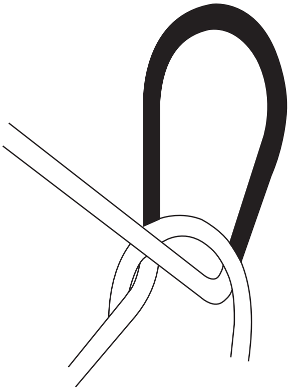
Underlap: this is the other section of stitch in a warp knitted fabric. The yarn is horizontal and appears at the back of the fabric (see Fig. 9.19). It can cover 14 needle spaces or more depending on the design of machine and fabric.

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

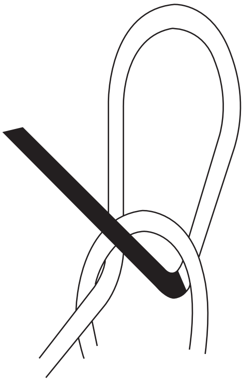
Closed lap: if an overlap and the next underlap are made in opposite directions to each other, a closed lap is then produced (see Fig. 9.21). A



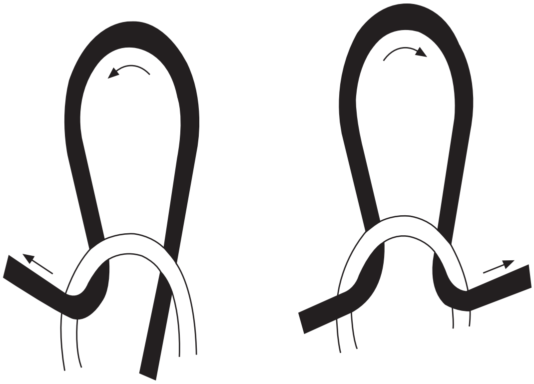
9.17 Warp knitted fabric.



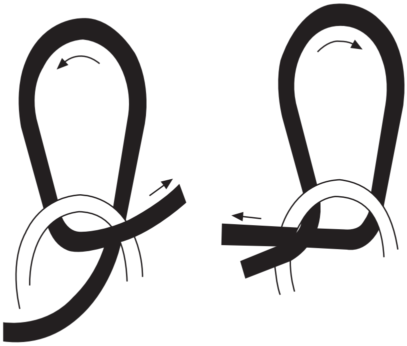
9.18 Overlap.



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.

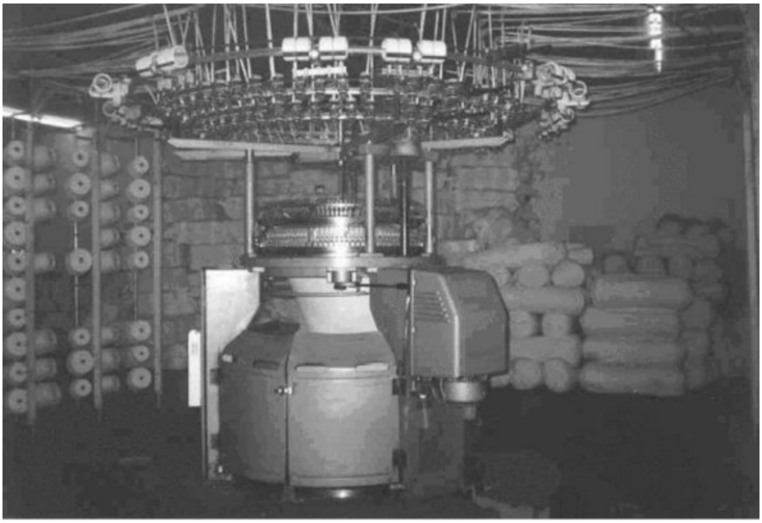
- Production rates in circular knitting are generally higher than flat knitting, due to higher velocity and higher number of knitting (cam) systems.
- Flat knitting machines have more versatility than circular knitting machines. More complex fabric designs can be produced by flat knitting machines.
- 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

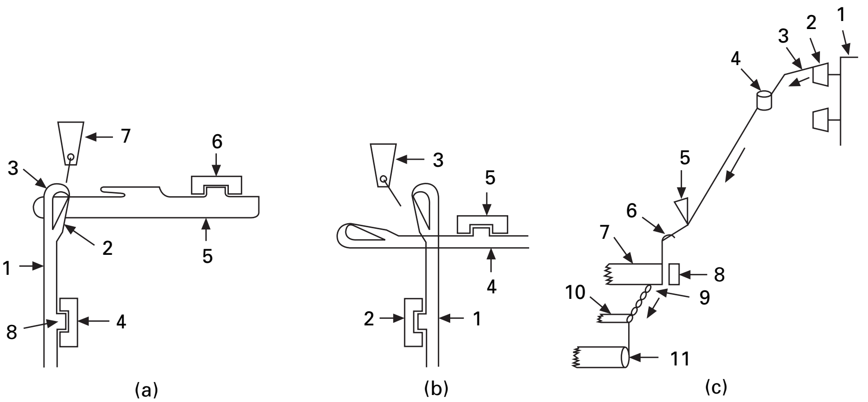
In circular knitting (Fig. 9.22), the machine gauges and the machine diameters range from 4 to 32 needles per inch and 8 to 48 inches in diameter, respectively. They can run at the speeds of 76 rpm and may have up to 132 yarn feeders.[1,2]

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.

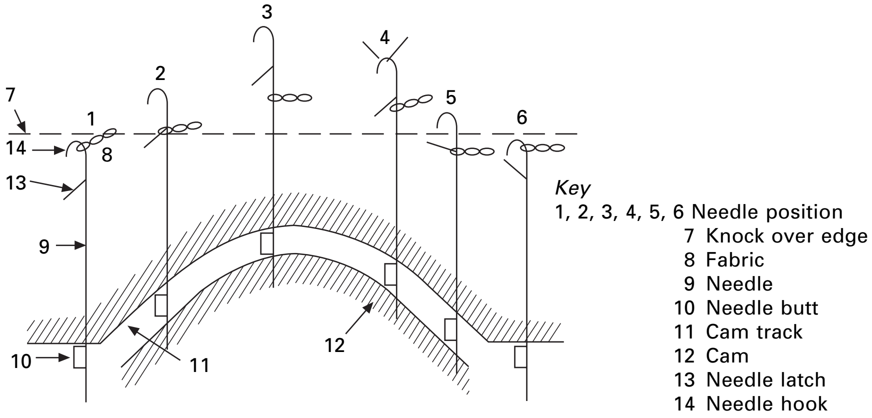
Stitch formation

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:

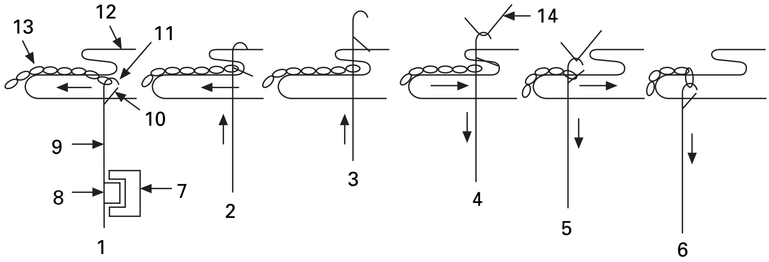
1. Rest position. The needle is in rest position with the needle positioned outside the cam. The sinker moves towards the machine centre (1st position in Figs 9.24 and 9.25).

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



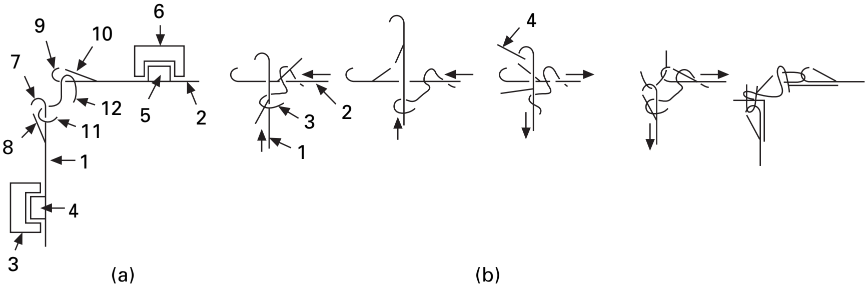
9.24 The needle position in cam track.



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.



(a) (b)

Key

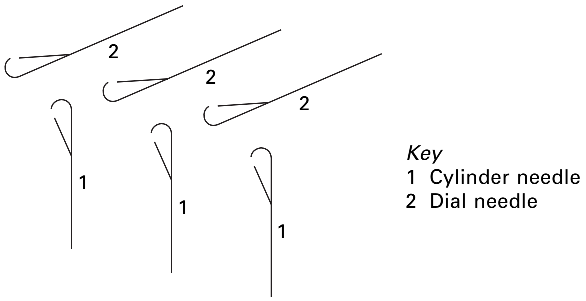
1	Cylinder needle
2	Dial needle
3	Cylinder cam
4	Cylinder needle butt
5	Dial needle butt
6	Dial cam
7	Cylinder needle hook
8	Cylinder needle latch
9	Dial needle hook
10	Dial needle latch
11	Cylinder stitch
12	Dial stitch

Key

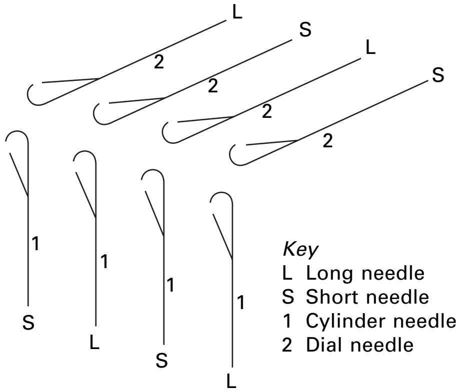
1	Cylinder needle
2	Dial needle
3	Fabric
4	Yarn

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



9.27 Rib setting (gating).



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.

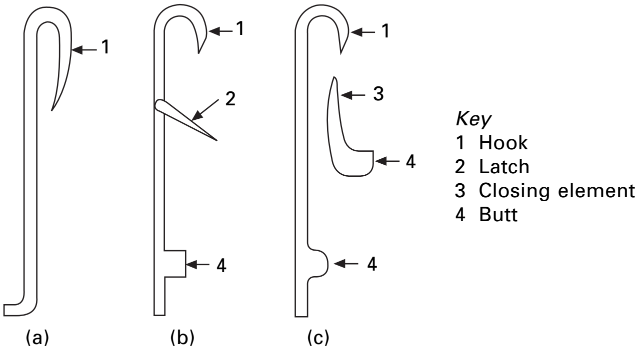
The coordination between the cylinder and the dial cams can be classified into three groups, the synchronised timing, the delayed timing and the advanced timing. At the synchronised timing, the cylinder and the dial needle are pulled down at the same point of the cylinder cam and the dial cam. This timing 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

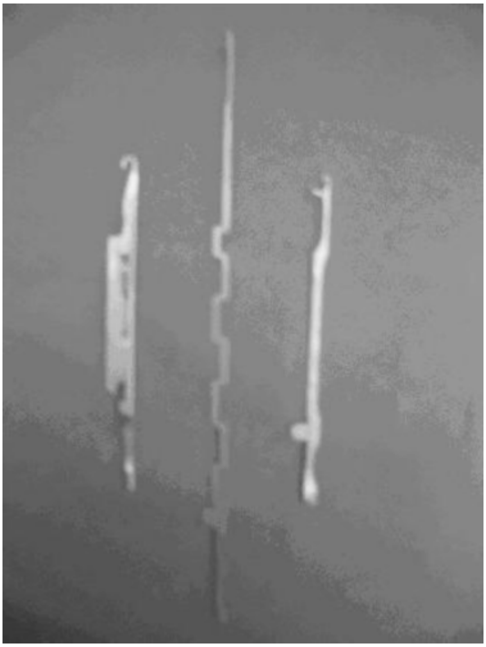
Needle: on circular knitting machines, latch and compound needles are generally used, while bearded needles are seldom used (see Fig. 9.29). They have different shapes and dimensions depending on the machine type and the fabric design. They are generally controlled by the needle cam. The hook of a bearded 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.

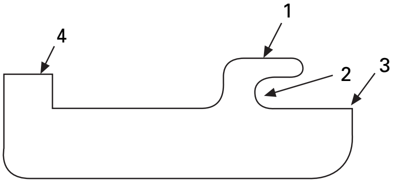
Cam: the cam controls the movement of the needle or sinker (holding down-knocking over). Basic and simple fabric designs can be produced by using just the cam block, however, complex fabric designs need different needle control systems such as pattern wheel, pattern drum or electronic selection devices,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

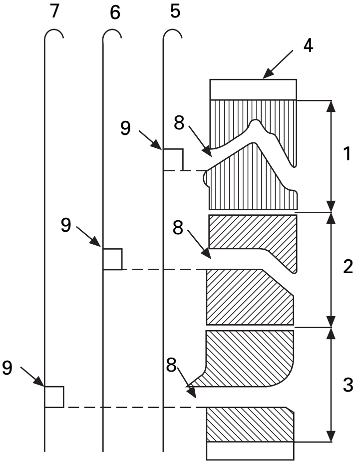


Key
1 Nib
2 Throat
3 Knock-over edge
4 Butt

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

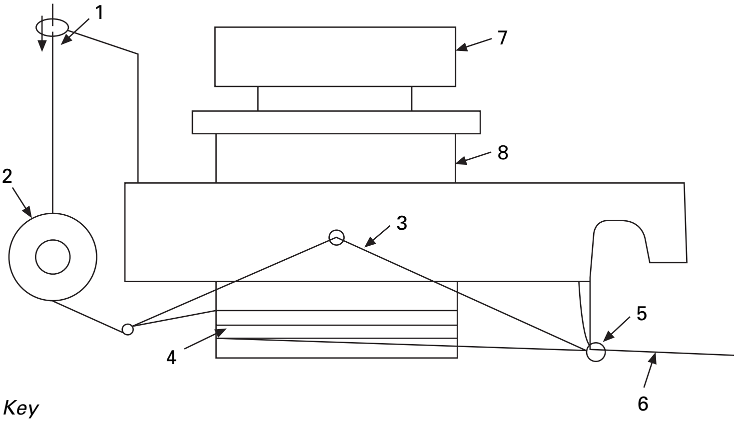
1	Knit cam for stitch
2	Tuck cam for tuck stitch
3	Miss cam for float stitch
4	Cam block
5, 6, 7	Needle with different butt position
8	Cam track
9	Needle butt (needle 5 moves through cam 1 to produce a stitch, needle 6 moves through cam 2 to produce tuck stitch and needle 7 moves through cam 3 to produce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

9.32 Illustration of changeable cam.

9.33 Changeable cam.

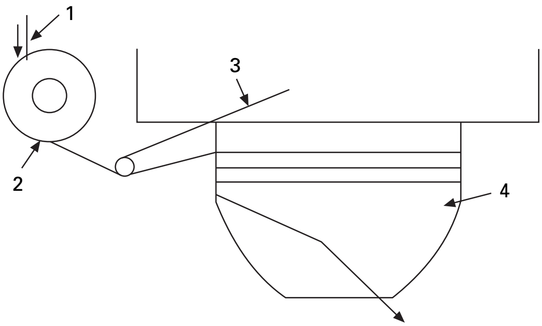
a large pattern area and most of the feeders have varying yarn consumptions per unit time (see Fig. 9.35).

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.

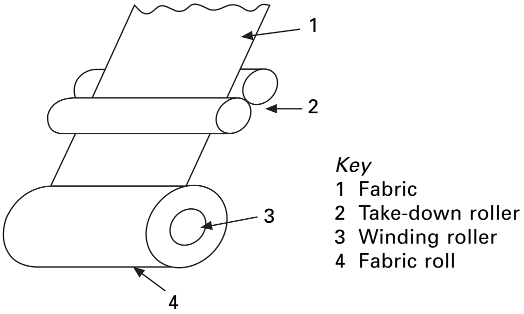


Key
1 Yarn
2 Yarn brake system
3 Yarn feeler (yarn knock-off device)
4 Yarn coiler

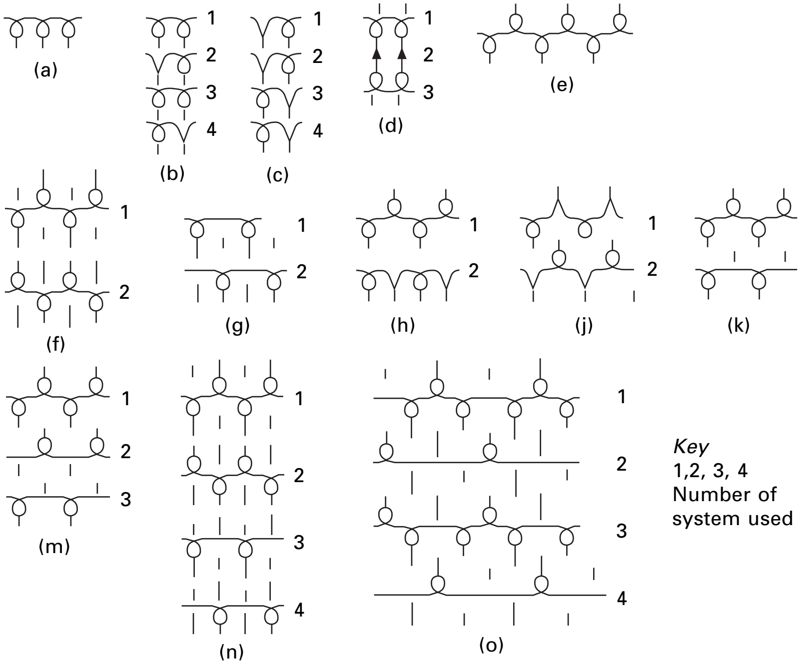
9.35 Negative yarn delivery system.

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

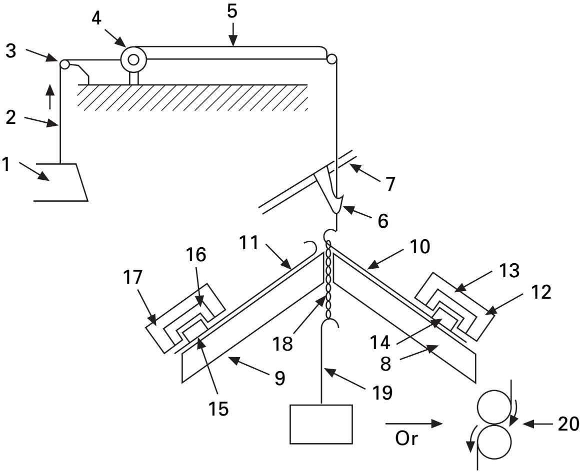
9.38 V bed flat knitting machine.

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



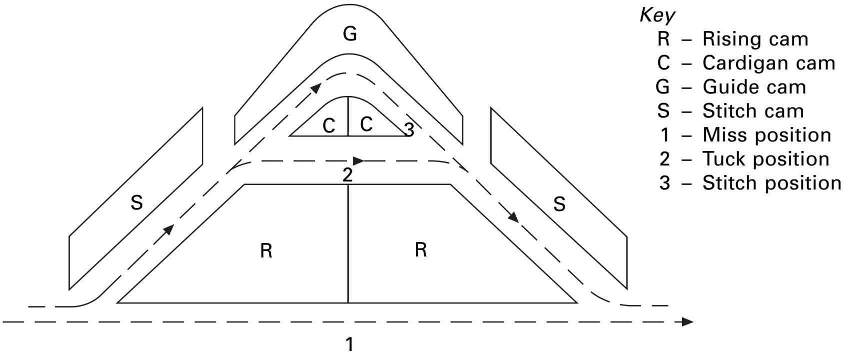
Key

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

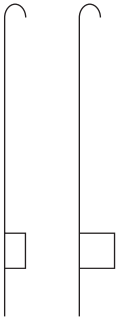
9.39 Illustration of hand-operated V bed flat knitting machine.

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.

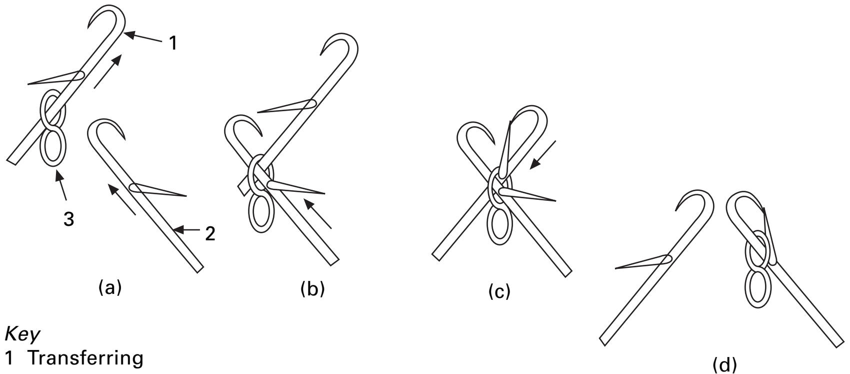
active or inactive position. If it is in the active position, both needle types (short and long butt) are raised by the cardigan cam (position 3 in Fig. 9.40), if it is in the inactive position, both needle types stay in the tucking position. If it is in the semi-active position, the needle with a long 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



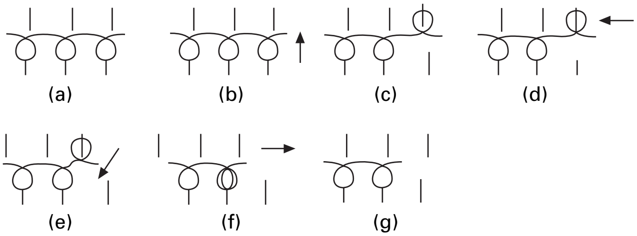
Key
1 Transferring needle
2 Receiving needle
3 Fabric

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.

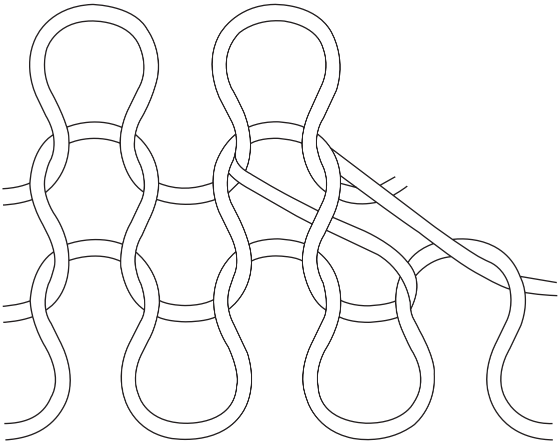
different fabric designs. As seen from Figs 9.43 and 9.44, a loop has been transferred from the front needle bed into a needle on the rear needle bed (see Figs 9.43(b) and 9.43(c)). Then, the rear needle bed is racked sideways by one needle space (see Fig. 9.43(d)). A loop on the needle at the rear needle 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.

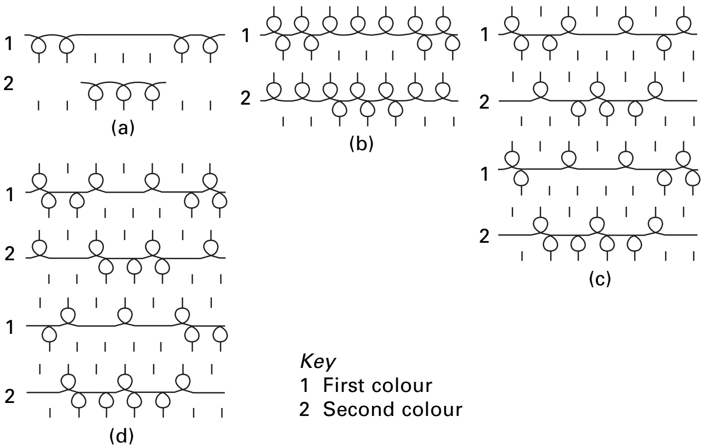
whole garment design, etc., can be produced on flat knitting machines. Figure 9.45 gives the stitch diagrams of two-colour jacquard fabric with a different fabric design on the back (horizontally striped backing, vertically striped backing, birds eye backing, miss backing).

9.4.3 Properties of basic weft knitted fabrics

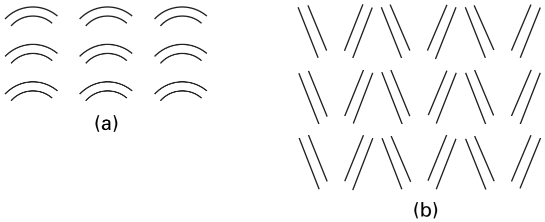
There are four primary structures; plain, rib, purl and interlock, from which all weft knitted fabrics are derived. The main properties of these fabrics are described below.

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.

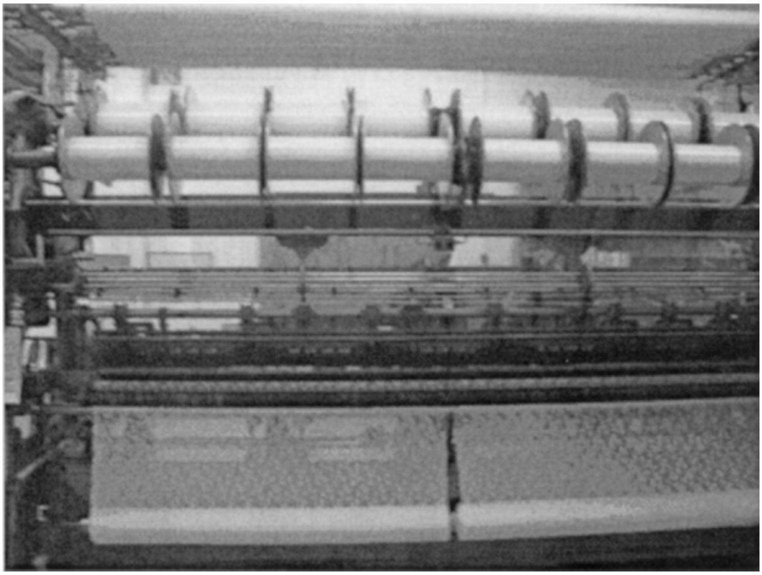
Purl knit fabric

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]

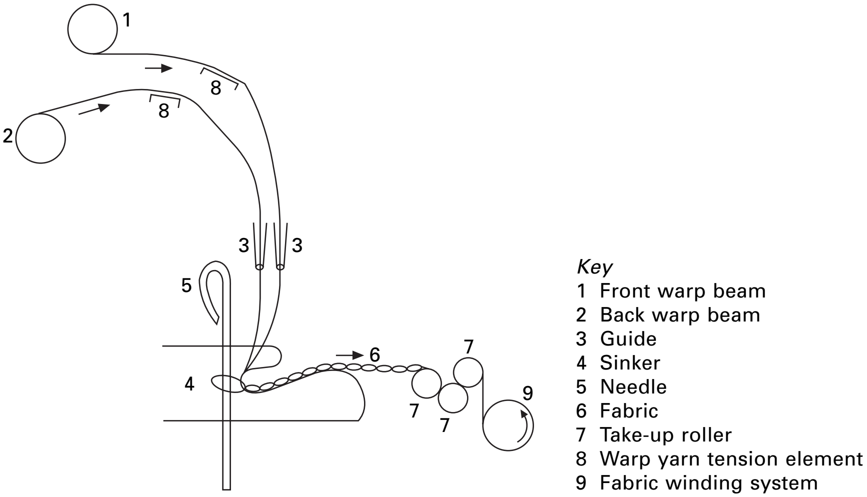
Main machine parts

Needle

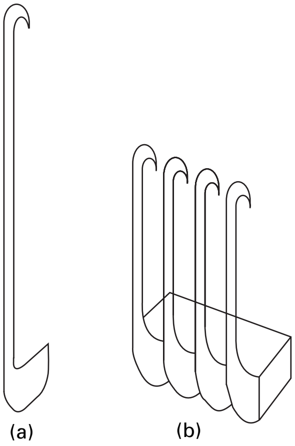
Nowadays, compound needles are widely used on Tricot machines. The main part of the needle is set in tricks cut in the needle bed of the machine, while the closing part of the needle is set in a separate bar. The closing part of the needle along the machine bed consists of segments half an inch long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

Sinker

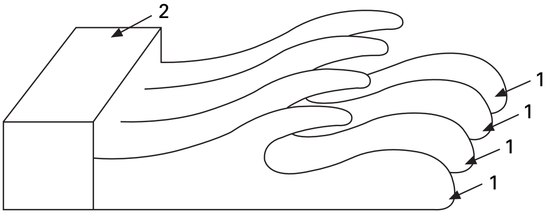
Sinkers, placed between each needle, are set into a sinker bar (see Fig. 9.50). Sinker segments one inch long are placed along the sinker bar.



9.48 Illustration of Tricot machine.



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



Key
1 Sinker
2 Sinker unit

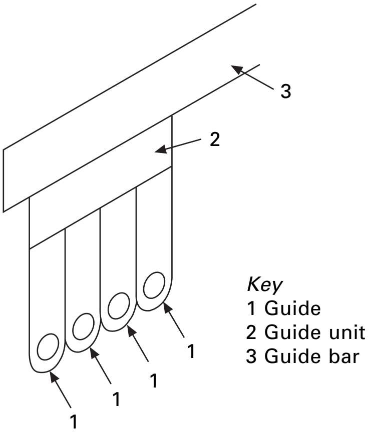
9.50 Sinker unit.

Guide bar and guides

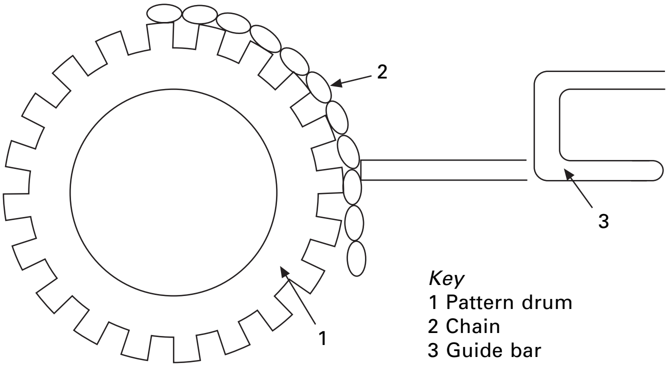
Each yarn end fed from a warp beam is passed through the eye of a guide. The guide segments are one inch long and placed into the guide bar (see Fig. 9.51). The guide bars have two motions, swing and shogging. The guide bars swing between needles and they also shog sideways to produce overlap and underlap. 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.

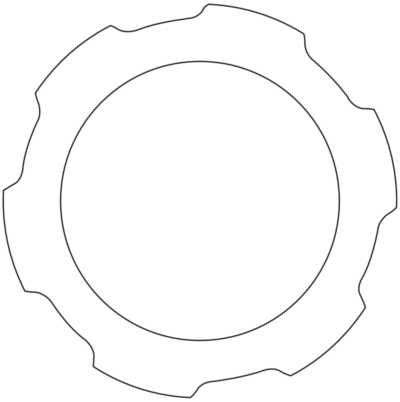


9.52 Pattern mechanism.

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



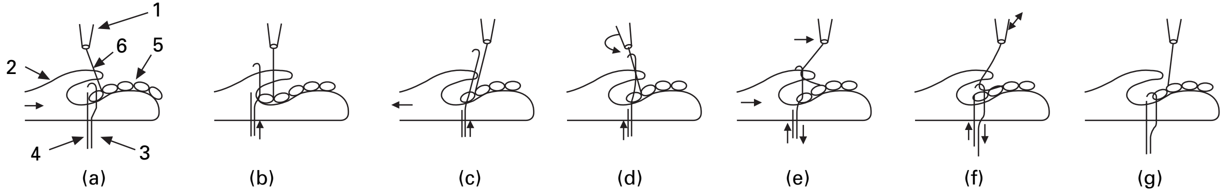
9.53 Pattern disc.

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.

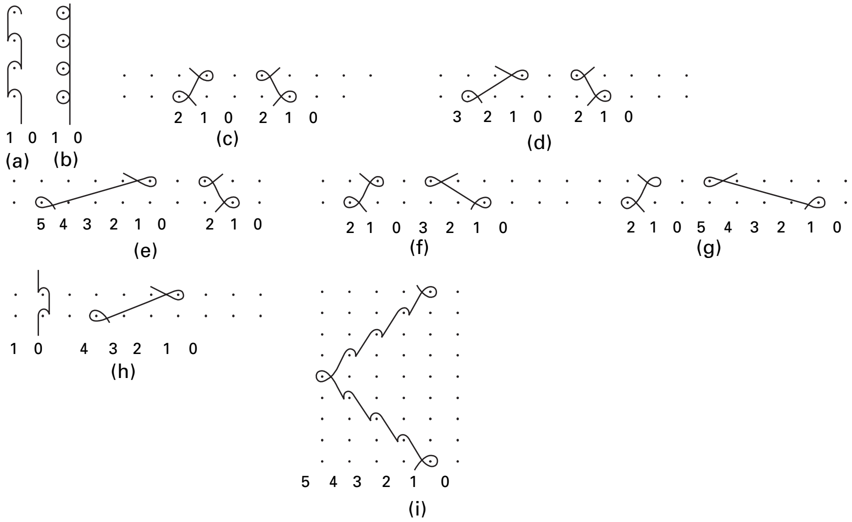
(g) The needle descends to the knockover position, the guide bar is in the centre of the underlap shogging movement and the knitting cycle is complete.

Basic fabric types

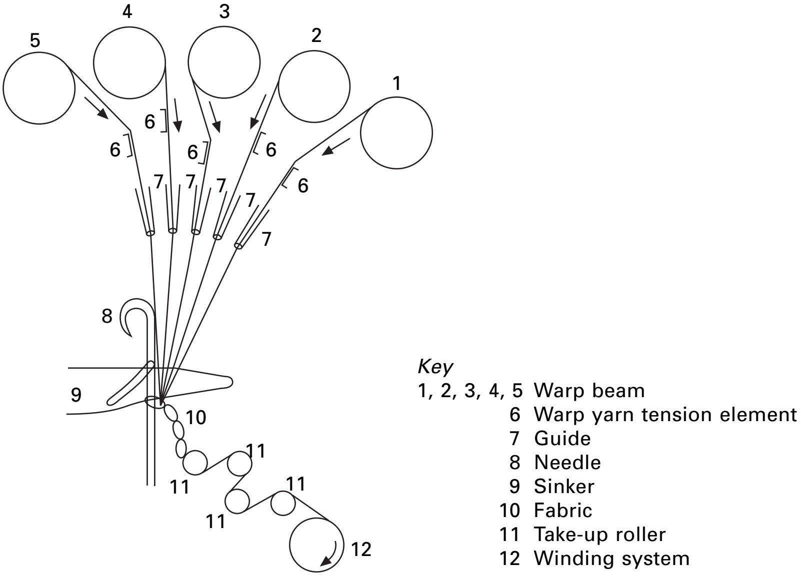
There are several basic fabric designs used in Tricot machines such as ‘atlas lapping’, ‘tricot’, ‘locknit’, ‘satin’, ‘reverse locknit’, ‘sharkskin’, ‘queen’s cord’ (see Fig. 9.55). All of these fabrics are produced by one or two fully threaded guide bars. Although it is difficult to produce a pillar 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).

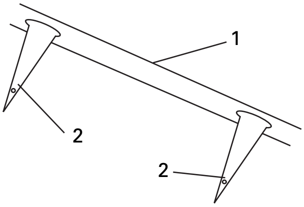


9.56 Illustration of Raschel machine.

Properties of machine elements

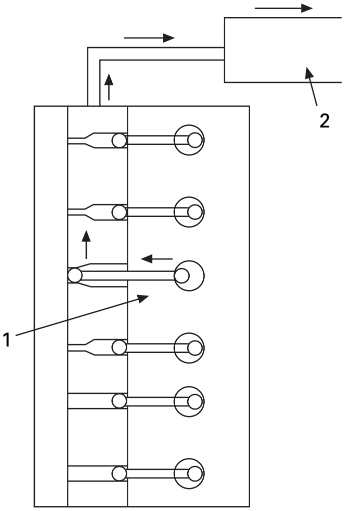
The original needle on a Raschel machine is a latch needle, however, most modern Raschel machines are built today with compound needles. Compound needles are set into Raschel machines as in a Tricot machine while the latch needles in segment form one inch long are placed along the needle bar. Two types 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.



Key
1 Guide bar
2 Guide finger

9.57 Pattern guide bar.



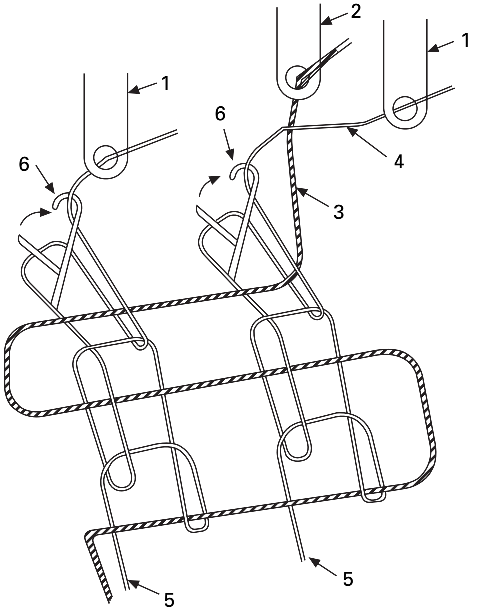
Key
1 Cam system
2 Guide bar

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



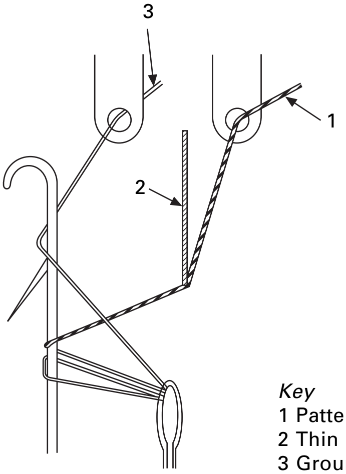
Key
1 Guide for pillar stitch
2 Guide for laying-in
3 Yarn for laying-in
4 Yarn for pillar stitch
5 Pillar stitch
6 Needle

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.



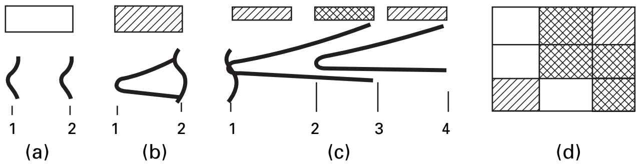
Key
1 Pattern yarn
2 Thin metal of fall plate
3 Ground yarn

9.60 Fall plate technique.

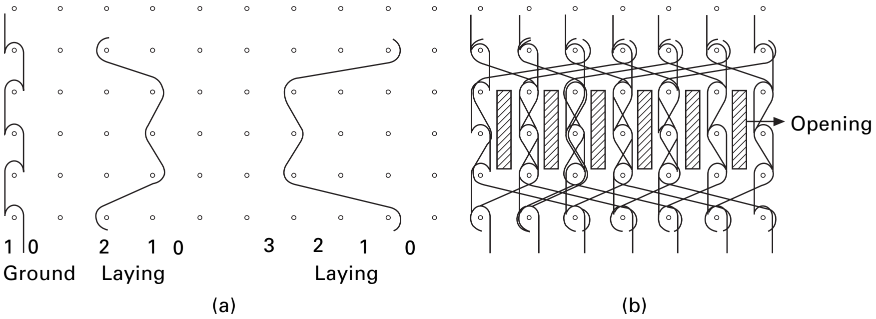
Jacquard mechanisms, weft insertion magazines and double needle beds are also available on Raschel machines. In jacquard knitting, jacquard guide bars that take a yarn from a bobbin are used, in addition to other conventional guide bars, which usually take yarn from a warp beam to produce a pillar stitch. 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

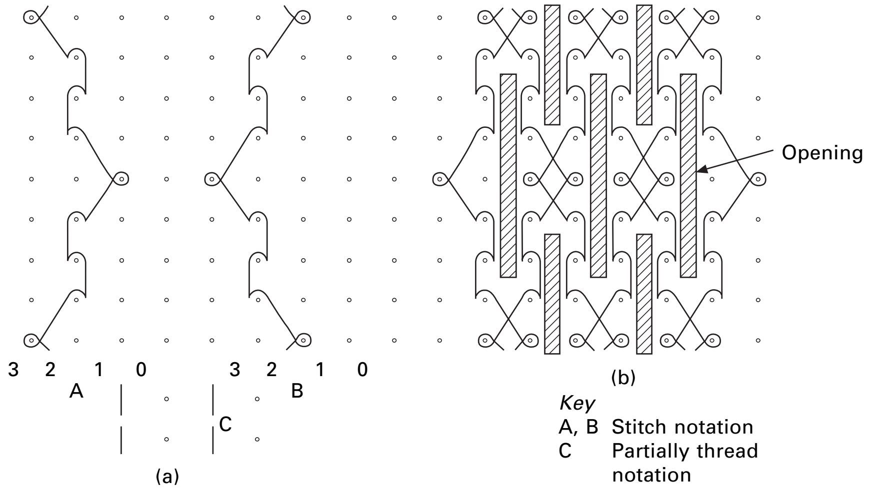
There are many different types of fabric designs that can be produced on Raschel machines. One of them is net fabric. Net fabrics can be produced by vertical pillars or interlacing pillars. On net fabrics with vertical pillars, the guide bars are usually fully threaded and net appearance is obtained 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

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

(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

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

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

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.

9.10 References

1. Iyer C, Mammel B, Schach W, *Circular Knitting: Technology, Process, Structures, Yarns, Quality*, Bamberg, Meisenbach GmbH, 1995.
2. Spencer D J, *Knitting Technology*, Oxford, Pergamon Press, 1989.
3. Horrocks A R, Anand S C, *Handbook of Technical Textiles*, Cambridge, Woodhead Publishing, 2000.
4. Raz S, *Flat Knitting: The New Generation*, Bamberg, Meisenbach GmbH, 1991.
5. Paling D F, *Warp Knitting Technology*, London, Harlequin Press, 1952.
6. Raz S, *Warp Knitting Production*, Heidelberg, Melliand, 1987.
7. Uçar N, 'Faults in Knitted Fabrics and Production Calculation', *Short Courses*, Istanbul, 1997.
8. Araujo M D De, Smith G W, 'Spirality of Knitted Fabric, Part I: The Nature of Spirality', *Textile Research Journal*, 1989 **59**(5) 247–256.
9. Banerjee P K, Alaiban T S, 'Geometry and Dimensional Properties of Plain Loops Made of Rotor Spun Cotton Yarns, Part III: Spirality of Wale Line', *Textile Research Journal*, 1988 **58**(6) 287–290.
10. Banerjee P K, Alaiban T S, 'Geometry and Dimensional Properties of Plain Loops Made of Rotor Spun Cotton Yarns, Part IV: The Shape of the Loop', *Textile Research Journal*, 1988 **58**(6) 365–369.
11. Burnip M S, Abbas M S, 'The Dimensional Behaviour of Weft Knitted Fabrics Produced from Blended Fiber Yarns', *Journal of the Textile Institute*, 1973 **64**(10) 702–703.
12. Lord P R, Mohamed M H, Ajgaonkar D B, 'The Performance of Open End, Twistless and Ring Yarns in Weft Knitted Fabrics', *Textile Research Journal*, 1974 **44**(6) 405–414.
13. McKinney M, Broome E R, 'The Effects of Laundering on the Performance of Open End and Ring Spun Yarns in Jersey Knit Fabrics', *Textile Research Journal*, 1977 **47**(3) 155–162.
14. Sharma I C, Ghosh S, Gupta N K, 'Dimensional and Physical Characteristics of Single Jersey Fabrics', *Textile Research Journal*, 1985 **55**(3) 149–156.
15. Zurek W, Cislo R, Bialek U, Dziewiecka M, 'Physical Properties of Weft Knitted Fabrics', *Textile Research Journal*, 1986 **56**(4) 241–248.

16. Heap S A, Greenwood P F, Leah R D, Eaton J T, Stevens J C, Keher P, ‘Prediction of Relaxed Dimensions of Cotton Knits – The Starfish Project, Part II: Shrinkage and The Reference State’, *Textile Research Journal*, 1985 **55**(4) 211–222.
17. Kaswell E R, Barish L, Lermond C A, ‘A Study of the Comparative Comfort Properties of Nylon Bulk-Yarn Knitted Fabrics with those Prepared from Cotton, Wool and Continuous Filament Man Made Fiber Yarn’, *Journal of the Textile Institute*, 1961 **52**(9) P508–P523.
18. Knapton J J F, Ahrens F J, Ingenthron W W, Fong W, ‘The Dimensional Properties Wool Fabrics, Part I: The Plain Knitted Structures’, *Textile Research Journal*, 1968 **38**(10) 999–1012.
19. Knapton J J F, ‘Factors Affecting the Stable Dimensions of Double Jersey Structures’, *Journal of the Textile Institute*, 1974 **65**(6) 293–299.
20. Knapton J J F, Ahrens F J, Ingenthron W W, Fong W, ‘The Dimensional Properties Wool Fabrics, Part II: 1 × 1, 2 × 2 Rib and Half Cardigan Structures’, *Textile Research Journal*, 1968 **38**(11) 1013–1026.
21. Postle R, Munden D L, ‘Analysis of the Dry-Relaxed Knitted Loop Configuration, Part II: Three Dimensional Analysis’, *Journal of the Textile Institute*, 1967 **58**(8) 352–365.
22. Postle R, ‘Dimensional Stability of Plain Knitted Fabrics’, *The Journal of the Textile Institute,* 1968 **59**(2) 65–77.
23. Uçar N, Karaka H C, ‘Effect of Lyocell Blend Yarn and Pile Type on the Properties of Pile Loop Knit Fabrics’, *Textile Research Journal*, 2005 **75**(4) 352–356.
24. Uçar N, Ertu rul , ‘Predicting Circular Knitting Machine Parameters for Cotton Plain Fabrics Using Conventional and Neuro-Fuzzy Methods’, *Textile Research Journal*, 2002 **72**(4) 61–366.
25. Uçar N, Karaka H C, Sariünal S, ‘The Comparison of the Performance of Acrylic Flat Knit Products of Different Fabric Designs’, *2nd International Textile Clothing & Design Conference*, Croatia, University of Zagreb 2004.
26. Shinn W E, ‘An Engineering Approach to Jersey Fabric Construction’, *Textile Research Journal*, 1955 **25**(3) 270–277.
27. Uçar N, Realff M L, Radhakryshnaiah P, Uçar M, ‘Objective and Subjective Analysis of Knitted Fabric Bagging’, *Textile Research Journal*, 2002 **72**(11) 977–982.
28. Uçar N, ‘Prediction of Curling Distance of Dry Relaxed Cotton Plain Knitted Fabrics, Part I: Theoretical Analysis of Moments on the Loop that Force the Fabric to Curl’, *Journal of Textile Engineering*, 2000 **46**(4) 109–117.
29. Uçar N, ‘Prediction of Curling Distance of Dry Relaxed Cotton Plain Knitted Fabrics, Part II: Experimental Study and Regression Analysis for Prediction of Curling Distance’, *Journal of Textile Engineering*, 2000 **46**(4) 118–122.
30. Hamilton R J, Postle R, ‘Bending and Recovery of Wool Plain Knitted Fabrics’, *Textile Research Journal*, 1974 **44**(5) 336–343.
31. Szomanski W M, Postle R, ‘Measurement of Torsion in Monofilament Textile Structures’, *Textile Research Journal*, 1970 **40**(8) 762–764.
32. Hamilton R J, Postle R, ‘Shear Properties of Wool Plain Knitted Fabrics’, *Textile Research Journal*, 1976 **46**(4) 265–272.
33. Uçar N, Kalao lu F, Bahtiyar D, Bilaç O E, ‘Investigating the Drape Behavior of Seamed Knit Fabric with Image Analysis’, *Textile Research Journal*, 2004 **74**(2) 166–171.
34. Li Y, Zhu Q, Yeung K W, ‘Influence of Thickness and Porosity on Coupled Heat and Liquid Moisture Transfer in Porous Textiles’, *Textile Research Journal*, 2002 **75**(5) 435–446.

35. Coplan M J, ‘Some Moisture Relations of Wool and Several Synthetic Fibers and Blends’, *Textile Research Journal*, 1953 **12**(11), 897–916.
36. Crow R, Osczevski R J, ‘The Interaction of Water with Fabric’, *Textile Research Journal*, 1998 **68**(4) 280–288.
37. Fourt L, Sookne A M, Frishman D, Harris M, ‘The Rate of Drying of Fabrics’, *Textile Research Journal*, 1951 **1**(1), 26–33.
38. Hsieh Y, ‘Liquid Transport in Fabric Structures’, *Textile Research Journal*, 1995 **65**(5) 299–307.
39. Holcombe B V, Hoschke B N, ‘Dry Heat Transfer Characteristics of Underwear Fabrics’, *Textile Research Journal*, 1983 **53**(6) 368–374.
40. Uçar N, Yilmaz T, ‘Thermal Properties of 1 × 1, 2 × 2, 3 × 3, Rib Knit Fabrics’, *Fibers & Textiles in Eastern Europe*, 2004 **12**(3) 34–38.
41. Uçar N, Boyraz P, ‘Measurement of Fuzz Fibers on Fabric Surface Using Image Analysis Methods’, *Fibers and Polymers*, 2005 **6**(1) 79–81.
42. Chen P L, Barker R L, Smith G W, Scruggs B, ‘Handle of Weft Knit Fabrics’, *Textile Research Journal*, 1992 **83**(4) 200–210.
43. Amirbayat J, Hearle J W S, ‘The Anatomy of Buckling of Textile Fabrics: Drape and Conformability’, *Journal of the Textile Institute*, 1989 **80**(1) 51–69.
44. Gaucher M L, King M W, Johnston B, ‘Predicting the Drape Coefficient of Knitted Fabrics’, *Textile Research Journal*, 1983 **53**(5) 297–303.
45. Ertu rul , Uçar N, ‘Predicting Bursting Strength of Cotton Plain Knitted Fabrics Using Intelligient Techniques’, *Textile Research Journal*, 2000 **70**(10) 845–851.

10

Cotton weaving technology

I DORAISWAMY and A BASU, The South India
Textile Research Association, India

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.

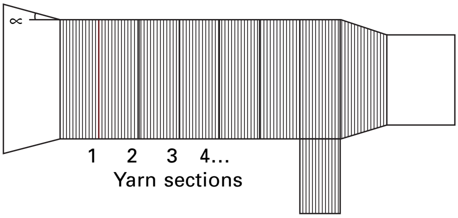
The various weaving processes are dealt with in the same sequence as they occur in the weaving of a fabric. Also, for better appreciation of the basic principles of weaving, for most of the explanations, features of the earlier generations of machinery are also mentioned along with those of contemporary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

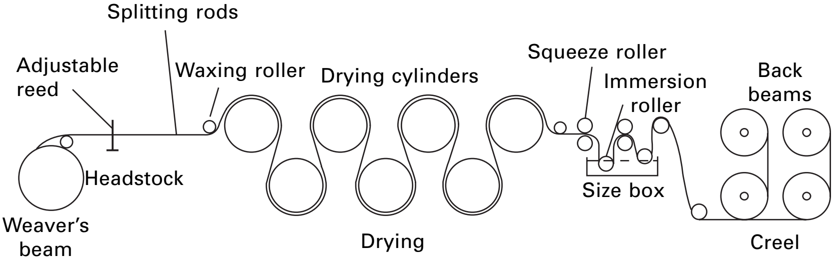
10.2.2 Warp sizing

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

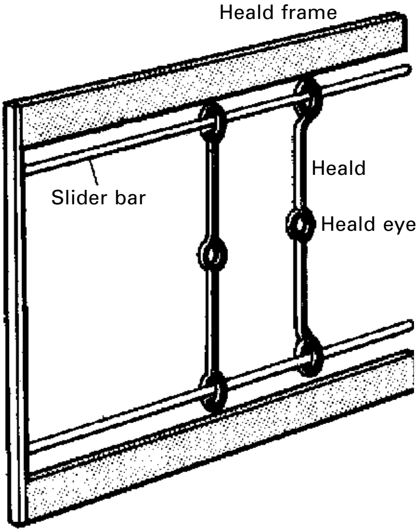
Drawing-in and denting form an essential link between the designing of a fabric and the working parts of the loom. Drawing-in is the threading of



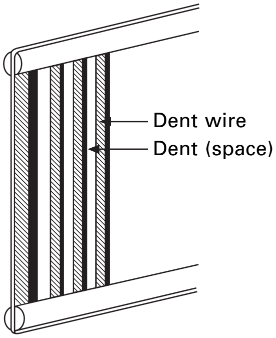
10.2 Multi-cylinder sizing machine.

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.

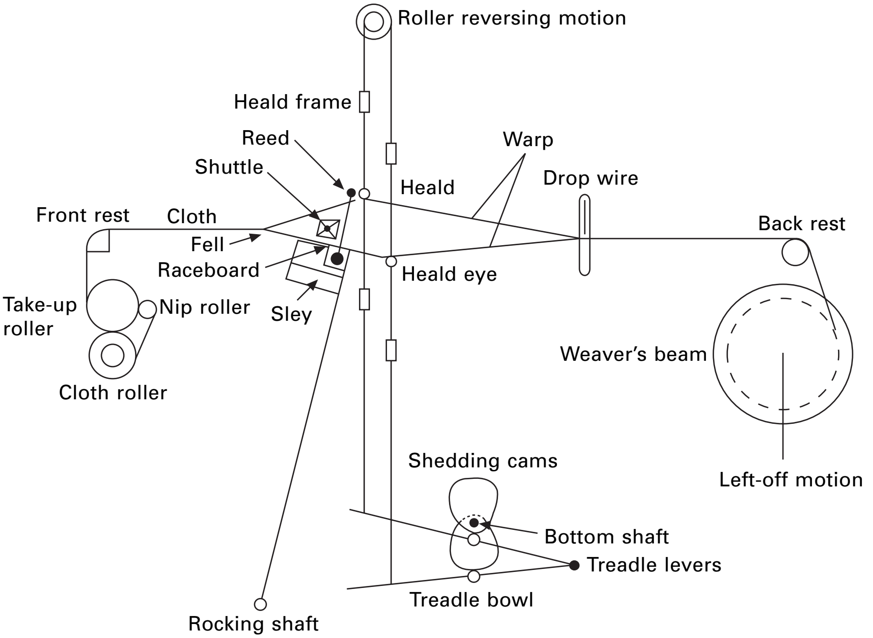
a closed comb-like structure. The spaces between the metal strips are known as dents. Reeds are identified by a reed number which is the number of dents per unit width. The reed holds one or more warp yarns in each dent. Denting plans describe the arrangement of the warp ends in the reed which controls 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.

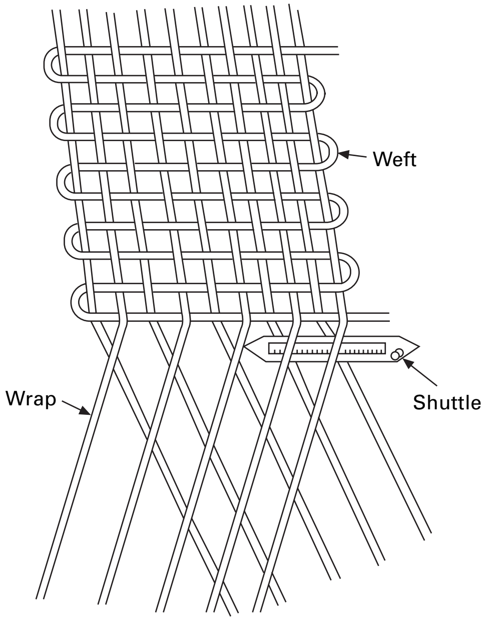
The yarns from the back rest roller are brought forward. Each end of the yarns from the beam is threaded through the eye of a drop wire. The drop



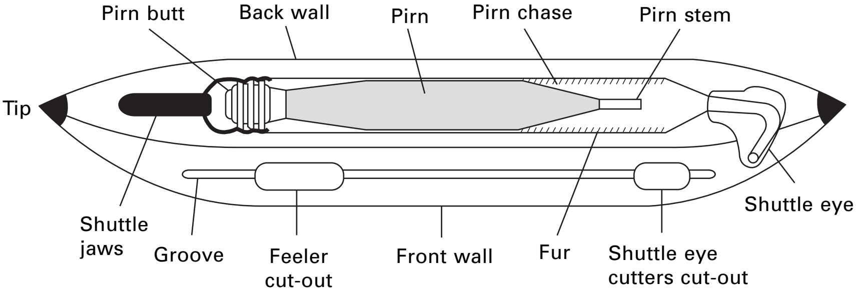
10.5 A cross-section through the loom.

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

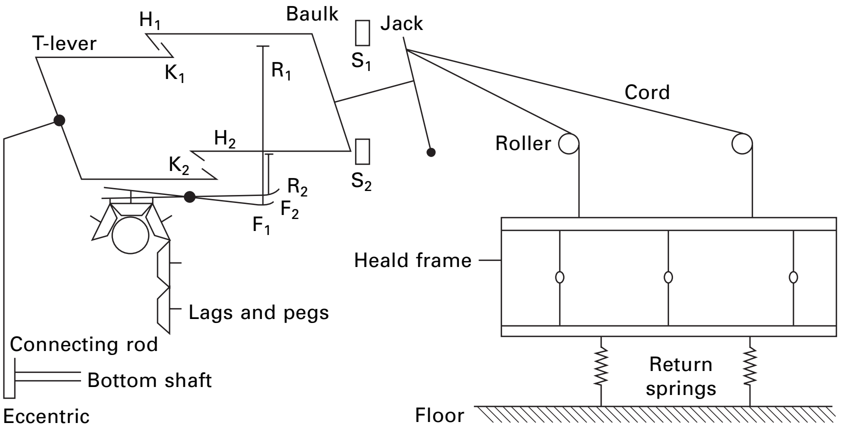
The shedding mechanism is operated by two shedding cams. The shedding cams are mounted on the bottom shaft in the case of plain weave design which needs to employ only two heald frames. However, wherever the design requires operating more than two heald frames, separate tappet shafts fitted to the bottom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

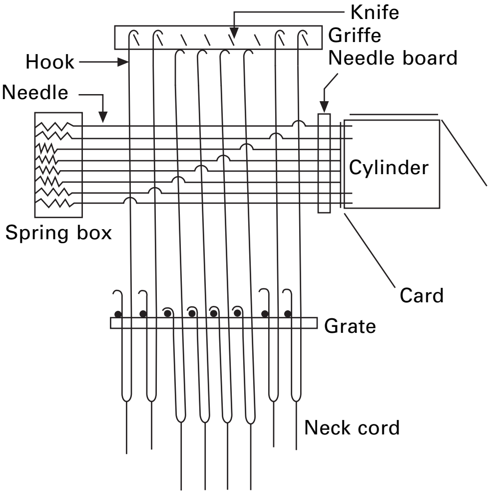
Jacquard shedding

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

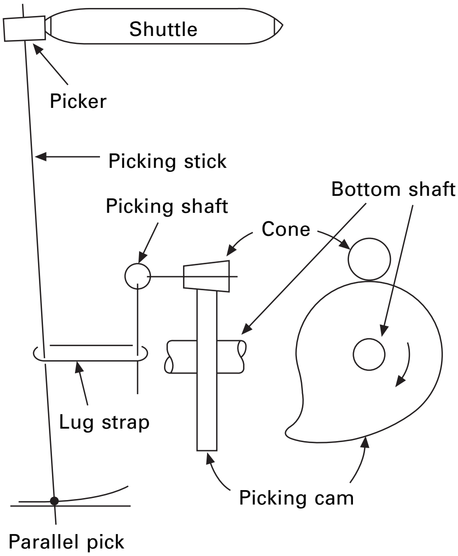


10.9 Single-lift and single-cylinder jacquard.

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.

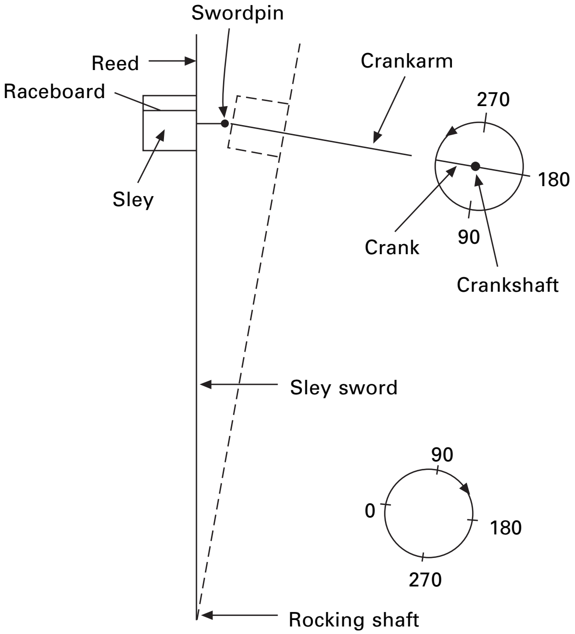
Beating-up

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.

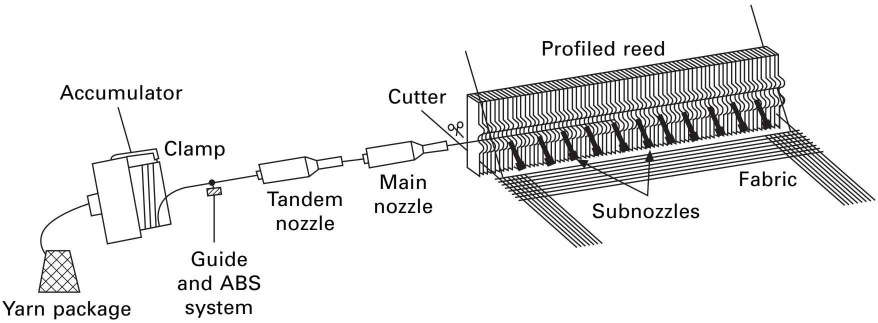
In practice these looms are named after their weft insertion system. To distinguish from shuttle looms, these machines are called shuttleless looms or shuttleless weaving machines which are considered to be the second generation of weaving machines. The first projectile weaving machine was introduced 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

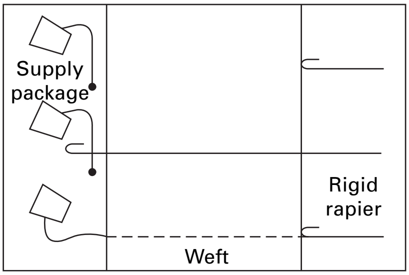
In water-jet weaving machines the weft yarn is inserted by highly pressurized water. These looms are similar in many ways to air-jet looms but they differ in construction, operating conditions and performance. Since water is used for weft insertion, warp and weft yarns must be water insensitive. The 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

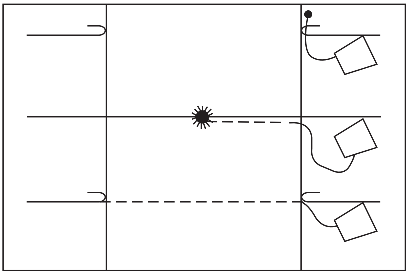
In rapier weaving, a rigid or flexible rapier is used to insert the weft yarn across the warp sheet. The rapier head picks up the weft yarn and carries it through the shed. The rigid rapier is a metal bar generally with a circular cross-section. The flexible rapier has a tape-like structure that can 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

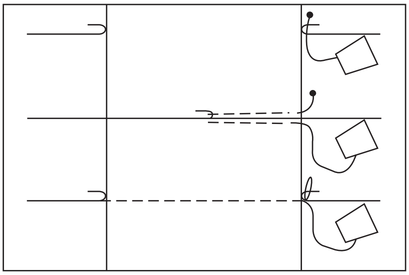
In single rapier machines, the rigid rapier enters the shed from one side and on reaching the other end grips the weft yarn tip and pulls it across the weaving machine while retracting (Fig. 10.13). This would mean that half of the rapier traverse is wasted and thus loom speeds are low. The single rapier 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.



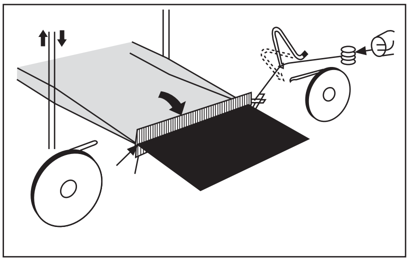
Single rigid rapier



Double rigid rapier (Dewas system)



Double rigid rapier (Gabler system)



Double flexible rapier system

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.

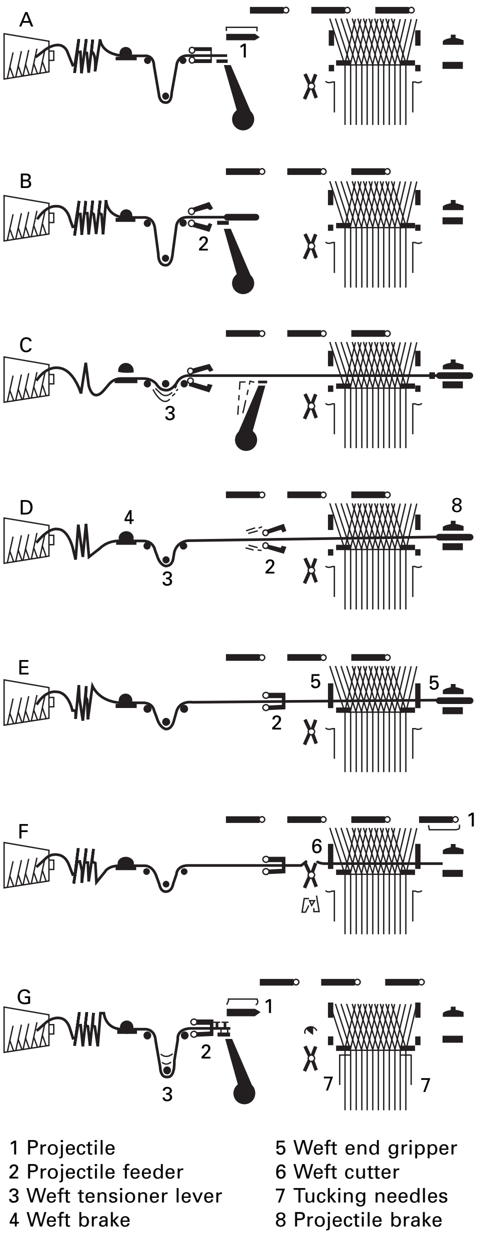
A very wide range of fabrics can be woven on rapier weaving machines. In these machines weft patterning is achieved more easily without reducing machine speeds, so rapier weft insertion is very popular in fancy weaving, where frequent pattern changes have to be made or when different types of yarn made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



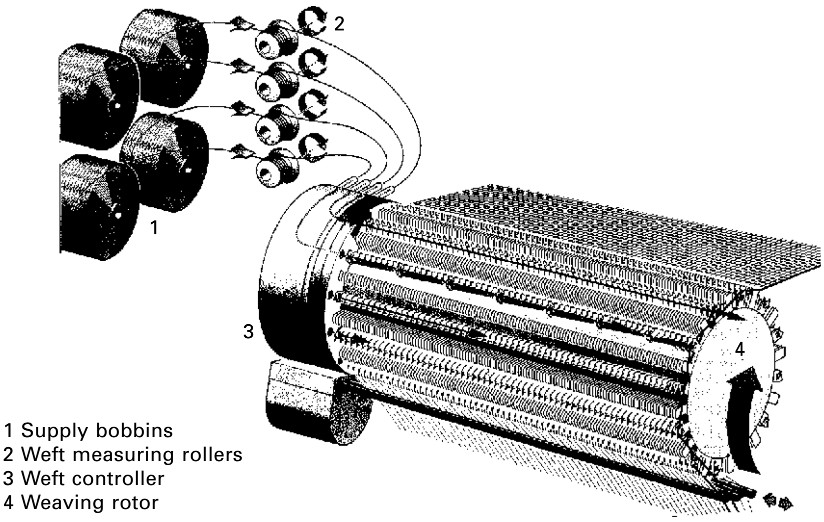
10.14 Filling insertion sequence with projectile (courtesy of Sulzer).

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

Adanur S, 2001, *Handbook of Weaving,* Pennsylvania, USA, Technomic Publishing Co. Inc.

Marks R. and Robinson A.T.C, 1976, *Principles of Weaving,* Manchester, UK, The Textile Institute.

Ormerod A, 1983, *Modern Preparation and Weaving Machinery*, UK, Butterworths & Co.

Talukdar M.K, Sriramulu P.K. and Ajgaonkar D.B., 1998, *Weaving Machines, Mechanisms & Management*, India, Mahajan Publishers Pvt., Ltd.

Vincent J.J, 1980, *Shuttle-less Looms*, UK, The Textile Institute, Manchester.

11

Dyeing of cotton and cotton products

D KING, CSIRO Textile and Fibre Technology, Australia

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.

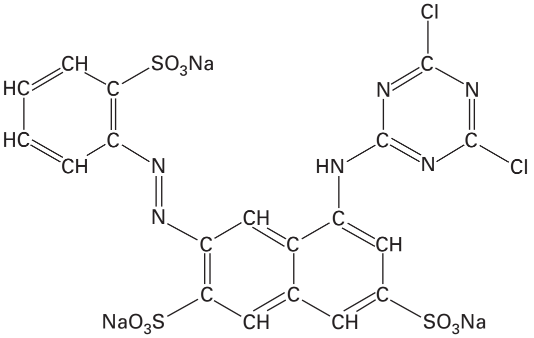
11.2.1 Equilibrium and dye structure

The absorption of dyes by cotton during the dyeing process can be described as a chemical equilibrium as in eqn 11.1 below.

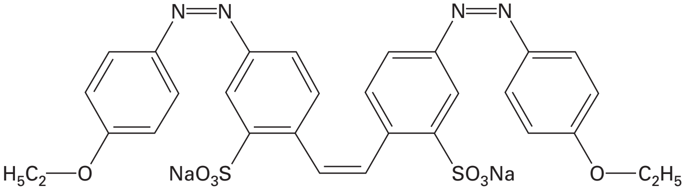
$$D_{\text{bath}} \rightleftarrows D_{\text{fibre}} \qquad 11.1$$

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.

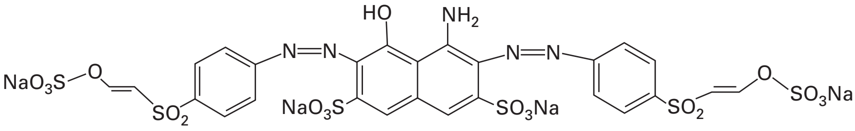
The alternative approaches to attaining acceptable fastness are the formation of an insoluble coloured complex within the fibre (azoic, sulphur and vat dyes) or the formation of dye-fibre covalent bonds (reactive dyes). These dyes will be discussed later in the chapter, however, the same



CI Reactive Red 1



CI Direct Yellow 12



CI Reactive Black 5

11.1 Typical cotton dyes.

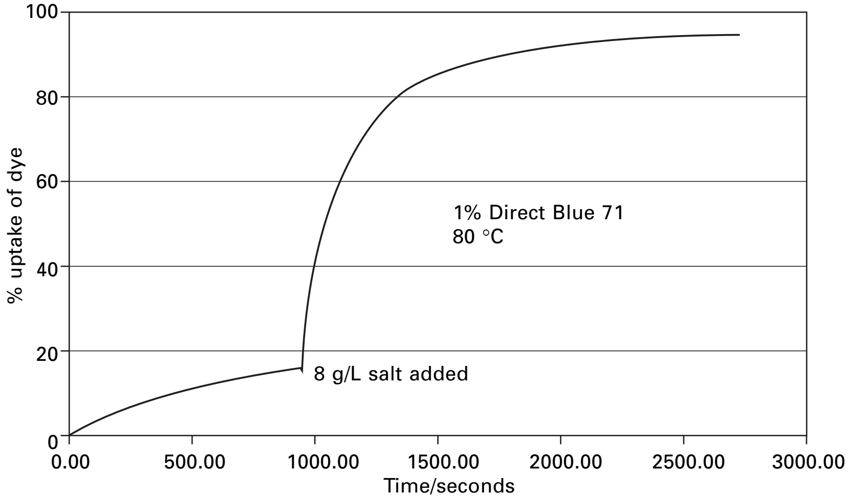
principles apply to the dye absorption process regardless of subsequent chemical reactions.

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.

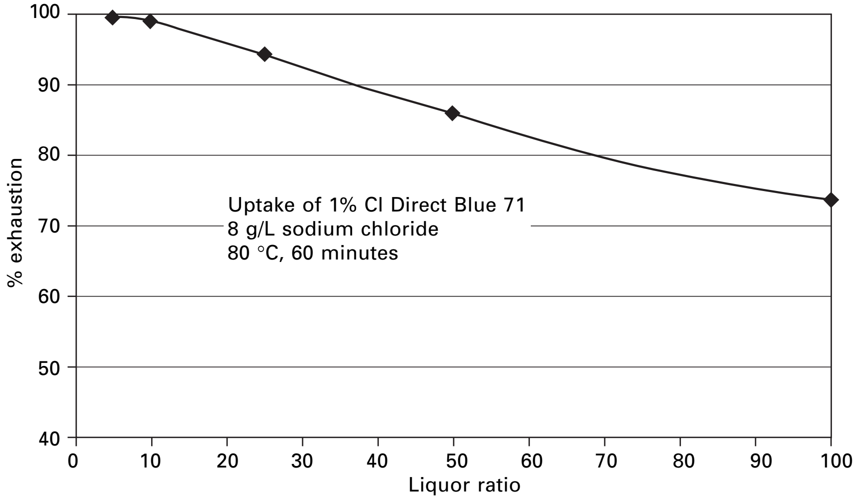


11.2 Exhaustion of direct cotton dye – effect of salt addition.

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

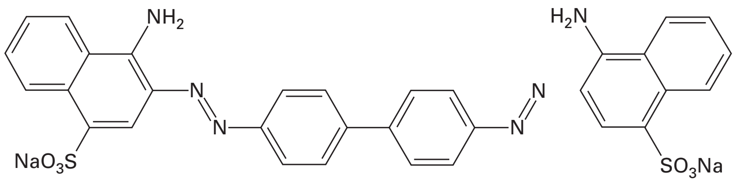
Studies of dyeing have shown that the absorption of dyes by cotton is an exothermic process. The implication of this fact is that if dyeing is carried out to equilibrium, then lower temperatures favour higher exhaustion of dyes. One might conclude from this that dyeing should be carried out at room temperature, 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

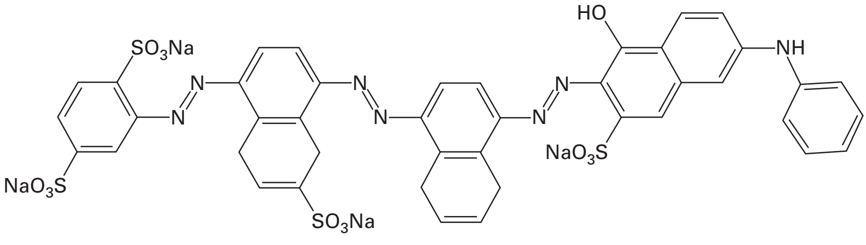
In 1884 Bottiger discovered that the diazo dye, Congo Red, coloured cotton without the necessity for pre-treatment with a metal salt (a so-called 'mordant'). This finding led to the synthesis of related dyes which were referred to as the 'direct' dyes due to their ease of application. The dyes are generally 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.

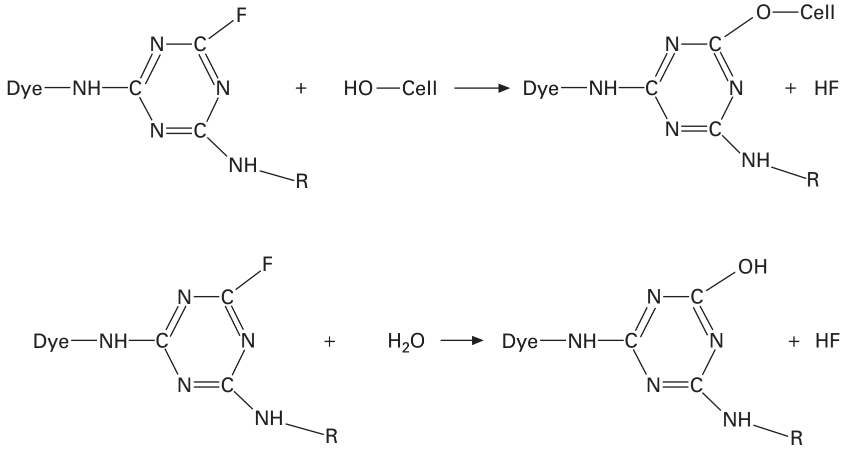
rinsed. There are a number of possible stages at which salt can be added to the dyebath during the dyeing process, generally either at the commencement of dyeing or during the high-temperature stage, depending on the affinity of the particular dye.

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.

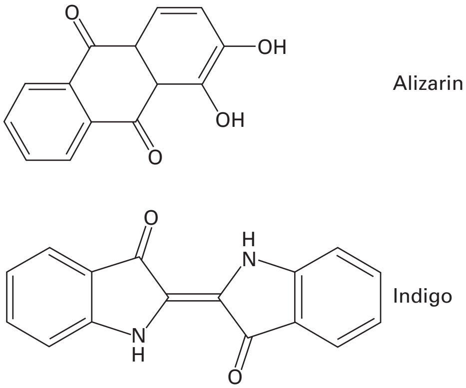
11.5 Vat, sulphur and azoic dyes

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.

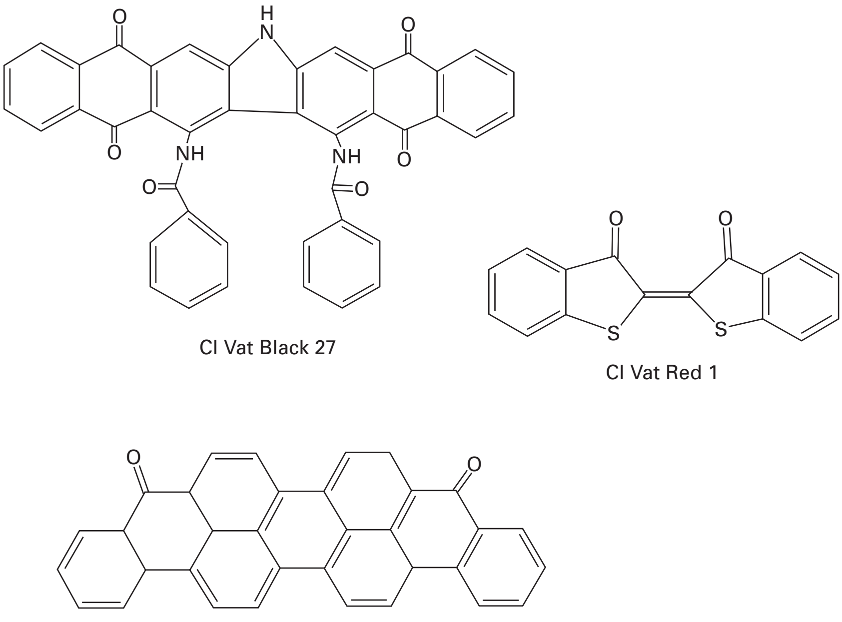
11.5.1 Vat dyes

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



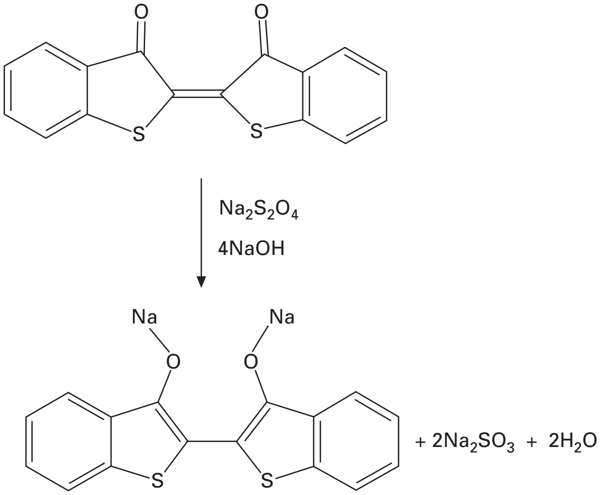
11.6 Traditional vat dyes.


CI Vat Black 27

CI Vat Red 1

CI Vat Blue 20

11.7 Modern vat dyes.



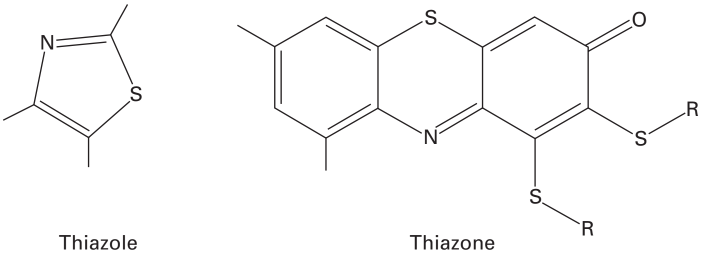
11.8 Vat dyes: conversion to leuco form.

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



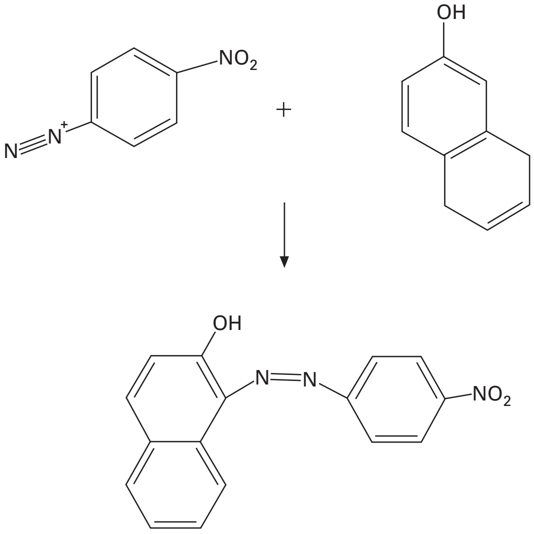
11.9 Heterocyclic groups found in sulphur dyes.

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

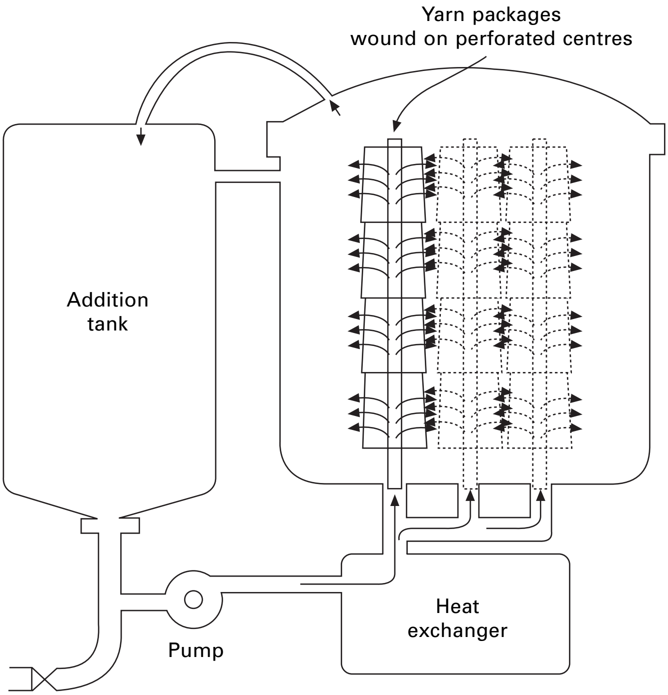
- pumped circulation of the dye liquor
- a sealed system which can be pressurised
- microprocessor control of heating and flow.

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.

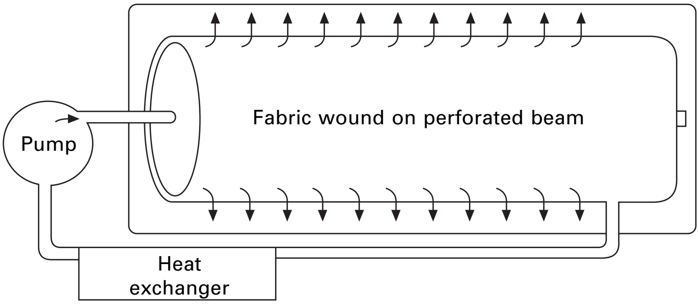
The other major types of exhaust dyeing machinery are those used for dyeing cotton in fabric form. There are four main types, the beam, beck, jet and jig. A typical beam dyeing machine is shown in Fig. 11.12; fabric is wound onto a perforated shaft and the dye liquor is pumped radially through the fabric 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.



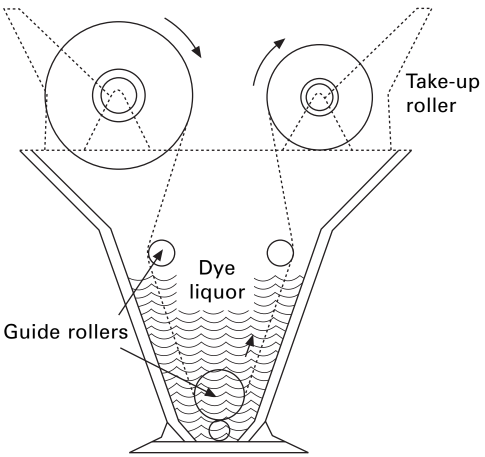
11.11 Package dyeing machine.



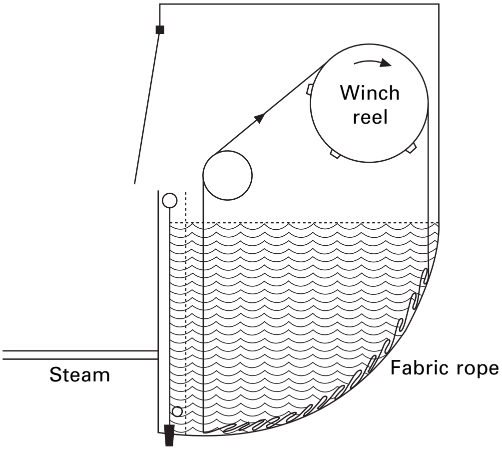
11.12 Beam dyeing machine.

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.

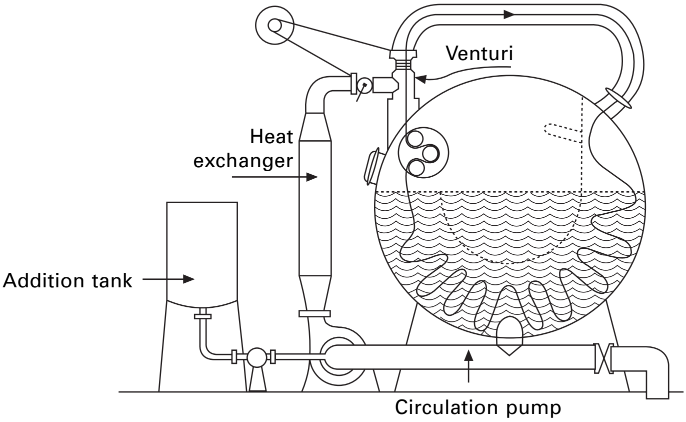
11.7 Semi-continuous dyeing

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:

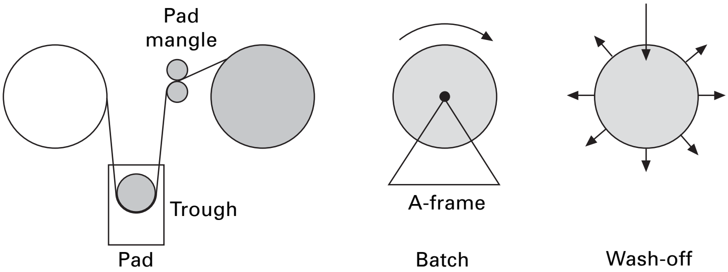
X g/L reactive dye (up to 100 g/L)
1–2 g/L wetting agent
<70 g/L sodium silicate
5–30 g/L caustic soda
pad on at 60–80% pickup, room temperature
store for up to 24 hours
rinse

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.

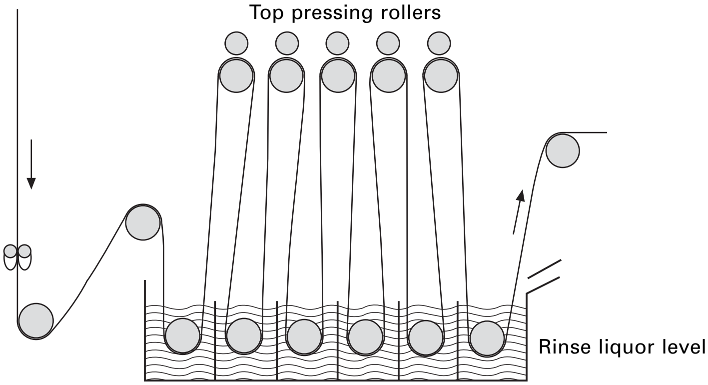
separate alkali and dye solutions which are mixed in the padding trough. The design of padding troughs and mechanisms to use minimum volumes of liquor also reduces the risk of excessive hydrolysis. For batching, fabric is generally wound onto beams which are stored on an A-frame, a device which slowly 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.

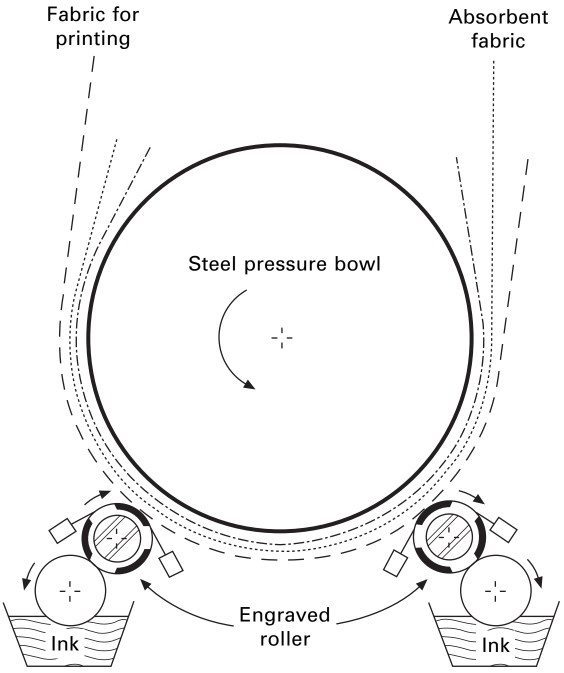
applied by continuous methods and, as mentioned in previous sections, it is the most important process for application of vats, sulphur dyes and azoic combinations.

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

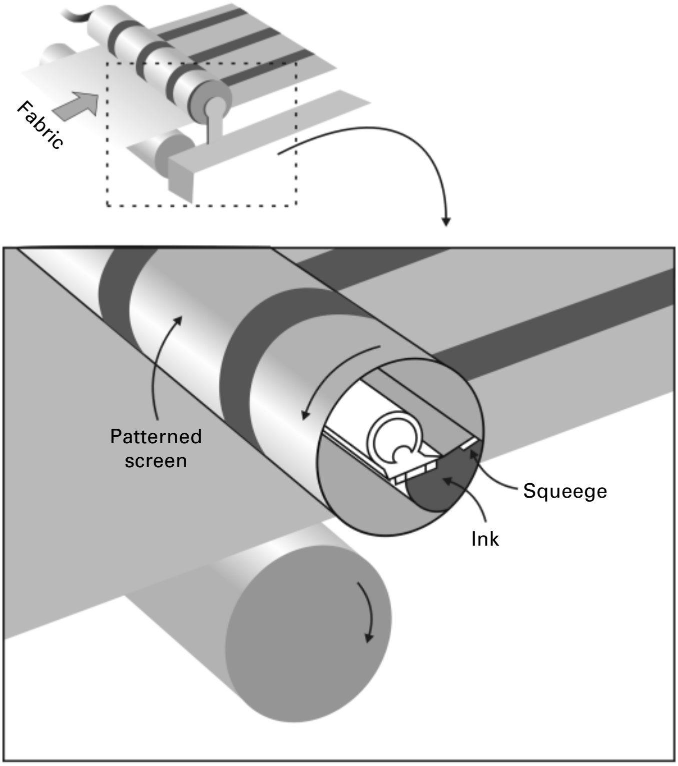


11.18 Two-colour roller printing machine.

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).

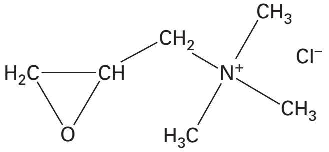
11.11 Future trends

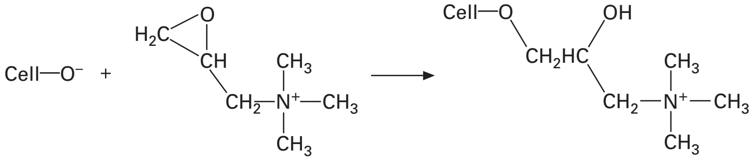
One of the main research avenues pursued in order to improve the affinity of dyes for cotton (and to use less salt) has been pre-treatment with cationic compounds. There have essentially been two approaches:

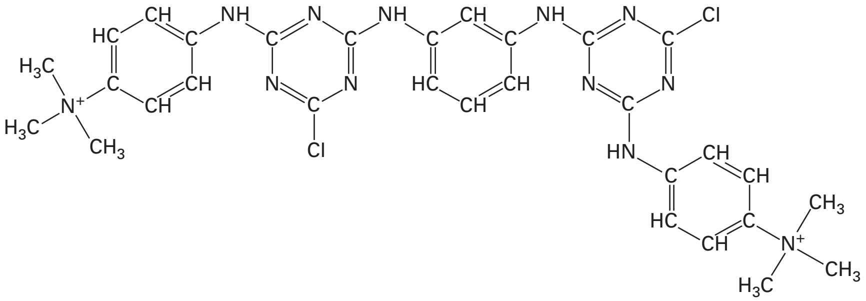
1. The use of low molecular weight chemicals which form covalent bonds to the cotton fibre.
2. The use of cationic resins.

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).

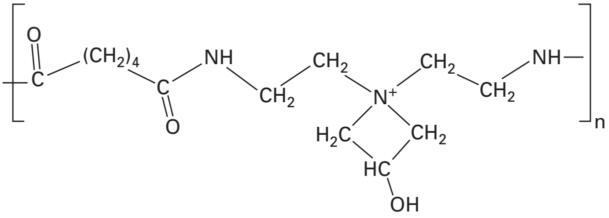
The alternative approach to the use of low molecular weight reactive compounds is to use high molecular weight polymers containing cationic groups. The polyamide-epichlorohydrin resin Hercosett (Fig. 11.23) was applied by a pad-bake process and led to very good exhaustion of reactive dyes under salt 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.

11.13 References

Anon, (2005) 'Affordable, environmentally sustainable dyeing' *Aust. Textiles & Fashion*, 25, 22-23, .

Brown D, (1987) 'Effect of colorants in the aquatic environment' *Ecotox. Environ. Safety*, 13, 139.

Burkinshaw S M, Lei X P and Lewis D M, (1989) 'Modification of cotton to improve its dyeability – reactive resins' *J. Soc Dyers Colorists,* 105, 391.

Capponi M, Metzger E, Giamara A, (1961) 'The development of the Drimarene class of reactive dyes' *American Dyest. Rep.*, 50, 505.

Cook C C, (1982) 'Aftertreatments for improving the fastness of dyes on textile fibres' *Rev. Prog. Coloration* 12, 73.

Dawson T L, Hawkyard C J, (2000) 'A new millennium of textile printing' *Rev. Prog. Coloration* 30, 7.

Easton J R, (1995) 'The problem of colour – The dyemaker's view' in *Colour in Dyehouse Effluent,* Cooper P ed. SDC Publications Bradford.

Esche S P, (2004) 'Direct dyes – their application and use' *AATC Review* (Oct) 14.

Evans G E, Shore J and Stead C V, (1984) 'Dyeing behaviour of cotton after pretreatment with reactive quaternary compounds', *J. Soc Dyers Colorists* 100,304.

Fortress F, Ward G C, (1962) 'New advances in machinery for pressure dyeing of synthetic fabrics' *American Dyest. Rep.*, 51, 400.

Gregory P, (2000) 'Colouring the Jet Set', *Chem. In Britain* 36 (Aug) 39.

Guest R A, Wood W E, (1989) 'Sulphur Dyes' *Rev. Prog. Coloration* 19, 63.

Herbert D F, Barkhuysen F A, Van Rensburg N J J, (1983) SAWTRI Technical Report No 523 – August 1983.

Hunter R J, (1981) *Zeta Potential in Colloid Science Principles and Applications*, Academic Press, London.

Lewis D M, (2004) 'Modern Reactive Dyes' in *Kirk-Othmer Encyclopedia of Chemical Technology* Wiley, New York.

Matsui M, Meyer U, Zollinger H, (1988) 'Dye-fibre bond stabilities of dyeings of Bifunctional reactive dyes containing a monochlorotriazine and a β-hydroxyethylsulphone sulphuric acid ester group' *J. Soc Dyers Colorists* 104, 425.

McLaren K (1983) *The colour science of dyes and pigments* Hilger, Bristol.

McCleary H R, (1953) 'Fundamentals of the dyeing of cellulosic fibers' *Textile Research Journal* 23, 673.

Owen P, (2003) 'Digital Printing' *AATC Review* 3(9), 10.

Perkins W S, (1996) *Textile Coloration and Finishing*, Carolina Academic Press, Durham NC.

Phillips D, (1996) 'Environmentally friendly, productive and reliable; priorities for cotton dyes and dyeing processes' *J. Soc Dyers Colorists* 112, 183.

Raper D P, (1962) 'Future developments in Procion dyeing' *American Dyest. Rep.* 51, 479.

Rattee I R, (1984) 'Reactive dyes for cellulose 1953–1983' *Rev. Prog. Coloration* 14, 55.

Ribitsch V, Stana-Kleinscheck K, (1998) 'Characterising Textile Fibre Surfaces with Streaming Potential Measurements' *Text. Res J.* 68(10) 701–707.

Robinson S, *A History of Printed Textiles* (1969) Studio Vista, London.

Rupin M, Veaute G, Balland J, (1970) 'Utilisation de composes reactifs epoxy- ammonium quaternaries dans la teinture de la cellulose en colorants directs et reactifs' *Textilveredlung* 5, 829.

Rys P, Zollinger H, (1972) *Fundamentals of the Chemistry and Application of Dyes* Wiley-Interscience London.

Shore J, (ed.), (1995) *Cellulosics Dyeing* SDC Publications, Bradford, UK.

Skelly K, (2000) 'Cellulose reactive dyes: recent developments and trends' *Rev. Prog. Coloration* 30, 21.

Smith B, (1989) 'Pollution source reduction – Part III Process alternatives' *American Dyest. Rep.* 78(5) 32.

Trotman E R, (1984) *Dyeing and Chemical Technology of Textile Fibres*, 6th edn Griffin, High Wycombe, UK

van Bergen A, de Haas M, Kuster W, (1999) 'Textile Printing Report' *Textile Chemist and Colorist* 31(7), 224.

Wyles D H, (1983) 'Functional design of coloration machines' in *Engineering in Textile Coloration* Duckworth C, ed., SDC Publications, Bradford.

Part III

Quality and other issues

12

Testing cotton yarns and fabrics

L HUNTER, CSIR and Nelson Mandela Metropolitan
University, South Africa

12.1 Introduction

In this highly competitive global market, the survival of a textile company will greatly depend upon its ability to meet demanding quality specifications through optimised manufacturing and testing regimes, within acceptable price and delivery time frames. Textile testing forms an essential link in the quality assurance and quality control chain and may be divided broadly into two major types, namely subjective and objective, Slater[1,2] having reviewed both. This chapter deals largely with the objective or instrument testing of yarn and fabric physical and related properties inasmuch as they relate to their subsequent performance.

Clearly, the intended application of the yarn or fabric is critical in determining which properties, and therefore tests, are important. For example, for fabric to be used in children's nightwear, flammability (e.g. the Limiting Oxygen Index – LOI) would be of paramount importance, whereas for fabrics to be used in parachutes, bursting and tear strength, impact resistance and air permeability would be critically important. Nevertheless, generic or general testing of yarns and fabrics is often carried out irrespective of their end-use so as to ensure consistency in the yarn and fabric and to detect any changes suggesting possible production problems. Ultimately, wearer (field) trials would provide the most reliable measure of actual performance, but these are expensive, time consuming and difficult to organise and design in such a way that meaningful and accurate results are obtained.

In carrying out any tests it is important to as far as possible use accepted test methods ensuring that the correct sampling, sample preparation and handling, atmospheric conditions (e.g. 20 °C ±2 °C and 65% ± 2% RH), conditioning time and instrument calibration are adhered to. ASTM D3777 deals with the writing of specifications for textiles. Standards test method organisations include:

- AATCC (American Association of Textile Chemists and Colorists)
- ASTM (American Society for Testing of Materials)

- BSI (British Standards Institution)
- BIS (Bureau of Indian Standards)
- DIN (Deutsche Industrie Norm) German National Standards
- EN (European Norm)
- ISO (International Standards Organization)
- JIS (Japanese Industrial Standards)

It should be noted that BS, EN and DIN standards now largely use ISO designations.

Ideally, there should be a written pre-agreement between the buyer (customer) and seller (supplier) as to the test method and specifications to be adhered to, thereby avoiding potential ambiguity and dispute. This should also preferably include agreement as to which independent/arbitration testing house or laboratory should be used in the event of claims and disputes. In addition, and at the very least, there should be available for comparative testing purposes, either a reference or 'benchmark' yarn/fabric sample, possibly the yarn/fabric sample on the basis of which the purchase was agreed upon, or a similar yarn/fabric sample from the same source, previously used and found to be acceptable. For more in-depth treatment of yarn and fabric testing and quality related aspects, the reader is referred to various textbooks and reviews (see section 12.4).

12.2 Yarn testing

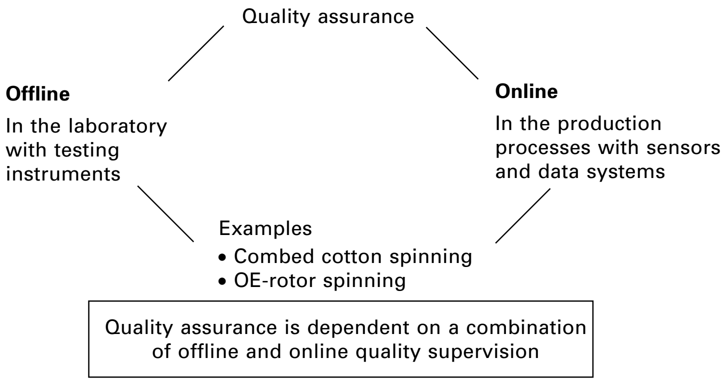
12.2.1 Introduction

The yarn represents the final outcome of the fibre processing or yarn manufacturing part of the fibre to fabric textile pipeline. Prior to the yarn it is still possible, within certain limits, to take corrective action should problems or mistakes have occurred during the earlier processing stages. Once the yarn has formed, any corrective action is limited to yarn clearing (i.e. removal of gross or unwanted faults), uptwisting and singeing. The properties of the yarn largely determine subsequent fabric manufacturing performance and efficiency (also sewing performance) as well as the properties, aesthetic and functional, of the fabric and end-product. Yarn quality control, and the associated testing of those yarn properties which determine the yarn quality, are therefore crucial in ensuring that the yarn meets the requirements of the subsequent fabric manufacturing stages as well as of the fabric and end product. Preferably the process should be one of quality assurance and total quality management (TQM) rather than quality control only, so that the yarn meets the necessary quality requirements cost-effectively without the need for any corrective action or excessive rejects or waste. A further important reason for the accurate measurement of yarn properties is that the yarn often changes hands, i.e., is sold and therefore subject to buyer–seller contractual agreement and specifications, as well as potential claims. The results obtained can be compared with international by accepted 'norms' or 'benchmark' values, such as Uster® Statistics and Yarn Hairiness Grades [http://www.cogetex.ch/Services/Sujets/Uster/GraphsYQ.html]

The testing or monitoring of yarn properties (Fig. 12.1) can take place either on-line during spinning (e.g. rotor and air-jet spinning) and winding, or more commonly off-line, such as measuring the yarn evenness and tensile properties, or both. It is conceivable that in years to come, on-line monitoring will become the norm, even to the extent that the yarn tensile properties (e.g. breaking strength and elongation), which are virtually impossible to measure non-destructively on a continuous on-line basis, could be deduced from the relevant measured fibre properties and those yarn properties, such as twist, linear density and evenness, which can be measured on-line.

Integrated (comprehensive) and automatic yarn testing is increasingly becoming the norm, certain instruments often combining capacitance and optical technologies, simultaneously measuring properties, such as yarn mass (linear density) unevenness (irregularity), imperfections (thin and thick places and neps), hairiness and its variations, diameter and diameter unevenness, density (derived), shape, relative and absolute count (linear density) and neps classified according to type (i.e. fibrous neps, trash and dust). Such systems also produce variance length curves and yarn quality profiles and direct comparison with standard or benchmark values, yarn specifications and customer values. Some comprehensive integrated 'dynamic' yarn systems 'dynamically' measure strength, weak places, elongation, shrinkage, friction, abrasion, linting, faults, entanglements, diameter, hairiness, etc.

This section deals with the testing of those yarn properties commonly specified or used, individually or collectively, as a measure of yarn quality, the correct sampling procedures being critical (ASTM D2258). Yarn properties,



12.1 Method of applying quality assurance (source: Uster Technologies).

such as twist liveliness (residual torque) and stiffness, although of some importance, are not widely tested and will therefore be referred to only in passing.

12.2.2 Count (linear density)

Count (linear density) is a fundamental structural parameter of a yarn, and the average count and its variations are of paramount importance in virtually all facets of textile performance and specifications, undue variations in yarn count, or off-specification count, leading to problems in terms of fabric mass and barré, and often to claims. Traditionally, the average yarn count (linear density) and its variation (CV) are determined by weighing a number 100 m lengths of yarn (e.g. ASTM D861, ASTM D1059, ASTM D1907, ASTM D2260, BS2010, BS2865, ISO 1144, DIN 53830, part 1). Linear density (count) variations (CV), based upon the weighing of 100 m lengths, of less than 2% are generally considered acceptable. Ideally, 20 to 30 × 100 metre lengths of yarn, preferably each coming from a different yarn bobbin or package, should be tested. The count of cotton yarn can be expressed in any one of the following three systems:

1. Tex count (linear density): weight in grams of 1000 m of yarn (i.e. mg/m or g/km)
2. Cotton count (Ne): number of 840 yd lengths in a pound
3. Metric count (Nm): number of 1000 m lengths of yarn in one kilogram. The conversion from one system to the other is as follows:

$$\text{tex} = \frac{590.6}{\text{Ne}} = \frac{1000}{\text{Nm}} \qquad 12.1$$

Today ‘relative count’ and count deviations, from the nominal (or set) value, can also be determined on optical or capacitance type instruments (DIN 53817, part 2), even on-line, although in the case of the latter, it could be influenced by variations in the fibre type (dielectric constant) and moisture content within the test length.

12.2.3 Twist

Twist is one of the fundamental constructional parameters for yarns. Average twist levels and twist variations are reflected in the yarn tensile properties, thickness, bulk, stiffness and handle. These, in turn, are reflected in the yarn performance during the subsequent fabric manufacturing processes and ultimately in the corresponding fabric properties.

Traditionally, twist was counted manually by the direct twist counting method (ASTM D1423, BS 2085) where the operator would clamp the yarn test length (popularly 25 mm for singles yarn and 500 mm for two-ply yarn) under a pre-determined tension, and then untwist the yarn, using a 'dissecting needle' until all the twist is removed. Today, twist is more commonly measured automatically, using different test methods and techniques, for example, double-untwist-retwist test, untwist-retwist tests described in ASTM D-1422, multiple untwist-retwist and twist-to-break, the test length popularly being 50 cm, typically 100 tests per yarn lot are measured, it also being possible to measure the twist (helix angle optically). The yarn twist is expressed in terms of turns per metre (or turns per centimetre) and the CV of twist in percentage, noting the gauge length. Standard test methods include BS 2864, DIN 53830-4, see also ASTM D1244. Twist results may be assessed using 'norms or standards', such as the Testex Twist Statistics, variation in yarn twist being particularly important. Various instruments and test methods are available for testing yarn twist (e.g. Zweigle Automatic Twist Tester D 302 and Semi-automatic Twist Tester D 314).

It is generally accepted that the twist in yarns of different counts (linear densities) is comparable when the twist factor (and helix angle) is constant, twist factor or multiplier being defined as follows:

1. Tex twist factor = turns/m $\sqrt{}$tex or alternatively (α_{tex}) = turns/cm $\sqrt{}$tex
2. Metric twist factor (α_m) = turns/m/$\sqrt{}$ N_m
3. Cotton count twist factor (α_e) = turns/inch/$\sqrt{}$$N_e$

where N_m = metric count and N_e = English cotton count.

Conversion from one unit (system) to the other can be done as follows:

$$
\begin{aligned}
\alpha_e &= 0.033\ \alpha_m = 0.104\ \alpha_{tex} \\
\alpha_{tex} &= 0.0316\ \alpha_m = 9.57\ \alpha_e \\
\alpha_m &= 3.16\ \alpha_{tex} = 30.3\ \alpha_e
\end{aligned}
$$

where α_{tex} = turns/cm $\sqrt{\text{tex}}$

Because of their different structure, notably the presence of wrapper fibres, which cannot be untwisted, rotor (open-end) yarn twist is difficult to measure accurately and specific test methods have been devised for this purpose. The single untwist-retwist method is often applied, giving an indication of yarn structure rather than of real twist *per se.*

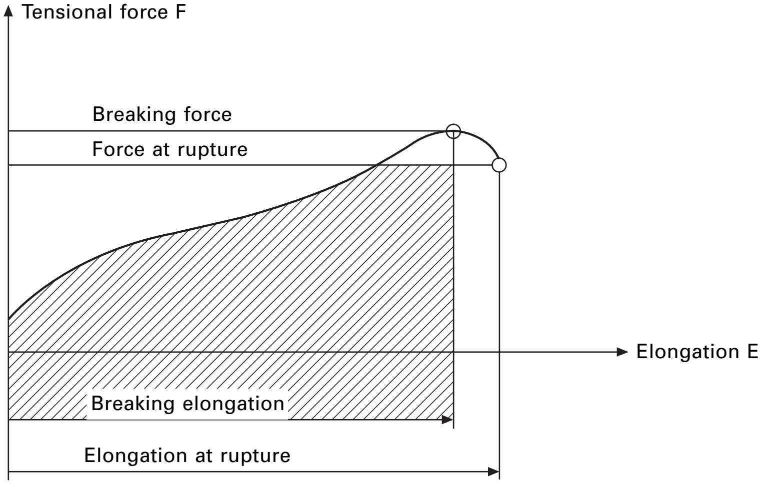
12.2.4 Twist liveliness (torque)

Another fairly important yarn quality parameter is its twist or torque liveliness (residual torque) since this can be reflected in the snarling potential of the yarn and in fabric properties, such as knitted fabric spirality (see ISO 3343). In the main, twist liveliness is related to the twist level and unbalanced twist, and heat setting of the yarn. A low or balanced twist (in the case of plied yarn) will produce a yarn with little, if any, inclination towards twist liveliness. Similarly, good heat setting can reduce, if not eliminate, twist liveliness, even in the case of highly unbalanced twist.

Twist liveliness can be measured by taking a metre of yarn and allowing it to twist around itself by suspending a light weight from the centre of the yarn and bringing the two ends together. Liveliness is then expressed in terms of the number of turns per metre that the yarn twists upon itself. Alternatively, the two ends of a 50 cm length of yarn are clamped under a certain tension and a light weight suspended from the centre of the segment, after which the one clamp is moved slowly towards the other and their distance apart recorded as soon as the yarn begins to snarl.

12.2.5 Tensile properties

The tensile properties of a yarn rank as one of its most important quality characteristics, since they largely determine the efficiency with which the yarn can be converted into fabric as well as the tensile properties of the final product. By tensile properties is normally meant the breaking strength and extension (elongation) at break of the yarn, including their distributions as well as the occurrence of weak places. A distinction can be made between the breaking force (breaking strength), the maximum force registered, and force at rupture, the force registered before the two yarn ends separate (see Fig. 12.2), similarly with elongation. Normally, breaking strength and breaking elongation are measured and reported. Sometimes the strength and extension are combined into a work-to-break (toughness), a measure of the ability of a yarn to do work or absorb energy, expressed in Newton metres or Joules. Actually it is the area under the force-elongation curve, up to the maximum force (Fig. 12.2). Other yarn parameters, such as Young's Modulus, or initial modulus, can also be determined.



12.2 Yarn tension force vs elongation (source: Uster Technologies).

The mean breaking strength is important since it gives an indication of overall yarn strength which will be reflected in the fabric strength and it also provides a measure, though not always a reliable one, of the strength of the weak places. Nevertheless, everyone is familiar with the saying ‘a chain breaks at its weakest link’, indicating that it is the weak places in a yarn and not the average yarn strength, which frequently determine a yarn’s performance, or breakage pattern, during winding, weaving and knitting. It is therefore important to obtain a measure of the isolated weak places in a yarn, in addition to the average strength, since the latter generally does not provide a sufficiently accurate measure of the isolated weak places.

There are a number of different tensile testers on the market, both manual and automatic, and they can broadly be divided into single thread and multi-thread (skein or hank) testers, with the former far more popular and providing a great deal more valuable information than the latter. The single-thread testers provide information on the average or mean strength as well as on the distribution of strength, whereas the multi-thread testers give a more composite picture of strength, with the values being affected by the weaker strands in the skein e.g. ASTM D1578 and BS 6372. The single-thread strength tests also provide values for the yarn extension at break which is very important since it provides a measure of the yarn brittleness, a property sometimes even more important than the breaking strength itself. Various standard test methods are available for testing yarn tensile properties, including BS 1932, DIN 53834, ASTM D2256, ASTM D1578.

Tensile testers can operate according to three different principles (see ASTM D76):

1. Constant rate of yarn extension (the most popular), where the yarn is extended at a constant rate, e.g., Uster® Tensorapid UTR 4, and Tensojet 4, Instron and Premier Tensomaxx 7000.
2. Constant rate of load, where the load on the yarn is increased at a constant rate.
3. Constant rate of traverse, which is a hybrid of the first two but is no longer all that common except in the case of pendulum type multi-thread testing instruments.

Because of the general variability of a staple fibre yarn, it is necessary to carry out a relatively large number of tests so as to obtain a reliable average or mean, about 100 tests per yarn sample generally being the absolute minimum, with 200 to 400 tests preferred, except where a reliable measure of the isolated weak places is also required in which case some 30,000 tests or more may be required, a high correlation being found between isolated weak places (e.g. strength of the P0.01 percentile value) and the number of weft breaks per 100,000 picks. The yarn is generally clamped under a pre-set tension and at a pre-determined gauge length, typically 50 cm. Tests can take place at a certain rate of extension, or at a certain average breaking time (e.g. 20 s) or at very high speeds (e.g. 400 m/min).

An example of a high-speed tensile tester is the Uster® Tensojet 4 (Fig. 12.3), testing at 30,000 breaks per hour (400 m/min), thereby providing an accurate measure of the isolated weak places which play an important role in determining weavability. It is important to remember that the different results obtained from the different types of testers can vary and even the results obtained on the same type of tester will vary, if, for example, the time to break or rate of strain is not kept constant. In general, the following parameters are used to provide an overall picture of the yarn tensile properties:

- mean breaking strength (e.g. cN or gf)
- breaking tenacity (e.g. cN/tex or gf/tex)
- CV of breaking strength (%)
- mean extension (elongation) at break (%)
- CV of extension (%)
- work-to-break (cN.cm or N.m)
- isolated weak places (for example, the percentage of breaks which have a strength and/or elongation below a certain threshold level, such as 4 cN/tex and 2%, respectively).
- skein strength is generally given as the count-strength-product (CSP) which represents the product of the force (e.g. pounds-force or kilograms-force) required to break the skein and the cotton count (Ne) or tex of the yarn.

12.3 Uster® Tensojet (source: Uster Technologies).

To allow the strength of yarns differing in linear density (or count) to be compared and also to provide more universal strength standards, the breaking strength of a yarn is often divided by its linear density (tex) to give what is termed 'tenacity' (e.g. cN/tex) and which is almost, but not entirely, independent of the actual yarn linear density. For quality control purposes, the tensile values obtained for a yarn can be compared with external standards (e.g. Uster® ISO) or internal (in-house) standards. Dynamic and integrated tensile testing, where the running yarn is subjected to a predetermined constant tension, provides a measure of yarn strength, elongation, isolated weak places, friction, abrasion, hairiness and evenness and lint (fly) generation under simulated manufacturing conditions, is also carried out.

12.2.6 Evenness

Introduction

The terms yarn evenness, unevenness, regularity and irregularity are often used interchangeably and taken to refer to the same yarn characteristic, namely the uniformity or evenness of the yarn mass per unit length (linear density), measured capacitively (ASTM D1425), or of the yarn cross-sectional size or diameter, measured optically. This characteristic is important from two perspectives, namely from an aesthetic or appearance point of view and from a technical or functional (performance) point of view, since unevenness (i.e. thinner or thicker segments) in the yarn cross-section, is commonly associated with variations in the yarn strength and elongation. In practice, yarn evenness is most frequently measured using capacitance, as opposed to optical, techniques which means that it is assessed in terms of changes in segment mass (linear density) rather than in terms of cross-sectional volume (bulk) or diameter, assuming the dielectric properties (notably moisture and fibre blend) of the yarn are constant. Nevertheless, recent evenness testers enable both capacitance and optical measurements to take place simultaneously, sometimes as an option. Examples of modern yarn evenness testers include: Uster® Tester 4-SX (Fig. 12.4) Keisokki KET 80, III/B and Premier iQQU AL1 CENTER. Optical testers include the Zweigle Yarn Detector G 580 (using infra-red light) and the Keisokki Laserspot III Hairiness and Evenness (Diameter) Testing instrument which functions on the principle of Fresnel diffraction of a laser beam.

According to Basu,[3] research has shown that some 42% of the total yarn irregularity is due to the raw material, some 40% due to the condition of the ringframe and 18% due to the roving irregularity. The irregularity (unevenness) added by each processing stage in the yarn manufacturing process is additive, as follows:

$$\mathrm{CV_R} = \sqrt{\mathrm{CV}_1^2 + \mathrm{CV}_2^2} \qquad 12.2$$

12.4 Uster® Tester 4 (source: Uster Technologies).

where CV_R is the resultant irregularity, say of the yarn; CV_1 is the irregularity of the input material (the roving); CV_2 is the irregularity added by the spinning process (ring frame).

Drafting waves introduced into the yarn during spinning have a wavelength of approximately 2.8 times the staple length; while those in the yarn introduced during the roving process will have a wavelength 3.2 × the draft × the staple length. Greater random irregularity or drafting waves in the yarn produce 'cloudiness' in the fabric, as opposed to the patterned (regular) or moiré effect produced by regularly occurring (periodic) irregularity or faults.

In keeping with the conventional approach, the overall yarn evenness characteristics will be grouped and discussed under three headings, namely unevenness (irregularity), imperfections (relatively small and frequent thin and thick places and neps) and faults (grosser and less frequent faults, such as slubs, fly and very long or extreme thin and thick places). For more in-depth treatment of yarn irregularity the reader is referred to various publications.[4]

Unevenness

Enormous strides have been made in the measurement of yarn evenness, both in terms of the speed and the detail of the measurement. Modern evenness testers, which incorporate both capacitance and optical measurement techniques, enable the following yarn properties to be accurately measured, or derived, within one minute:

- mass unevenness (short term (1 to 10 times fibre length)[3], medium term (10 to 100 times fibre length)[3] and long term (more than 100 times fibre length)[3], also spectrograms and variance length curves)
- imperfections (thin and thick places and neps)
- hairiness
- count (linear density), relative and absolute
- diameter
- density
- surface structure
- trash
- dust.

It is also possible to diagnose periodic faults by means of gearing diagrams and ratios, using a database contained in the software of the tester. Furthermore, the appearance of the yarn and its faults, as it would appear on a taper board or in a woven or knitted fabric, may be simulated and evaluated on a screen, and agreed upon quality properties can also be displayed in the form of a pie chart for easy assessment of 'off-quality' properties.

Yarn unevenness (mass unevenness) can be numerically expressed in terms of either the coefficient of variation (CV_m in %) or linear irregularity (U_m in %), commonly measured with an effective 'cut' or measurement length of 8 mm. CV_m (in %) is more commonly reported, being shortened to CV (%).

$$\mathrm{CV}(\%) = \frac{s}{\bar{x}} \times 100 \qquad 12.3$$

where s = standard deviation $\bar{x}$; $\bar{x}$ = mean (or average).

For continuous measurement: $\mathrm{CV}(\%) = \frac{100}{\bar{x}} \sqrt{1/L} \int_0^L (x_\mathrm{I} - \bar{x})^2 \, dl$

$$\mathrm{U}(\%) = \frac{100}{\bar{x} L} \int_0^L |x_i - \bar{x}| dl \qquad 12.4$$

dl = an elemental length of material and L is the total length of yarn measured. For completely random variation $CV_m = 1.25\ U_m$

The values obtained can then be compared with the appropriate specifications or standard values (e.g. Uster Statistics at www.cogetex.ch/Services/Sujets/TechSpecs. html).

The limiting (or ideal) irregularity CV_{lim}, of a cotton yarn, derived from Martindale's[5] general equation, in which a completely random arrangement of fibres is assumed, may be calculated as follows:

$$CV_{lim}(\%) = 106/\sqrt{n} \qquad 12.5$$

(although sometimes $CV_{lim}(\%) = 100/\sqrt{n}$ is also used)

$$= 106\sqrt{\frac{F}{\text{tex} \times 1000}} \qquad 12.6$$

where F = fibre fineness (in mtex); tex = yarn linear density in mg/m (i.e. tex units); n is the average number of fibres in the yarn cross-section = tex × 1000/F.

From this, the irregularity index I, a measure of the effectiveness with which the spinner has converted the available fibre into a yarn, can be calculated as follows:

$$I = CV_{\text{actual}}/CV_{\text{lim}} \qquad 12.7$$

CV_{actual} being the actual (or measured) irregularity.

Imperfections

Imperfections (i.e. thin and thick places and neps) affect the appearance of the yarn and that of the subsequent fabric, while thin places, generally of higher twist (because of twist running into it), could also represent weak places in the yarn. Imperfections can be measured at different threshold levels, for example:

- Thin places: –30%, –40% and –50% i.e. either 30%, 40% and 50% below the average yarn linear density, or cross-section, more typically – 50% for both ring-spun and rotor-spun yarns.
- Thick places: 35%, 50%, 75% and a 100%, greater than the average yarn linear density, more typically 50% for ring-spun and rotor-spun yarns. These thin and thick places are generally equal in length to the mean fibre length.
- Neps: 140%, 200%, 280% and 400% greater than the average yarn linear density, calculated on the basis of a 1 mm segment length, the maximum length being limited to 4 mm, typically being 200% for ring-spun yarns and 280% for rotor-spun yarns. The neps could be due to the raw material (e.g. immature fibres or vegetable matter) or to processing (e.g. during ginning and carding). It is also possible to optically classify neps as 'process neps' or 'seed coat neps' (trash type).

The frequency of imperfections is normally expressed as the number per 1,000 m. If the number is above 30, the frequency generally follows the normal distribution, while if it is below 30 it follows a Poisson distribution.

Faults

Yarn faults, such as thick places and slubs, are generally due to poor drafting (e.g. a bundle of short fibres not being drafted and travelling into the yarn as a cluster or clump of fibres) or fly being caught in the fibrous strand. In addition to causing a fabric blemish or fault, the more severe yarn thick places and slubs can also cause yarn breakages during fabric manufacturing, either because they generally contain a relatively low twist and are therefore intrinsically weak or if they get caught in yarn guides, e.g., heald eyes, knitting needles and sinkers, etc. It is therefore important in practice to monitor and control yarn faults.

As already mentioned, yarn faults are generally more serious than yarn imperfections, and consist of thick places, slubs and thin places. Whereas imperfections are generally expressed as the number per 1000 metres, the grosser faults as such are expressed per 100,000 m because of their relatively low frequency. The more serious types of yarn faults, termed objectionable faults, generally lead to a fabric defect (or fault) and therefore should be removed by clearing during winding. Very thin places could also lead to either a yarn break during winding or fabric manufacturing or to a thin place (line) in the fabric and should preferably also be removed during clearing. It is commonly stated, however, that a very faulty yarn cannot be transformed into a good quality yarn merely by clearing, as the clearing of excessive faults in the yarn will adversely affect winding efficiency and economics and could produce a yarn with an excessive number of knots or splices which themselves may lead to problems during fabric manufacturing and in the fabric itself. Yarn faults are generally classified according to both their length and cross-section.

As in the case of yarn irregularity and imperfections, yarn faults can be measured and cleared using either optical or capacitance systems. Both are used, although the capacitance systems, such as the Uster® Classimat Quantum, Premier Class *i* and Keisokki Classifault CFT are the most popular. Certain systems, such as the Uster® Classimat Quantum (combining capacitance and optical sensors), also enable foreign fibre classification and measurement of vegetable matter content as well as the simulation of the effects of faults in the yarn and fabric and the determination of yarn count. On-line monitoring and classifying of yarn faults and count deviations on rotor-spining machines is also provided using systems such as Corolab XQ (www.saurer.de).

12.2.7 Diameter

Various instruments optically measure the yarn diameter and its variation, including imperfections and faults (see also previous sections). For example, the two-dimensional optical diameter of yarns is measured on evenness testers, such as the Uster® Tester 4-SX fitted with digital-analog opto-electronic sensors (infra-red) together with a high-resolution line scan camera. Optical yarn diameter unevenness can also be measured, the results not being influenced by the colour of the yarn; the effective measuring (field) length, for example, being 0.3 mm. The results can provide much the same information and can be analysed in much the same way as that for capacitance based yarn mass results.

The shape (roundness) of the yarn can also be determined. From the yarn count and cross-sectional area, the yarn density can be calculated, density depending upon the yarn type and twist. For example, the density of a combed ring-spun yarn is of the order of 0.5 g/cm^3, that of a carded ring-spun yarn of the order of 0.8 g/cm^3 and that of a rotor-spun carded yarn of the order of 0.4 g/cm^3. Yarn diameter can also be monitored on-line during winding. The Zweigle Yarn Detector G580 uses an opto-electronic (infra-red) principle to measure the yarn diameter and its variation, including imperfections and moiré. The Lawson-Hemphill Yarn Analysis Software (YAS) system also measures the yarn diameter, imperfections and faults optically, using a camera (CCD array).

12.2.8 Hairiness

Hairiness normally refers to fibre ends, fibre loops and fibres of varying length (wild fibres) protruding from the surface (or body) of the yarn, frequently as fibre tails. Although hairiness is desirable in certain types of fabrics, notably soft knitteds, brushed fabrics and flannels, it is undesirable in other fabrics, such as shirting. Yarn hairiness affects the fabric surface appearance and properties, including fabric pilling, handle and comfort (thermal insulation). Yarn hairiness also plays an important role in weavability, since the protruding hairs tend to catch on adjacent yarns causing yarn breakages and loom stoppages. It is particularly important in air-jet weaving. In fact, one of the main objectives of sizing is to smooth down the hairs on the yarn, i.e., to reduce yarn hairiness, thereby improving yarn weaving performance. Yarn hairiness positively affects the heat and wear generated when the yarn runs over metal or other surfaces, such as travellers and yarn guides. Variations in yarn hairiness can be particularly problematic, being reflected in variations in fabric surface appearance, and can cause fabric barré and streakiness, it therefore being important that yarn hairiness remains acceptably constant within a certain application and yarn consignment. It is now possible to measure yarn hairiness on-line, for example, on programmable yarn clearers, such as the Uster® Quantum, Yarn Hairiness Grades helping to visualise various levels of hairiness, e.g., (www.Uster.com).

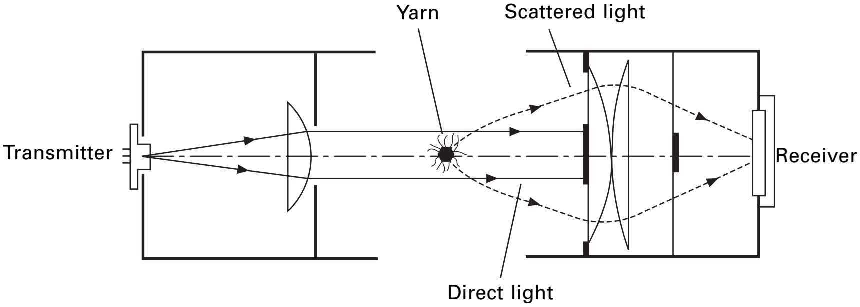
Many different hairiness measuring instruments and test methods (e.g. ASTM D5647), as well as measures of hairiness are used, including a module on the Uster® Tester 4, Shirley Yarn Hairiness Tester and Zweigle G 566 and G 567 Hairiness Tester. In some cases, the number of hairs protruding beyond a certain distance (e.g. 3 mm) from the yarn surface or axis, are measured, while in other cases the overall hairiness of the yarn is measured and expressed as a hairiness index. In the case of the Uster® Tester 4-SX (Fig. 12.5), hairiness is measured over approximately 1 cm lengths of yarn at the same time as the yarn evenness is measured and the results expressed in terms of the hairiness, H, representing the total length of yarn protruding from the yarn surface, for example, a value of 6 for H indicates that the total length of protruding hairs is 6 cm over the distance of 1 cm. Yarn hairiness diagrams, spectrograms, etc., can also be provided, as well as the variation in yarn hairiness, expressed as the standard deviation, sh, or coefficient of variation CV_H = sh/H × 100. The standard deviation, sh, is more commonly used. Barella and co-workers have produced a number of reviews on yarn hairiness.[6]

12.2.9 Yarn appearance

Traditionally, a yarn appearance and grade allocation have been subjectively assigned to yarn wrapped on an inspection or tapered board (blackboard), a number being assigned according to, for example, ASTM standard D-2255, but today this can be done either electronically or by simulation. Electronic grading and simulation systems enable the yarn blackboard or fabric appearance to be simulated using systems such as the Loepfe MillMaster Visual System, Zweigle OASYS® Optical Sensing Unit, YAS Yarn Analysis System of Lawson-Hemphill and Premier CYROS with the appropriate software (see also in section 12.2.6.).

12.2.10 Linting and fly

An important yarn quality parameter is its linting or fly generating propensity during winding, knitting and weaving. If a yarn sheds a great deal of lint and fly, it will contaminate the surrounding atmosphere, creating a health hazard, as well as building up on machine parts, guides, etc., possibly leading to machine damage, stoppages, yarn breakages and the need for frequent cleaning.



12.5 Yarn hairiness measurement (source: Uster Technologies).

Accelerated wear on certain machine components can also result. In addition to this, fly can get caught up in the fabric, forming a blemish which resembles a nep. Fly is generally due to excessive short fibres and possibly weak or damaged fibres in the yarn and to the yarn structure.

An example of an instrument on the market for measuring fly or linting potential is the Zweigle Staff Tester G 556. This instrument also provides a measure of the nepping potential of the yarn, i.e., the tendency for the yarn to form neps (fibre bundles or clusters) when it is abraded during knitting and weaving, since this could be reflected in knitting and weaving performance and the appearance of the fabric. Basically, the yarn is drawn over a knife edge and over itself (it is twisted with itself), and the amount of fly shed over a certain test length is then determined by catching and weighing the fly. Simultaneously, the number of neps is determined as the yarn enters the test zone and as it leaves again, the difference providing a measure of the nepping propensity of the yarn. Fly or linting potential is expressed as a percentage based upon the mass of yarn tested, while nepping potential is expressed as the number of neps per unit length.

12.2.11 Yarn abrasion

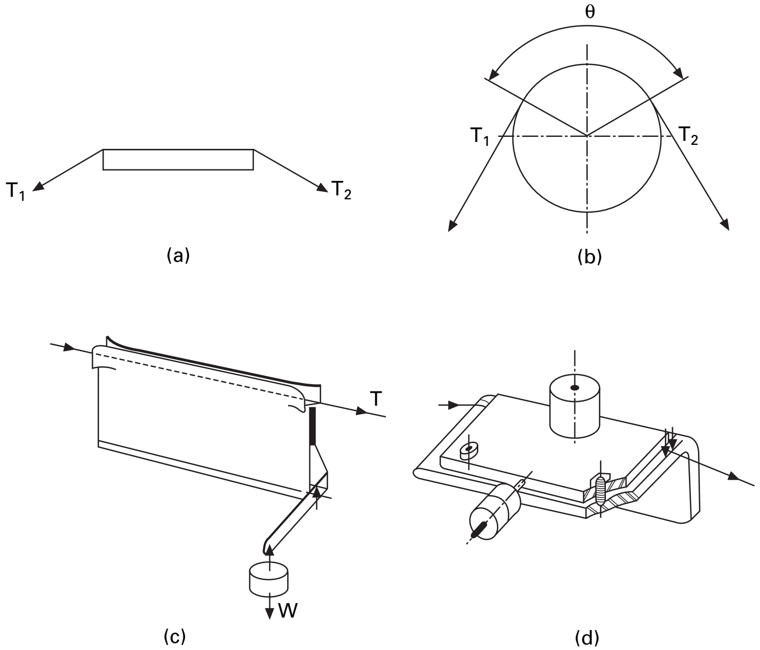
Although yarn abrasion resistance is an important property, particularly from the view of weavability, it is not all that commonly measured, mainly because it is not easy to measure this parameter accurately under conditions which simulate those which the yarn will experience during weaving. Another consideration is that if the yarn is to be sized then it is really the abrasion resistance of the sized yarn which needs to be measured as this would be quite different from that of the unsized yarn, being greatly affected by the type, level and levelness of the size applied. Examples of yarn abrasion testers are on the market, include the Zweigle Staff Tester G 556 and G 552 Abrasion Tester and Reutlingen Weaving Tester G 545, the latter working on the principle that a tensioned yarn web is cyclically abraded and flexed over rods, with the number of cycles required to cause one or more yarns to break or a certain change in the yarn appearance (or neppiness) being noted and used as a measure of the ability of the yarn to withstand abrasion.

12.2.12 Friction

The friction of cotton yarns is mainly important when it comes to machine knitting, particularly when knitting relatively fine yarns on high-speed knitting machines. By and large, two types of yarn friction, or a combination thereof, are measured, namely yarn-to-metal (or occasionally yarn-to-ceramic friction) and yarn-to-yarn (ASTM D3412), since these represent the types of friction mostly encountered in practice. The yarn friction determines the frictional forces and tension developed by the yarn as, for example, it slides over yarn guides, tensioning devices, knitting needles and sinkers, the yarn itself, or other yarns. If the yarn friction is excessive, the tension generated in the yarn could exceed its breaking strength, thereby causing yarn breakages, for example, during winding or knitting. The most effective, and widely used, means for reducing friction is to apply a lubricant, for example, using a solid paraffin wax disc, to the yarn as it is wound onto the package, during winding or during rotor-spinning. Sometimes a lubricant (or softener) is applied to the dye-bath, subsequent to package dyeing, while in some cases an emulsion lubricant is applied during winding, for example, by means of a lick-roller.

Various commercial friction testers and test methods (e.g. ASTM D3108) are available, most of these measuring the tension generated in the yarn as it passes over a cylindrical or flat metal surface, or itself, the yarn-to-metal coefficient of friction (µ) can be estimated by measuring the yarn tension (T_1) prior to the surface and that (T_2) after the surface (Fig. 12.6) using the following classical capstan equation:

$$T_2/T_1 = e^{\mu\Theta} \text{ and } T_2 = T_1 e^{\mu\Theta} \qquad 12.8$$



12.6 Diagrams showing methods of applying tension to yarns: (a) flat plate; (b) capstan; (c) and (d) twin flat plate system (source: P.J. Kruger, *Text. Month*, Feb. 1970).

where Θ = total angle of contact (in radians) between the yarn and the cylinder and e = the base (2.718) of natural (napierian) logarithms. For a gate (flat) type of frictional surface, the relevant equation is:

$$T_2 = T_1 + 2\mu N \qquad 12.9$$

where N is the normal force (pressure) applied to the yarn.

Ideally the coefficient of friction of cotton yarns destined for knitting should be 0.15 (or lower), although the actual value depends to some extent upon the conditions under which it is measured. Examples of commercial friction testers include the Lawson-Hemphill (hand-held, with statistics), Schlafhorst Friction Tester Textechno H. Stein, Zweigle μ-Meter G 532 I, Rothschild F-Meter R-2088 and SAWTRI Yarn Friction Meter (WIRA).

12.2.13 Miscellaneous yarn tests

- Wrapper fibres on rotor-spun yarns (e.g. GAG Yarn Analyser, Engineering College of Aachen).
- Yarn Bulk, e.g., WRONZ Yarn Bulkometer (WIRA).
- Yarn Shrinkage e.g., ASTM D2259-02 and/or AS2001-5-6 'Determination of Dimensional Change of Yarn and Sewing Thread'.

12.3 Fabric testing

12.3.1 Introduction

Fabric properties are determined by the fibre content, yarn and fabric construction and any chemical and mechanical treatment applied to the yarn or fabric.[7] These need to be assessed within the context of the requirements of the specific end-use for which the fabric is destined, within the broad categories of clothing (apparel) textiles, home textiles and industrial (technical) textiles. With respect to clothing, aspects relating to the fabric aesthetics or appearance generally dominate (Table 12.1),[8] while in the case of industrial textiles, technical and performance related properties predominate. Table 12.2 illustrates the diversity of requirements for different applications.[9]

Consumer studies[10] have shown that the main requirement for clothing are ease-of-care performance, elegance (aesthetics) and durability (i.e. acceptable or reasonable wear life). The performance and appeal, or perceived 'quality', of fabrics destined for apparel depend upon a number of mechanical and physical properties, such as handle, resistance to abrasion and pilling, drape, crease recovery, dimensional stability and comfort, the importance of which depends upon the intended end-use and the customer's expectations as well as in the case of apparel, on the customer's wear conditions and garment fit. Wear is the consequence of a number of factors which reduce the

Table 12.1 Fabric properties that are related to tailoring performance, appearance in wear, and handle[8]

Property	Test	Tailoring performance	Wear appearance	Handle
Physical	Thickness	–	–	+
	Mass per unit area	+	+	+
Dimensional	Relaxation	+	+	–
	Shrinkage			
	Hygral expansion	+	+	–
Mechanical	Extensibility	+	+	+
	Bending properties	+	+	+
	Shear properties	+	+	+
Surface	Compression properties	–	–	+
	Friction	–	–	+
	Surface irregularity	–	–	+
Optical	Lustre	–	+	–
Thermal	Conductivity	–	–	+
Performance	Pilling	–	+	–
	Wrinkling	–	+	–
	Surface abrasion	–	+	–

+ Important; – less important.
Source: De Boos, 1997.[8]

serviceability and acceptability of a product, including abrasion, tearing, bending, stretching, rubbing (abrasion), laundering and cleaning (see ASTM D3181).

In practice, mechanical damage or breakdown is generally much more important than chemical damage (including that due to laundering and light) in determining wear life. Generally, the inclusion of one or more laundering cycles together with abrasion and pilling tests improve actual wear prediction, it being important that the tests subject the fabric to relative low and random abrasive forces. Kothari[12] divided fabric properties into six different groups as shown in Table 12.3. Table 12.4[12] provides a more specific example for a shirt.

12.3.2 Wrinkle and crease-recovery

The tendency for a fabric or garment to wrinkle or crease (ASTM D-123) when subjected to sharp folds (bends, creases or wrinkles) under pressure (load) during wear or laundering, is very important from an appearance point of view, also having a bearing on 'ease-of-care' related properties (durable press, easy-care, minimum-iron, etc.) In effect, it is not so much the ability of the fabric to withstand creasing or wrinkling that is important, but its ability to regain its original shape and smooth appearance, from such creases

Table 12.2 Some examples of special parameters for different end-uses of fabrics/garments[9]

Item	Special requirements
Garments for Australia	Improved light fastness, UV protection
Swimwear/beachwear	Chlorinated water/seawater fastness, colourfastness to light.
Towels and napkins	Absorbency.
Surgical gowns/apparel	Anti-bacterial properties, colourfastness to autoclaving, absorbency.
Woollen merchandise	Moth proofing.
Fire-fighters apparel	Flame proofing.
Defence textiles	Rot proofing.
(Tents/Canvas, etc.)	Protective textiles.
Parachute cloth	Air permeability.
Soil-resistant products	Soil-releasing fluorocarbon treatment.
Oil industry applications	Oil-repellent finishes.
Household curtains & drapery	Tensile strength, colourfastness to light, flammability.
Bathmats/table mats	Colourfastness: migration into PVC.
Upholstery	Abrasion resistance.
Industrial uniforms	Strength, oil/soil repellency, flammability.
Sportswear	Abrasion resistance, seam strength & colourfastness to perspiration.
Baby/children's wear	Colourfastness to saliva.
Nightwear	Flammability.
Rainwear	Water repellency, breathability.
Garments for arctic conditions	Ability to withstand extreme cold: flexing/strength at low temperatures.

and wrinkles, i.e., its wrinkle recovery or crease recovery that is important. Therefore, in testing a fabric for this important property, wrinkles or creases, more popularly the latter, are inserted into a fabric specimen under carefully controlled conditions of pressure and fold sharpness, the wrinkle recovery or crease recovery being measured after the load has been removed and the fabric allowed a certain period to recover.

Wrinkle and crease recovery is particularly important for cotton, since untreated cotton is notoriously poor in this respect and considerable research and development work over many decades has been directed towards developing chemical treatments that improve this property without an unacceptable loss in other desirable properties, such as softness, comfort and durability. There are various test methods for measuring fabric wrinkle and crease recovery,[13] it being possible to divide these into two broad categories, namely those which involve the insertion of a single sharp crease and those which insert a family of largely random creases or wrinkles in the fabric. In both cases, the conditions of deformation, i.e., of wrinkle and crease insertion, as well as the conditions of recovery, are critically important and need to be

Table 12.3 Classification of different properties[11]

Woven fabrics	Knitted fabrics	Nonwoven fabrics
1. Structural Properties • Warp and weft linear densities • Warp and weft twist levels • Warp and weft thread densities (number per unit length) • Warp and weft crimp levels • Cover factor • Mass per unit area • Fabric thickness • Fabric skew and bow	• Structure • Yarn linear density • Yarn twist • Courses and wales per unit length • Cover factor • Mass per unit area • Fabric thickness • Spirality	• Fibre orientation in web and bonding method • Fibre fineness • Fibre length • Fibre crimp • Mass per unit area and uniformity • Fabric thickness or bulk density
2. Mechanical properties[a] • Tensile strength • Tear strength • Bursting strength • Abrasion strength • Pilling resistance • Snag resistance • Fatigue (tension, bending and shear)	3. Comfort-related transmission properties[b] • Air permeability • Water vapour permeability • Resistance to penetration of liquid water • Resistance to flow of heat • Electrical conductivity	
4. Low stress mechanical properties[c] • Tensile properties • Compressional properties • Bending properties • Shear properties • Buckling behaviour • Roughness and frictional properties	5. Aesthetic properties • Drape • Crease recovery • Wrinkle recovery	6. Other physical properties and end-use specific tests • Dimensional stability • Flammability • Impact tests • Absorbency • Delamination

a. Related to utility performance and durability.
b. To flow of fluids, heat and electricity.
c. Related to handle and tailorability.

carefully controlled and consistent. Very important, too, are the atmospheric conditions, relative humidity in particular, and the fibre moisture content during both creasing and recovery.

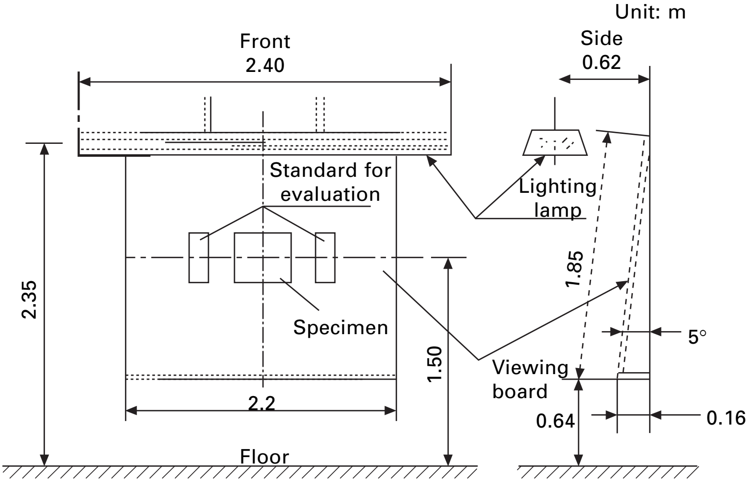
A popular method used by industry to assess the fabric wrinkle recovery is AATCC Test Method 128 'Wrinkle Recovery of Fabrics: Appearance Method' in which wrinkles are induced in the fabric under standard atmospheric

Table 12.4 The utility-value analysis graphics[12]

1st-level objective: long use of the shirt without losing its properties		
2nd level objectives:		
1. Fabric quality	2. Sewing quality	3. Usage quality
	3rd-level objectives:	
1.1 The fabric should not wrinkle easily	2.1 The seams should not open out	3.1 The colours should not fade after washing
1.2 It should not pill	2.2 The seams should not come off	3.2 The colours should not change in dry cleaning
1.3 It should absorb sweat		3.3 The colours should not change in the light
1.4 It should resist stretching		3.4 The colour purity should be good
1.5 It should not wear out easily		3.5 The size should not change after washing
		3.6 The colours should not pale after ironing
		3.7 The colours should not change by rubbing and should not dye other materials
		3.8 The cloth should not include toxic materials
	Criteria	
Wrinkling angle (ISO 9867)	2.1.1 Seam slippage (BS 3320)	3.1.1 Colour fastness to washing (ISO 105 C06)
1.2.1 Pilling (ISO BS 5811–1986)	2.2.1 Seam strength (BS 3320)	3.2.1 Colour fastness to dry cleaning (ISO D01)
1.3.1 Water penetration (ISO 811–1992)		3.3.1 Light fastness (ISO 105 B02)
Tearing strength (BS 4304–1986)		3.4.1 Dimensional stability to washing (DIN 53920)
1.5.1 Abrasion resistance		3.5.1 Colour fastness to ironing (ISO 105 B01)
1.5.2 (BS 5690)		3.6.1 Colour fastness to perspiration (ISO 105 EO4)
		3.7.1 Colour fastness to rubbing (ISO 105 × 12)
		3.8.1 Aromatic amine test (MAK Amin IIIA-1.2)

conditions using a standard wrinkling device under a predetermined load for a prescribed period of time. The specimen is then reconditioned and rated for appearance by comparing it with three-dimensional reference standards (AATCC Wrinkle Recovery Replica). The viewing conditions are illustrated in Fig. 12.7. The same method has been adopted by the International Organisation of Standardisation (ISO 9867) and Japanese Industry. Nevertheless, this suffers from the disadvantage that it is subjective and that fabric colour and pattern have a significant effect on the perception of wrinkles. Considerable research has led to the development of objective assessment techniques. Xiaobo *et al.*[14] for example, reported on a new method based upon computer vision (photometric stereo technology combined with ANFIS adaptive neural fuzzy inference systems) for evaluating the fabric wrinkle grade objectively. Fan *et al.*[15] have discussed various objective methods of measuring and characterising wrinkle recovery, including stylus (contact), laser scanning and image analysis.

In the case of crease recovery testing (using, for example, a Shirley Crease Recovery Tester) the fabric specimen (either wet or dry) is creased and compressed under a specified load and atmospheric conditions for a predetermined period (e.g. 5 min) after which the load is removed and the specimen allowed to recover, once again under specified conditions and time (e.g. 5 min), and the recovery angle (crease recovery angle) measured. Test methods include AATCC 66, BS EN 22313, ISO 2313. This test is frequently used to assess durable-press and easy-care related properties of treated cotton fabrics.



12.7 Lighting equipment for viewing test specimens (source JISL 1905: 2000).

12.3.3 Surface smoothness after repeated laundering

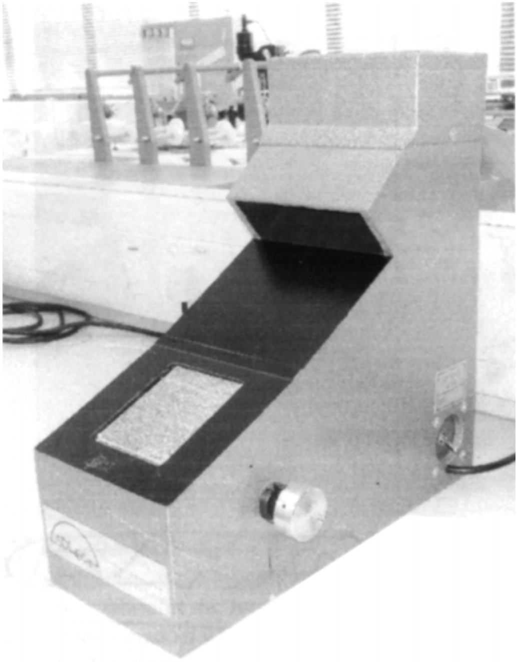
AATCC Test Method 124 (ISO 7768) is designed for evaluating the appearance, in terms of smoothness, of flat fabric specimens after repeated home laundering, this providing a measure of the durable-press and easy-care, or minimum-iron properties of the fabric. The test procedure and evaluation method are almost the same as in the two methods mentioned above, except for the difference in specimen preparation and standard replicas. The Fabric Appearance Evaluator (Fabric Eye) of the Institute of Textiles and Clothing, Hong Kong Polytechnic University can be used to obtain an objective 3-D measure of the surface smoothness of the fabric.

12.3.4 Pilling propensity[15]

The appearance and aesthetic quality of clothing as well as of upholstery are influenced by the fabric propensity to surface fuzzing and pilling. Pills (ASTM D-123), tightly entangled clusters or balls of fibres attached to the fabric by means of one or more fibres, are developed on a fabric surface in four main stages; fuzz formation, entanglement, growth and wear-off.[16] It begins with the migration of fibres to the outside yarn surface causing fuzz to emerge on the fabric surface. Due to friction, this fuzz becomes entangled, thus forming pills which remain attached to the fabric by long fibres.

The pilling resistance of fabrics is normally tested by simulated wear through tumbling, brushing or rubbing on a laboratory testing machine. The specimens are then visually assessed by comparison with visual standards (either actual fabrics or photographs) to determine the degree of pilling on a scale ranging from five (no pilling) to one (very severe pilling). Figure 12.8 shows a viewing device for pilling assessment. The observers are guided to assess the pilling appearance of a tested specimen on the basis of a combined impression of the density and size of pills and degree of colour contrast around the pilled areas.

Several test methods (ASTM, ISO, BS and JIS) have been established for assessment of pilling propensity. They differ in the way the specimens are treated to simulate wear conditions and create a ‘pilled’ appearance. In BS EN ISO 12945-1 and BS 5811, specimens are mounted on polyurethane tubes and tumbled randomly, under defined conditions, in a cork-lined box, such as the ICI pilling box (see Fig. 12.9) for an agreed period of time (say five hours). In ASTM D 4970 and ISO 12945-2[14] pilling formation during wear is simulated on the Martindale Tester. The face of the test specimen is rubbed, under a light pressure, for a specific number of movements, against the face of the same mounted fabric in the form of a geometric figure. Figure 12.10 shows a Martindale Tester. In ASTM D 3511 (Brush Pilling Tester), and D3512 and D 3514, and DIN 53867 and JIS L 1076 pilling and other



12.8 Viewing device for pilling assessment.

12.9 ICI Pilling Box Tester.

changes in surface appearance which occur in normal wear, are simulated by brushing the specimens to free fibre ends, by random rubbing action produced by tumbling specimens in a cylindrical test chamber lined with mildly abrasive materials (e.g. cork liners), and by controlled rubbing against an elastomeric

12.10 Martindale Tester.

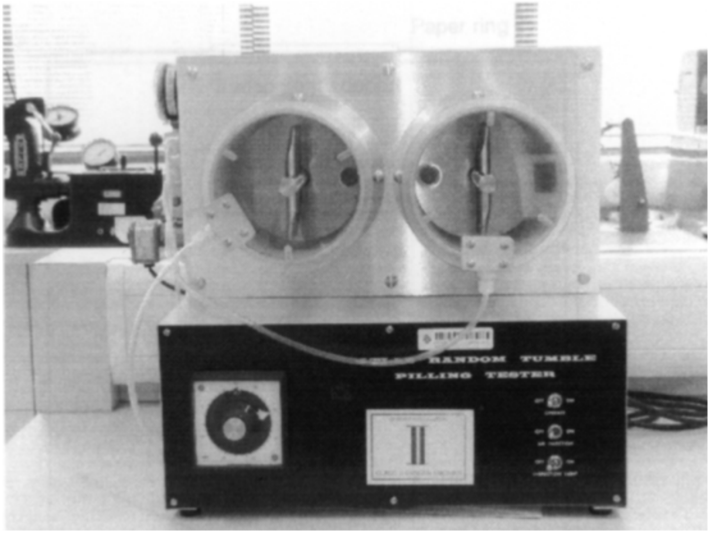
pad having specifically selected mechanical selected properties, respectively. Figure 12.11 shows a Random Tumble Pilling Tester (ASTM D3512). The Japanese standard JIS L 1076 covers six types of testers, similar to those in the ISO, BS and ASTM standards.

The kind of pilling tester used has significant effect on the test results, the most suitable tester depending upon the type of fabric (e.g. knitted or woven) and on the anticipated wear conditions. The chosen tester for the performance evaluation should best simulate the actual wear condition. Cooke and Goksoy[17] compared the results of various pilling testers. Goktepe[18] investigated the pilling performance of fabrics in the wet state. He found that use of the Martindale tester resulted in worse pilling grades than the other two testers, and different pilling testers have different sensitivities for various fibre, yarn and fabric parameters.

The subject of fabric pilling has been reviewed by Ukponmwan,[19,20] while Fan *et al.*[15] have discussed various objective methods of measuring pilling. Chen and Huang[21] reported on an objective method of assessing pilling, based upon optical projection and image analysis, which, it is claimed, eliminates the effects of fabric colour and pattern. Automated three-dimensional grading of pilling (pill density and size distribution), fuzziness and other surface properties are possible using systems, such as the SDL Atlas Pill Grade.

12.3.5 Fabric stiffness

Fabric bending stiffness is very important in terms of drape, making-up performance and comfort, and many testers and test methods are available for measuring fabric stiffness, including the Shirley Fabric Stiffness Tester.



12.11 Random Tumble Pilling Tester.

This stiffness tester is based upon the cantilever principle, with the fabric specimen being slid slowly over the edge of a platform until the front edge reaches a certain angle (45°), after which the length of the projecting specimen is read off from the sliding ruler, and used to calculate the bending length, flexural rigidity and bending modulus of the fabric (ASTM D1388, BS 3356, DIN 53362). The fabric stiffness measurement also forms an important component of composite/integrated tests, such as Kawabata and FAST (CSIRO's Fabric Assurance by Simple Testing) systems.

12.3.6 Drape[15]

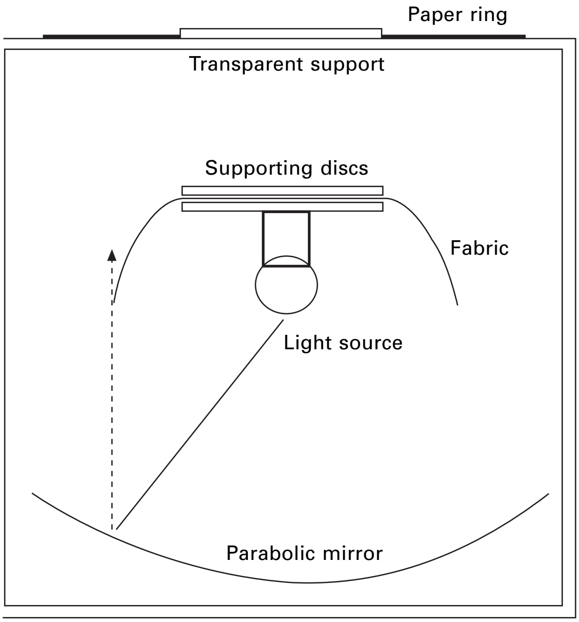
Drape is one of the most important apparel fabric properties, affecting garment appearance, beauty, fit and comfort. It is also important for home textiles, notably drapes and upholstery. The outstanding property of a textile fabric, which distinguishes it from other materials, such as paper or steel, is its ability to undergo large, recoverable draping deformation by buckling gracefully into rounded folds of single and double curvature.[22] According to the *Textile Terms and Definitions* of the Textile Institute,[23] drape is defined as 'The ability of a fabric to hang limply in graceful folds, e.g., the sinusoidal-type folds of a curtain or skirt'. It refers to the fabric shape as it hangs under its own weight. Cusick[24] defined the drape of a fabric as 'a deformation of the fabric produced by gravity when only part of the fabric is directly supported'. Drape appearance depends not only on the way the fabric hangs in folds, etc., but also upon the visual effects of light, shade and fabric lustre at the rounded folds of the fabric as well as on the visual effects of folding on colour, design and surface decoration.[25] A fabric is said to have good draping qualities when it adjusts into folds or pleats under the action of gravity in a manner which is graceful and pleasing to the eye,[26] the actual assessment greatly depending upon such factors as fashion, personal preference, human perception, etc.

Drape is a complex combination of fabric mechanical and optical properties and of subjectively and objectively assessed properties. Furthermore, there is frequently an element of movement, for example, the swirling movement of a skirt or dress, and therefore dynamic, as opposed to static, properties are also involved. In recent years, therefore, a distinction has been made between static and dynamic drape.

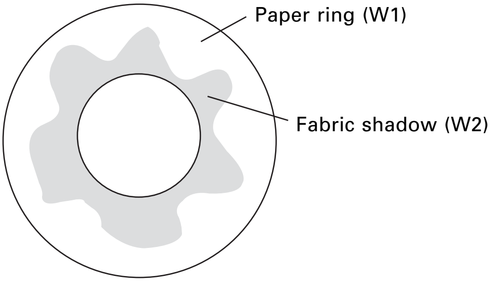
Although drape is usually assessed subjectively, considerable research has been carried out with the view to its objective measurement, and to relate the drape so measured to objectively measure fabric mechanical properties, notably bending and shear stiffness. The most widely adopted method is to allow a circular disc of fabric to drape into folds around the edges of a smaller circular platform or template. Such instruments are commonly referred to as 'drapemeters'.

Cusick[24,27] developed what has become known as Cusick's drapemeter (Fig. 12.12)[28] which has become the standard method of measuring drape coefficient. It uses a parallel light source which causes the shape of the draped fabric to be projected onto a circular paper disc. The drape of a fabric is popularly defined as the area of the flat annular ring covered by the vertical projection of the draped fabric expressed as a percentage of the arc of the flat annular ring of fabric, this being termed the drape coefficient.[24] In practice, the contour of the fabric is often traced onto the paper and cut out for weighing.[29] Cusick[29] defined the drape coefficient ($DC\%$) as the weight of the paper of the drape shadow (W_2) expressed as a percentage of the paper weight (W_1) of the area of the full annular ring (Fig. 12.13).[28] Test methods include BS 5058/EN 9073. A measure of 100% on this instrument, indicates a completely rigid (stiff) fabric while a value of 0% represents a completely limp fabric, the values in practice ranging from about 30% for a loose, open weave rayon fabric to about 90% for a starched cotton gingham, and about 95% for stiff nonwovens.[30] Since different template sizes can be used, which influence the drape coefficient, the diameter of the template must be given together with the drape result. Ideally, the template size should be such that the measured drape coefficient falls between 40 and 70%.

Table 12.5 gives drape coefficients given by Sudnik,[31] using an improved version of Cusick's drapemeter. Sudnik also concluded that the optimum drape coefficient depends upon fashion and end-use. Typical examples of 'drapemeters' include those of CUSICK, F.R.L., I.T.F. and the M.I.T. Drape-O-Meter. Other principles of drape measurement include the force to pull a



12.12 Cusick's Drapemeter (source: Chung 1999).[28]



12.13 Drape image (source: Chung 1999).[28]

Table 12.5 Drape coefficients (%)[31]

End use	Template A (24)	Template B (30)	Template C (36)
Lingerie	<80	<40	<20
Underwear	65–90	30–60	15–30
Dresswear	80–95	40–75	20–50
Suitings	90–95	65–80	35–60
Workwear, rainwear	>95	75–95	50–85
Industrial	>95	>95	>85

Source: Sudnik.[31]

circular fabric sample at a constant speed through a ring, the force being termed the 'drape resistance' of the fabric. Collier[32] developed a digital drapemeter while Matsudaira *et al.*[33] used an image analysis system to measure static and dynamic drape. Vangheluwe and Kiekens[34] also used image analysis (video digital camera and computer-based image processing system) to measure the drape coefficient, while Stylios *et al.*[35] developed a new generation of drape-meters, enabling 3D static and dynamic drape to be measured by means of CCD camera as vision sensor. Image analysis enables many measurements to be made in a relatively short time.

Hunter and Fan[15] have given a detailed review of drape, including its prediction, dependence upon fabric bending and shear properties, as well as internet-based and other modelling and dynamic, as opposed to static drape. Also included is the role of drape in 3D visualisation and CAD internet apparel systems. Various reviews on drape and related properties have been published.[15,30,36-40]

12.3.7 Fabric objective measurement and handle[15]

Discerning and quality-conscious consumers require that their clothing satisfy their requirements and expectations in terms of appearance, fit and comfort, both when new and for an acceptable wear period thereafter. The clothing manufacturer, on the other hand, requires that the fabric is easy to tailor, passes through the making-up (garment manufacturing) process easily and without undue problems and that the finished garment has a good appearance. Traditionally, the quality of fabrics and 'fitness for purpose', including their performance during making-up (tailoring) and in the garment, were assessed subjectively in terms of the fabric handle (referred to as fabric handle or hand), by experts (judges) in the clothing industry. In assessing the fabric (e.g. AATCC Evaluation Procedure 5), these experts used sensory characteristics, such as surface friction, bending stiffness, compression, thickness and small-scale extension and shear, all of which play a role in determining garment making-up (tailorability) and appearance during wear.

Because of the way handle was assessed, i.e. by tactile/touch/feel, and the terminology used, i.e., 'fabric handle or hand', it is sometimes incorrectly assumed that the assessment was purely aimed at arriving at a subjective measure of the fabric tactile-related properties (i.e. handle). In fact, in reality the fabric handle, when so assessed by experts, provided a 'composite' measure of the overall garment-related quality of the fabric, including garment making-up, comfort, aesthetics, appearance and other functional characteristics (see Table 12.1). Nevertheless, although such experts were highly skilled and their judgement sensitive and reliable, the end result was still subjective and qualitative by nature and suffered from the inherent weakness of all subjective assessments, being amongst other things dependent upon the skills, training, background (cultural and other) of the evaluator . In the light of the above, the need to develop an objective (i.e. instrument) measurement system for assessing fabric quality became apparent, fabric objective measurement (FOM) being such an integrated system of measurement. The FOM instruments were designed so as to measure the low deformation forces encountered when the fabric is manipulated by hand and also during the garment making-up (tailoring) process and removes much of the guesswork from garment manufacturing. Two important FOM systems have appeared on the market, namely the Kawabata (KES-F and KES-FB) and CSIRO FAST (Fabric Assurance by Simple Testing) systems.

It is largely the small-scale deformation properties, notably extensibility, shear stiffness, hysteresis, bending stiffness and hysteresis and lateral compression that play a role in fabric making-up and appearance. Although originally developed essentially for wool and wool blend (worsted) fabrics, these systems are finding increasing application in other areas and fibres, for example, cotton shirting fabrics. The reader is referred to Fan *et al.*[15] for a detailed overview of the subject of FOM and to Yick *et al.*[41] for details of its application to cotton and cotton blend fabrics. Yick *et al.*[41] concluding that the scientific basis for the application of fabric objective measurement techniques (FAST and KES-F) can be extended to shirt production, enabling difficulties during the manufacturing process to be predicted.

12.4 Colourfastness[42]

An important quality parameter of dyed and printed fabrics is the fastness of the colours (e.g. BS 1006, BS EN 20105), for example, to light, weathering, water (washing), chlorinated water (pool water), sea water, perspiration, rubbing, gas fumes, ozone and dry cleaning (e.g. AATCC TM 132 and ISO 105-AO1), and various tests are used to measure colour fastness under conditions simulating those which the fabric is expected to encounter during use. Often the staining of or transfer of colour to, an adjacent (multifibre) fabric is measured together with the loss in colour of the test specimen, with standard grey-scales commonly used as a means of assessment or colour change can be measured instrumentally (AATCC 153 and ISO 150-A02). On the standard scale, five grades (5 to 1) are commonly used, 5 indicating no visible change and 1 substantial change. Eight grades (8 to 1) are commonly used for light fastness, 8 representing the highest level of fastness.

12.4.1 Light (daylight)

This test is aimed at determining the potential change in colour when the fabric is exposed to daylight, ‘artificial’ or ‘simulated’ daylight, at different temperatures and humidity, generally being used for testing purposes (AATCC 16, 177, 180, 181, ISO 105-BO1 and BO2. Test options include xenon-arc lamp (continuous or alternating light), carbon-arc (continuous light) or daylight.

The test specimen is exposed, together with a standard specimen, and the colourfastness assessed (rated) subjectively by comparing the colour change, using AATCC grey-scales under prescribed lighting and viewing conditions. Light fastness evaluation can also be done against a simultaneously exposed series of AATCC Blue Wool Light Fastness Standards. Instrumental evaluation, using a spectrophotometer, is also possible.

12.4.2 Ozone

This test assesses the colourfastness to ozone in the atmosphere, under two different sets of exposure, namely at room temperature and at a relative humidity not exceeding 67% and at a higher temperature and relative humidity. In both cases, the test and control specimens are exposed to the ozone under the pre-selected atmospheric temperature and relative humidity, until the control specimen exhibits a change in colour corresponding to the standard, this cycle being repeated until a definite change in the colour of the test specimen occurs or for a predetermined number of cycles. Examples of test methods include AATCC 109 and 129 and ISO 105-G03

12.4.3 Rubbing (crocking)

The resistance to rubbing and cross-staining (colour transfer) of a colour can be assessed under either wet or dry conditions using, for example, electronic or other crockmeters or rubbing fastness testers (BS 4655, BS 1006, ISO 105, AATCC 8/165, AATCC 116, DIN EN ISO 105, JIS 0801, 0849, 1084). The fabric specimen is clamped on a base board, in such a way that no wrinkles are formed when rubbed against the rubbing device. There are various other rubbing and crockmeter testers and test methods as well as what is referred to as resistance to colour change due to flat abrasion (frosting), screen wire and emery (e.g. AATCC 119 and 120).

12.4.4 Water

The test specimen, backed by a multi-fibre test fabric, is immersed in water at a specified temperature and for a specified time, occasional stirring ensuring complete wetting of the specimen. The specimen is then passed through squeeze rollers to remove excess liquor and placed between either glass or plastic plates in the perspiration tester under specified conditions of pressure, temperature and time. The specimen is heated in an oven and air-dried, after which the colour change and staining of the multi-fibre test fabric are assessed. Examples of test methods include DIN EN ISO 105-E01 and AATCC 107.

12.4.5 Chlorinated (pool) water

Tests, e.g., AATCC 162 and DIN EN ISO 105-E03, assess the fabric colourfastness to chlorinated water, such as that which would be encountered in a swimming-pool. The fabric specimen is agitated in a dilute chlorine solution under pre-determined temperature, time, pH and water hardness conditions. After drying, the specimen is assessed for colour change.

12.4.6 Seawater

The test measures the colourfastness of dyed or printed fabrics to seawater, using specially prepared (artificial) seawater of a specific composition. The test specimen, backed by a multi-fibre fabric, is soaked in the seawater solution, at room temperature, which is occasionally stirred. Squeeze rollers remove excess water from the specimen to bring its weight to within the required range, after which it is placed between glass or plastic plates in a perspiration tester. The change in the specimen fabric colour as well as the staining of the multi-fibre test fabric provides a measure of the colourfastness to seawater. Examples of test methods include DIN EN ISO 105-E02, AATCC 106.

12.4.7 Domestic and commercial laundering

This test assesses colourfastness when the fabric undergoes domestic or commercial laundering. Examples of test methods include DIN EN 105-C06, AATCC 61.

12.4.8 Perspiration

This test provides a measure of the colourfastness of a fabric to acid perspiration, such as could be encountered in the underarm areas of a shirt. The test, using an AATCC perspiration tester, Perspirometer or other similar device, assesses the colourfastness to acid perspiration. The test specimen is immersed in the perspiration solution which is occasionally stirred, after which the excess solution is removed by squeeze rollers, so as to reduce the wet specimen weight. After this the fabric is placed between plates, subjected to the required pressure and dried at a raised temperature. The change in colour of the test specimen is assessed after conditioning. Test methods include DIN EN ISO 105-E04, AATCC 15.

12.4.9 Acids and alkalis

Specimens are steeped in, or spotted with, the required solutions and then tested for changes in colour with reference to the grey-scales (AATCC 6 and IS 105-E05 and E06).

12.5 Weathering test

Examples of accelerated weathering test instruments include the Weather-Ometer®, Fade-Ometer®, Xenotest® and Apollo Light and Weather Fastness Tester (James Heal) enabling both weather fastness and light fastness to be tested under controlled temperature and humidity conditions, water spray being included for weathering tests. Applicable test methods include:

- AATCC 111 and 186.
- Fade-Ometer:® AATCC 16E, ASTM G 155 – cycle 4, ISO 105 B02/B06.
- Weather-Ometer:® AATCC 16E, ASTM G 155 – Cycle 4, ISO 105 B02/B04/B06.
- Xenotest:® AATCC 16 Option H, ISO 105 B02/B04/B06.
- Light-fastness testers (accelerated) e.g.,
  - MercuryTungsten Lamp (BS 1006 UK/TN).
  - Xenon Arc Testers (BS 1006 UK/TN).

12.6 Dimensional stability

Excessive change, particularly shrinkage, in fabric dimensions can represent a serious problem in virtually all textile applications, more particularly in clothing. Dimensional stability to laundering (washing), including drying, therefore forms an important quality and test requirement. Dimensional change has been defined[43] as a generic term for percentage changes in the length or width of a fabric specimen subjected to specific conditions.

Various test methods are used for testing the dimensional stability of fabrics, the choice of test method often depending upon the particular application (end-use) of the fabric. Standardised washing machines and tests, to assess fabric or garment performance under repeated home laundering cycles, have been developed (e.g. AATCC 888C, 96, 124, 130, 135, 142, 143, 150, 172 and 179). One example of a popular test method, which includes both washing and tumble drying (e.g. five cycles) is AATCC 135.[44] An industry norm for such a test on cotton single jersey is, for example, no more than 8% shrinkage in either length (wale) or width (course) direction. Automatic washing machines, such as the Whirlpool Washcator and the AATCC Launder-Ometer® (AATCC 61, 86, 132, 151 and 190), are specially designed, constructed and programmed to carry out standard tests, such as BS EN 250 77/26 330 and ISO 5077/6330, DIN EN ISO 3759/26 330/

25 077). More recently, accelerated washing and drying tests (in something like 15 minutes, e.g. Quickwash Plus^{TM} system) and the rapid measurement of shrinkage have been introduced, these tests also enabling colour fastness, pilling and finish durability to be measured (e.g. AATCC 187). Systems for automatically measuring fabric dimensional change have also been developed (e.g. Vision and Quickview^{TM}).

The actual changes in fabric dimensions during a test depend upon a number of factors, including the following:

- test medium (liquor), for example, solvent or water, more usually the latter
- liquor to goods ratio
- type and severity of mechanical agitation
- liquor temperature
- number of cycles
- method of drying, for example, line drying, flat drying or tumble drying, the latter generally causing the largest change in dimensions.

12.7 Abrasion resistance

12.7.1 Introduction

The useful life (wear durability) of a textile product is, in many cases, the most important quality factor and property to estimate, by means of laboratory tests. Many studies have been undertaken in an attempt to do so, and these have been discussed.[43–50] During its use, whether it be in apparel, home textiles or industrial textiles, a fabric can be subjected to various mechanical/physical (e.g. rubbing and flexing) actions and chemical actions which lead to changes in the fabric appearance and functionality and ultimately to it no longer being acceptable, either from an appearance or functional point of view. Various laboratory instruments and test methods, particularly fabric abrasion resistance, have been developed over many decades in an attempt to simulate, or at the very least estimate, wear performance and durability. Many of these have for various reasons, been discontinued, it being notoriously difficult to simulate the great variety and complexity of the conditions which a fabric experiences in the diversity of possible end-use applications. Nevertheless, testing of abrasion resistance has remained an important measure of fabric durability since abrasion is one of the main factors involved in fabric wear and failure.

Abrasion during use not only contributes to the failure of the fabric, it also contributes to changes in fabric appearance, such as fuzzing, pilling and frosting (colour change), as well as to changes in fabric performance properties, long before mechanical fracture or rupture occurs. Frequently the consumer will consider a fabric to have reached the end of its useful life on the basis of such properties rather than on the basis of fabric mechanical failure, such as tearing, rupturing, etc. It is, however, generally not possible to draw a meaningful conclusion on the expected wear life (durability) of a fabric based upon abrasion resistance only. During laundering, for example, both chemical and mechanical actions (damage) are involved in the fabric wear or damage.

One or more of three forms of abrasion occur most frequently, namely flat (or surface) abrasion, edge abrasion and flex (bending) abrasion. In practice, flat abrasion occurs as a result of a rubbing action of the fabric surface, either against itself or against another surface, the latter could be one or more of many widely different materials. Edge abrasion, sometimes also referred to as cuff abrasion, frequently takes place at collars and cuffs, and can be a combination of flat and flex abrasion. Flex abrasion mostly occurs as a result of flexing and bending during use, sometimes this also occurring over a sharp edge. It is also referred to as internal abrasion, where fibres rub against fibres or yarn against yarn within the fabric, although sometimes an external object, such as a sharp edge, is also involved, fabric surface properties and lubrication greatly affecting flex abrasion results.

Most abrasion test instruments and methods attempt to provide a measure of one or more of these three different types of abrasion. In practice, however, the fabric may be subjected to all three forms of abrasion. Stoll,[46] for example, stated the wear of army uniforms comprised 30% plane (flat) abrasion, 20% edge and projection abrasion, 20% tear and 10% other mechanical actions. He defined a wear index (WI) as follows: WI = 0.50 (flex abrasion) + 0.20 (flat abrasion) + 0.30 (tear resistance). Elder[45] suggested the following for wear resistance (WR): WR = 0.3 (flat abrasion) + 0.2 (edge abrasion) + 0.3 (flex abrasion) + 0.2 (tear resistance). Not only does the abrasion resistance or durability of a garment or other textile product depend upon the properties of the fabric but it also depends upon the conditions it encounters during wear (even the fit of a garment in the case of apparel).

In the main, three components are involved during abrasion, namely fibre breakage or cutting, fibre removal and fibre attrition (or mechanical breakdown of the individual fibres, e.g. fibrillation), with the first-mentioned two generally the main components of fabric failure. The abrasion resistance of the fabric is in practice quantified by the number of cycles required to produce either a hole or a certain loss in strength or weight, change in colour (appearance), change in air permeability or a change in thickness.

- flat (or relatively flat) abrasion (usually the fabric is rubbed against a fabric or other abradent, such as emery paper, under different pressures)
- flex abrasion
- combination of flat and flex abrasion.

12.7.2 Flat abrasion

Flat abrasion test results are greatly dependent upon variations in fabric surface smoothness (including fabric structure) and friction, fabric thickness and yarn diameter as well as on the ability of the fibres themselves to withstand mechanical forces. Flat abrasion tests therefore tend to provide a better indication of wear performance in applications, such as upholstery and carpets, where the main wear action is a rubbing one, on the surface of the fabric held in a flat position.

Examples of flat abrasion testers include Martindale (ASTM D4966, BS 5690), Stoll (ASTM D3885 and D3880), Taber (ASTM D3884) and Schiefer (ASTM D4158). Probably one of the most popular flat abrasion testers is the Martindale Abrasion Tester (Fig. 12.10), also used for testing pilling propensity, in which a test specimen is rubbed against an abradant (usually an abradant fabric) at pre-determined pressure in a continuously changing direction. Rubbing is continued either for a pre-set number of cycles after which the mass loss and change in appearance are determined or else it is continued until a pre-defined end point is reached, for example, until two fabric threads are ruptured or a hole is formed; as per ASTM 4966 and 4970, BS 3424/5690, BS EN 530, BS EN ISO 12947 – 1, – 2, –3 and –4, ISO 5470 (rubber or plastic coated fabric) and JIS L 1096.

12.7.3 Edge abrasion

Edge abrasion takes place when the wear or abrasion occurs along the fabric edge, generally a folded edge, such as in the edge or fold of the collar of a shirt or the cuff of a sleeve. Tests include the AATCC 'Accelerotor', a rapid tumble test where the sample is folded and stitched prior to testing to accentuate abrasion of edges and laundering and tumble-drying of mock trouser cuffs. Evaluation of the fabric can then be done visually.

12.7.4 Flex abrasion

The Stoll-Flex Abrasion Tester applies uni-directional abrasion to a tensioned strip of fabric drawn over an abrasion bar, the fabric being bent or flexed as it is rubbed against (over) the bar (ASTM D3885).

12.7.5 Tumble abrasion

Tumble abrasion, such as that occurring in the AATCC 'Accelerotor' test, tends to correlate best with that occurring in the use and laundering of sheets. AATCC Accelerotor (AATCC 93) is used for both wet and dry abrasion, samples being tumbled in a circular cylinder, lined with an appropriate abrasion material, a rapidly rotating impeller/propeller shaped rotor creating the tumbling action, beating the sample against the drum wall.

12.8 Fabric strength

Fabric strength is generally regarded as one of the main properties determining wear performance and durability, although it is more important in applications such as upholstery, sheeting and shirting material and industrial textiles than in apparel textiles. Even if strength is not a specific requirement for a certain end-use, for example in knitwear, such as cardigans, it is nonetheless still often used as a measure of fabric quality and deterioration during use. In the main, three types of strength tests are carried out, namely tensile, bursting, and tear, the specific test selected in practice depending upon both the type of fabric (for example knitted or woven) and the intended end-use. Other tests carried out include the peel strength of bonded or laminated fabrics.

12.8.1 Tensile strength

Tensile testing refers to those cases where the force (load) is applied unidirectionally, usually on a strip of fabric, for example in either the warp or weft direction in the case of a woven fabric. The test could either be a ravelled strip test (ASTM D5035) or grab test (ASTM D5034), carried out on what are generally referred to as 'universal testers' e.g., Instron, Micro-CX, Statimat M or ME, which enable the fabric extension (elongation) at break, elastic recovery, etc., to be measured as well. They generally operate on the constant rate of extension principle, with the rate of extension variable according to the test method and the requirements. Test methods include ASTM E-4, D5034, BS 1610/0.5, BS 2576, BS EN 10002-2, DIN 51221/1, DIN ISO BS EN 13934-1.

12.8.2 Bursting strength

Bursting strength represents a composite and simultaneous measure of the strength of the yarns in all directions (biaxial) when the fabric is subjected to bursting type forces, applied by a ball or elastic diaphragm. In certain applications, such as in parachutes, filters and bags, the bursting strength of a fabric (woven, knitted or non-woven) is important. The fabric specimen, usually circular in shape, is usually securely clamped over an elastic (rubber) diaphragm in a ring (annular) clamp and subjected to a hydraulic load, the pressure required to burst the fabric being recorded (ASTM D3786 and D3787, BS 3424-38 and BS 4768, and ISO 2758/2759/3303/3689).

12.8.3 Tear strength

Although tensile strength is frequently taken as a measure of fabric serviceability, tear strength is preferable in this respect, since in many applications product failure occurs as a result of fabric tearing. A combination of tear strength and abrasion resistance is considered to be a fair indicator of the useful life of a fabric. A tear is defined[49] as a rupture, progressively along a line (thread by thread), caused by a moving fabric being caught in a sharp object which is sufficiently fixed in position to exert a tensile force on the fabric as it is moved away. Several methods are used to measure tear strength, e.g., tongue (double tear), rip (single tear, ASTM D2261, BS 4303), trapezoidal (ASTM D5587) and Elmendorf. A popular method of measuring the tearing strength of a fabric is by using a pendulum type tester, such as the Elmendorf Manual or Digital Tearing Testers (ASTM D 1424 and D 5734, ISO 1974 and 9290, BS EN ISO 13937).

12.9 Miscellaneous tests

The reader is referred to various books[11] and manuals (e.g. AATCC, ASTM, BS, ISO, DIN) for detailed information on the following and other fabric tests:

- Air permeability, which measures the resistance of a fabric to the passage of air, often at a specific drop in pressure across the fabric thickness (ASTM D737 and D6476, BS 5636, DIN EN ISO 9237 and JIS L1096A).
- Bagging, more important for knitted, as opposed to woven, fabrics, often occurring in the knee and elbow regions of a garment, particularly in the case of tight-fitting and in elastic garments and loose constructions.
- Barré (AATCC TM178).
- Barrier properties (AATCC 127).
- Bow and skewness (ASTM D3882).
- Breathability (AATCC 127 / ASTM D737).
- Colour and colour difference measurement and shade matching (e.g. AATCC Evaluation Procedure 6, 7 and 9).
- Comfort, generally related to factors such as moisture absorption and permeability and transport, wicking, insulation, softness (and scratchiness), air permeability (breathability), chemical properties and clothing fit.
- Cover factor.
- Electrostatic propensity and electrical properties BS 6524, ASTM D4238, AATCC 76 and 115.
- Fibre composition (ASTM D276, D629, AATCC 20, ISO 3072, ISO 1833).
- Flammability (e.g. vertical or horizontal), particularly important for children's nightwear and certain other applications (ASTM D1230 and

D4372, BS EN 13772, D5132,BS 5438,5722,5866, 5867,6249 and 6341, DIN 75200, DIN 66080 and ISO 6940 and 6941).

- Light fastness testers (accelerated) e.g.:
  - mercury-tungsten lamp (BS 1006 UK/TN).
  - xenon arc testers (BS 1006 UK/TN).
- Mass (weight) per unit area (e.g. BS 2471, BS 2866, ASTM D3776).
- Mildew and rot resistance (AATCC 30, BS 6085).
- Moisture content (ASTM D2654, D4920).
- Oeko-Tex 100, global certification scheme, for textiles which are not harmful to health and environment (www.oeko-tex.com).
- Perspiration test (AATCC), used to measure fabric colour fastness to water and perspiration (AATCC 15, 106 and 107, BS 1006, BS EN 20105 and DIN EN ISO 105-E04).
- Seam failure/strength (ASTM D1683).
- Seam slippage (ASTM D434, D4033 and D4034).
- Seam smoothness (AATCC 88B / 88C, ISO 7770).
- Sett (e.g. BS 2862, DIN 53 853, ASTM D3775).
- Sewing damage (ASTM D1908).
- Shearing (shear being one of the important factors affecting fabric drape) and making-up (tailoring performance).
- Snagging, mostly important for fabrics, particularly knitted fabrics with a raised surface, containing continuous filament yarns (ASTM D5362 and D3939).
- Soiling.
- Spirality, mostly a problem in single jersey fabrics, knitted from twist lively (usually highly twisted) yarns (ISO/CD 16322-1).
- Stiffness, important in determining fabric drape and handle and generally measured by the cantilever method (e.g. Shirley Bending Stiffness Tester) and incorporated in more comprehensive testing systems, such as Kawabata and FAST.
- Stretch and elastic recovery.
- Thermal resistance and transmission (ASTM D1518, BS 4745).
- Thickness test, various testers and test methods are available for testing fabric thickness under different pressures and pressure plate/foot of different sizes (ASTM D1777, BS 3424, ISO 3616/5084/9073).
- UV protection (AATCC 183, ASTM D6603-00, 6544-00, EN 13758, AS/NZS 4399).
- Water absorption (BS 3449).
- Water penetration resistance under pressure, or hydrostatic head tester (AATCC 127, BS EN 20811/3321/3424-24, ISO 811).
- Water repellency rain test, used to measure the fabric resistance to simulated rain, when the fabric is rubbed and rotated, the amount of water absorbed by the fabric specimen, determined by the increase in specimen weight,

providing a measure of water penetration (BS/DIN EN 29865 and ISO 9865). Certain tests (e.g. AATCC Rain Tester) enable the resistance of fabrics to water penetration at different water impacts, simulating rain, to be measured (AATCC 35 and 42, BS EN 20811). The WIRA Shower Tester (BS 5066) is also used to measure the fabric water absorption and penetration of a fabric when subjected to an artificial shower. Water Repellency (Spray) Test (AATCC TM 22 and ISO 4920) measures the resistance of a fabric to wetting by water.

- Water vapour permeability (BS 7209).
- Weathering which attempts to simulate the exposure of a fabric to sunlight (using fluorescent UV lamps), rain and dew, the fabric is exposed to cycles of light and moisture at elevated temperatures, water spray systems also being incorporated (ASTM D4329, JIS D0205, SAE Society of Automotive Engineers J2020).
- Weave (e.g. DIN EN 1049-02).
- Wettability (BS EN 24920, BS 4554).
- Whiteness (AATCC 110).
- Yarn Crimp (ASTM D3883, BS 2863).

12.10 General

The following reviews and books relevant to this chapter have appeared:

- drape[15,30,36-40]
- pilling[19,20,36]
- abrasion and wear[43,44,45,47,49,50]
- consumer studies[10]
- fabric surface wear[48]
- general[2,11,15,52]
- wrinkling[13]
- stiffness and shearing[37,38,39]
- fabric strength[50,53,54]
- fabric quality assessment[9,51]
- UV protection[55]
- yarn irregularity[3,4]
- yarn hairness[6].

12.11 Conclusions

Further technological developments in the area of yarn and fabric testing can be expected to focus on the following:

- on-line monitoring and testing
- integrated testing

- instrument measurement of yarn and fabric appearance-related properties
- knowledge-based systems (e.g. expert and artificial neural network systems) for prediction, diagnostic and trouble-shooting purposes
- internet-based standard test methods and benchmark and reference values and standards, also electronically linked to on-line and off-line testing systems.

12.12 References

1. Slater, K., Subjective Textile Testing, *J. Text. Inst.*, 1997, **88**, Part 1, (No. 2), 79.
2. Slater, K., Physical Testing and Quality Control, *Text. Prog.*, 1993, **23**, Nos 1/2/3.
3. Basu, A., Unevenness of Yarns and Preparatory Materials, Part I: Concepts and Causes, *Asian Text. J.*, March, 1999, 34.
4. Slater, K., Yarn Evenness, *Text. Prog.*, 1986, **14**, Nos 3/4.
5. Martindale, J.G., A New Method of Measuring the Irregularity of Yarns with Some Observations of the Origins of Irregularities in Worsted Slivers and Yarns, *J. Text. Inst.*, 1945, **36**, T35.
6. Barella, A. and Manich, A.M., Yarn Hairiness: A Further Update, *Text. Progr.*, 2001, **31**(4).
7. Weissenberger, W., Yarn and Fabric Quality Requirements in the Weaving Shed, *Text. Techn. Int.,* 1994, 113.
8. De Boos, A.G., 'The Objective Measurement of Finished Fabric', in Brady, PR (ed.), *Finishing and Wool Fabric Properties, A Guide to the Theory and Practice of Finishing Woven Wool Fabrics*, CSIRO, IWS, 1997, 44.
9. Nimkar, U., Phalgumani, G.R., Varadarajan, S. and Bhajekar, R., Quality Control in Textile and Clothing Industries, *Colourage*, Feb., 2001, XLVII.
10. Jacob, M. and Subramaniam, V., A Review on Consumer Studies, *Colourage*, 1987, **34**(23), 27.
11. Kothari, V.K., *Progress in Textiles: Science and Technology, Vol. I Testing & Quality Management*, IAFL Publications, 1999.
12. Özcan, G., Product Evaluation in Textile and Exchange Value, *ITB Int., Text. Bull.,* 2003, No. 1, 50.
13. Smuts, S., A Review of Wrinkling of Wool and Wool/Polyester Fabrics, *South African Wool & Text. Res. Inst. CSIR TexReport No. 1,* July, 1989.
14. Xiaobo, Y., Honggang, B. and Xiubao, H., Computer Vision Assessment of Fabric Wrinkle Grade, *Proc. Text. Inst. 83rd World Conf.*, May, 2004, 1392, Shanghai, China.
15. Fan, J., Yu, W. and Hunter, L., *Clothing Appearance and Fit: Science and Technology*, Woodhead Publishing Ltd., 2004.
16. Cooke, W.D., Pilling Attrition and Fatigue, *Text. Res. J.,* 1985, **55**(7), 409.
17. Cooke, W.D. and Goksoy, M., Problem of Predicting Pilling Performance Using Laboratory Test Method, *Mell. Textilber., Eng. Ed.,* 1988, **69**(4), 250, (E 34).
18. Goktepe, O., Fabric Pilling Performance and Sensitivity of Several Testers, *Text. Res. J.,* 2002, **72**(7), 625.
19. Ukponmwan, J.O., Appraisal of Woven Fabric Performance, *Text. Res. J.,* 1987, **57**(8), 445.
20. Ukponmwan, J.O., Mukhopadhyay, A. and Chatterjee, K.N., *Text. Progr.*, 1998, **28**(3).

21. Chen, X. and Huang, X. Objective Assessment of Fabric Pilling Based on Light Projection and Image Analysis, *Proc. Text. Inst. 83rd World Conference,* 2004, 1275, China.
22. Stump, D.M. and Fraser, W.B., A Simplified Model of Fabric Drape Based on Ring Theory, *Text. Res. J.,* 1966, **66**(8), 506.
23. *Textile Terms and Definitions,* (eleventh edition), Manchester, Textile Institute, 2002.
24. Cusick, G.E., The Dependence of Fabric Drape on Bending and Shear Stiffness, *J. Text. Inst*., 1965, **56**, T596.
25. Bishop, D.P., *Fabrics: Sensory and Mechanical Properties*: *Textile Progress* (Vol. 26, No. 3), Woodhead Publishing, 1996.
26. Chu, C.C. Hamburger, W.J. and Platt, M.M., Determination of Factors which Influence the Draping Properties of Cotton Fabrics, *USDA ARS*, Feb., 1963.
27. Cusick, G.E., The Resistance of Fabrics to Shearing Forces, *J. Text. Inst*., 1961, **52**, T395.
28. Chung, J., *The Effect of Assembly Methods of a Garment on Fabric Drape*, PhD Thesis, Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Jan., 1999.
29. Cusick, G.E., The Measurement of Fabric Drape, *J. Text. Inst*., 1968, **59**, 253.
30. Hu, J. and Chan, Y.F., Effect of Fabric Mechanical Properties on Drape, *Text. Res. J.,* 1998, **68**(1), 57.
31. Sudnik, Z.M., Objective Measurement of Fabric Drape: Practical Experience in the Laboratory, *Text. Inst. Ind.,* Jan., 1972, **10**, 14.
32. Collier, B.J., Measurement of Fabric Drape and Its Relation to Fabric Mechanical Properties and Subjective Evaluation, *Cloth. Text. Res. J.,* 1991, **10**(1), 46.
33. Matsudaira, M., Yang, M., Kinari, T. and Shintaku, S., Polyester 'Shingosen' Fabrics Characterised by Dynamic Drape Coefficient with Swinging Motion, *Text. Res. J.,* 2002, **72**(5), 410.
34. Vangheluwe, L. and Kiekens, P., Time Dependence of the Drape Coefficient of Fabrics. *Int. J. Cloth. Sci. Technol.*, 1993, **5**(5), 5.
35. Stylios, G., Wan T.R. and Powell, N.J., Modelling the Dynamic Drape of Garments on Synthetic Humans in a Virtual Fashion Show, *Int. J. Cloth. Sci. Technol.,* 1996, **8**(3), 95.
36. Jacob, M. and Subramaniam, V., A Review of the Literature on Drape and Pilling Properties of Textile Fabrics, *Colourage*, 8 Jan., 1987, **34**(1), 21.
37. Subramaniam, V., Bending Properties of Textile Structures I, II and III, *Indian Text. J*., Dec., 1980, **91**(3), 93, Jan., 1981, **91**(4), 95, Feb., 1981, **91**(5), 87.
38. Subramaniam, V., Non-linear Bending of Textile Materials, *Man-made Text. India,* 1981, **24**(8), 409.
39. Subramaniam, V., Chanchal, B., Vatsala, R. and Rajendran, B., Shearing Properties of Fabrics – A Review, Part I: Test Methods, *Man-Made Text. India*, 1983, **26**(6), 259.
40. Anon., Fabric Drape (A Review), *IWS F.A.C.T. Technical Information Letter,* March, 1981, **9**.
41. Yick, K-L., Cheng, K.P.S., Dhingra, R.C. and How, Y.L., Material Objectively Measured, *Text. Asia,* Nov., 1995, **26**, 65.
42. Sayed, U., and Pratap, M.R., Textile Testing: A Must for Production of Quality Goods – Part I. *Colourage*, March, 2002, **49**, 19.
43. Jacob, M. and Subramaniam, V., A Review of the Literature on Durability Studies of Fabrics, *Colourage,* 1987, **34**(5), 21.

44. Jacob, M. and Subramaniam, V., A Review of Literature on Wear Studies, *Colourage,* April, 1988, **35**, 17.
45. Elder, H.M., Wear of Textiles, *J. Consumer Studies Home Economics*, Blackwell Scientific Publ., 1978, **2**, 1.
46. Stoll, R.G., An Improved Mulipurpose Abrasion Tester and its Application for the Evaluation of the Wear Resistance of Textiles, *Text. Res. J.*, 1949, **19**, 394.
47. Galbraith, R.L., Abrasion of Textile Surfaces, Chapter 5, in *Surface Characteristics of Fibers and Textiles* (ed. Schick, M. J.), 1975, page 193, Marcel Dekker, Inc. New York.
48. Sirikasemlert, A., Xiaoming, T. and Dhingra, R.C., Superficial Performance, Characterisation of the Surface Behaviour of Fabrics During Simulated Wear, *Text. Asia*, March, 1996, 27, 73.
49. Higginbotham, R.S., Deterioration of Textiles in Use, *Textiles*, 1976, **5**, 40.
50. Taylor, H.M., Wear testing – an appraisal of the more significant methods and related equipment, *Text. Month,* June 1980, 71.
51. Vatsala, R. and Subramaniam, V., Assessment of Fabric Quality – Part I, *Text. Dyer Printer*, 1991, 21 Aug., and Part II, 1992, 4 March, 23.
52. Matsuo, T. and Suresh, M.N., The Design Logic of Textile Products, *Text. Progr.,* 1997, **27** (3).
53. Ukponmwan, J.O., Fabric Strength, *Colourage*, June, 1990, **37**, 19.
54. Scelzo, W.A., Backer, S. and Boyce, M.C., Mechanistic Role of Yarn and Fabric Structure in Determining Tear Resistance of Woven Cloth, Part I: Understanding Tongue Tear, *Text. Res. J.*, 1994, **64**(5), 291.
55. Hatch, K.L., Solar Ultraviolet Protection Clothing: What's Behind the Label? *AATCC Review*, **5**(8), Aug. 2005, 31.

13

Controlling costs in cotton production

T. TOWNSEND, International Cotton Advisory
Committee, USA

13.1 Introduction

World cotton production and consumption are trending higher, and the industry is being transformed by new technologies, including biotechnology. World cotton production reached 26 million tons in 2004/05, and biotech varieties accounted for about one-third. The average cost of cotton production varies widely across countries, but the cost of production for most producers is between 50 and 60 US cents per pound. While per capita consumption of cotton at the retail level is highest in developed countries, the strongest growth in both retail consumption and mill use of cotton is occurring in developing countries, particularly China (mainland), India and Pakistan.

The elimination of quotas as of January 2005 that limited trade in textiles and apparel for more than 30 years is leading to a shift in textile and apparel production toward China and other low-income producing countries, and the cotton industry is benefiting from increased consumption caused by lower retail prices of textile and apparel products. However, substantial distortions caused by government measures still exist in the market for cotton itself. International cotton prices have declined in real terms over the last six decades because of advances in technology, and this process is continuing. During the 1970s, 1980s and 1990s, the average world price of cotton was 70 cents per pound, but the average international price during the current decade is expected to be between 50 and 60 cents per pound, in line with the costs of production for most producers. See the appendix on pages 256–9 for a table showing cotton supply and use since the 1920s.

13.2 The economic importance of cotton

Cotton is one of the most important and widely produced agricultural and industrial crops in the world. Cotton is grown in more than 100 countries on about 2.5% of the world's arable land, making it one of the most significant in terms of land use after food grains and soybeans. Cotton is also a heavily traded agricultural commodity, with over 150 countries involved in exports or imports of cotton.

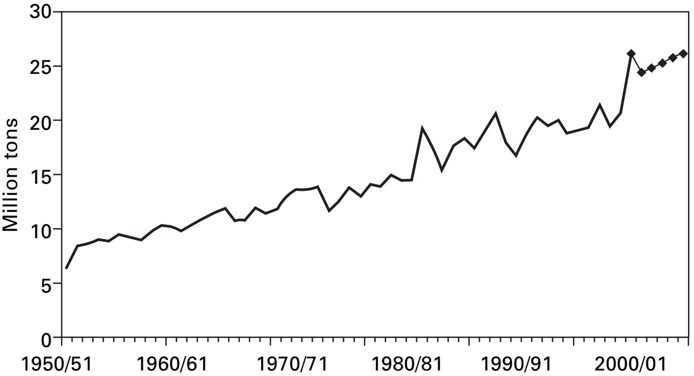
More than 100 million family units are engaged directly in cotton production. When family labor, hired-on farm labor and workers in ancillary services such as transportation, ginning, baling and storage are considered, total involvement in the cotton sector reaches an estimated 350 million people. It also provides employment to additional millions in allied industries such as agricultural inputs, machinery and equipment, cottonseed crushing and textile manufacturing. Cotton cultivation contributes to food security and improved life expectancy in rural areas of developing countries in Africa, Asia and Latin America. Cotton played an important role in industrial development starting in the 17th century and continues to play an important role today in the developing world as a major source of revenue. The value of 26 million tons of world cotton production in 2004/05 at an average world price of 52 cents per pound of lint, or $1.15 per kilogram, was $30 billion.

Cotton, unique among agricultural crops, provides food and fiber. A cellulosic fiber about 96% pure, cotton is one of the world's most important textile fibers, accounting for more than half of all the fibers used in clothing and household furnishings. Cotton is also used in industrial fabrics, and the by-products derived from cottonseed and stalks provide edible oil for human consumption and soap, industrial products, firewood and paper and high protein animal feed supplements. Cotton oil is the fifth largest edible oil consumed in the world.

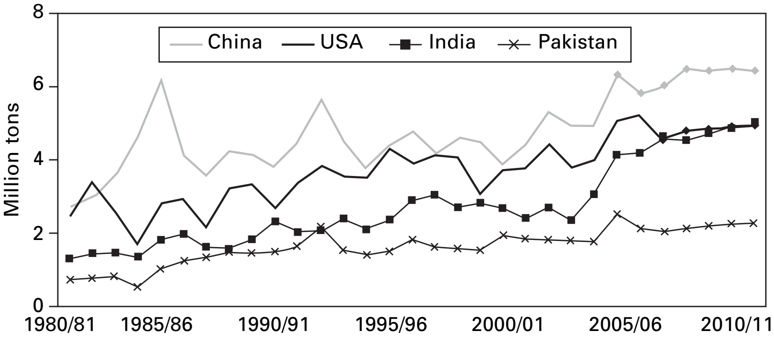
13.3 Production

The world cotton industry has experienced dramatic changes over the last five decades as production nearly quadrupled, rising from 6.6 million tons in 1950/51 to a record of 26.3 million tons in 2004/05 (Fig. 13.1). The average annual rate of growth in world production over the last five decades has been about 2.5% per year. Growth in cotton production was steady during the 1950s and 1960s but slowed during the 1970s because of slower world economic growth and limited gains in cotton yields. World cotton production exploded from 14 million tons in the early 1980s to 19 million tons in 1984/85, as market incentives and the widespread use of better seed varieties and better methods of plant protection led to increased yields. World production climbed to a record of nearly 21 million tons in 1991/92 but leveled off during the 1990s. With the commercial application of biotech cotton varieties beginning in 1996 and the expansion of cotton areas in Francophone Africa, Australia, central Brazil, western China, and Turkey, world production climbed to 26.2 million tons in 2004/05. The main cotton producers since the early 1980s are shown in Fig. 13.2.

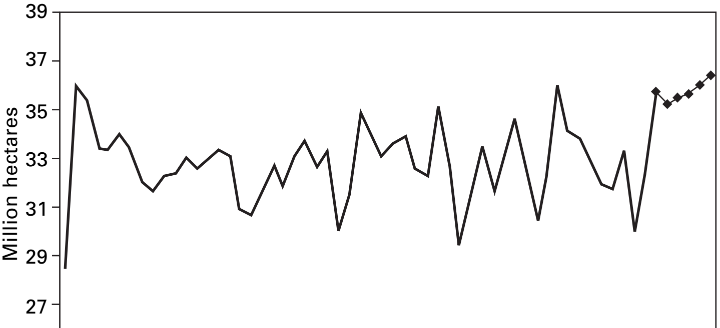
World area dedicated to cotton has fluctuated since 1950/51 between 28 million hectares and 36 million hectares (Figs. 13.3 and 13.4). While there



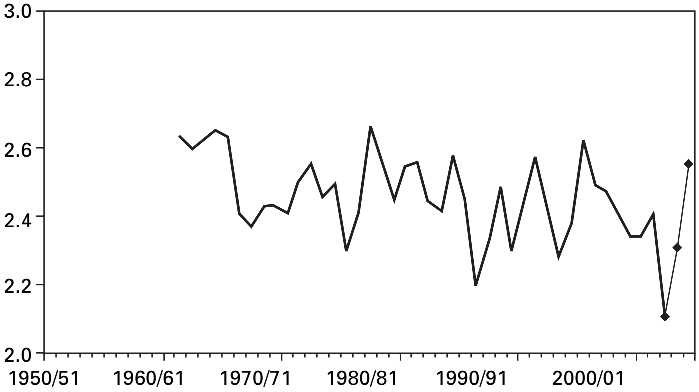
13.1 World cotton production.



13.2 Main cotton producers.



13.3 World cotton area.

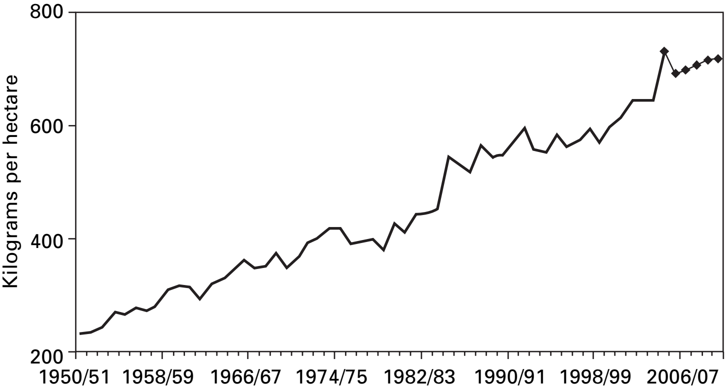


13.4 World cotton area, as a percentage of arable land.

have been dramatic reductions in cotton area in some regions since the 1950s, particularly in the USA, North Brazil and North Africa, there have been equally dramatic increases in Francophone Africa, Australia, China, India, Pakistan and the Middle East. With total area showing no tendency to rise, all the growth in world cotton production since the 1940s came from improved yields. The world cotton yield 50 years ago was 230 kilograms of lint per hectare. Yields rose steadily at an average rate of more than 2% per year during the 1950s and 1960s, and then grew more slowly from the mid-1970s until the mid-1980s. During the 1980s the world cotton yield rose dramatically and reached a record of nearly 600 kilograms per hectare in 1991/92. However, yields stagnated during the 1990s due to problems associated with diseases, resistance to pesticides, and disruption of production due to economic reasons. Yields began rising again in the late 1990s with improvements in seed varieties and the use of biotech varieties, and the world yield in 2004/05 reached more than 720 kilograms per hectare.

New technologies, more extensive use of existing technologies, and new areas dedicated to cotton cultivation have changed the structure of the world cotton market since the mid-1990s (Fig. 13.5). Among the new technologies, the most visible is genetic engineering of cotton. It is estimated that 24% of world cotton area accounting for more than one-third of world production was planted to biotech varieties in 2004/05, up from just 2% in 1996/97. Biotech cotton lowers the use of insecticides and, although it does not guarantee that cotton yields will be higher than with a non-biotech variety, it might lower the cost of production.

Cotton is produced in about one hundred countries, but production has traditionally concentrated in a few (Table 13.1). Over the last three decades, the four leading producing countries have accounted for an increasing share of world production. China (mainland), the United States, India and Pakistan accounted for 48% of world production in 1970/71 and 68% in 2004/05. The



13.5 World cotton yields.

Table 13.1 Top ten producers 2004/05

		Thousand tons	
1	China (M)	6,320	24.2%
2	USA	5,062	19.4%
3	India	4,080	15.6%
4	Pakistan	2,482	9.5%
5	Brazil	1,318	5.0%
6	Uzbekistan	1,150	4.4%
7	Turkey	900	3.4%
8	Australia	624	2.4%
9	Greece	390	1.5%
10	Syria	331	1.3%
	Others	3,472	13.3%
	World	26,129	100.0%

share of industrial countries (the USA, Australia, Spain and Greece) increased from 19% of world production in 1980/81 to 24% in 2004/05. Developing countries accounted for 61% of world production in 1980/81 and 66% in 2004/05. Cotton production in the former USSR declined during the last two decades, accounting for 19% of world production in 1980/81 and 7% in 2004/05.

Production in China (mainland), the largest producer, increased at an average annual rate of 5% during the 1980s and fluctuated within a range of 3.7 to 5.7 million tons during the 1990s. Production in China (mainland) rose to a record of 6.3 million tons in 2004/05. In the United States, cotton production increased from 2.4 million tons in 1980/81 to 3.3 million tons in 1990/91, and fluctuated between 3 and 4.3 million tons during the 1990s before rising to 5.1 million in 2004/05. Cotton production in India rose from 1.3 million tons in 1980/81 to 3.0 million in 1996/97. Thereafter, production fell to 2.3 million tons in 2002/03 before reaching a record of 4.1 million tons in 2004/05. Production in Pakistan expanded rapidly during the 1980s, growing from 700,000 tons in 1980/81 to 2.2 million tons in 1991/92. However, production fell in 1992/93 and remained below the 1991/92 level until 2004/05 when production rose to 2.5 million tons. In Africa, cotton production increased from 1.3 million tons in 1990/91 to 1.8 million tons in 1997/98, but low cotton prices discouraged African production in the years after. African production rose to two million tons in 2004/05. Francophone countries in West and Central Africa produced 1.1 million tons in 2004/05, accounting for 56% of production in the continent.

Cotton production in Brazil declined rapidly between the mid-1980s and the mid-1990s, and recovered in the second half of the decade. Production, which declined from 965,000 tons in 1984/85 to 310,000 tons in 1996/97, climbed back to 940,000 tons in 2000/01 and to 1.3 million tons in 2004/05, surpassing Uzbekistan and Turkey. Cotton production in Turkey increased from 650,000 tons in 1990/91 to 900,000 tons in 2004/05. Cotton production in Australia increased very rapidly during the 1980s and 1990s, from 100,000 tons in 1980/81 to 800,000 tons in 2000/01. Because of drought, production was only 624,000 tons in 2004/05. Cotton production in the European Union (EU) increased from 300,000 tons in 1990/91 to 500,000 tons in 2004/05.

13.3.1 Costs of production

The structure of production varies substantially from country to country and even from region to region in the same country, depending on relative resource endowments (Table 13.2). Countries with abundant capital, sophisticated systems of research and education and developed infrastructure for the supply of credit and inputs to farmers tend to rely on highly mechanized production systems utilizing purchased planting seeds and chemical inputs and employing very little labor per ton of output. Australia and the USA typify this production system, and the structure of production in the EU and Brazil is tending in this direction. Developing countries with relatively abundant land and labor and less intensively developed networks for the distribution of inputs tend to plant, cultivate and harvest cotton by hand and to use fewer purchased inputs per ton of production. In China (Mainland), Central Asia, South Asia, the Middle East, Africa and many areas in South America, cotton is tended mostly by hand. About 55% of world cotton area is irrigated, accounting for about 75% of word output. About 30% of cotton production is machine harvested. As a result, yields and costs of production vary greatly from country to country.

In 2003/04, the cost of production on one hectare ranged from less than $400 in some developing countries to almost $4,000 in Israel. Data from 30 countries indicate that the average cost of production of cotton in 2003/04

Table 13.2 Cost of production 2003/04 (US$)

Country/Region	Cost of Seed : cotton[1]		Variable Cash Expenses[2]		Net Cost [3]	
	Per Ha	Per Kg	Per Ha	Per Kg	Per Ha	Per Kg
Argentina, Santiago del Estero (Irrigated)	410.11	0.21	427.06	0.65	498.01	0.75
Argentina, Rainfed	328.97	0.22	336.60	0.67	392.48	0.78
Australia, Irrigated Upland	886.84		936.49	0.66	1,936.64	1.37
Bangladesh, *G. hirsutum*	406.61	0.25	214.07	0.36	238.14	0.40
Benin, National Average	484.43	0.46	551.39	1.23	597.17	1.33
Bolivia, National Average	457.27	0.28	547.83	1.01	666.45	1.22
Brazil, Central West (Cerrado)	1,122.07	0.31	1,049.13	0.80	1,277.40	0.98
Brazil, Northeast (Semi-arid, Rainfed)	354.06	0.24				
Bulgaria	436.26	0.36	619.59	1.40	674.24	1.52
Cameroon, National Average	324.37	0.27	362.59	0.74	407.51	0.83
China (Mainland), National Average	886.29	0.32	706.15	0.67	1,069.35	1.02
Colombia, Cesar	869.93	0.38	924.12	1.12	984.64	1.19
Colombia, Sinu	874.48	0.35	804.16	0.89	907.43	1.01
Côte d'Ivoire, Manual Cultivation	356.90	0.29				
Côte d'Ivoire, Animal Powered	416.43	0.29				
Ethiopia, Afar	495.05		344.01		861.40	
India, North Zone, Irrigated	357.42	0.21				
India, Central Zone, Irrigated	394.35	0.27				
India, Central Zone, Rainfed	302.85	0.31				
India, South Zone, Rainfed	411.31	0.32				
Iran, National Average	892.05	0.36	782.66	0.98	1,001.29	1.25
Israel, Upland/Pima	2,570.00		2,490.00		3,380.00	
Mali, National Average	388.18	0.34	545.97	1.15	626.94	1.32
Mexico, Central (South of Chihuahua)	1,059.83					
Mexico, Sonora (South)	1,578.60		1,445.85		1,773.80	
Nigeria, National Average	466.92		375.88			
Pakistan, Punjab	742.03	0.37	564.91	0.85	638.63	0.96
Paraguay	341.63	0.28				

Table 13.2 Continued

Country/Region	Cost of Seedcotton[1]		Variable Cash Expenses[2]		Net Cost [3]	
	Per Ha	Per Kg	Per Ha	Per Kg	Per Ha	Per Kg
Peru, Central Coast, Tanguis Cotton	1,133.43	0.92	1,161.39		1,360.59	
Philippines, Luzon	405.53	0.23	418.76	0.66		
Philippines, Mindanao	236.56	0.18	242.85	0.52		
Philippines, Visayas	250.54	0.17	268.55	0.50		
South Africa, Orange River – Irrigated Bt	810.89	0.16				
South Africa, North West (Stella) – Rainfed Bt	255.61	0.21				
Spain, National Average	2,027.53	0.58				
Sudan, Gezira	499.75	0.43	551.24	1.41	652.77	1.67
Tanzania, Eastern Cotton Growing, Area	164.46	0.16				
Togo, North Region	399.66	0.44	450.72	1.18	498.90	1.30
Togo, Central and South Region	516.93	0.57	565.06	1.48	613.24	1.60
Turkey, National, Average	1,208.80	0.32	1,534.37	1.12	1,827.47	1.34
Turkey, GAP, (Southeastern Anatolian Project)	970.00	0.26	1,322.32	0.98	1,566.32	1.16
Turkey, Çukurova	1,198.00	0.28	1,546.62	1.00	1,801.62	1.16
Turkey, Ege (Aegean)	1,305.00	0.34	1,647.18	1.20	1,968.18	1.44
Turkey, Akdeniz (Antalya)	1,555.00	0.39	1,932.54	1.34	2,274.54	1.58
USA, National Average	671.02		670.70	0.92	1,082.02	1.48
USA, Heartland	584.64		602.13	0.63	1,033.02	1.08
USA, Mississippi Portal	793.02		799.54	0.82	1,245.60	1.27
USA, Fruitful Rim	1,142.22		1,007.91	0.71	1,457.09	1.02
USA, Prairie Gateway	467.29		474.96	1.16	885.00	2.15
USA, Southern Seaboard	780.10		819.51	1.00	1,179.83	1.44
Vietnam, Highland	473.33	0.32	443.88	0.81	625.47	1.14

1. Cost of seed : cotton production does not include the cost of land rent.
2. Variable cash expenses include the cost of seed: cotton production plus ginning, but they do not include land rent and seed value.
3. Net cost is total cost (including economic and fixed costs) but does not include land rent and seed value.

was $1,140 per hectare, including the costs of growing, harvesting and ginning. Out of the total cost, the average cost of land rent was $240, and the average value of cottonseed sold after harvest per hectare of production was $166. Economic costs, such as management and administration, interest on capital, repairs and general farm overhead, and fixed costs, such as depreciation on equipment, averaged $115 per hectare. Consequently, the costs of production, net of land values, net of the value of cottonseed sales, and net of economic and fixed costs, averaged $620 per hectare in 2003/04.

Assuming an average total cost of production of $1,140 per hectare, the total cost of production of cotton on 32.1 million hectares in 2003/04 was approximately $37 billion. The value of world cotton production in 2003/04, 20.7 million tons of lint at an average price of 68 cents per pound, was about $31 billion. Consequently, the value of world cotton production in 2003/04 was about $6 billion less than the cost of production. Subsidies paid to growers accounted for about $4 billion in 2003/04, and the remaining $2 billion in economic losses would have been mostly accounted for by depreciation on equipment and lost wages for management and administration.

Based on a world yield of 642 kilograms of lint per hectare in 2003/04, the average total cost of production, including land, the value of cottonseed and economic and fixed costs, was $1.77 per kilogram of lint ($0.80 per pound). Excluding the cost of land rent and subtracting the value of cottonseed sold after harvest, the net cost of production averaged $1.14 per kilogram of lint ($0.52 per pound), and if economic and fixed costs are excluded, the resulting cash costs of production averaged $0.96 per kilogram ($0.44 per pound). These data indicate that the average land owner, producing cotton at average cost and gaining average yields in 2003/04, will tend to maintain or expand production when farm prices exceed 44 US cents per pound.

Costs of production vary substantially by region. Based on data from 2003/04 and using exchange rates that prevailed at that time, cotton production costs per kilogram of lint are the highest in Europe and the USA and the lowest in Asia, South America and Australia. The net cost of production per kilogram of lint (excluding the cost of land and subtracting the value of cotton seed; world average equal to $1.14) averaged $1.48 in the USA and $3.72 in Europe. Farmers in the USA, Greece and Spain are supported by government measures.

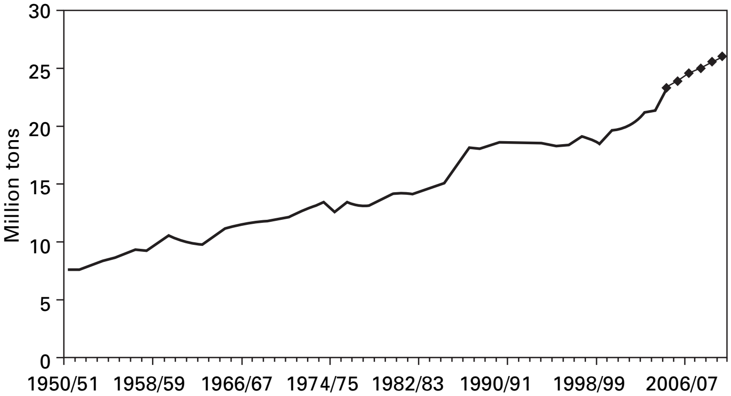
The net cost of production in Africa averaged $1.40 per kilogram, which is above the world average. An earlier study done using data from 2000/01 indicated that costs of production in Africa were less than the world average, but between 2000 and 2003, the CFA (currency of Francophone Africa) strengthened by more than 30% against the US dollar, changing cost of production measures. The net cost of production in South America averaged $1.09 per kilogram of lint in 2003/04, the average in Asia was $1.14 per kilogram and the average in Australia was $1.08 per kilogram.

The greatest source of variation in costs of production per kilogram of lint are caused by differences in the costs of ginning, economic costs and fixed costs. The cost of producing seed cotton is relatively stable across most countries, averaging $0.33 per kilogram and with a variation of only 3 cents per kilogram between the highest-cost and lowest-cost producing countries. However, when costs of ginning, seed values, economic costs and fixed costs are considered, variations among countries become apparent.

13.4 Consumption

World textile fiber consumption is driven by three major economic variables, income, population growth and fiber prices (Fig. 13.6). World final demand for textile fibers has increased at an impressive pace since the 1950s. From 7.6 million tons in 1950, textile fiber consumption increased to 56 million tons in 2004. While about 50% of the increase was the result of population growth, the remaining 50% was the result of higher income per capita, declines in real textile prices, and competition, which generated new uses for textile fibers. However, the rate of growth of fiber consumption has decelerated gradually. The average annual rate of growth of textile fiber consumption was 3.7% during the 1960s, 3.1% during the 1970s, 2.5% during the 1980s and 2.7% during the 1990s. Growth of the two major economic variables that determine textile consumption, income and population, decelerated during the 1990s compared with the 1960s.

An exogenous factor that has supported textile consumption in the last few years is the gradual integration of textile trade into World Trade Organization (WTO) rules. (The WTO is an international economic organization headquartered in Geneva. The WTO serves as the forum for negotiation of international trade rules among countries.) As of December 2004, just over half of world textile trade had already been gradually integrated, and on



13.6 World cotton mill use.

January 1 2005, all textile trade was integrated into WTO rules. Therefore, quotas agreed under the Multifiber Arrangement (MFA) no longer exist. Research by the Secretariat, using previous joint work with the Food and Agriculture Organization of the United Nations (FAO), suggests that because of textile quota elimination, the world would consume half a million tons more cotton by the end of 2005. A portion of the gains in cotton consumption due to quota elimination are likely to have occurred between 1995 and 2004, particularly since January 1 2002.

Consumer research and demand enhancement activities, especially those of Cotton Incorporated in the USA, have also supported cotton consumption. The budget of Cotton Incorporated is approximately $60 million per year, collected from US cotton producers and importers of textiles and apparel. Cotton Incorporated conducts textile research to enhance the quality of cotton products, and it spends about $38 million per year on direct consumer advertising to enhance cotton consumption at the retail level. Research by the Secretariat suggests that as a result of research and demand enhancement efforts, 300,000 tons more cotton per year has been consumed since 1998.

For cotton, competition with chemical fiber is an insidious challenge. At the start of the 20th century, cotton had a dominant share of the textile market. At the beginning of the 21st century, cotton is one of many fibers available and has been surpassed by polyester. Cotton consumption per capita has been almost constant since 1960, while total textile fiber consumption per capita more than doubled. Cotton's share of world textile fiber use fell from 79% in 1950 to below 40% in 2004.

Most of the increase in world cotton consumption at the end-use level during the 1980s and 1990s took place in industrial countries. However, since 2000, most of the increase in cotton end use is taking place in developing countries as consumers in China (mainland) and India accelerate their retail purchases. The share of developing countries in world mill consumption rose continuously from 61% in 1990/91 to 88% in 2004/05. Mill use in developed countries is headed lower.

The elimination of quotas will intensify competition, leading to lower prices for textiles. (Quotas are quantitative limits on imports of textile and apparel products. Beginning in the late 1950s and continuing until the end of 2004, the United States, Canada, and most countries in Europe limited imports of textiles and apparel by setting quotas on products from exporting countries. The quotas were designed to slow the growth of imports in order to protect domestic manufacturing industries.) Final consumers of textile products will benefit from increased supply and lower prices, which in turn could stimulate consumption growth to the benefit of lower-cost cotton textile and apparel industries. Cotton producers themselves will benefit from stronger demand for cotton fiber.

Long-term projections of world gross domestic product (GDP, a measure of total economic activity) and population growth suggest that world textile fiber consumption can expand at an annual average rate of 4% to reach 75 million tons in 2010. World cotton consumption is projected to expand at an annual average rate of 3.5% to reach 26 million tons in 2010. Cotton's share of the world textile fiber market is projected to decline to 37%. China (mainland), India, Pakistan and Turkey will remain major textile economies, with a dependency on cotton imports. Cotton consumption in China (mainland) is projected to surpass 10 million tons in 2009/10, 40% of world mill use.

13.4.1 Retail consumption

In 2003, developed countries as a group accounted for 44% of world cotton retail level consumption, and developing countries accounted for 52%. At the retail level, the USA is the largest consuming country, accounting for 21% percent of total cotton use in 2004. Per capita cotton consumption in the USA was 16 kilograms in 2004, compared with a world average of only 3.5 kilograms. High consumer incomes, a history of cotton consumption, consumer preferences in favor of cotton bolstered by industry advertising, and fashion trends that favor cotton explain the high level of per capita cotton use in the USA.

Retail consumption of cotton in Latin America accounted for 9% of world cotton use in 2000, and per capita consumption was 3.2 kilograms per year. Consumers in Brazil and Mexico account for two-thirds of Latin American retail level cotton use. Retail consumption in the EU-15 accounts for 16% of world cotton use, and per capita cotton consumption in Europe was about 7 kilograms in 2000. The lower level of per capita consumption of cotton in Europe compared with the USA reflects lower average income levels, less consumer-oriented retail structures, and differences in tastes and preferences between American and European consumers.

Retail consumption in Russia and other countries of the former USSR accounted for 2% of world cotton use in 2000, and per capita cotton use was below the world average at just 2.7 kilograms. Retail consumption in the Middle East, including Turkey, accounted for 6% of world use in 2000, and per capita consumption was equal to the world average at 3.6 kilograms per year. Africa, including South Africa and Egypt, accounts for only 2% of world cotton use at the retail level, and per capita consumption of cotton in Africa is less than 1 kilogram per year.

Retail consumption in Japan equalled 6% of world cotton use in 2000, and per capita consumption in Japan was 9 kilograms, 2 kilograms higher than the EU average, but lower than in the USA. Consumption in the rest of East Asia, including China, and in South Asia accounted for 31% of world cotton use at the retail level in 2000, but per capita consumption averaged just 1.8 kilograms because of low incomes and government policies that favor the use of polyester to conserve land devoted to cotton. One of the great challenges for the cotton industry is to raise per capita consumption in the countries with the largest populations, including China where cotton use per capita was just 1.9 kilograms in 2000, India, with per capita cotton use of 1.7 kilograms and Indonesia, with per capita use of 1.4 kilograms. It is hoped that rising incomes in India, Indonesia and China (mainland) will lead to increases in per capita cotton consumption during the current decade.

13.4.2 Mill consumption

Mirroring end-use consumption, world mill consumption of cotton was stagnant during the first half of the 1990s, growing by only 0.6% between 1990 and 1997, but increased rapidly thereafter (Table 13.3). In the early 1990s, mill consumption of cotton declined dramatically in Eastern Europe and the former USSR, from 2.5 million tons in 1990/91 to 730,000 tons in 1998/99, offsetting gains elsewhere in the world. Mill consumption of cotton in the former Council Mutual Economic Cooperation (COMECON) group of countries recovered to 900,000 tons in 2004/05. Mill consumption of cotton in industrial countries remained at about 4 million tons during the early 1990s, but declined rapidly after 1998/99 to 2.2 million tons in 2004/05. High cost structures and increased import competition from developing countries caused the cotton textile industries in many industrial countries to reduce production beginning in the late 1990s.

Mill consumption of cotton in developing countries increased at an annual rate of 3.9%, from 8.5 million tons in 1980/81 to 12.3 million tons in 1990/91. Growth of mill consumption decelerated during first seven years of the 1990s to an average annual rate of 2.7% reaching 14.3 million tons in 1997/

Table 13.3 Top ten cotton consumers

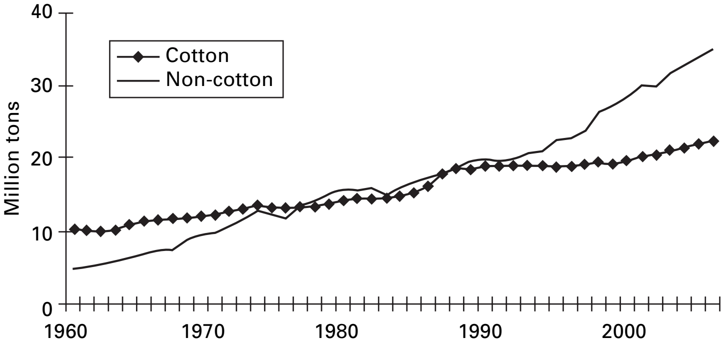
		Thousand tons	
1	China (M)	8,200	35.0%
2	India	3,300	14.1%
3	Pakistan	2,300	9.8%
4	Turkey	1,550	6.6%
5	USA	1,361	5.8%
6	Brazil	935	4.0%
7	Indonesia	490	2.1%
8	Mexico	450	1.9%
9	Thailand	450	1.9%
10	Bangladesh	394	1.7%
	Others	3,970	17.0%
	World	23,400	100.0%

98, but regained strength since 1998/99, growing at an average annual rate of 5% to reach 20 million tons in 2004/05. The bulk of the increase since 1998 occurred in China (mainland), but important expansions were also registered in India, Pakistan and Turkey. As a result, the processing of cotton continued to concentrate in developing countries, and their share of world mill consumption rose from 67% in 1990/91 to 86% in 2004/05, compared to 46% in 1970/71 and 28% in 1950/51.

For the past seven years, China (mainland) has been the driving force of the world textile industry. Between 1998/99 and 2004/05, the increase in mill consumption of cotton in China accounted for 91% of additional consumption worldwide. The Chinese industry processed 8.2 million tons of raw cotton in 2004/05, an increase of 4.3 million tons since 1998/99, and 35% of global mill use, up from 23% in 1998/99. The textile industry in China (mainland) is highly dependent on the export market, and China (mainland) has increased its share of world textile and apparel exports in the last six years. During the 1990s, mill consumption of cotton became more concentrated in the largest processing countries. In 1980/81, the six countries that are the largest processors today, China (mainland), India, Pakistan, the United States, Turkey, and Brazil, accounted for 51% of world mill consumption. These countries accounted for 57% of world mill consumption in 1990/91, and 76% in 2004/05.

13.4.3 Inter-fiber competition

World consumption of all textile fibers, including cotton, chemical fibers and wool, increased at an impressive pace, from 9.6 million tons in 1950, to 58 million tons in 2004 (Fig. 13.7 and Table 13.4). Several variables are associated with changes in cotton consumption, including growth in income and population, changes in cotton prices relative to prices of competing fibers, consumer preferences and changes in fashion. Fibers competing with



13.7 World fiber use.

Table 13.4 World consumption of major textile fibers

	Total	Cotton	Wool	Chemical fibers*			Cotton	Wool	Chemical fibers*		
				All 1,000 Metric tons	Non-Cellulosics	Cellulosics			All Percent	Non-Cellulosics	Cellulosics
1960	15,153	10,356	1,495	3,302	702	2,600	68.3	9.9	21.8	4.6	17.2
1961	15,102	10,085	1,505	3,512	830	2,682	66.8	10.0	23.3	5.5	17.8
1962	15,339	9,902	1,501	3,936	1,080	2,856	64.6	9.8	25.7	7.0	18.6
1963	16,003	10,147	1,475	4,381	1,331	3,050	63.4	9.2	27.4	8.3	19.1
1964	17,256	10,830	1,460	4,966	1,687	3,279	62.8	8.5	28.8	9.8	19.0
1965	18,182	11,318	1,473	5,391	2,052	3,339	62.2	8.1	29.6	11.3	18.4
1966	18,796	11,539	1,545	5,712	2,371	3,341	61.4	8.2	30.4	12.6	17.8
1967	19,212	11,695	1,473	6,044	2,730	3,314	60.9	7.7	31.5	14.2	17.2
1968	20,434	11,763	1,565	7,106	3,578	3,528	57.6	7.7	34.8	17.5	17.3
1969	21,248	11,911	1,604	7,733	4,178	3,555	56.1	7.5	36.4	19.7	16.7
1970	21,741	12,105	1,500	8,136	4,700	3,436	55.7	6.9	37.4	21.6	15.8
1971	23,037	12,493	1,480	9,064	5,609	3,455	54.2	6.4	39.3	24.3	15.0
1972	24,417	12,903	1,578	9,936	6,377	3,559	52.8	6.5	40.7	26.1	14.6
1973	26,031	13,288	1,443	11,300	7,640	3,660	51.0	5.5	43.4	29.3	14.1
1974	25,267	12,986	1,262	11,019	7,487	3,532	51.4	5.0	43.6	29.6	14.0
1975	24,717	13,047	1,358	10,312	7,353	2,959	52.8	5.5	41.7	29.7	12.0
1976	26,537	13,211	1,515	11,811	8,601	3,210	49.8	5.7	44.5	32.4	12.1
1977	27,025	13,117	1,478	12,430	9,149	3,281	48.5	5.5	46.0	33.9	12.1
1978	28,246	13,415	1,481	13,350	10,032	3,318	47.5	5.2	47.3	35.5	11.7
1979	29,440	13,897	1,558	13,985	10,614	3,371	47.2	5.3	47.5	36.1	11.5
1980	29,580	14,295	1,567	13,718	10,476	3,242	48.3	5.3	46.4	35.4	11.0
1981	29,731	14,124	1,576	14,031	10,827	3,204	47.5	5.3	47.2	36.4	10.8
1982	28,895	14,248	1,556	13,091	10,145	2,946	49.3	5.4	45.3	35.1	10.2
1983	30,166	14,548	1,612	14,006	11,076	2,929	48.2	5.3	46.4	36.7	9.7

Table 13.4 Continued

	Total	Cotton	Wool	Chemical Fibers*			Cotton	Wool	Chemical fibers*		
				All 1,000 Metric tons	Non-Cellulosics	Cellulosics			All Percent	Non-Cellulosics	Cellulosics
1984	31,251	14,830	1,621	14,800	11,804	2,996	47.5	5.2	47.4	37.8	9.6
1985	32,813	15,768	1,625	15,420	12,489	2,931	48.1	5.0	47.0	38.1	8.9
1986	34,956	17,462	1,708	15,786	12,927	2,859	50.0	4.9	45.2	37.0	8.2
1987	36,546	18,226	1,754	16,566	13,741	2,825	49.9	4.8	45.3	37.6	7.7
1988	37,427	18,210	1,904	17,313	14,417	2,896	48.7	5.1	46.3	38.5	7.7
1989	38,227	18,677	1,861	17,690	14,747	2,943	48.9	4.9	46.3	38.6	7.7
1990	37,882	18,602	1,628	17,652	14,894	2,758	49.1	4.3	46.6	39.3	7.3
1991	38,069	18,562	1,801	17,706	15,273	2,433	48.8	4.7	46.5	40.1	6.4
1992	38,871	18,627	1,757	18,488	16,161	2,327	47.9	4.5	47.6	41.6	6.0
1993	39,109	18,544	1,649	18,916	16,587	2,329	47.4	4.2	48.4	42.4	6.0
1994	40,334	18,369	1,723	20,242	17,939	2,303	45.5	4.3	50.2	44.5	5.7
1995	40,720	18,353	1,554	20,813	18,377	2,436	45.1	3.8	51.1	45.1	6.0
1996	42,245	18,770	1,440	22,035	19,765	2,270	44.4	3.4	52.2	46.8	5.4
1997	45,034	19,007	1,361	24,666	22,396	2,270	42.2	3.0	54.8	49.7	5.0
1998	45,443	18,669	1,293	25,481	23,254	2,227	41.1	2.8	56.1	51.2	4.9
1999	47,073	19,120	1,393	26,560	24,485	2,075	40.6	3.0	56.4	52.0	4.4
2000	49,553	19,739	1,380	28,434	26,219	2,215	39.8	2.8	57.4	52.9	4.5
2001	49,789	20,102	1,361	28,326	26,244	2,082	40.4	2.7	56.9	52.7	4.2
2002	52,298	20,813	1,308	30,177	28,052	2,125	39.8	2.5	57.7	53.6	4.1
2003	54,165	21,256	1,206	31,703	29,432	2,271	39.2	2.2	58.5	54.3	4.2
2004	57,833	22,434	1,219	34,180	31,689	2,491	38.8	2.1	59.1	54.8	4.3

Sources: ICAC, Commonwealth Secretariat, International Wool Secretariat, and Fiber Economics Bureau.

cotton include natural fibers and chemical fibers, primarily polyester. Cotton's share of world textile fiber use fell from more than 70% in the 1950s to less than 50% by the end of the 1970s. Cotton did better in the 1980s. However, cotton's share of world textile fiber fell below 40% in 2002. Over the last five decades, cotton experienced an erosion of both price and non-price competitiveness.

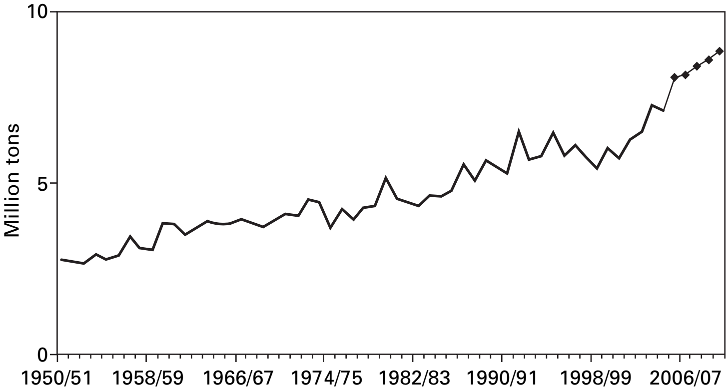
Cotton's major advantages over its primary competitors in the chemical fiber complex include wearing comfort, natural appearance, moisture absorbency, its status as a renewable resource and the important economic role of cotton in many producing countries. However, cotton also suffers from several disadvantages relative to chemical fibers, including contamination introduced during harvest, ginning and handling, annual fluctuations in the quantity and quality of production and consequent variability in prices. Cotton also has difficulty meeting the needs of modern spinning equipment for strength, uniformity and other quality parameters.

Relative fiber prices are extremely important in determining fiber market shares. During most years in the 1980s and 1990s, cotton prices were higher than prices of polyester, explaining much of the decline in fiber market share for cotton during those years. However, since 1998/99, cotton prices have been lower and polyester prices have been higher. As a consequence, cotton consumption rose at an average rate of 4% per year during the period from 1998 to 2004, compared to average growth of 1.5% per year in the two decades prior to 1998.

One common area of misunderstanding is the relationship between oil prices and prices of polyester fiber. Many people assume that because polyester is derived from chemicals refined from oil, that increases in crude oil prices lead to increases in polyester prices. However, the precursor chemicals used to make polyester account for only a small fraction of oil consumption, and each of the chemicals have multiple uses. As a consequence, there are separate markets for the chemicals used to make polyester, and those markets have little correlation with oil prices. Therefore, prices for polyester fiber are not determined by the price of oil, and in fact there is almost no statistical correlation between oil prices and polyester fiber prices.

13.5 Trade

World trade in cotton rose from 2.6 million tons in 1950/51 to 4 million tons in the early 1970s and reached 5.8 million tons in 1986/87. Cotton imports averaged 5.9 million tons during the 1990s and climbed to a record of 7.3 million tons in 2004/05 (Fig. 13.8). Among the top seven cotton producing countries, only Uzbekistan does not rank among the top seven consuming countries. Trade accounted for 28% of world cotton production in 2004/05, and the value of world exports was $8.4 billion.



13.8 World cotton imports.

World trade in cotton is projected at 7 million tons in 2004/05. Production is falling behind mill use in China (mainland), Pakistan, India and Turkey. The four countries accounted for 15% of world imports in 2000/01 and for an estimated 37% in 2004/05, while imports by the rest of the world decline. In 2005/06, world trade in cotton is projected to reach 8 million tons and the share of the four countries is projected to reach 49% of world cotton imports.

The largest and most significant impetus to the growth of world trade in cotton is provided by a sharp increase of cotton use in China (mainland) (Table 13.5). A record surge of cotton imports by China (mainland) to 1.9 million tons, or 26% of world imports in 2003/04, led world trade to a record. With the reduction of stocks in China (mainland) to minimum levels, the government began to provide full support to imports by issuing sufficient import quotas as a measure to balance supply and use, reduce domestic prices and make the textile industry more competitive. Imports by China (mainland) are estimated at 1.5 million tons in 2004/05 and are projected to reach 2.8 million tons in 2005/06.

For the third season in a row Turkey is the second largest importer of cotton accounting for 650,000 tons or 8% of world imports in 2004/05. The textile industry in Turkey continues to expand, driven by rising exports of textiles and apparel to Europe, USA and other markets. Between 2000/01 and 2004/05, mill use in Turkey rose by 300,000 tons and reached 1.45 million tons. Because cotton production in Turkey remains behind increasing use, imports remain a significant source of supply. Turkey was the largest importer of cotton in 2001/02 with imports estimated at 624,000 tons. In 2002/03 and 2003/04 imports were at 516,000 tons. The USA provides General Sales Manager-102 credit guaranties to Turkey and is the largest supplier of cotton to Turkey. In 2003/04, Turkey imported 317,000 tons from the USA accounting for 61% of total imports, the same as in 2002/03. About $120 million of USA cotton sales to Turkey or 31% of all imports were registered

Table 13.5 Top six cotton importers 2004/05

		Thousand tons	
1	China (M)	1,394	19.4%
2	Turkey	750	10.5%
3	Indonesia	511	7.1%
4	Thailand	480	6.7%
5	Bangladesh	394	5.5%
6	Mexico	365	5.1%
	Others	3,277	45.7%
	World	7,171	100.0%

under the GSM 102 program in 2002/03 and $170 million or 36% of all imports in 2003/04. Greece was the second largest supplier of cotton to Turkey, accounting for 82,000 tons or 16% of imports in 2003/04. Syria and Central Asia are other major suppliers of cotton to Turkey, accounting for approximately 6% each. An increase in cotton production in Turkey in 2004/05, estimated at 50,000 tons, could result in a similar reduction in imports.

India became one of the leading importers of cotton starting in 1999/2000 because of reduced production due to reduced planted area and drought. During the same period, Indian mill consumption was stable at around 2.9 million tons, supported by strong exports of cotton yarn and textile exports to Asian markets, USA, Canada and Mexico. In 2001/02, India imported 520,000 tons of cotton accounting for 8% of world imports. Indian area and yields rose during 2004/05, resulting in a crop of 3.9 million tons and as a result of increased domestic supply, imports by India declined to 150,000 tons. In 2005/06 Indian imports are projected to increase to 175,000 tons.

Because of reduced domestic production, low prices and increased demand for fine count yarns, India became one of the largest importers of extra-fine cotton, with imports of this category reaching 40,000 tons in 2003/04. Most extra-fine cotton was imported from Egypt and the USA. It is expected that India will remain the major importer of extra-fine cotton in 2004/05. Cotton consumption in Pakistan continues to expand rapidly in response to export-driven demand. During 2004/05, cotton mill use in Pakistan rose by 10% and reached 2.3 million. Imports by Pakistan doubled during 2003/04 to 400,000 tons, but is projected decline in 2004/05 to 200,000 tons because of increased production. Projected decline in domestic supply of cotton in 2005/06 in Pakistan could lead to an increase of imports to 290,000 tons.

The largest share of increased world import demand was met during the past three seasons by exports from the USA (Table 13.6). Large supplies of cotton in the USA, declining mill use and the effects of the marketing competitiveness provisions of the government program, known as the marketing

Table 13.6 Top six cotton exporters 2004/05

		Thousand tons	
1	USA	3,048	39.9%
2	Uzbekistan	850	11.1%
3	Australia	420	5.5%
4	Brazil	360	4.7%
5	Mali	268	3.5%
6	Greece	263	3.4%
	Others	2,434	31.8%
	World	7,643	100.0%

loan and Step 2, led to record US exports of 3 million tons in 2003/04. In 2004/05, US exports are expected to decline to 2.75 million tons because of a projected decline in imports by producing countries, but the USA will still account for 40% of world exports. In 2005/06, US exports are projected to exceed 3 million tons because of expected record imports by China (mainland).

The other largest exporters are Uzbekistan, Australia, West Africa and Brazil. Together these countries will account for 33% of world shipments in 2004/05. Because of a projected decline in import demand during 2004/05, exports by most of the major exporters are expected to decline, except for Uzbekistan where because of projected rebound in production exports are projected to increase by 14% to 730,000 tons, and Brazil, where an expected sharp increase in production could cause exports to double.

Exports from Uzbekistan were mostly declining from 1.3 million tons in 1992/93 to 650,000 tons in 2003/04. The reason for the steady decline in exports was a decline in production and increased mill use. In 2004/05, production in Uzbekistan is projected to rebound and exports are projected to increase to 760,000 tons, accounting for 11% of world exports. Cotton area in Uzbekistan is projected to remain stable during the next several seasons. At the same time, Uzbekistan is expected to continue expansion of spinning capacity, increasing utilization of cotton domestically and reducing the availability of supplies for exports.

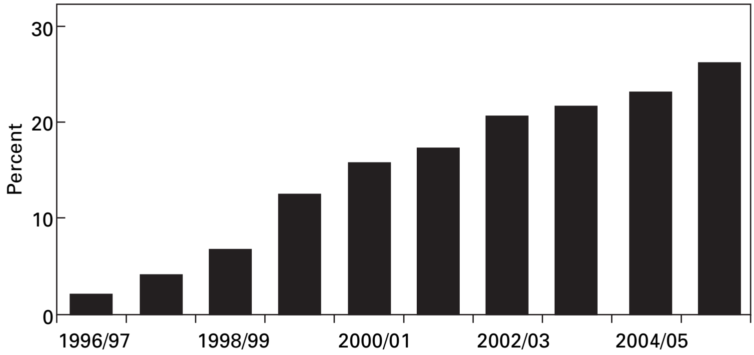
Between 1991/92 and 2002/03, Brazil was a net importer of cotton. During the past several seasons cotton production began to rise rapidly because of new high yielding commercial production in Central Brazil, including, Mato Grosso. In 2003/04, cotton production in Brazil exceeded consumption by almost half a million tons. Exports by Brazil estimated at 210,000 tons in 2003/04 are projected to double in 2004/05 to 400,000 tons. A large crop is projected for Brazil in 2005/06, and Brazil will likely remain a net exporter of 450,000 tons of cotton.

Exports from the Currency of Francophone Africa (CFA) zone reached a record of 1.1 million tons in 2003/04, an increase of more than 200,000 tons from 2002/03. Cotton production in the CFA zone reached a record of 1.03 million tons in 2001/02, an increase of 300,000 tons. Political difficulties in Cote d'Ivoire impeded shipments from the region, leading to a build up of large stocks estimated at over 500,000 tons in 2002/03. Exports from the CFA zone are estimated at 790,000 tons in 2004/05, because of reduced import demand, and at 1.1 million tons in 2005/06 accounting for 15% of world exports 2004/05.

Australian production suffered from severe drought during the past several seasons leading to a sharp decline in exports. In 2004/05, Australian exports fell to 420,000 tons compared with 850,000 tons in 2000/01. Australian cotton production in 2004/05 is projected to increase to 610,000 tons from 350,000 tons in 2003/04. Exports from Australia are projected to increase to 550,000 tons during 2005/06 as a result of increased production. Australia will account for only 7% of world exports in 2004/05, compared with 14% during 2000/01.

13.5.1 Biotech cotton

Biotech cotton is entering the world textile trade pipeline in increasing volumes as a result of growing world production and exports from the USA and Australia and textile exports from China (mainland) (Fig. 13.9). Based on the production shares of biotech cotton in exporting countries, it is estimated that biotech cotton accounted for 34% of world exports in 2002/03 and 36% in 2003/04. In 2004/05 the share of biotech cotton in world exports is declining to 31% because of an expected decline in export volumes from the USA and Australia. A larger share of world production will be consumed domestically in China (mainland). In 2003/04, an estimated 64% of all exports of biotech



13.9 GE cotton area.

cotton went to Asia and Oceania (not counting the Middle East) compared with 58% in 2002/03.

Based on domestically produced and imported biotech cotton, especially in China (mainland), it is estimated that 60% of mill use in Asia and Oceania were accounted for by biotech cotton in 2003/04 compared with 31% in 2002/03. Taking into account that Asia and Oceania account for more than 65% of world exports of cotton textiles, it is evident that the share of biotech cotton in textiles traded in major markets in Europe and America is rising. Despite an increasing share of biotech cotton traded in the world, there are no price differentials for biotech and non-biotech cotton fiber, or textiles containing biotech cotton. There is no evidence of rejection of biotech cotton by any segment of the market or region. In practice, markets do not identify biotech cotton content, but rather evaluate cotton properties based on quality characteristics.

13.5.2 China (mainland)

Substantial impacts on world textile trade have been caused by the entry of China (mainland) into the World Trade Organization in late 2001. The textile industry in China (mainland) is highly dependent on the export market, and can be sensitive to world affairs. Nonetheless, low labor costs and Chinese government policies have improved the country's competitiveness compared with other textile exporting developing countries, and China (mainland) has increased its share of world textile and apparel exports in the last four years. China (mainland) became the leading supplier of textile manufactures to the USA market, the largest retail market for textiles and apparel in the world.

China (mainland's) success in the world textile market stems from an early recognition that the development of its textile complex had to focus on where it was most competitive, in the apparel sector. China (mainland) has a substantial labor cost and supply advantage compared with other major textile and apparel producers. Development of the competitive apparel production sector served as a catalyst for expanded investments in modernization of the capital-intensive textile sector. China (mainland) has invested heavily in the modernization of the textile and apparel sectors during the past ten years, and investments in the textile sector rose by 80.4% in 2003 alone reaching $10.7 billion according to the National Bureau of Statistics. China (mainland) imported $11.8 billion worth of textile machinery between 2000 and June 2003 according to International Textile Manufacturers Federation (ITMF) data. As a result, China (mainland) became the world's largest textile economy, the largest exporter of textiles and clothing, the largest cotton and chemical fiber producer, with the textile sector generating 10% of GDP. Per capita fiber consumption in China (mainland) rose from 8.3 kg in 2000 to

10.8 kg in 2002, and the population is rising by 11–12 million annually to reach 1.32 billion in 2005. The rate of growth of retail apparel sales in China (mainland) reached 20% in January–February 2005 compared to a year earlier and the rate of growth in rural areas is outpacing urban sales. China (mainland) is positioned to increase its market share with the elimination of quotas. However, other developing countries could find new opportunities with open competition.

13.5.3 Turkey

A similar strategy of modernization and investments was implemented by Turkey, where combined exports of textiles and clothing rose from $474 million in 1980 to $15.180 billion in 2003. During that period exports of textiles rose by 1,428% while exports of apparel rose by 7,487% reaching $9.4 billion. In 2004 apparel output in Turkey rose by 5.5% in volume compared to 2.8% growth recorded in 2003, while textile output rose by 4.2% in 2004 after declining by 0.9% in 2003. Turkey's top export market is the EU, while exports of cotton apparel suffered a 4.3% decline in the USA in 2004, losing to rising volumes from China (mainland), India and Pakistan.

13.5.4 India

India has been developing its textile and apparel sectors at impressive growth rates. Between 1980 and 2003, exports by both sectors in India rose by 647%. In India, the second largest cotton processing country, mill consumption of cotton between 1990/91 and 1997/98 increased at an average annual rate of 4.3%, or seven times more rapidly than world consumption growth. Demand for Indian textile products has been supported mainly by very strong exports, in particular exports of cotton yarn. Taking advantage of relatively low costs of cotton processing, Indian exports to other Asian markets increased faster than to other destinations between 1990/91 and 1997/98. In addition, promotion of exports to the USA, Canada and Mexico, as well as to Latin American countries has been developed since 1996. Nonetheless, Indian mill consumption of cotton remained at 2.9 million tons between 1998/99 and 2003/04, due to increased competition from China (mainland) and other textile exporters. However, Indian mill consumption of cotton is projected to rise by 12% in 2004/05 to reach 3.4 million tons because of improved competitive advantage of cotton yarn and apparel production in India and the expansion of exports of textiles and apparel.

In 2005/06 Indian cotton consumption is projected to reach 3.4 million tons or 14% of world mill use. One of the important effects of lower cotton prices is an increase in the market share of cotton in India, and as a result a decline in the output of man-made fibers. During most of 2004, cotton prices in India were lower than cotton prices in China (mainland). In December 2004 monthly output of man-made fibers was the lowest since February 2004, while cotton yarn and fabric output reached a record rising by 7.4% during 2004. India has been one of the three top winners of the post-quota era along with China (mainland) and Pakistan, exercising a competitive advantage in yarn and fabric production. India's apparel production began rising strongly during the second half of 2004 and by December 2004, rose 38.2% in volume compared with December 2003.

13.5.5 Pakistan

In Pakistan, during the past 20 years, more emphasis was given to the development of the textile sector compared with clothing industries, and the combined export growth between 1980 and 2003 was 770%. However, recently Pakistan began to expand apparel and fabric production, while reducing exports of cotton yarn due to increased competition from Indian yarns and increased domestic demand for yarns from weavers and knitters. Knitwear exports from Pakistan soared 35.8% during 2004.

13.5.6 Winners and losers

The elimination of quotas provided an opportunity for large competitive textile producers like China (mainland), India and Pakistan to increase their market share. However, the elimination of quotas will also intensify competition in the open marketplace and will necessitate and stimulate a number of developing countries to restructure their textile economies investing in the modernization of the sectors where their competitive advantage lies in an attempt to capture a larger share of the market. The end of quotas lowers the barriers to entry by new exporters with a wider range of products and could lead to lower prices for textiles. Countries enjoying a guaranteed quota earlier, or quota-free access to the most lucrative markets, could lose market share if their products are of low quality and not competitive. Quality, product innovation, reliability, demand responsiveness, market proximity, quick turnover and preferential tariffs are become increasingly important competition factors.

In 2005, Mexico lost its advantage of quota-free access to the US market provided by the North American Free Trade Agreement (NAFTA) trade regime, but will continue to have an advantage of market proximity and tariff-free access. As a result Mexico could lose market share to China (mainland). Similarly, countries of Central and Eastern Europe and the Mediterranean will lose the advantage of quota-free access to the EU, but will continue to benefit from market proximity and duty-free access.

Market shares in textile trade of countries with quota-free and duty-free access to large markets in the USA or EU, but with relatively weak industries or/and remote locations, such as Bangladesh (EU and USA agreements), Mauritius (EU agreement), Sub-Saharan Africa (African Growth and Opportunity Act, or AGOA, an agreement providing preferential access to the USA market for textile and apparel products from Africa), Hong Kong (large quotas) and countries in similar positions could decline.

13.6 Government measures

An important factor explaining the location of cotton production in relatively high-cost countries is government measures that distort production and trade (Table 13.7). Direct income and price supports for cotton worldwide ranged between $3.8 billion in 1997/98 and $5.8 billion in 2001/02. For 2004/05, direct income and price support programs for cotton are estimated at $4.7 billion. Fourteen countries representing three-fourths of world cotton production offered direct income and price support programs to cotton growers in 2001/02, a season of record low prices, resulting in higher production and forcing the burden of adjustment to low cotton prices onto growers in countries that did not provide similar measures of protection. Developed countries and China (mainland) accounted for 86% of assistance provided worldwide.

In 2004/05, the greatest government assistance per pound of cotton production was provided by the European Union to producers in Greece and Spain, with support averaging 95 cents per pound of lint production, or approximately $1.1 billion in total. Support in the EU is paid to cotton ginners, and ginners are required to provide the support to farmers based on seed cotton deliveries adjusted for quality. The amount of support paid to each farmer is based on the difference between market prices at the time of harvest and a target price set by the EU. The EU does not try to restrict cotton imports in order to keep domestic prices above the world level. The EU announced in 2004 that 65% of the value of support for cotton will be paid to farmers directly and decoupled from current cotton production beginning in January 2006. This means that beginning in 2006, cotton farmers in Greece and Spain will receive 65% of the support they used to receive whether they continue to produce cotton or not, and only 35% of government support will be based on current production. This change, known as decoupling, will lead to lower production. The EU produced 500,000 tons in 2004/05, and cotton production is forecast to decline by one-fourth by 2006/07.

In 2004/05, direct support to cotton farmers in the USA averaged 20 cents per pound of production, about equal to the average since the early 1980s. The total value of direct support was $2.2 billion. Support in the USA included payments to farmers based on the difference between average farm prices and a target price. US growers also received a fixed payment based on

Table 13.7 Level of direct assistance provided by governments to the cotton sector

(a) Through production programs*

Country	2003/04			2004/05**		
	Production 1,000 tons	Average assistance per pound produced US cents	Assistance to production US$ Millions	Production 1,000 tons	Average assistance per pound Produced US cents	Assistance to production US$ Millions
China (mainland)	4,871	12	1,303	6,320	8	1,145
USA	3,975	12	1,021	5,025	20	2,244
Greece	320	108	761	400	95	836
Spain	98	108	233	110	95	230
Turkey	910	1	22	900	6	115
Egypt	198	2	9	285	14	89
Mexico	68	4	6	138	16	49
Benin				125	12	34
Colombia				61	8	11
All Countries	10,440	15	3,354	13,364	16	4,753

* Income and price support programs only. Credit and other assistance not included.

** Preliminary.

Table 13.7 Continued

(b) Through export program

	2003/04			2004/05**		
Country	Exports 1,000 tons	Average assistance per pound exported US cents	Assistance to exports US$ Millions	Exports 1,000 tons	Average Assistance per pound exported US cents	Assistance to exports US$ Millions
USA	2,996	4	235	2,745	6	375
Upland cotton	2,878	3	190	2,574	3	165
Pima	118	17	45	171	56	210
Egypt	89	1	2	130	3	8
India				150	2	7
Total	3,085	3	237	2,875	6	383

* Preliminary.

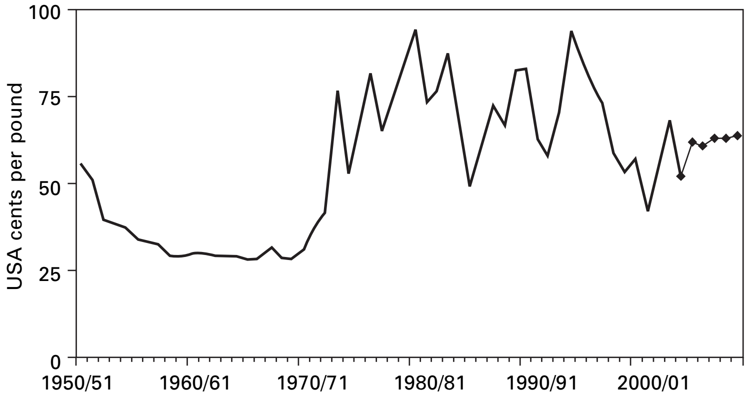
historical production. As in Europe, the USA does not attempt to restrict cotton imports in an effort to bolster domestic prices. Elements of the US cotton program came under specific criticism from the international community during the Doha Round of trade negotiations under the auspices of the WTO because of the unique roll played by cotton in the economies of many developing countries. During the Doha Round talks, the USA agreed to lower or eliminate subsidies to cotton, but only within the context of an overall agreement on agriculture.

The value of government support for the cotton sector of China (mainland) is estimated at 8 cents per pound in 2004/05, or about $1.1 billion. In contrast to Europe and the USA, China does not provide direct payments to cotton growers but instead uses a complex system of import quotas and licenses to restrict trade and maintain domestic prices above the world level. The Government of China claims in the WTO that it does not subsidize cotton, but the differential between international prices and equivalent domestic prices in China, adjusted for quality and common location, are persistent and substantial and well documented.

Government measures that boost cotton production have a negative impact on average international cotton prices in the short run. However, if subsidies were eliminated, production would expand in other countries within two to three seasons in response to higher prices, and many researchers feel that the long run impact of government measures on cotton prices is probably small. Nevertheless, the distortions to cotton production caused by government measures are significant. In the absence of government support for cotton and other commodities, cotton production in the USA would decline by an estimated one-third over several seasons, and production in China (mainland) would probably fall by about one-tenth. As a consequence, between two and three million tons of cotton production would shift from Europe, the USA and China toward lower cost producing countries if government measures were eliminated.

13.7 Prices

International cotton prices have declined over time due to more efficient production practices. During the 1950s and 1960s, as production rose while consumption was affected by growth in the use of chemical fibers, cotton prices generally trended lower (Fig. 13.10). The Cotlook A Index, an indicator of world cotton prices (method of calculation), dropped from more than 50 cents per pound in 1950 to less than 30 cents by the end of the 1960s. During the 1970s cotton prices were influenced by the same factors of inflation, rising demand, concerns about trade embargoes and increases in production costs that affected all commodity markets, and the Cotlook A Index rose to more than 70 cents per pound. During the ten years to 1985/86 international cotton prices averaged 75 cents per pound. Between 1985/86 and 1994/95,



13.10 Cotlook A Index.

prices averaged 70 cents per pound, and in the nine years to 2004/05, prices averaged 60 cents per pound.

Several factors influenced the long-term decline in average prices, among which are new technologies, more extensive use of existing technologies, and new area dedicated to cotton. Nevertheless, despite distortions caused by government measures, cotton supply and demand are price-responsive. Average international prices rebounded from a 19-year low of 42 cents per pound in 2001/02 to 68 cents in 2003/04 before falling to an average of 52 cents in 2004/05.

When adjusted for inflation, cotton prices have declined since the 1950s. In 2005 US dollars, the Cotlook A Index fell from nearly $4 per pound in the early 1950s to approximately $1.2 in the early 1970s. With the rise in commodity prices in the mid-1970s, the Cotlook A Index climbed to more than $2 per pound but has tended lower in real terms since and collapsed to $0.43 per pound in 2001/02, the lowest since the invention of the cotton gin in 1793. Despite the increase in average yields, real average revenue per hectare of cotton also declined over the last five decades. In 2005 US dollars per hectare at an average world yield, the average revenue from cotton fell from about $2,000 in the early 1950s to $1,000 in the late 1960s. In the mid-1970s, the average revenue rose to about $2,400 per hectare but relapsed to $1,000 during the 1990s. Average revenue per hectare is estimated at $830 in 2004/05.

13.8 Future trends

World production and consumption in 2009/10 are estimated at approximately 27 million tons, and world trade is estimated at 9 million tons, including imports by China (mainland) of 4 million tons. New technologies, the development of new areas dedicated to cotton and government measures are expected to continue to support cotton production in the next five seasons.

Area dedicated to biotech cotton varieties is expected to climb to 40% of world area accounting for 50% of cotton production. The average world yield is expected to surpass 800 kilograms per hectare. Over the next five years, cotton consumption is expected to expand at an annual rate of 3%. Consumption in China (mainland) is projected to climb to 11 million tons in 2009/10, approximately 40% of world mill use. Cotton's share of the world textile fiber market is projected to remain near 40%.

Because of the increasing importance of China (mainland) to the world cotton market, net trade between China and the rest of the world will continue to play an important role in determining cotton prices. World ending stocks are projected to average 45% of global consumption over the next five years, down from 50% on average from 1997/98 to 2004/05. In contrast, the stocks-to-use ratio (the ratio of stock on 31 July each year (the end of the season) divided by consumption during the season – a measure of how tight stocks are relative to demand (used as a key indicator of the direction of prices)) outside China (mainland) is expected to average 70% over the next five seasons, sharply up from an average of 40% during the 1990s.

Year-to-year changes in cotton production are determined by marginal costs, not by average production costs. Therefore, cotton prices tend toward the marginal cost of the most efficient producers, not the world average production cost. Costs of production worldwide are coming down. At current exchange rates, marginal production costs – and in the case of more efficient producers, total costs – are below 55 cents per pound in several countries. Competing chemical fibers will put additional pressure on cotton prices. The consequence will be lower average prices over the next decade compared to the 70 cent average of the last 30 years, and the Cotlook A Index is expected to average between 45 and 55 cents per pound between 2005 and 2015.

13.9 Sources of further information

Statistical information about the world cotton industry is available from three main sources. The International Cotton Advisory Committee provides comprehensive statistics on world cotton supply, use and prices by country from the 1920s. The ICAC provides extensive information on fiber use and market share by country, government measures, trade by country of origin and destination, and statistics on production and trade in cotton yarn and woven cotton fabric. In addition, the ICAC provides technical information on cotton production practices, costs of production, and new technologies affecting cotton production. Information is available at www.icac.org.

The US Department of Agriculture has several important web sites for cotton information. Data on area, yield and production by state, as well as reports on input use in cotton are available from the National Agricultural Statistics Service at www.USDA.Gov/Nass/. Data on consumption, market share, production and trade are available from the Economic Research Service at www.ERS.USDA.gov/Briefing/cotton. Data on trade in cotton and reports from USA agricultural attaches in embassies around the world are available from the Foreign Agriculture Service at www.FAS.USDA.gov/Cotton.

A private company in Liverpool, UK publishes an industry magazine and information service known as *Cotton Outlook* at www.cotlook.com. This is the best source for data on cotton prices. The International Textile Manufacturers Association, ITMF, provides valuable statistics on industry capacity and textile machinery shipments at www.ITMF.org. The International Cotton Association in Liverpool provides data on arbitration of disputes that arise from trade in cotton. Their address is www.LCA.org.uk.

Several interesting books for general readership have been published in the past year dealing with different aspects of cotton and providing insight into the culture and workings of the international cotton industry. The best for objective information about the economics of the cotton industry is, *The Travels of a T-Shirt in the Global Economy*, by Pietra Rivoli. Another book, *Big Cotton*, by Stephen Yafa provides insights into the role of cotton in the industrial revolution and how cotton has influenced the politics of the United States. A third book, *The King of California*, looks at the history of one family in California that became the largest cotton producer in the USA.

A number of magazines and industry journals provide in-depth reports on various subjects of national and international interest to the cotton industry. In addition to *Cotton Outlook* mentioned earlier, there is *Cotton International (CI) World Report* from Meister Publishing. A free weekly newsletter is available at www.ciworldreport.com/newswire.

A magazine, *Cotton Bangladesh*, contains stories about the structure of the cotton textile industries in South Asia. Contact them at CottonBangladesh@aol.com.

An excellent source of information about developments in the textile industries of Asia, especially China (Mainland) is the magazine, *Textile Asia*, published in Hong Kong. Contact them at www.textilasia-businesspress.com.

13.10 References

All statistics and information in this chapter were sourced from publications of the Secretariat of the International Cotton Advisory Committee.

Appendix: World cotton supply and use

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
26/27	0	0	6,365	0	3,294	0	3,553		
27/28	0	0	5,288	0	3,201	0	2,826		
28/29	0	0	5,973	0	3,158	0	3,132		
29/30	0	0	6,073	0	3,135	0	2,806		
30/31	**0**	**0**	**5,895**	**0**	**2,947**	**0**	**2,762**		
31/32	0	0	6,081	0	2,875	0	2,897		
32/33	0	0	5,507	0	2,829	0	2,879		
33/34	0	0	6,004	0	3,125	0	2,995		
34/35	0	0	5,300	0	2,820	0	2,502		
35/36	0	0	6,023	0	2,859	6,343	2,971		
36/37	33,096**	201**	7,018	0	3,227	7,007	3,093		
37/38	0	0	8,346	0	2,818	6,384	2,749		
38/39			6,422	0	2,569	6,609	2,557		
39/40	0	0	6,353	0	2,723	6,557	2,811		
40/41	**0**	**0**	**6,934**	**0**	**1,643**	**6,130**	**1,467**		
41/42	0	0	6,223	0	1,587	5,597	1,262		
42/43	0	0	5,813	0	1,244	5,312	834		
43/44	0	0	5,399	0	938	4,987	880		
44/45	0	0	5,329	0	895	4,997	1,097		
45/46	22,305	209	4,651	6,509	1,882	5,350	2,005	5,696	1.06
46/47	22,547	211	4,757	5,696	2,118	6,134	2,084	4,259	0.69
47/48	23,914	230	5,501	4,259	2,077	6,486	1,935	3,270	0.50
48/49	25,425	254	6,450	3,270	2,524	6,341	2,419	3,351	0.53
49/50	28,732	249	7,154	3,351	2,628	6,749	2,767	3,708	0.55
50/51	**28,537**	**233**	**6,645**	**3,708**	**2,724**	**7,638**	**2,636**	**2,678**	**0.35**
51/52	36,040	234	8,427	2,678	2,661	7,657	2,671	3,417	0.45
52/53	35,448	246	8,736	3,417	2,612	8,044	2,594	4,070	0.51

Appendix: (continued)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports (Thousand metric tons)	Consumption	Exports	End stocks	S/U* Ratio
53/54	33,422	271	9,068	4,070	2,877	8,443	2,916	4,626	0.55
54/55	33,445	267	8,930	4,626	2,756	8,678	2,686	4,862	0.56
55/56	34,078	279	9,508	4,862	2,882	8,972	2,830	5,349	0.60
56/57	33,417	275	9,183	5,349	3,409	9,352	3,438	5,124	0.55
57/58	32,032	283	9,053	5,124	3,092	9,343	3,061	4,810	0.51
58/59	31,657	308	9,760	4,810	3,043	9,942	2,937	4,609	0.46
59/60	32,326	318	10,286	4,609	3,788	10,531	3,772	4,407	0.42
60/61	**32,445**	**314**	**10,201**	**4,407**	**3,804**	**10,231**	**3,667**	**4,551**	**0.44**
61/62	33,057	297	9,832	4,551	3,463	9,982	3,367	4,532	0.45
62/63	32,633	320	10,444	4,532	3,638	9,845	3,450	5,260	0.53
63/64	32,968	330	10,877	5,260	3,879	10,362	3,910	5,845	0.56
64/65	33,366	345	11,504	5,845	3,811	11,165	3,721	6,312	0.57
65/66	33,133	359	11,898	6,312	3,809	11,429	3,712	6,879	0.60
66/67	30,915	350	10,836	6,879	3,934	11,618	3,974	6,032	0.52
67/68	30,670	351	10,780	6,032	3,828	11,752	3,805	5,068	0.43
68/69	31,692	374	11,856	5,068	3,718	11,772	3,640	5,240	0.45
69/70	32,658	348	11,379	5,240	3,932	12,010	3,880	4,724	0.39
70/71	**31,778**	**369**	**11,740**	**4,656**	**4,086**	**12,173**	**3,875**	**4,605**	**0.38**
71/72	33,024	392	12,938	4,681	4,031	12,721	4,111	4,799	0.38
72/73	33,818	402	13,595	4,851	4,528	13,034	4,640	5,358	0.41
73/74	32,558	418	13,615	5,434	4,408	13,469	4,294	5,727	0.43
74/75	33,285	418	13,926	5,727	3,734	12,641	3,814	7,373	0.58
75/76	30,001	390	11,706	7,352	4,188	13,336	4,183	5,770	0.43
76/77	31,513	393	12,385	5,770	3,951	13,122	3,806	5,232	0.40
77/78	34,966	396	13,860	5,232	4,250	13,133	4,239	5,963	0.45
78/79	34,000	380	12,933	5,963	4,320	13,703	4,346	5,257	0.38
79/80	33,100	425	14,084	5,255	5,093	14,127	5,073	5,257	0.37

Appendix: (Continued)

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
80/81	**33,667**	**411**	**13,831**	**5,152**	**4,555**	**14,215**	**4,414**	**4,994**	**0.35**
81/82	33,948	442	14,991	4,994	4,405	14,147	4,373	5,852	0.41
82/83	32,569	445	14,479	5,852	4,350	14,452	4,261	5,926	0.41
83/84	32,137	451	14,499	5,926	4,617	14,655	4,309	6,121	0.42
84/85	35,217	546	19,247	6,121	4,602	15,108	4,520	10,247	0.68
85/86	32,792	532	17,461	10,247	4,763	16,589	4,479	11,366	0.69
86/87	29,503	518	15,269	11,366	5,516	18,198	5,755	8,251	0.45
87/88	31,238	564	17,609	8,251	5,094	18,117	5,121	7,668	0.42
88/89	33,522	546	18,301	7,668	5,654	18,470	5,726	7,312	0.40
89/90	31,640	549	17,365	7,312	5,431	18,675	5,293	6,146	0.33
90/91	**33,050**	**574**	**18,978**	**6,146**	**5,220**	**18,574**	**5,073**	**6,709**	**0.36**
91/92	34,710	596	20,677	6,709	6,497	18,636	6,091	9,312	0.50
92/93	32,238	557	17,943	9,313	5,690	18,634	5,525	8,694	0.47
93/94	30,430	554	16,861	8,694	5,766	18,496	5,911	7,028	0.38
94/95	32,114	584	18,762	7,028	6,458	18,278	6,312	7,561	0.41
95/96	36,056	564	20,330	7,561	5,805	18,405	5,999	9,129	0.50
96/97	34,111	575	19,599	9,129	6,134	19,049	6,049	9,844	0.52
97/98	33,746	595	20,094	9,844	5,737	18,990	5,973	10,672	0.56
98/99	32,846	569	18,705	10,674	5,390	18,451	5,508	10,937	0.59
99/00	31,929	598	19,095	10,937	6,034	19,603	6,111	10,359	0.53
00/01	**31,766**	**612**	**19,457**	**10,359**	**5,734**	**19,845**	**5,881**	**9,953**	**0.50**
01/02	33,381	644	21,490	9,953	6,229	20,305	6,448	10,771	0.53
02/03	29,924	645	19,294	10,771	6,538	21,235	6,676	8,661	0.41
03/04	32,190	644	20,720	8,661	7,292	21,325	7,255	8,111	0.38

Appendix: (Continued)

(Thousand metric tons)

	Area (000 Ha)	Yield (kgs/ha)	Production	Beginning stocks	Imports	Consumption	Exports	End stocks	S/U* Ratio
04/05 est.	35,757	733	26,219	8,111	7,171	23,400	7,643	10,450	0.45
05/06 proj.	35,238	689	24,272	10,450	8,078	23,925	8,078	10,795	0.45
06/07 proj.	35,490	699	24,814	10,795	8,191	24,609	8,191	11,001	0.45
07/08 proj.	35,657	709	25,286	11,001	8,313	25,090	8,313	11,197	0.45
08/09 proj.	36,011	716	25,787	11,197	8,482	25,575	8,482	11,409	0.45
09/10 proj.	36,421	718	26,165	11,409	8,788	26,084	8,788	11,491	0.44

* Stocks-to-use ratio equals ending stocks divided by consumption.

** Annual average during 1934–1938.

14

Health and safety issues in cotton production and processing

P J WAKELYN, National Cotton Council, USA

14.1 Introduction

Health and safety are key components of responsible production and processing of cotton and of a responsible management system for cotton operations. Workers handle and process cotton in many work operations from planting the cottonseed, to the finished cotton textile (i.e., from 'field-to-fabric' or from 'dirt-to-shirt') – production, harvesting, ginning, yarn and fabric manufacturing, and preparation, dyeing and finishing. Each cotton industry sector has its own particular health and safety considerations. This chapter addresses the more pertinent health and safety issues for each sector of the cotton industry.

In the USA, health and safety guidelines and regulations are issued or promulgated and enforced by the US Occupational Safety and Health Administration (OSHA), which is part of the US Department of Labor (DOL). The purpose of OSHA is to ensure that the employers maintain a safe and healthful workplace. In the UK, health and safety regulations and guidelines are developed and enforced by the Health & Safety Executive (HSE). The mission of the HSE is to protect people's health and safety by ensuring risks in the changing workplace are properly controlled. Australia incorporates government occupational health and safety legislation into a best management practice (BMP) approach (Chaudhry, 2004; Slack-Smith, 2000; Australian Cotton Industry, 2006) for cotton production. Adoption of the BMP system is used by growers as a positive feature in marketing Australian cotton, because it demonstrates safe pesticide use and ecologically safer practices for workers and the surrounding communities.

In addition to regulations and guidelines by the individual countries, there are voluntary standards for occupational health and safety developed by international organizations, such as the International Organization for Standardization (ISO) and the European Union (EU), European Committee for Standardization (CEN). ISO standards are routinely adopted or incorporated by reference by over 100 countries and include standards for agriculture, (ISO ICS 65 Agriculture Standards (2006)), and textiles (ISO ICS 59 Textile and Leather Technology (2006)), as well as standards for quality management (ISO, 9000) and environmental management (ISO 14000) (ISO 9000 and ISO 14000,2006), which are among ISO's most widely known standards ever. ISO 9000 and ISO 14000 standards are implemented by some 760,900 organizations in 154 countries. ISO 9000 has become an international reference for quality management requirements in business-to-business dealings, and ISO 14000 enables organizations to meet their environmental challenges. The American Conference of Governmental Industrial Hygienists (ACGIH), an independent standard setting organization is the USA, has threshold limit values ('TLVs'; worker/workplace exposure limits) for hazardous substances and exposures (ACGIH, 2006) that some countries (e.g., Canada) in the world routinely adopt or incorporate by reference into their regulations.

Most of the about 80 countries in the world where cotton is grown and/or processed have workplace health and safety regulations, procedures, and guidelines and routinely adopt international standards to help provide safe and healthful workplaces. The USA occupational health and safety standards and guidelines are comprehensive and represent a good model for cotton industry segments in other countries to consider. In this chapter, USA safety and health regulations and guidelines are used, for the most part, as illustrations of prudent occupational health and safety procedures for providing safe and healthful workplaces in the various cotton industry segments.

US OSHA agriculture standards (29 Code of Federal Regulation [CFR] 1928) apply to cotton production and ginning. US OSHA general industry standards (29 CFR 1910) apply to post-harvest cotton operations (i.e., warehouses and textile manufacturing and processing). In addition, the US Occupational Safety and Health Act (Sec. 5(a)(1) of the 'OSH Act') requires the employer to maintain a safe and healthful workplace.

Both hazard – anything that can cause harm (e.g., chemicals) – and risk – the chance, high or low, that someone will be harmed by the hazard – are discussed. Hazard is the innate nature of the product, whereas risk is determined by exposure. Thus a monomer or dye component may be a hazardous substance but the insoluble polymer or dyed fabric (i.e., the final product) are not a risk because there is no exposure to the hazard.

When cotton is grown and processed (including yarn manufacturing and wet processing) in a responsible manner, the production and processing of cotton should not have any adverse effects on the worker (because of acute or chronic effects), the consumer (because of acute or chronic effects), or the environment (through crop protection product/chemical use, external emissions, wastewater effluents, and solid wastes) (Wakelyn, 1994).

14.2 Cotton production

The agricultural transitions to mechanized power, and from mechanical to chemical to genetically engineered tools, have increased farm productivity, but have not decreased the health and safety stresses upon farmers (Batie and Healy, 1980, 1983 (or the original publication in 1980); Martin and Olmstaed, 1985). Since the early 1960s, agriculture has become one of the most hazardous occupations (Batie and Healy, 1983; Mutal and Donham, 1983), mainly because of modern farm equipment. Cotton production potentially has most of the same health and safety considerations as other row crops.

The production of cotton in the developed countries is heavily mechanized and is dependent on chemical based production systems. The proper use and handling of crop protection products is the most important health and safety activity in cotton production in developed as well as developing countries. Health hazards of pesticide/crop protection products application, disposal of pesticide containers and many other aspects of pesticide storage, handling and disposal have caused damage to human life and the environment in the past and still do in some of the about 80 countries (59 countries grow at least 5000 ha) where cotton is grown. The development of new crop protection products, less persistent and less toxic to humans, has been helpful in reducing risks to human life and the environment. Many countries like the USA have strict regulations for approval of crop protection products (US EPA, 2006) as well as strict worker protection standards for pesticide handlers and agricultural workers for application of crop protection products (US EPA, 2006a) and regulations for safe storage and disposal of used containers (US EPA, 2006b). These regulations, if followed, greatly reduce health risks to workers and the environment.

There are occupational safety and health requirements for all mechanical equipment (29 CFR 1928.51-53) and guides to protect workers from heat stress (US OSHA, 2002, 2006; US OSHA/EPA, 1993). Because of the high temperatures, the state of California in 2006 finalized regulations for heat stress (CAL OSHA, 2006). There are also heat stress requirements in the worker protection standard (WPS) (US EPA 2006a).

14.2.1 Safety with agricultural equipment and machinery

Many farm accidents and fatalities involve mechanized farm equipment and machinery. Many times these accidents and fatalities occur with children. There is a US OSHA standard for the protection of employees from the hazards associated with moving machinery parts of farm field equipment, farmstead equipment, and cotton gins used in any agricultural operation (29 CFR 1928.57). Proper machine guarding and equipment maintenance according to manufacturers recommendations can help prevent accidents. Specific requirements for cotton gins are discussed in section 14.3.

Tractor-related accidents are the leading cause of agricultural death in the US. US OSHA has regulations for roll-over protective structures (ROPS) for tractors used in agricultural operations (29 CFR 1928.51) and for protective frames and enclosures for wheel type agricultural tractors (29 CFR 1928.52-53). Using protective equipment, such as seat belts on tractors, and personal protective equipment (such as safety gloves, coveralls, boots, hats, aprons, goggles, face shields) also can significantly reduce farming injuries.

14.2.2 Worker protection standard for agricultural pesticides

There are anecdotal stories of adverse effects of prolonged exposure of pesticide use on cotton, such as a community reputed to have high levels of the chlorinated hydrocarbon, toxaphene, in fish. Dichlordiphenyltrichloroethane (DDT) is still found in soil samples and birds and small animals can be scarce in fields treated with agricultural chemicals. A much greater awareness of potential harm to workers and the community and government regulations has led the cotton industry in all developed countries and in most developing countries now to be very vigilant in regulating and monitoring pesticide use.

Overview of the WPS

The Australian BMP program (Chaudhry, 2004; Slack-Smith, 2000; Australian Cotton Industry, 2006) and the US Worker Protection Standard (‘WPS’, 40 CFR 170) (US EPA, 2006a; NCC, 2004, 2005) are aimed at reducing the risk of pesticide poisonings and injuries among agricultural workers and pesticide handlers. The US WPS contains requirements for

- pesticide safety training
- notification of pesticide applications
- use of personal protective equipment
- restricted entry intervals (REI) following pesticide application (e.g., for carbofuran, a broad spectrum insecticide, the REI is 48 hrs following application)
- decontamination supplies
- emergency medical assistance.

The WPS covers two types of employees on farms from occupational exposure to agricultural pesticides:

- Pesticide handlers – those who mix, load, or apply agricultural pesticides; clean or repair pesticide application equipment or assist with the application of pesticides in any way.

- Agricultural workers – those who perform tasks related to the cultivation and harvesting of plants on farms or in greenhouses, nurseries, or forests. Workers include anyone employed for any type of compensation (including self-employed) doing tasks related to the production of agricultural plants on an agricultural establishment.

There are some WPS requirements that apply to all persons and some that apply to anyone who handles pesticide application equipment or cleans or launders pesticide-contaminated personal protective equipment

Summary of WPS requirements

- Pesticide safety training and safety posters – training is required for all workers and handlers, and a pesticide safety poster must be displayed.
- Access to labeling and site-specific information – Handlers and workers must be informed of pesticide label requirements. Central posting of recent pesticide applications is required.
- Notification to workers – workers must be notified about treated areas so they may avoid inadvertent exposures.
- Personal protective equipment – personal protective equipment must be provided and maintained for handlers and early-entry workers.
- Protection during applications – applicators are prohibited from applying a pesticide in a way that will expose workers or other persons. Workers are excluded from areas while pesticides are being applied.
- Restricted-entry intervals – restricted-entry intervals must be specified on all agricultural plant pesticide product labels. Workers are excluded from entering a pesticide-treated area during the restricted-entry interval, with only narrow exceptions.
- Decontamination supplies – Handlers and workers must have an ample supply of water, soap, and towels for routine washing and emergency decontamination.
- Emergency assistance – transportation must be made available to a medical care facility if a worker or handler may have been poisoned or injured. Information must be provided about the pesticide to which the person may have been exposed.

WPS glove requirements for workers, handlers, and pilots

All agricultural pesticide handlers and early-entry workers covered by the WPS are permitted to wear separate glove liners beneath chemical-resistant gloves and agricultural pilots do not have to wear chemical-resistant gloves when entering or exiting aircraft. Handlers and early-entry workers may choose whether to wear the liners. The liners may not be longer than the chemical-resistant glove, and they may not extend outside the glove. The liners must be disposed of after ten hours of use, or whenever the liners become contaminated. Lined or flocked gloves, where the lining is attached to the inside of the chemical-resistant outer glove, remain unacceptable. Regulatory action was taken to reduce the discomfort of unlined chemical resistant gloves, especially during hot or cold periods. Additionally, chemically resistant gloves do not add any appreciable protection against minimal pesticide residues found around the cockpit of an aircraft.

Avoiding heat illness

The WPS requires employers to take any necessary steps to prevent heat illness (too much heat stress) while personal protective equipment is being worn. The special clothing and equipment worn for protection from exposure to pesticides can restrict the evaporation of sweat. In addition, pesticides are absorbed through hot, sweaty skin more quickly than through cool skin. The many precautions against heat illness that employers should take are summarized in section 14.2.3.

14.2.3 Heat stress

High air temperatures and humidities put agricultural workers at special risk of heat illness (CAL OSHA, 2006; US OSHA, 2006). In the US, worker compensation claims for heat illness among agricultural workers are among the highest of any occupation. Pesticide handlers and early entry workers are at even greater risk. As stress from heat becomes more severe, there can be a rapid rise in body temperature and heart rate. Mental performance can be affected with an increase in body temperature of 2 °F (1.1 °C) above normal. An increase of 5 °F (2.8 °C) can result in serious illness or death. EPA/OSHA's *A Guide to Heat Stress in Agriculture* (US OSHA/EPA, 1993) offers practical, step-by-step guidance for non-technical managers on how to set up and operate a heat stress control program. The worker needs to be trained, the workload needs to be reduced, shade needs to be available as well as plenty of water (US OSHA, 2002 and 2006; California 2006).

As discussed above, the WPS also has requirements to prevent heat illness. Some of the requirements to prevent heat illness are:

- Training. Train workers and supervisors how to control heat stress and how to recognize symptoms of heat illness.
- Monitoring and adjusting workloads. Take into account the weather, workload, and condition of the workers, and adjust work practices accordingly. Higher temperatures, high humidity, direct sun, heavy

workloads, older workers, and workers unaccustomed to heat are more likely to become ill from heat. Things to do:
  - monitor temperature, humidity, and workers' responses at least hourly in hot environments;
  - schedule heavy work and PPE-related tasks for the cooler hours of the day;
  - acclimatize workers gradually to hot temperatures;
  - shorten the length of work periods and increase the length of rest periods;
  - give workers shade or cooling during breaks; and
  - halt work altogether under extreme conditions.
- Drinking. Make sure employees drink at least the minimum required amounts of water to replace body fluid lost through sweating. Thirst does not give a good indication of how much water a person needs to drink.

14.3 Harvesting and ginning

14.3.1 Harvesting

About 75% of world cotton production is hand picked and 25% is harvested by machines. Hand harvesting can be a source of ergonomic problems. There should be work practices in place that helps prevent such wrist and back injuries. If the cotton is mechanically harvested, the US OSHA standard for the protection of employees from the hazards associated with moving machinery parts of farm field equipment and farmstead equipment (29 CFR 1928.57) or similar practices should be followed. Proper machine guarding and equipment maintenance according to manufacturers recommendations can help prevent accidents.

14.3.2 Ginning

Since cotton ginning is essentially a continuation of harvesting, it is considered to be an agricultural operation (Wakelyn *et al.*, 2005). The only standards that US OSHA can apply to agricultural operations are the agriculture standards in 29 CFR Part 1928 (US OSHA, 2002a) and the few general industry standards referenced in 29 CFR 1928.21. The general industry standards that apply to cotton gins include, the Hazard Communication Standard (29 CFR 1910.1200) and temporary labor camps (29 CFR 1910.142). Machine guarding of cotton gins is covered by 29 CFR 1928.57. OSHA's cotton dust standard at 29 CFR1910.1043(a)(2), specifically excludes cotton ginning from coverage. The dust in the cotton ginning workplace should be considered a 'nuisance' dust or 'particulate not otherwise regulated' (29 CFR 1910.1000) not as cotton dust. In some countries cotton dust regulations may apply to ginning and it is prudent health and safety practice to keep dust levels below 1 mg/m^3 respirable dust.

If hazards are found at cotton ginning operations that are not covered by specific regulations, there should be practices in place to address all hazards to workers. For example, standards for the control of hazardous energy ('lockout/tag out'; 29 CFR 1910.147), confined space (29 CFR 1910.146), and noise (29 CFR 1910.95) do not specifically apply to cotton gins in the US. However, the gin workplace should be monitored and, if there is risk of these hazards, consideration should be given to voluntarily complying with these regulations in efforts to keep a safe and healthful workplace.

Machine guarding for cotton gins

Machine guarding (29 CFR 1928.57) is the only US agriculture standard specifically for cotton gins. At the time of initial assignment and at least annually thereafter, the employer should instruct every employee in the safe operation and servicing of all covered equipment at the gin with which he is or will be involved, including at least the following safe operating practices:

1. Keep all guards in place when the machine is in operation.
2. Stop the engine, disconnect the power source, and wait for all machine movement to stop before servicing, adjusting, cleaning, or unclogging the equipment, except where the machine must be running to be properly serviced or maintained, in which case the employer shall instruct employees as to all steps and procedures which are necessary to safely service or maintain the equipment.
3. Make sure everyone is clear of machinery before starting the engine, engaging power, or operating the machine.
4. Lock out electrical power before performing maintenance or service on farmstead equipment.
5. Where guards are used to provide the protection required, they shall be designed and located to protect against inadvertent contact with the hazard being guarded.

14.4 Yarn and fabric manufacturing

The health and safety concerns for the processing of cotton into yarn and fabric are similar to those for the textile processing of most staple fibers (Wakelyn, 1997). Accidents can occur on all types of cotton textile machinery, though the frequency rate is low. Effective guarding and training of operators is important as is described below (section 14.4.1). Noise can also be a problem, particularly in older textile mills (section 14.4.2). Since spinning sometimes requires high temperatures and high humidification of air, heat stress can also be a problem for textile workers. Well designed and maintained air-conditioned plants are replacing the primitive methods of trying to control temperature and humidity, In addition, the worker needs to be trained, the workload needs to be reduced, shade needs to be available as well as plenty of water, as was discussed in section 14.2.3. Cotton dust can be a major health and safety concern in yarn manufacturing of cotton (see section 14.4.3).

14.4.1 Machinery guarding

Effective guarding of the moving parts presents problems and need constant attention. Training of operators in safe practices is essential and efforts need to prevent repairs to machinery while it is in motion. The facility should identify energy sources, provide necessary equipment and train personnel to ensure that all hazardous energy sources are turned off while working on equipment. Inspections should be performed on a regular basis to ensure that all lockout/tagout procedures are followed and that workers do not remove machine guards while equipment is operating. The US OSHA standard for textile safety, 29 CFR 1910.262, applies to the design, installation, processes, operation, and maintenance of textile machinery, equipment, and other plant facilities in all plants engaged in the manufacture and processing of textiles, except those processes used exclusively in the manufacture of synthetic fibers. Other standards covering issues of occupational safety and health, which are of general application, are incorporated by reference in this rule. General safety requirements are in 29 CFR 1910.262 (c), including means of stopping machines, machine guarding, housekeeping, identification of physical hazards. 1910.262 (d) addresses openers; 1910.262 (e) cotton cards; 1910.262 (h) slashers (where size is applied); and 1910.262 (j) drawing frames, roving, combers, spinning, and twisters.

14.4.2 Noise

Noise can be a problem in some yarn and fabric manufacturing operations, particularly in older yarn manufacturing operations and in weaving operations that do not use shuttleless looms. In most modern textile operations the noise levels are below 90 dBA, the US standard (29 CFR 1910.95), and most likely below 85 dBA, which is when hearing conservation programs are required in the US and the noise standard in many countries. The US hearing conservation program (29 CFR 1910.95b), required when noise levels exceed 85 dBA, includes noise-level monitoring, audiometric testing and making hearing protection available to all employees when noise levels cannot be engineered below 90 dBA. The abatement efforts of machinery manufacturers and industrial noise engineers are continuing to decrease noise levels as machinery speeds increase. The main solution for high noise levels is the use of more modern, quieter equipment.

14.4.3 Inhalation/respiratory disease (cotton dust)

Inhalation of cotton-related dust generated during the textile manufacturing operations, where cotton fiber is converted into yarn and fabric, has been shown to cause an occupational lung disease, byssinosis, in a small number of textile workers (The Task Force for Byssinosis Prevention, 1995; US OSHA, 1985; Schilling and Rylander, 1994). It usually takes 15 to 20 years of exposure to higher levels of dust (above 0.5 to 1.0 mg/m^3) for workers to become reactors.

Cotton dust is an airborne particulate matter released into the atmosphere as cotton is handled or processed in textile processing. It is a heterogeneous, complex mixture of botanical trash, soil, and microbiological material (i.e., bacteria and fungi), which varies in composition and biological activity (Wakelyn *et al.*, 1976). The etiological agent and pathogenesis of byssinosis are not known (The Task Force for Byssinosis Prevention, 1995; Nichols, 1991; Pickering, 1991; Rohrbach, 1991). Cotton plant trash associated with the fiber and the endotoxin from gram-negative bacteria on the fiber, plant trash, and soil are thought to be the causative or to contain the causative associated with worker reaction to dust. The cotton fiber itself, which is mainly cellulose, is not the causative, since cellulose is an inert dust that does not cause respiratory disease (Jacobs and Wakelyn, 1998). In fact, cellulose powder has been used as an inert control dust in human exposure studies.

The US OSHA regulations for cotton dust apply to textile processing and weaving but do not apply to handling or processing of woven or knitted materials, harvesting, ginning, warehousing, classing/merchandizing, or knitting operations. OSHA permissible exposure limits (PEL) for cotton dust measured as an eight-hour time-weighted average with the vertical elutriator cotton dust sampler are (US OSHA, 1985, 2006a):

1. yarn manufacturing, 200 μg/m^3
2. textile mill waste house, 500 μg/m^3
3. slashing and weaving, 750 μg/m^3
4. waste processing (waste recycling and garneting), 1000 μg/m^3.

The US OSHA cotton dust standard requires that these PELs be complied with using engineering controls and work practices. There are also requirements for monitoring, medical surveillance, and information and training for workers. Washed cotton may also be used to comply with the cotton dust standard. A mild water washing of cotton, by batch kier washing systems (The Task Force for Byssinosis Prevention, 1995; Perkins and Olenchock, 1995) and continuous batt systems (Wakelyn *et al.*, 1986; US OSHA, 1985), reduces the residual level of endotoxin in both lint and airborne dust to below levels associated with a zero percentage change in acute reduction in pulmonary function as measured by forced expiratory volume in one second (FEV_1) (The Task Force for Byssinosis Prevention, 1995).

Levels of endotoxin from Gram-negative bacteria generated during the processing of cotton are associated with the occupational respiratory disease that affects some textile workers (Glindmeyer *et al.*, 1991, 1994; Castellan, *et al.*, 1987; The Task Force for Byssinosis Prevention, 1995). Washed cotton is determined by levels of potassium and water-soluble reducing substances (WSRS) in the washed lint (Perkins and Olenchock, 1995). OSHA has accepted several mild washing systems as qualifying as 'washed cotton' exemptions under the cotton dust standard (US OSHA, 1985, 2000):

1. Mild washing by the *continuous batt system or a rayon rinse system* is with water containing a wetting agent, at not less than 60 °C, with water-to-fiber ratio of no less than 40:1, with bacterial levels in the wash water controlled to limit bacterial contamination of the cotton.
2. The *batch kier washing system* is with water containing a wetting agent, with a minimum of one wash cycle followed by two rinse cycles for each batch, using fresh water in each cycle, and with bacterial levels in the wash water controlled to limit bacterial contamination of the cotton.
   a. For *low* temperature, at not less than 60 °C, with water-to-fiber ratio of no less than 40:1, or
   b. For *high* temperature, at not less than 93 °C, with a water-to-fiber ratio of no less than 15:1.

Control studies in experimental cardrooms and a longitudinal study of a large multi-mill population of workers processing cotton and synthetic fibers suggest that, in today's world, appropriate engineering controls in cotton textile processing areas, along with work practices, medical surveillance, and personal protective equipment for the most part can eliminate incidence of workers' reaction to cotton dust (Glindmeyer, 1991, 1994; The Task Force for Byssinosis Prevention, 1995). In US textile mills today, workers are not getting respiratory disease due to exposure to cotton-related dust. This should be true in all textile mills where dust exposures are controlled and workers are medically monitored.

14.5 Wet processing (preparation, dyeing, and finishing)

Prior to dyeing, printing and finishing, cotton fibers, yarns, and fabrics require pretreatments (referred to as 'preparation') to remove natural and other impurities (Cotton Incorporated, 1996). The common preparation processes for cotton include singeing, desizing, scouring, bleaching, and mercerization. Cotton is dyeable in fiber form (raw stock), yarn, or fabric form with an extensive number of dye classes, including, azoic, direct, indigo, pigment, reactive, sulfur, and vat dyes. The selection of the appropriate dyes and dyeing processes for cotton is based on numerous factors depending on the application for which the dyed cotton fibers are to be used. Cotton finishing operations include durable press/easy care, flame retardancy, soil release, water repellency and stain-resistance.

Many chemicals and processes are used in the preparation, dyeing and finishing of cotton. Workers can be exposed to formaldehyde and other finishing chemicals such as flame retardants and strain-resistant/water repellent finishes that can be of concern.

The safety standards for textile machinery also apply to preparation, dyeing and finishing operations: 29 CFR 1910.262 (p) covers bleaching equipment for cotton; (s) mercerizing ranges; (u)-(v) dyeing; (dd) printing; (oo) handling caustic soda and potash; and (rr) workroom ventilation for all workrooms in which potentially toxic chemicals are used.

14.5.1 Potential dye hazards

Dyes exist as powders, liquids, pastes, granules, pellets tablets, and other forms. They all are a potential source of exposure to the worker that handles them. Some dyes pose a significant risk to health while others do not. All dyes can be used safely as long as exposures are adequately controlled. Work practices are one of the biggest factors determining exposure to dyes in the workplace.

Powdered dyes can be an inhalation and sensitization problem and some dyes have been removed from use because of their potential to cause chronic health effects (US National Institute of Occupational Safety and Health (NIOSH), 1997; UK Health and Safety Executive (HSE), 2005; Imada, 2005). To prevent some of the problems with powdered dyes, most dyes today are sold as a paste (already partially solublized) and work practices.

Control of dust from dye handling operations

The manual transfer of powder dyes from bulk containers to smaller process containers generates significant amounts of dust. Worker exposure to dye dust through breathing or skin contact can result in adverse health effects such as occupational asthma, eczema, and severe allergic reactions. In addition, benzidine, benzidine congener (o-tolidine and o-dianisidine) and some other azo dyes, which by reductive cleavage of one or more azo groups may release one or more aromatic amines, are recognized as potential occupational carcinogens because of their carcinogenic amine breakdown products (see

Table 14.1 and discussion below). Therefore, dye exposures should be limited to the lowest feasible concentrations to prevent these health problems.

Workers in powder dye handling operations should be protected from dust exposure with the following combination of controls: hazard information, adequate ventilation, redesigned bulk containers, and appropriate work practices (US National Institute of Occupational Safety and Health (NIOSH), 1997; UK HSE, 2005; The Ecological and Toxicological Association of Dyes and Organic Pigments Manufacturers (ETAD), 1997).

- Know the hazard: find out what happens if you get the dye on your skin or in your eyes; if you breath in dye dust, vapors, or mist; if you swallow the dye; and the acute and chronic health effects from exposure to the dye. Read the material safety data sheet.
- Ventilation: semi-downdraft ventilation booths are recommended for use during the manual transfer of dyes.
- Work practices: workers should use slow, smooth movements when handling dye to keep dust concentrations low. Dye transport distances between the bulk and process containers should be kept to a minimum. The height at which the dye is dropped into a container should also be kept to a minimum. Workers should avoid skin contact with the dyes by using protective clothing such as gloves, long-sleeved shirts, and aprons.

Reactive dyes

Reactive dyes have a high degree of water solubility and chemically bond to cotton. Fiber reactive dyes are brighter, longer-lasting, and easier-to-use than other cotton dyes and are extensively used in women's and other apparel. If they are ingested or inhaled they can react within the body (UK HSE, 2005a). Sometimes this can affect the body's immune system causing the person to be sensitized to that dye. Sensitization may mean that that the next time a person is exposed to the same dye, their body could react dramatically, even if the amount is very small. Reactive dyes can be respiratory and/or skin sensitizers, however skin sensitization is rare.

Sensitization is unpredictable. Some may become sensitized, others may suffer no adverse effects. There is no validated test procedure for assessing the propensity of an individual reactive dye to cause respiratory sensitization. Thus, it is prudent to handle all reactive dyes as if they are respiratory sensitizers. All practicable steps should be taken to reduce exposure of employee to reactive dyes, thereby reducing the risk of someone becoming sensitized. If someone does become sensitized, take steps to prevent their symptoms from becoming worse by avoiding any contact with that dye. The health hazard from reactive dyes is only a concern before the application to the fabric – there is no known risk to anyone handling or wearing the dyed materials.

Table 14.1 List of carcinogenic amines produced by decomposition of azo dyes

MAK III	Chemical name	CAS no.	German & EU regulations	OEKOTEX	Japan EcoMark
Category 1	4-Aminobiphenyl	92-67-1	*	*	*
	Benzidine	92-87-5	*	*	*
	4-Chloro-o-toluidine	95-69-2	*	*	*
	2-naphthylamine	92-59-8	*	*	*
Category 2	o-Amnoazotoluene	97-56-3	*	*	*
	2-Amino4-nitrotoluene	99-55-8	*	*	*
	p-Chloroaniline	106-47-8	*	*	*
	2,4-Diaminoanisole	615-05-4	*	*	*
	4,4′-Diaminobiphenylmethane	101-77-9	*	*	*
	3,3′ Dichlorobenzidine	91-94-1	*	*	*
	3,3′-Dimethoxybenzidine	119-90-4	*	*	*
	3,3′-Dimethylbenzidine	119-93-7	*	*	*
	3,3′-Dimethyl-4,4″ diaminobiphenylmenthane	838-88-0	*	*	*
	p-Cresidine	120-71-8	*	*	*
	4,4′-Methylene-bis-(2-chloroaniline)	101-14-4	*	*	*
	4,4′-Oxydianiline	101-80-4	*	*	*
	4,4′-Thiodianiline	139-65-1	*	*	*
	o-Toluidine	95-53-4	*	*	*
	2,4-Toluyendiamine	95-80-7	*	*	*
	2,4,5-Trimethylaniline	137-17-7	*	*	*
	o-Anisidine	90-04-0	*	*	*
	p-Aminoazobenzene	60-90-3	*	*	*
	2,4-Xylidine	95-68-1	-	*	*
	2,6-Xylidine	87-62-7	-	*	*

* indicates that the amine is subject to the indicated regulations.

Benzidine and benzidine congener azo dyes

Many of the direct dyes that used to be used on cotton are benzidine-based dyes. US OSHA, US NIOSH and other groups in the world have extensively reviewed the literature on benzidine-based dyes (US NIOSH, 1978, 1980, and 1980a). Available studies indicate that some benzidine-based dyes cause cancer in experimental animals because they are converted in animals and humans to benzidine. Benzidine-based dyes may contain residual amounts of benzidine as well as other substances such as 4-aminobiphenyl that are considered to be human and animal carcinogens. There is evidence from animal studies that o-tolidine, o-dianisidine, and dyes based on o-tolidine are carcinogenic and that dyes based on o-tolidine and o-dianisidine, except for metalized dyes based on o-dianisidine, may be metabolically converted to the parent compounds. Dyes manufactured from o-dianisidine and o-tolidine may also contain residual amounts of the respective parent compounds.

From the accumulated evidence, US OSHA and US NIOSH conclude that benzidine-based dyes are potential human carcinogens. In a Special Hazard Review, US NIOSH recommended that the commercial use of benzidine-based and benzidine congener dyes be discontinued and appropriate substitutes be utilized. US OSHA also concluded that exposure of workers to the dyes should be reduced to the lowest feasible levels. The use of dyes derived from benzidine, o-tolidine, and o-dianisidine has been discontinued in the USA and the EU but could still be used in some developing countries.

Other azo dyes

Azo dyes make up 60–70% of all dyes used and are the most important chemical class of dyes. Many of the dyes used on cotton are azo dyes (e.g., fiber reactive, direct, azoic). Some azo dyes, if absorbed by the human body, can undergo reduction decomposition to form carcinogenic amines due to enzymes in the body that have reduction properties. Currently this includes the 24 amines classified as substances known to be human carcinogens (Group III A 1 of the German MAK III list) and substances that are animal carcinogens, i.e., potential human carcinogens (Group III A 2) that are shown in Table 14.1. (The number of amines varies according to the different regulations because the regulations were drawn up at different times. When regulations are revised in the future, they will presumably cover all 24 amines.)

Azo dyes that produce carcinogenic amines due to reduction decomposition are subject to regulations in the European Union, the German government, through the German Goods Ordinance (ETAD, 1998), and the Oeko-Tex Standard 100 (Austrian and German eco-label association; see Oeko-Tex Association, 2006 and Oeko-Tex Initiative, 2006) and Japan Eco-label (Imada, 2005). Not all azo dyes that are made using the amines listed in Table 14.1

as a raw material are regulated/banned, only the azo dyes that can break down producing these amines. Only about 5% of azo dye structures are affected by these regulations and they are largely already phased out for textiles in the EU and US. A dyeing facility should get verification from the supplier or dyes manufacturer that the dyes they use are not subject to the EU and German restrictions (EC, 2002). Testing to verify that a dye is not subject to regulation involves conducting reduction degradation tests with extracts of the dye and analyzing the amines that are produced. It is important to note that different dyes with the same color index number can produce different results due to differences in the purity of the raw materials and in their impurities.

14.5.2 Skin irritation/dermatitis

Handling or processing conventional US cotton does not cause skin irritation/dermatitis. Cellulose is essentially an inert substance and nothing on the fiber surface is known that could cause dermatitis problems. However, it is remotely possible that some very atypical cottons that have been treated with substances that are not approved for use or that are off-grade and perhaps are highly microbiologically damaged might cause skin irritation. These rare atypical cottons should be evaluated on a case-by-case basis, if they are to be used in a conventional way. The processes for preparation of cotton for dyeing and finishing should remove anything that could cause skin irritation.

Some dyes used to color textiles are allergic contact dermatitis (ACD) allergens (Hatch *et al.*, 2003). Hatch *et al.* (2003) showed by positive patch-test results that patients can have colored clothing ACD. They recommend that the term ‘textile-dye ACD’ be used to name cases of ACD in which the patient’s skin eruption is due to direct contact with dye molecules and the term ‘colored-textile ACD’ for cases in which the patient’s skin eruption was due to transfer of dye from a textile to the skin.

14.5.3 Formaldehyde

Formaldehyde is a component of some finishes used on cotton (e.g., formaldehyde and formaldehyde containing resins are used to impart easy care/durable press properties to cotton fabrics; the precondensate-ammonia flame retardants). Dyeing and finishing operations potentially can expose workers to formaldehyde in concentrations that exceed workplace exposure limits, if proper control procedures are not followed, since it can be released to the workplace during finishing operations and from some dyed and finished cotton fabrics.

It was classified in 1987 by the US EPA as a 'probable human carcinogen' (an animal carcinogen and limited evidence that it is a carcinogen in humans) under conditions of unusually high or prolonged exposure (US EPA, 1987). Since that time studies of industrial workers have suggested that formaldehyde is associated with nasopharyngeal cancer and possibly leukemia. In June 2004, the International Agency for Research on Cancer (IARC) reclassified formaldehyde as a known human carcinogen for nasopharyngeal cancer (IARC, 2004, 2004a; Anonymous, 2004). Non-cancer effects of exposure to low airborne concentrations of formaldehyde are sensory irritation of the mucous membranes of the eyes and the respiratory tract, and cellular changes in the nasal cavity (US EPA, 1987, 1991; IARC, 2004, 2004a).

The US OSHA workplace permissible exposure limit (PEL) for formaldehyde (29 CFR 1910.1048) is 0.75 ppm of air as an eight-hour time-weighted average concentration and 2 ppm of air as a 15-minute short-term exposure limit (STEL) (US OSHA, 2006b). These limits have to be met with engineering controls and work practices; there are also requirements for monitoring, medical surveillance, and information and training for workers. The ACGIH threshold limit value (TLV) for formaldehyde is 0.3 ppm short term exposure limit (STEL/ceiling) (ACGIH, 2006).

Exposure to formaldehyde from cotton textiles is controlled (i.e., reduced to an insignificant level) by the chemical technology low emitting formaldehyde resin technology and formaldehyde-free wrinkle resistance finishes (Welch, 1990, 2000; Welch and Andrews, 1989) and by increased ventilation. It should be noted that in the 1980s, the US Consumer Product Safety Commission (US CPSC) studied the effects of various dyeing and finishing treatments, including durable-press finishing of cotton (US CPSC, 1984), and found no acute or chronic health problems of concern to consumers due to exposures to formaldehyde or other finishing chemicals from textiles (Robbins, *et al.*, 1984; Robbins and Norred, 1984).

14.5.4 Brominated flame retardants

The flame retardants of most concern are polybrominated diphenyl ethers (PBDE). Penta-BDE and octa-BDE are banned in Europe and some states in the US. Deca-BDE, which is used along with antimony oxide to backcoat fabrics to meet the British flammability standard for upholstered furniture (BS 5852), has been thoroughly reviewed and is not considered toxic, although Denmark and some other EU countries want it banned also. Hexabromocyclododecane (HBCD), used to backcoat upholstery fabric, is also under review in the EU. Antimony oxide, which is usually used with brominated flame retardants to convey flame resistance is being reviewed in the EU.

14.5.5 Perfluorinated chemicals

The degradation/breakdown of short-chain fluorinated alcohols (mixed short-chained perfluorinated telomers), used as finishes to make textiles resistant to water, stains, and grease, are thought to be sources in the environment of perfluorooctanoic acid (PFOA). PFOA is persistent in the environment, it has been detected in low levels in wildlife and humans, and animal studies conducted have indicated effects of concern. PFOA is under consideration in the US to be classified as a 'likely' human carcinogen (Schultz and Dodd, 2005; Ritter, 2004). Eight US companies that make or use PFOA and related chemicals were asked by the US EPA (Jan. 25, 2006) to voluntarily (voluntary initiative is the '2010/2015 PFOA Stewardship Program'; http://www.epa.gov/opptintr/pfoa/pfoastewardship.htm) reduce releases of those chemicals and to limit the amount of PFOA in products by 95% by 2010 and to work toward eliminating exposure to PFOA from other chemicals by no later than 2015.

Perfluorooctyl sulfonate (PFOS), which was used in the 3M Scotchgard stain-resistant finish, and related compounds were voluntarily phased out of use in the US May 2000 (effective the end of 2002) following negotiations between US EPA and 3M, because data showed it to be persistent, bioaccumulative, and toxic (Ritter, 2004). In 2002 the Organization for Economic Cooperation and Development (OECD) found exposure to PFOS causes liver damage and death in laboratory animals (OECD, 2002). 3M has found substitutes for the specific PFOS chemicals of concern that were used in a wide range of their products. These are smaller telomers that are not sulfonates. PFOS also is being considered for restricted use in the UK (UK Defra, 2005). Most companies no longer use these fluorinated chemicals for fear of liability. Most, if they use fluorinated chemicals, use ones that are not potential sources of PFOA or PFOS.

14.5.6 Solvents

Millions of workers are exposed to solvents on a daily basis. Health hazards associated with solvent exposure include toxicity to the nervous system, reproductive damage, liver and kidney damage, respiratory impairment, cancer, and dermatitis. Solvents share many chemical, physical, and biological properties that warrant attention be directed to them as a group. In addition, many solvent groups or individual substances have special properties requiring more specialized control measures. US OSHA standards for permissible exposure limits (PELs) (see below) and the hazard communication standard (HCS) (see section 14.5.5) would apply. Work practices and engineering controls to limit exposures below the PEL (29 CFR 1910.1000) and material safety data sheets (MSDSs) are required.

14.5.7 Air contaminants

The air contaminants standards (29 CFR 1910.1000) are intended to reduce the risk of occupational illness for workers by reducing permissible exposure limits (PEL) for chemicals. PELs are eight-hour time-weighted average (TWA) exposures. To achieve compliance with the PEL, administrative or engineering controls must first be determined and implemented, whenever feasible. When such controls are not feasible to achieve full compliance, personal protective equipment, work practices, or any other protective measures are to be used to keep employee exposure below the PEL. ACGIH has TLVs for hazardous substances (ACGIH, 2006) as does HSE in the UK and ISO, the EU, and most countries in the world. In the case of a mixture of contaminants, an employer has to compute the equivalent exposure when the components in the mixture pose a toxic effect on the same target organ to a worker's health.

14.5.8 Hazard communication

The Hazard Communication Standard HCS (29 CFR 1910.1200) requires all employers to provide information to their employees on the hazardous chemicals to which they are exposed through written hazard communication programs, labels and other forms of warning, material safety data sheets (MSDS), training programs, and recordkeeping. A substance is a 'hazardous chemical' if it is a 'physical hazard' or a 'health hazard' (29 CFR 1910.1200 (c)). A flammable or explosive liquid is a 'physical hazard'. A flammable liquid means 'any liquid having a flashpoint below 110 °F (37.8 °C), except any mixture having components with flashpoints of 100 °F (37.8 °C) or higher, the total of which make up 99% or more of the total volume of the mixture'. 'Health hazard' means 'a chemical for which there is statistically significant evidence based on at least one valid study that acute or chronic health effects may occur in exposed employees'.

Chemical manufacturers and importers are required to review the available scientific evidence concerning the hazards of chemicals they produce or import, and to report the information to manufacturing employers who use their products (29 CFR 1910.1200(b)). If a chemical mixture has not been tested as a whole to determine whether the mixture is a hazardous chemical, the mixture is assumed to present the same hazards as do the components that comprise 1% or greater of the mixture or a carcinogenic hazard if it contains a component in concentration of 0.1% or greater that is a carcinogen (29 CFR 1910.1200(a)(5)).

The globally harmonized system (GHS) of classification and labeling of hazardous chemicals was adopted by the United Nations in 2003. The goal of the GHS is to promote common, consistent criteria for classifying chemicals according to their health, physical and environmental hazards, and to develop compatible labeling, material safety data sheets for workers, and other information based on the resulting classifications.

Countries are now considering adoption of the GHS into their national regulatory systems. The goal is to have as many countries as possible implement the GHS by 2008. This involves changing the criteria for classifying health and physical hazards, adopting standardized labeling requirements, and requiring a standardized order of information for MSDS. A harmonized system would lead to greater consistency among countries and thereby promote safer transportation, handling and use of chemicals. Harmonized criteria, symbols and warnings will promote improved understanding of hazards and thus help to protect workers and other potentially exposed populations. A more uniform, 'harmonized' system should also reduce costs for companies involved in international trade.

14.6 Consumers

By the time cotton textiles reach the ultimate consumer, there should be nothing known of or extractable from the original cotton fiber that would cause any health concerns to consumers (Wakelyn, 1994). However, various dyeing and finishing treatments that cotton fabrics go through can leave residues on the fabric or release substances that could cause irritation to consumers, if the treatments are not properly applied.

14.7 Future trends

In cotton production there most likely will continue to be more emphasis on environmental stewardship and less use of crop protection products. The products used will be less persistent and less toxic to non-target species. In dyeing and finishing there will be stricter requirements for chemicals used. Also preparation, dyeing, and finishing processes will use less energy and water. The image of cotton production and processing should be greatly improved and workers in cotton industry segments will be safer. We are already seeing this with agricultural workers in areas where biotech cottons are being grown.

14.8 References

American Conference of Industrial Hygienists (ACGIH) (2006), TLVs and BEIs.

Anonymous (2004), 'Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxy-2-propanol', *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, Vol. 88, 2–9 June 2004, http://www-cie.iarc.fr/htdocs/announcements/vol88.htm.

Australian Cotton Industry (2006), Best Management Practices Manual (see http://www.cottonaustralia.com.au/bmpindex.html and http://www.crdc.com.au)

Batie SS and Healy RG eds (1980), *The Future of American Agriculture as a Strategic Resource*, Washington DC, The Conservation Foundation.

Batie SS and Healy RG (1983), 'The Future of American Agriculture', *Scientific American*, 248(2): 45–53.

California Occupational Safety and Health Standards Board (CAL OSHA)(2006), Heat illness prevention, effective 27 July 2006, General Industry Safety Order, Chapter 4, Subchapter 7, Article 10, New Section 3395 (http://www.dir.ca.gov/oshsb/heatillnessemergencytextbrdconsider.pdf).

Castellan RM, Olenchock SA, Kingsley KB and Hankinson JL (1987), 'Inhaled endotoxin and decreased spirometric values: an exposure-response relationship for cotton dust', *New England J. of Medicine*, 317, 605–610.

Chaudhry R (2004), 'The Australian Best Management Practices Program', *ICAC Recorder*, Vol. XXII, No. 1 March 2004, pp 14–17.

Cotton Incorporated (1996), *Cotton Dyeing and Finishing: Technical Guide*, Cotton Incorporated, Cary, NC, 1996.

Ecological and Toxicological Association of Dyes and Organic Pigments Manufacturers (ETAD) (1997), *Handling Dyes Safely*.

Ecological and Toxicological Association of Dyes and Organic Pigments Manufacturers (ETAD) (1998), Information Notice No. 6, German ban of use of certain azo compounds in some consumer goods (http://www.etad.com/information/information 6.html).

EC (2002), EU Directive 2002/61/EC of the European Parliament and of the Council of 19 July 2002, 'amending for the 19th time Council Directive 78/769/EEC relating to restrictions on the marketing and use of certain dangerous substances and preparations (azocolourants) (2002), *Off J European Communities* 11.9, L243/15-L243/18.

Glindmeyer HW, Lefants JJ, Jones RN, Rando RJ, Abdel HM and Weill H (1991), 'Exposure-relationship declines in lung function of cotton textile workers: relationship to current workplace standards', *Am. Rev. Respir. Dis.*, 144, 675–683.

Glindmeyer HW, Lefants JJ, Jones RN, Rando RJ and Weill H (1994), 'Cotton dust and across-shift changes in FEV_1 as predictors of annual change in FEV_1', *Am. J. Respir. Care Med.*, 149, 584–590.

Hatch KL, Motschi H and Maibach HI (2003), 'Textile-dye and colored-textile allergic contact dermatitis', *Exog Dermatol* 2, 206–209.

IARC (2004a), 'Formaldehyde', 5. Summary of Data Reported and Evaluation (7 Sep 2004), http://www-cie.iarc.fr/htdocs/monographs/vol88/formal.html

Imada K (2005), 'Regulations concerning azo dyestuffs', http://textileinfo.com/en/tech/imada/sennryou/page05.html

International Agency for Research on Cancer (IARC) (2004), 'IARC Classifies Formaldehyde as Carcinogenic to Humans', Press Release No. 153, 15 June 2004 http://www.iarc.fr/ENG/Press_Releases/pr153a.html

International Organization for Standardization (ISO) ICS 65 Agriculture Standards (2006), http://webstore.ansi.org/ansidocstore/dept.asp?dept_id=440

International Organization for Standardization (ISO) ICS 59 Textile and Leather Technology (2006), http://webstore.ansi.org/ansidocstore/dept.asp?dept_id=420)

International Organization for Standardization (ISO 9000 (Quality Management) and ISO 14000 (Environmental Management) (2006), (http://www.iso.org/iso/en/iso9000-14000/understand/inbrief.html)

Jacobs RR and Wakelyn PJ (1998), 'Assessment of toxicology (respiratory risk) associated with airborne fibrous cotton-related dust', in *Proc. 1998 Beltwide Cotton Conf.*, National Cotton Council, Memphis, TN, pp. 213–220.

Martin PL and Olmstead AL (1985), 'The Agricultural Mechanization Controversy', *Science*, 227: 601–606.

Mutel CF and Donham KJ (1983), *Medical Practices in Rural Communities*. Springer-Verlag, New York, pp. 77–78.

National Cotton Council/Progressive Farmer (2004), *Be smart, be safe with farm chemicals*, http://www.cotton.org/tech/safety/wps/upload/Be-Smart-Be-Safe-with-Farm-Chemicals.pdf

National Cotton Council (2005), *Worker protection standard*, http://www.cotton.org/tech/safety/wps/index.cfm

Nichols PJ (1991), 'The search for the aetiological agent and pathogenic mechanisms of byssinosis: *in vivo* studies', in *Proc. of the 15th Cotton Dust Research Conference*, Jacobs RR, Wakelyn PJ and Domelsmith, LN, eds, National Cotton Council, Memphis, TN, pp. 307–320.

Organization for Economic Cooperation and Development (OECD) (2002), 'Hazard assessment of perflorooctane sulfonate (PFOS) and its salts', http://www.oecd.org/dataoecd/23/18/2382880.pdf

Oeko-Tex Association (2006), http://www.oeko-tex.com/en/main.html.

Oeko-Tex initiative (2006), International Association for Research and testing in the field of Textile Ecology. (Eco-Tex Standard 100).

Perkins Jr HH and Olenchock SA (1995), 'Washing cotton by batch processes to control dust and endotoxin', *Ann. Agric. Environ. Med.*, 2, 1.

Pickering CAC (1991), 'The search for the aetiological agent and pathogenic mechanisms of byssinosis: a clinician's view of byssinosis', in *Proc. of the 15th Cotton Dust Research Conference*, Jacobs RR, Wakelyn PJ, and Domelsmith LN, eds, National Cotton Council, Memphis, TN, pp. 298–299.

Ritter SK (2004), 'Polyfluorinated alcohols shown to be key source of bioaccumulating perfluorocarboxylic acids', *Chem & Eng News*, 82(24), 44–45.

Robbins JD and Norred WP (1984), 'Bioavailability in Rabbits of Formaldehyde from Durable Press Textiles', *Final Report on CPSC IAG 80-1397*, USDA Toxicology and Biological Constituents Research Unit, Athens, GA, 1984.

Robbins JD, Norred WP, Bathija A, and Ulsamer AG (1984), 'Bioavailability in rabbits of formaldehyde from durable press textiles', *J. Tox. Environ. Health*, 14, 453–463.

Rohrbach MS (1991), 'The search for the aetiological agent and pathogenic mechanisms of byssinosis: a review of *in vitro* studies', in *Proc. of the 15th Cotton Dust Research Conference*, Jacobs RR, Wakelyn PJ and Domelsmith LN, eds, National Cotton Council, Memphis, TN, pp. 300–306.

Schilling R and Rylander R (1994), 'Cotton dust', in *Organic Dusts, Exposure, Effects, and Prevention*, Rylander R and Jacobs RR, eds, CRC Press (Lewis Publishers), Boca Raton, FL, USA, pp. 177–191.

Schultz WG and Dodd JS (2005), 'PFOA called likely human carcinogen', *Chem & Eng News* 83(27), 5.

Slack-Smith P (2000), 'Managing environmental issues in cotton production: Australian Best Management Practices (BMP)', *Cotton – Global Challenges and the Future*, Papers presented at a Technical Seminar, 59th Plenary Meeting of the International Cotton Advisory Committee (ICAC), Cairns, Australia, Nov. 9, 2000, p. 12.

The Task Force for Byssinosis Prevention (1995), 'Washed cotton, a review and recommendations regarding batch kier washed cotton', *Current Intelligence Bulletin*, 56, US Department of Health and Human Service, NIOSH, Aug. 1995.

UK, Dept for Environment, Food, and Rural Affairs (Defra) (2005), 'Consultation on proposed national action to restrict the use of perfluorooctane sulphonate (PFOS) and substances that degrade to PFOS'. http://www.defra.gov.uk/corporate/consult/pfos/index.htm

UK Health and Safety Executive (HSE) (2005), *Dyestuffs: safe handling in textile finishing*, Dyeing and Finishing Information Sheet No. 3; *Dust control in dyestuff handling*, Dyeing and Finishing Information Sheet No. 6.

UK HSE (2005a), *Reactive dyes: Safe handling in textile finishing*, Dyeing and Finishing Information Sheet No. 5.

US Consumer Product Safety Commission (CPSC) (1984), *Status Report on Formaldehyde in Textiles Portion of Dyes and Finishes Project*, US Consumer Product Safety Commission, Washington, DC, Jan. 3, 1984.

US Environmental Protection Agency (EPA) (1987), 'Formaldehyde', Integrated Risk Information System (IRIS), http://www.epa.gov/iris/subst/0419.htm

US EPA (1991), *Formaldehyde risk-assessment update*, Office of Toxic Substances, US Environmental Protection Agency, Washington, DC, June 11, 1991.

US EPA (2006), Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), 7 US Code 136; Federal, Food, Drug and Cosmetic Act (FFDCA) (1996) as amended by the Food Quality Protection Act (FQPA).

US EPA (2006a), *Worker protection standard*, 40 Code of Federal Regulation Part 170 (http://www.epa.gov/oppfead1/safety/workers/amendmnt.htm).

US EPA (2006b), Pesticide Management and Disposal: Standards for Pesticide Containers and containment, Final Rule (40 CFR Parts 9, 156, 165), 71 Federal Register page 47329–47437, 16 August 2006.

US National Institute of Occupational Safety and Health (NIOSH) (1978), 'Direct Blue 6, Direct Black 38, and Direct Brown 95 Benzidine Derived Dyes', *NIOSH Current Intelligence Bulletin* No. 24 (1978, April 17).

US NIOSH (1980), *Benzidine-Based Dyes*, NIOSH criteria document, 80–109 (1980).

US NIOSH (1980a), *Health Hazard Alert: Benzidine-, o-Tolidine-, and o-Dianisidine-Based Dyes,* NIOSH Alert, 81-106 (1980, December).

US NIOSH (1997), 'Reduction of worker exposure to powdered dye through ventilation, work practice controls and limiting bulk container height', *NIOSH Hazard Controls*, HC13, Publication 97–107 (1997, June 26).

US OSHA (1985), 'Occupational exposure to cotton dust, Final Rule', *Federal Register*, 50, pp. 51120–51179, Dec. 13, 1985.

US OSHA (2000), 'Washed cotton, 29 CFR 1910.1043(n)'; Occupational exposure to cotton dust, Direct Final Rule', *Federal Register*, 65, pp. 76563–76567, Dec. 7, 2000.

US OSHA (2002), *Heat stress card*, OSHA Publication 3154, http://www.osha.gov/Publications/osha3154.pdf

US OSHA (2002a), 'Standards that apply to cotton gins, OSHA Standard Interpretation' http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=24189

US OSHA (2006), *Heat stress, Hazards and possible solutions*, http://www.osha.gov/SLTC/heatstress/recognition.html

US OSHA (2006a), 'Standard for Occupational Exposure to Cotton dust', US Code of Federal Regulations, 29 CFR 1910.1043, (a) Scope and application and (c) Permissible exposure limits and action levels.

US OSHA (2006b), 'Standard for Occupational Exposure to Formaldehyde', US Code of Federal Regulations, 29 CFR 1910.1048.

US OSHA and the US Environmental Protection Agency (EPA) (1993), *A Guide to Heat Stress in Agriculture*, http://are.berkeley.edu/heat/heat.stress.epa-98.guide.htm.

Wakelyn PJ (1994), 'Cotton: environmental concerns and product safety', in *Proc. 22nd Int. Cotton Conf., Bremen*, Harig H and Heap SA, eds, Faserinstitut Bremen e.V., Bremen, Germany, pp. 287–305.

Wakelyn PJ, (1997), 'Cotton Yarn Manufacturing', *ILO Encyclopaedia of Occupational Health and Safety*, 4th edn, Chapter 89, Textile Goods Industry, Ivester AL and Neefus JD, eds, International Labour Office. Geneva, Switzerland, pp 89.9–89.11.

Wakelyn PJ, Greenblatt GA, Brown DF and Tripp VW (1976), 'Chemical properties of cotton dust', *American Industrial Hygiene J.*, 37, 22–31.

Wakelyn PJ, Jacobs RR and Kirk IW, eds (1986), *Washed Cotton; Washing Techniques, Processing Characteristics and Health Studies*, United States Department of Agriculture. New Orleans, LA.

Wakelyn PJ, Thompson DW, Norman BM, Nevius CB and Findley DS (2005), 'Why Cotton Ginning is Considered Agriculture', *Cotton Gin and Oil Mill Press* 106(8), 5–9.

Welch CM (1990), 'Durable press finishing without formaldehyde', *Text. Chem. Color.*, 22(5), 13–16.

Welch CM (2000) 'Formaldehyde – free durable press finishing' in *Surface Characteristics of Fibers and Textiles*, Pastore DM and Kiekens P, eds, Marcel Dekker, Ind., New York, NY, 2000, chap. 1, pp. 1–32.

Welch CM and Andrews BA (1989), 'Ester crosslinks: a route to high performance nonformaldehyde finishing of cotton', *Text. Chem. Color.*, 21(2), 13–17.

15

Recycling of cotton

B J COLLIER, J R COLLIER, Florida State
University, USA, S PETROVAN, University of
Tennessee, USA and I I NEGULESCU,
Louisana State University

15.1 Introduction

Cotton recycling fits into the broader scope of materials recovery from solid waste generated by producers and consumers of a range of products. This chapter looks at the issues surrounding recycling and the research into specific recycling efforts involving cotton textile products. The stage is set by describing current methods for dealing with textiles in the solid waste stream. The pattern of recycling is then begun with a discussion of the sources of cotton fibers, followed by detailed descriptions of mechanical and chemical recycling processes. The latter involve dissolution of cotton fibers and other cellulosic materials in environmentally safer solvents than those traditionally used to produce regenerated cellulosic fibers. Future trends are discussed and further sources of information given.

15.2 Textile life cycle and waste treatment choices

Environmental imperatives have induced researchers, producers, and consumers to examine and pay attention to the life cycle of products from raw material to waste and disposal. This approach provides a framework for analyzing environmental issues and determining the role and economics of recycling as a method for reducing waste and environmentally disadvantageous disposal (Domina and Koch, 1997). It is understood in applying this approach that much of the environmental impact of a textile product is determined at the design stage by the materials and processes selected (Heely and Press, 1997).

Cotton, and indeed all textiles, require significant energy input for production and processing, and also for laundering and dry cleaning in the consumer's hands. Once an article is no longer serviceable, its ultimate fate is then considered. All these stages from raw material to final disposition are analyzed when a life cycle analysis is performed. The American Fiber Manufacturers Association conducted such an assessment for a polyester knit blouse that included energy requirements and emissions for each step from manufacture through consumer use, but did not consider environmental impacts of disposal (Smith and Barker, 1995). Cotton textiles would probably require more energy in processing and use, and there are additional environmental costs in growing cotton such as pesticides and fuel for large farm machinery. These costs can be balanced against the biodegradability of cotton in discarded items and possibilities for using cotton as a cellulose source for other products. As with all solid waste, there are three primary options for handling textile products no longer considered serviceable by the owner: reuse, disposal, and recycling.

15.2.1 Reuse

Governmental and private programs encourage the reuse of a number of consumer products, textiles among them. Textiles are in fact good candidates for reuse because there are so many options and outlets for clothing and household items. In addition, the US Environmental Protection Agency (EPA) considers that reusing products is even better than recycling because they do not require reprocessing into new or different items (US Environmental Protection Agency, 2005b).

Between 1990 and 2003, the US exported nearly 7 billion pounds of used clothing and worn textile products around the world (World Trade Atlas, 2005). Most of the recycling firms in developed countries are small, family-owned businesses (Rivoli, 2005). In the US the industry as a whole employs approximately 10,000 semi-skilled and marginally employable workers at the primary processing level, and creates an additional 7,000 jobs at the final processing stage. Primary and secondary processors account for annual gross sales of $400 million and $300 million respectively. Industry members are able to recycle 93% percent of the waste they process without producing any new hazardous waste or harmful by-products. Textile recyclers export 61% of their products, thus reducing the US trade deficit. Documented export sales of recycled clothing from the US exceeded $217 million in 1999 (US Census Bureau, 2005).

Worldwide, particularly in developed countries, there are many opportunities for donating or selling used textile products (Chang *et al.*, 1999). Second-hand stores offer sellers and buyers of used clothing and other textile items an exchange forum that keeps the items in the use channel and out of the waste stream. Thrift stores and consignment stores are also outlets for used textiles. Non-profit charitable organizations and churches in various countries accept donations of such items as well, either for domestic distribution or for needs around the world. These organizations and stores often however cannot use all of the donated items and give or sell them to rag makers, or look to materials recovery facilities (MRFs) for reprocessing and recycling (Platt, 1997). The used textile items thus become the starting materials in the recycling process.

Textile items that are reclaimed before disposal can be turned into useful, though low-value, products. All that is usually required is cleaning and cutting. Examples are rags cut from used cotton denim jeans (Denim, Reclaimed, 2005) and diapers retired from diaper services and sold as rags (100% Cotton Rags, 2005).

15.2.2 Disposal

Textile waste is generated by both producers and consumers. Scraps from fiber production, spinning and weaving, and apparel manufacturing, the post production waste, can be collected and recycled into a variety of products. The fiber content in these waste streams is known, making it simpler to target appropriate recycled products (Chang *et al.*, 1999). In addition, it is usually clean and requires less processing during recycling. Post-consumer waste, on the other hand, contains a mixture of fibers, and often dyes, finishes and other additives as well.

Textile waste is part of the solid waste stream that is dealt with in a variety of ways by local government entities throughout the world. In developed countries textiles account for about 4% of the municipal solid waste that must be dealt with in some fashion (Chang *et al.*, 1999; US Environmental Protection Agency, 2005b). The most common methods of solid waste disposal are landfilling and incineration. Recycling is a distant third, primarily because the economics of current recycling processes are not favorable. As the first two disposal methods become less environmentally attractive however, recycling and reuse, the non-disposal alternative described above, become attractive (Grasso, 1995).

Landfilling

Landfilling or burying, a traditional method of dealing with solid waste, while subject to environmental toxicity concerns, was generally considered sufficient for the volume of waste until the last century. Much of the waste placed in landfills was composed of natural materials, such as cotton, and was therefore considered biodegradable. With the advent of synthetic materials and the increase in consumption of both durable and non-durable goods, landfills are filling up, motivating a closer look at alternatives such as recycling. As reported by EPA, the number of US landfills decreased from 7,924 sites in 1988 to 1,767 in 2002, indicating the problem with this disposal method (US Environmental Protection Agency, 2005b).

The biodegradability of cotton makes landfilling an appropriate disposal method for cotton textiles. Problems arise when the fiber is blended with synthetics that are not so easily decomposed. In a study of cotton/polypropylene nonwovens, Warnock found that the cotton core of the composite webs disintegrated when buried in soil, but the polypropylene fibers were not affected after 16 weeks (Warnock and Ferguson, 1997). Landfilling is therefore not as attractive for general textile waste, which is often a mixture of fibers.

Incineration

An alternative to burying solid waste in landfills is incinerating it in large combustion facilities. This controlled burning process reduces the volume of waste and can capture the water generated to convert to steam for heating systems or to generate electricity (US Environmental Protection Agency, 2005b). The energy produced can in fact provide the fuel for the combustion process, decreasing the need for fossil fuels, and can also provide excess energy for other uses such as steam generation. An obvious disadvantage is the generation of carbon dioxide and any volatile pollutants produced by the burning.

15.3 Cotton sources

Primary cotton sources for recycling into current products are cotton rags and linters. Indeed, cotton rags and linters have been the main source of fibers for papermaking dating from the first century and remain today the best material for long lasting quality papers. These sources are high in alpha cellulose, which is the cellulose in the fiber that is not dissolved in 17.5% sodium hydroxide. The higher the alpha cellulose content in the fiber, the better quality and longer lasting the paper that can be manufactured. In addition these sources do not contain any lignin and only require a mild cooking process to clean them for the ultimate paper or other products.

15.3.1 Linters and gin waste

Cotton linters are very short fibers that adhere to the cottonseed even after ginning (Mauney, 1984). Unlike cotton fibers, linters only grow to 5 mm or less and have a thicker secondary wall at the seed surface, accounting for their resistance to removal during ginning. They can however be removed in a subsequent mechanical delinting processes. Typical yield for cottonseed is about 9% linters (Cherry and Leffler, 1984).

Before being converted into various products, linters are physically cleaned to remove seed hulls and other plant matter (Temming *et al*, 1973), and are then bleached. The physical and chemical cleaning produces linters with the appropriate physical and chemical properties for the targeted end use. A low viscosity, following from a reduced degree of polymerization, and the high purity of the cellulose from the cleaning are desirable properties for higher value products such as regenerated cellulose fibers and films. Clean fibers are also required for fine writing paper and filter paper. Uses for lower grade linters are padding and stuffing for mattresses, upholstery, and pillows (Collier and Tortora, 2000).

Short fibers are also collected as waste from cotton gins and yarn spinners. About 4% by weight of gin waste, which includes these short fibers as well as motes and trash, is generated for every bale of cotton fiber processed. With a worldwide production in 2004-2005 of 120 million bales (Collins, 2005), there is a significant amount of short fibers that are recovered and sold to plants making padding, batting, and other coarse nonwovens (Baker and Griffin, 1984). Such products are also made from short fibers combed from cotton slivers during the spinning process. These fibers, called noils, are collected by the spinner and resold.

15.3.2 Rags

Textile waste products that are all cotton have found use primarily in wiping cloths and rags. The absorbent nature of cotton is an advantage in such products. They can also be made into rag rugs, although most of these now use new rather than recycled fabric.

Most of the rags recycled into paper products are new cotton clippings which come from various textile mills and garment factories. They are collected by rag dealers and recycling organizations. The rags and cotton wastes are sorted and graded into over 140 different categories for reuse and recycling (Reading Textile Recycling Project, n.d.). The following grades are graded in the top category for rag papers: unbleached muslins, white shirt cuttings, bleached underwear cuttings, bleached flannel cuttings, bleached shoe cuttings, blue denims, and fancy shirt cuttings. White or unbleached new rags are better than colored ones because they require milder cooking and bleaching, resulting in minor thermochemical degradation and ultimately higher durability and permanence in the manufactured papers.

The quality and durability of paper made from rags are necessary properties for such specialty papers as:

1. banknotes and security papers
2. life insurance policies and legal documents where permanence is of primary importance
3. technical papers, such as tracing paper, vellums, intermediate, blue print and other reproduction papers
4. high-grade bond letterheads for concerns where appearance is of great importance
5. light-weight specialties, such as cigarette, carbon and bible papers
6. high-grade stationery paper, where beauty, softness, and fine texture are demanding.

The main steps from the cotton rags or wastes to the high-quality paper are: mechanical treatment to open the rags for easy dirt removal; removing of foreign matter; cutting for preventing roping in the boiler; dusting; removing of metallic items on magnetic rolls; chemical cooking and bleaching; beating; sizing; and finally paper formation. The cooking step is done using weak lime or caustic soda solutions to minimize chemical degradation of the alpha cellulose. Bleaching is also done at low chlorine concentrations (~ 0.05%) in the form of calcium or sodium hypochlorite. Sizing too should be done with a minimum amount of chemicals for the high-quality papers described above that are expected to last a long time. Chemicals and other additives should be kept at a minimum to prevent degradation of cellulose in time due to side reactions and consequently reducing paper permanence.

15.4 Mechanical reprocessing

Pre- and postconsumer waste is subjected to solely mechanical action to render the textiles into a near fibrous form that can then be processed into other, usually lower value, products.

15.4.1 Preparation

Sorting

Textile products that are recovered from the solid waste stream are usually sorted before being directed to reuse or recycling. Most recycling businesses prefer to sort the waste themselves to assure that the textiles are separated and graded by experienced workers capable of recognizing fiber contents and categories of materials for subsequent destinations (Textile Recycling Association, n.d.). A high percentage of textile products from this sorting step will be directed to reuse or to high-quality papers as described above. Other items will enter the recycling stream, based on fiber content and presence of dyes or finishes.

Shredding

A simple and often used mechanical process for recycling textile waste is shredding or tearing the item into very small pieces that can then be reformed into nonwovens or can be used as padding or stuffing (Fig. 15.1). The advantage of these end uses is that mixed fiber waste is acceptable because the primary function is a factor of bulk volume, not of specific fiber properties. In addition, the appearance of the products is not of primary importance because they are usually covered by other materials. Examples are car insulation, roofing felts, loudspeaker cones, panel lining, and furniture padding (Textile Recycling Association, n.d.).

15.1 Shredded textile waste.

Another area where shredding of cotton products has shown promise is reprocessing of denim fabric and garments. These are usually recognizable and can be separated fairly easily during sorting. A wide variety of recycled products are possible. Denim waste has even been made into pencils by combining with binders and reforming.

15.5 Chemical recycling

Chemical recycling involves use of separated generic fiber types as starting materials for entirely new products. The most commercially successful such process is the melting of polyester soda bottles to spin new polyester fibers. Although there is not an analogous example using cotton fibers, the area of chemical recycling of cotton has received much research attention in the last several years. There is significant potential for further work to balance the economics and develop viable recycling of cotton textiles into new regenerated cellulosic fibers or other products.

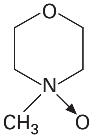
15.5.1 Lyocell

The traditional method for producing regenerated cellulose fibers is the viscose process in which the cellulose is reacted with carbon disulfide to form cellulose xanthate and then dissolved in caustic soda to form a viscous solution. This solution is spun into a coagulation bath containing sulfuric acid and mineral salt to regenerate the cellulose into viscose rayon. The process significantly reduces the degree of polymerization of the cellulose in order to dissolve it and, due to environmental considerations, is severely restricted in the US and other countries.

A more environmentally friendly process, developed in the 1980s, resulted in a new commercial fiber, lyocell. Lyocell fibers are made by dissolving cellulose directly in N-methylmorpholine N-oxide (NMMO) (Fig. 15.2). The lyocell solvent dissolves cellulose by intermolecular interaction only by the formation of hydrogen bond complexes (Johnson, 1969). The near monohydrate form (NMMO•H_2O) is used to produce Tencel® and Lyocell® fibers from blends of dissolving pulps of cellulose. In the commercial process the cellulose solution is spun into a water bath to regenerate cellulosic fibers. The lyocell solvent has essentially no vapor pressure, and therefore over 99% of the solvent can be recovered by filtering, dewatering, and evaporation. Favorable process economics are dependent upon the high solvent recovery rate.

The lyocell process was recognized by the United Nations for its environmentally benign impact since the solvent is biodegradable and lyocell production does not involve derivatization of the cellulose; any waste products are minimal and non-hazardous (Cole, 1992). Lyocell fibers are among the group of textiles that are publicized by the industry as environmentally improved textile products (EITP) (Moore *et al.*, 1999), and as such, production of these fibers from recycled cotton is a doubly advantageous approach.

Experimental work has been conducted to determine the applicability of the lyocell process for forming cellulosic fibers from cotton and cotton/polyester blend fabrics (Negulescu *et al.*, 1998). If all cotton fabrics are used, they are shredded and then dissolved in the lyocell solvent. For cotton/polyester blends the polyester was separated by alkaline hydrolysis to terephthalic acid by precipitation in an acidic environment after removing the cotton. The cotton was then dissolved in the lyocell solvent. Whether from cotton or cotton/polyester blends, the lyocell solution can be converted to either fibers or films by extrusion into water. The degree of polymerization (DP) of cotton may vary between 3,000 and 15,000 (Rydholm, 1965), whereas the typical dissolving pulp used for Tencel® and Lyocell®

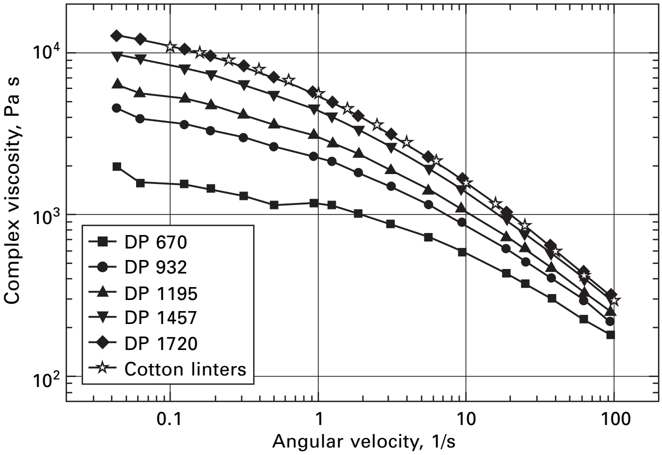


15.2 N-Methyl Morpholine N-Oxide.

fibers is less than 1,000. Therefore, recycled cotton cellulose could be blended with cellulose from other sources to prepare lyocell solutions with appropriate properties.

Cellulose from other sources such as cotton linters, as well as office wastes and agricultural residues could be blended with recovered cotton to form lyocell fibers. The behavior of lyocell solutions from these various sources has been studied and compared to solutions formed with commercial dissolving pulps (Dever *et al.*, 2003; Collier *et al.*, 2000). Cotton linters can be used to prepare lyocell solutions similar to those made with wood cellulose dissolving pulps. Due to the higher DP of cellulose from cotton linters, the viscosity is higher than that of dissolving pulp solutions (Fig. 15.3). Typically commercial lyocell solutions are prepared from dissolving pulps of different DPs. Recycled cotton therefore offers an additional source for blending with other materials to achieve the desired viscosity for spinning.

In addition to spinning fibers, solvent systems for cellulose from various sources were investigated for textiles and other products. Lyocell nonwoven webs have been made using the meltblowing process (Luo *et al.*, 2001) and work continues in this area. Wood pulp, rather than the purer dissolving pulp, was used, demonstrating the applicability of alternative cellulose sources for these processes. Solution viscosity is critical for nonwovens processing. Lyocell nonwoven webs have fibers equal to or smaller than those of cotton, making them superior to air laid or water laid nonwovens for some applications. Since these nonwovens are 100% cellulose they exhibit much higher absorbency than traditional melt processed nonwovens composed of synthetic polymers.



15.3 Complex viscosity of lyocell solutions prepared from cotton linters and wood dissolving pulps with different degrees of polymerization.

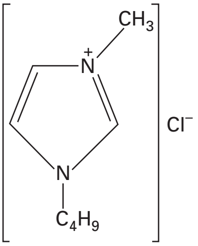
15.5.2 Ionic liquids

A relatively new class of solvents, ionic liquids, has become available and like the lyocell solvent, they have essentially no vapor pressure. The bulk of the work on ionic liquids has been reported in the last four years (Rogers, 2005). They are considered to be green solvents with regard to a lack of vapor formation, but their toxicity in aqueous environments is not yet determined (Seddon, 1997; Huddleston *et al.*, 2001). Some of the ionic liquids are water soluble and others are not.

The ionic liquid 1,3,-dibutylimidazolium chloride ([C_4mim]Cl) (Fig. 15.4) has been shown to be a good solvent for cellulose (Swatloski *et al.*, 2002). Other ionic liquids that also dissolve cellulose are similar [C_4mim] compounds with the chloride ion replaced by other strong hydrogen bond acceptors including Br, SCN, BF_4, or PF_6 (Swatloski *et al.*, 2002). Apparently the anion disrupts the intramolecular hydrogen-bonding of the cellulose hydroxyl groups thereby enabling the cellulose to be dissolved. The strong chloride activity enables dissolution of up to at least 25 wt% of cellulose and at a faster rate than traditional cellulose solvents.

Contacting the cellulose solution in [C_4mim]Cl with water, ethanol or acetone significantly reduces the cellulose concentration reportedly due to competition for hydrogen bonding with cellulose, causing separation of the cellulose and solvent (Swatloski *et al.*, 2002). The [C_4mim]Cl solvent is regenerated as in the lyocell process by filtration, dewatering and evaporation. Recovery and cost of solvent will dictate the economics of the process. If other water soluble ionic liquids are used, they can be recovered in the same fashion. If they are not water soluble, phase separation and recovery can be used. It should be possible to alter all ionic liquids and their properties by ion exchange.

In an initial examination of this ionic liquid solvent system, regenerated cellulosic fibers from [C_4mim]Cl were produced using bleached cotton fibers (DP 2000), rayon yarn (600 denier/98 filaments from North American Rayon DP 700), and bleached wood pulp (International Paper DP 1056). The properties of these fibers were dependent upon processing conditions and cellulose



15.4 Chemical structure of 1-butyl-3-methylimidazolium chloride ([C_4mim]Cl).

source (Table 15.1). The solutions made with cotton fiber produced finer fibers because they were able to be drawn down without breaking. These regenerated fibers from cotton also had lower elongation than those from other sources, but tenacities similar to the rayon source fibers.

Other applications of the regenerated cellulose from ionic liquids are macroscopic particles (powders and nanoparticles); macromolecular inclusions (enzymes and other bioactive molecules and metal-oxide particles, and molecular binding agents for metal); complexing, reactive dyes; and pH responsive sensors (Rogers, 2005). Magnetite was dispersed in an ionic liquid-cellulose solution, coagulated with water, and reconstituted as flocs, washed, dried and milled. The resulting cellulose-encapsulated magnetite exhibited magnetic properties (Rogers, 2005).

The biomolecule laccase from *Rhus vernificera* was used to demonstrate enzymatic activity of entrapped biomolecules in cellulose films prepared from ionic liquids solutions. This naturally occurring enzyme degrades lignin for subsequent separation from cellulose and is used as a catalyst for polyphenolic degradation of waste materials. Activity of the enzyme was maintained even though encapsulated (Turner *et al.*, 2004). A mercury (II) sensitive membrane was prepared by encapsulating 1-(2-pyridylazo)-2-naphthol within a cellulose membrane cast from an ionic liquid solution (Rogers, 2005). Homogeneous acetylation of cellulose has been accomplished in an ionic liquid solution (Wu *et al.*, 2004). Ionic liquids have also been used to solution blend cellulose with polyacrylonitrile and with polyethylene glycol (Rogers, 2005; Anderson *et al.*, 2002).

15.5.3 Conversion to chemicals

Cotton is the purest major cellulosic resource and can be considered as a starting material for the manufacture of a practically unlimited number of chemical products, by derivatization, depolymerization, carbonization, or purification. Cellulose derivatization is the most important route to various chemical products which are then used as such or may be further converted to regenerated cellulose products. Conversion of recycled cotton to cotton derivatives is based on the reaction of cellulose primary and secondary hydroxyl

Table 15.1 Properties of fibers spun from ionic liquid

Cellulose source	Denier	Tenacity (g/den)	Breaking elongation (%)
Cotton	11.3	3.38	3.8
Rayon	38.6	3.43	18.7
Dissolving pulp	27.3	4.41	7.6

Compiled from data in Rogers, 2005.

groups by reacting with an array of reagents and may include further derivatization of obtained products.

Esterification is one of the most important substitution reactions on cellulose and is generally carried out in strongly acid medium to give cellulose esters such as cellulose nitrate, sulfate, phosphate, formate, acetate, propionate, butyrate, aceto-propionate, and aceto-butyrate. From a commercial standpoint, the most important derivatization reactions are nitration and acetylation, producing nitrocellulose and acetylcellulose which have been made into fibers and films. Nitrocellulose has been used for some time in manufacturing explosives, plastics and lacquers. Acetylcellulose is also broadly used to make products of various end-uses. The nitration reaction is performed in a nitration medium consisting of nitric acid, sulfuric acid and water, while acetylation is done in a mixture of acetic acid, acetic anhydride and an acid catalyst.

Etherification is the second cellulose derivatization route and is carried out in alkaline medium with alkyl halides as etherifying agents, resulting in many cellulose ethers such as methyl, ethyl, propyl, isopropyl, butyl, isobutyl, amyl, methyl-ethyl, methyl-hydroxyethyl, methyl-hydroxypropyl, carboxymethyl, benzyl, to name but a few. The end-use properties of cellulose derivatives mainly depend on the esterification or etherification agent, cellulose degree of polymerization, and the degree of substitution. The degree of substitution (DS) is defined as the average degree of substitution per glucose unit from the derivative polymeric chain and may vary from zero to a maximum of three, if all three hydroxyl groups from a structural unit are substituted.

In a demonstration of derivatization of recycled cotton, nonwovens of low apparent density were prepared by carding together recycled cotton fibers and cotton fibers previously carboxymethylated with chloroacetic acid (DS of 0.3) (Negulescu *et al.*, 2005).

$$\begin{aligned}&\mathrm{CELL(OH)_3 + nClCH_2CO_2H}\\&\mathrm{+\ nNaOH \rightarrow CELL(OH)_{3\text{-}n}(OCH_2CO_2Na)_n + nNaCl}\end{aligned} \qquad 15.1$$

where *n* reflects the degree of substitution, DS, which is the average number of carboxymethyl [-CH_2COO^-] groups per anhydroglucose unit of cellulose.

The resulting nonwoven webs were treated subsequently with aqueous solutions of urea (U), saturated aqueous melamine (M) solution, or the adduct of phosphoric acid with urea (A), and dried at 110 °C. The nitrogen content determined from the add-on amounts of nonwovens was around 0.04–0.2g N/g fabric, depending upon the reagent and the type of nonwoven. The carboxymethylated bagasse/cotton nonwoven treated with the adduct solution retained A corresponding to a nitrogen content of 0.053g/g nonwoven and to a phosphorus content of 0.059g/g nonwoven. Finally the treated nonwovens were stabilized with a concentrated lyocell solution also obtained from recycled cotton fibers. The nonwoven products were aimed as fertilizing components in nonwoven geotextiles or as filtering media for sequestering heavy metals.

Cellulose depolymerization is another route to a broad class of cellulosic products. Cellulose in industrial products has a much lower DP than native cotton and can be obtained from cotton and other natural sources using mechanical and thermochemical methods to reduce the length of the polymeric chains. Cotton and cotton waste are used to manufacture different grades of cellulosic products, depending on the DP required. Dissolving pulps and cellulose grades to be used for chemical derivatization are prepared by a multistep chemical treatment process comprising prehydrolysis, pulping and bleaching to reduce the DP to a range between 350 and 800, depending on the final product. The alpha-cellulose content should be 95% or higher.

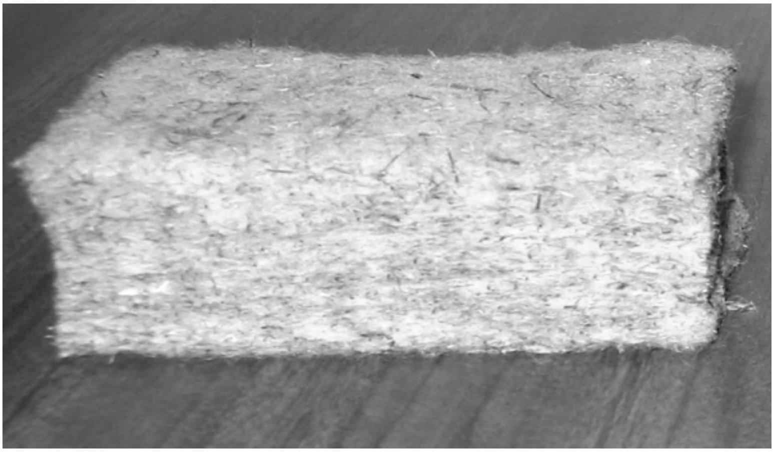
Microcrystalline cellulose, or micronized cellulose, is the grade of cellulose with the lowest DP, generally lower than 300. The best raw material for this type of product is cotton or cotton waste, mainly when it comes to uses in the field of medicine or as food additives.

Cellulose depolymerization can proceed to simple sugar or glucose by hydrolysis (chemical or enzymatic) and the product can be used as a chemical or for making fuel by fermentation. Carbonization of cellulose from cotton waste at about 700 °C results in activated carbon or carbon fibers with a wide range of applications (Iwamoto and Nakamura, 1998; Nakamura and Iwamoto, 1998).

Pure cellulose can be also manufactured from cotton waste. By a proper combination of prehydrolysis, alkaline pulping, and bleaching sequences, cellulose with a purity as high as 99.9% alpha-cellulose can be obtained (Abou-State, 1977; Abou-State and Abd El Megeid, 1977).

15.6 Future trends

As the economics of collecting and sorting textile waste become more favorable, and the pressure for environmentally friendly products spreads, recycling of cotton and other textile waste will see increased interest. The technologies and products categories have been developed and await successful marketing efforts and consumer interest. Lower value end uses, as described in sections 15.3 and 15.4 above should see growth, much of which will be in the area of nonwoven products. These are simple and easy to manufacture, not requiring significant capital or labor investment nor demanding a high price. One of the primary operations is the formation of composite webs by blending together recycled cotton fibers with other cellulosic or synthetic fibers using a carding machine (Fig. 15.5). The webs can be then stabilized in final nonwoven products by melting the synthetic component (Negulescu *et al.*,

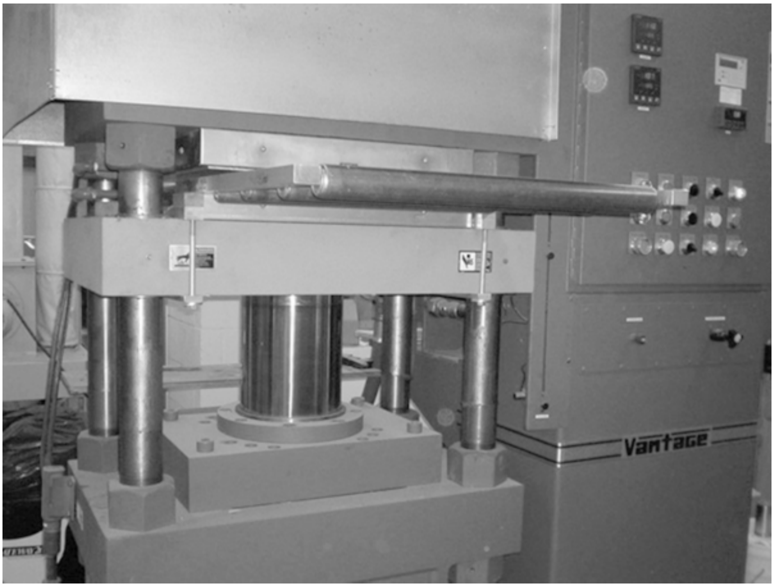


15.5 Webs of recycled cotton fibers carded with coarser bagasse fibers.

2004) or using lyocell solutions (Negulescu *et al.*, 2003). Panels and boards of pre-established densities, according to their end-use, can be easily manufactured by pressing (Fig. 15.6).

Chemical recycling should see increased research, development, and subsequent commercialization. Use of lyocell and ionic liquids to dissolve and reform cellulosic materials with and without inclusion of particles to alter properties will enable the use of cotton based materials in new areas and enhancements of other applications. Traditional uses of cotton are as fibrous products whether woven or nonwoven. With these new solvents however films, membranes, flacks, particles and extruded and processed forms can be achieved. Traditional polymer processing and forming operations will not need to be significantly altered to handle the solutions. Film and membrane casting of polymers are well established and capable of handling these viscous solutions. Lyocell solutions derived from recyclable cotton fibers have been used also for stabilization of composite nonwoven webs made of recycled cotton fibers carded together with coarser fibers derived from annual plants (Negulescu *et al.*, 2003). Extrusion and resin transfer molding can be adapted to processing these solutions by controlled contact with water, acetone or an alcohol, and adjustments made to remove the solvent and contact liquid. Shrinkage or void formation as the solvent is removed should be controlled by process changes.

Other polymers are also soluble in the lyocell and/or ionic liquids solvents making it possible to form intimate blends of cellulose and the other polymer. Furthermore, with controlled solubilities it could be possible to form multiple thin layer membranes or films from solution. Dispersing or dissolving other components in the solution enables encapsulation of these components in the



15.6 Press used for forming nonwovens from composite webs.

fibers or films. The other components can be biocides, pigments, etc., and due to incorporation into the fibers their effects should be more permanent.

15.7 Sources of further information

The research literature, as cited below, covers much of the work in chemical recycling. Current activities and players in the recycling area are easily found on the internet. The Council for Textile Recycling in the US (www.textilerecycle.org) and the Textile Recycling Association in Britain (www.textilerecyclingass.sageweb.co.uk) have general web pages that provide links to other sources. These sources include buyers and sellers of textile waste and used products, manufacturers of recycling equipment, and local governments with collection and recycling programs. EPA's Jobs Through Recycling (JTR) program offers grants designed to expand recycling and reuse markets for commodities like textiles (US Environmental Protection Agency, 2005a).

15.8 References

100% Cotton Rags, (2005). Retrieved 8/23/2005 from http://www.tinytots.com/shopping/cotton_rags/rags.html.

Abou-State, M.A., (1977). Chemical Cotton with an Exceptional High Degree of Purity from Egyptian Cotton Waste Fibers, *Chemistry and Industry*, **18**, 767–768.

Abou-State, M.A. and Abd El-Megeid, F.F., (1977). Effect of Some Chemical Treatments on the Reactivity of Purified Egyptian Cotton Waste Fibers Towards Xanthation, *Fiber Science and Technology*, **10**(4), 273–280.

Anderson, J.L., Ding, J., Welton, T. and Armstrong, D.W., (2002). Characterizing Ionic Liquids on the Basis of Multiple Salvation Interactions, *Journal of the American Chemical Society*, **124**, 14248–14254.

Baker, R. and Griffin, Jr., A.C., (1984). Ginning, in *Cotton*, R.J. Kohel and C.F. Lewis (eds), Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 397–436.

Chang, Y., Chen, H.-L. and Francis, S., (1999). Market Applications for Recycled Post Consumer Fibers. *Family and Consumer Sciences Research Journal*, **27**, 320–340.

Cherry, J.P. and Leffler, H.R., (1984). Seed, in *Cotton*, R.J. Kohel and C.F. Lewis (eds), Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 511–569.

Cole, D.J., (1992). A New Cellulosic Fibre – Tencel, in *Advances in Fibre Science*, S.K. Mukhopadhyay (ed.), Manchester, UK: The Textile Institute.

Collier, B.J. and Tortora, P.G., (2000). *Understanding Textiles*, Upper Saddle River, NJ: Prentice-Hall.

Collins, Keith, (2005). Report to USDA Cotton Board, Charleston, SC, September 9, 2005.

Denim, Reclaimed, (2005). Retrieved 8/23/2005 from http://www.allrags.com/denim.htm.

Dever, M., Collier, B.J., Petrovan, S. and Collier, J.R., (2003). Lyocell Solutions from Undervalued Cellulose Sources, *Clothing and Textiles Research Journal*, **21**(4), 167–173.

Domina, T. and Koch, K., (1997). The Textile Waste Lifecycle, *Clothing and Textiles Research Journal*, **15**(2), 96–102.

Grasso, M.M., (1995). Recycled Textile Fibers: The Challenge for the Twenty-First Century. *Textile Chemist and Colorist*, **27**(5), 16–20.

Heely, J. and Press, M., (1997). Design and the Environment, *Textiles Magazine*, **4**, 13, 23–24.

Huddleston, J.G., Visser, A.E., Reichert, W.M., Willauer, H.D., Broker, G.A. and Rogers, R.D. (2001). Characterization and Comparison of Hydrophilic and Hydrophobic Room Temperature Ionic Liquids Incorporating the Imidazolium Cation, *Green Chemistry*, **3**, 156–164.

Iwamoto, M. and Nakamura, K., (1998). Carbon Fibers from Waste Cotton and Manufacture Thereof. Patent Application JP 96-274820.

Johnson, D.L., (1969). *Compounds Dissolved in Cyclic Amine Oxides,* 3 June, USP 3,447,939.

Luo, M., Roscelli, V.A., Camarena, S., Neogi, A.N., Yancey, M.J. and Gaddis, P.G., (2001). *Process for Melt Blowing Lyocell Fibers*, USP 6,306,334 B1.

Mauney, J.R., (1984). Anatomy and Morphology of Cultivated Cottons, in *Cotton*, R.J. Kohel and C.F. Lewis (eds), Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 59–79.

Moore, M.A., Money, A. and Orzada, B., (1999). An Examination of Environmental Awareness in the Textile Industry. *Textile Chemist and Colorist*, **31**(4), 27–31.

Nakamura, K. and Iwamoto, M., (1998). Antibacterial Activated Carbon Fibers with Good Tensile Strength and Manufacture Thereof. Patent Application JP 96-328863.

Negulescu, I.I., Kwon, H., Collier, B.J., Collier, J.R. and Pendse, A., (1998). Recycling Cotton from Cotton/Polyester Fabrics, *Textile Chemist and Colorist*, **30**(6), 31–35.

Negulescu, I.I., Chen, J., Robeck, J., Sun, L., Zhang, X., Parikh, D.V. and Yachmenev, V.G., (2003). Lyocell Stabilized Nonwoven Composites, *Proceedings of the 13th Annual International TANDEC Nonwovens Conference*, November 18-20, Knoxville, TN (CD-ROM).

Negulescu, I.I., Chen, Y., Chiparus, O.I. and Parikh, D.V., (2004). Composite Nonwoven Materials Based on Kenaf and Other Natural Fibers, in *International Development of Kenaf and Allied Fibers*, A. Liu (ed.), Minneapolis, MN: CCG International Inc., pp. 84–98.

Negulescu, I.I., Chen, Y., Zhang, X., Sun, L. and Parikh, D.V., (2005). Chemistry of Cellulosic Nonwovens: Cotton-Bagasse Nonwovens Bearing Carboxylic and Amide or Amine Groups, *Proceedings, 2005 Beltwide Cotton Conference*, New Orleans, LA, Jan 4–7 (CD-ROM).

Platt, B., (1997). *Weaving Textile Reuse into Waste Reduction*. Washington, DC: Institute for Local Self-Reliance.

Reading Community Enterprise Agency, (n.d.). Reading Textile Recycling Project, retrieved 8/23/2005 from http://www.rdea.org/textilerecycling.htm.

Rivoli, P., (2005) *The Travel of a T-shirt in the Global Economy*, Hoboken, NJ: John Wiley and Sons.

Rogers, R.D., (2005). *Advanced Materials Utilizing ILs as Enabling Solvents*. 10th NIChE Conference: Ionic Liquids, South Bend, IN, February 21–22.

Rydholm, S.A., (1965). *Pulping Processes*, New York: Interscience Publishers, John Wiley & Sons.

Seddon, K.R., (1997). Ionic Liquids for Clean Technology, *Journal of Chemical Technology and Biotechnology*, **68**, 351–356.

Smith, G.G. and Barker, R.H., (1995). Life Cycle Analysis of a Polyester Garment. *Resources, Conservation and Recycling*, **14**, 233–249.

Swatloski, R.P., Spear, S.K., Holbrey, J.D. and Rogers, R.D. (2002). Dissolution of Cellulose with Ionic Liquid, *Journal of the American Chemical Society*, **124**, 4974–4975.

Temming, H., Grunert, H. and Huckfeldt, H. (1973). *Temming-Linters*, Germany: Peter Temming AG.

Textile Recycling Association, (n.d.). Textile Recycling, retrieved 8/23/2005 from http://www.textilerecyclingass.sageweb.co.uk/recycling.htm.

Turner, M.B., Holbrey, J.D., Spear, S.K. and Rogers, R.D., (2004). Production of Bioactive Cellulose Films Reconstituted from Ionic Liquids, *Biomolecules*, **5**, 1379–1384.

US Census Bureau (2005). Secondary Materials and Recycled Textiles Association, Textile Recycling Fact Sheet, retrieved 23/8/2005 from http://www.textile recycle.org/facts.pdf.

US Environmental Protection Agency (2005a). Jobs Through Recycling, retrieved 23/8/2005 from http://www.epa.gov/jtr/.

US Environmental Protection Agency (2005b). Municipal Solid Waste: Reduce, Reuse, and Recycle, retrieved 8/23/2005 from http://www.epa.gov/epaoswer/non-hw/muncpl/reduce.htm.

Warnock, M.M. and Ferguson, E.R., (1997). Effect of Soil Burial on Biodegradation of Selected Nonwovens. *Textile Chemist and Colorist*, **29**(11), 18–22.

World Trade Atlas (2005). Secondary Materials and Recycled Textiles Association, Textile Recycling Fact Sheet, retrieved 23/8/2005 from http://www.textile recycle.org/facts.pdf.

Wu, J., Zhang, J., Zhang, H., He, J.S. Ren, Q. and Guo, M. (2004). Homogeneous Acetylation of Cellulose in a New Ionic Liquid, *Biomacromolecules*, **5**(2), 266–268.

16

Nonwoven technology for cotton

G BHAT, University of Tennessee, USA

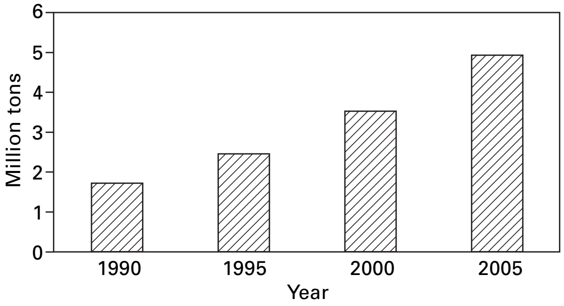
Traditionally fabrics have been produced by weaving or knitting, which involve conversion of fibers into yarns and subsequently arranging the continuous yarns into two-dimensional structures. In the past few decades, non-traditional fabrics, called nonwovens, have become more and more popular. Nonwovens are the fastest growing sectors of textile materials, and they continue to grow all over the world. A significantly large share of these are used as single use, or short life products, leading to disposability related problems. Many of these disposable products are used in health and hygiene applications. In such situations, cotton becomes the fiber of choice. Additional advantages of cotton include superior wet strength as well as a quick drying surface. Bleached cotton fibers have high levels of absorbency, are soft to the touch, breathable and biodegradable. However, there are other issues such as quality, processability and cost, which have limited the share of cotton to relatively low values among other fibers. With recent advances in science and technology, it is possible to obtain cleaner cotton at a cheaper price. Also, with increasing cost of petroleum products, and change in polymer and fiber supply market, synthetic fibers are becoming expensive, and the future looks brighter for cotton in nonwovens with increasing opportunities for growth. The methods of producing nonwovens, especially those applicable to cotton fibers, their application potential, the nonwoven market, and recent research in different areas for cotton nonwovens are discussed in the following sections.

16.1 Nonwovens

Nonwoven fabrics are flat, porous sheets or web structures that are made directly from separate fibers or from molten plastics or from plastic films by entangling fibers or filaments mechanically, thermally or chemically. According to the International Nonwovens and Disposables Association (INDA),[1] 'Nonwovens are a sheet, web, or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, and that are bonded to each other by any of several means.' Nonwovens can be produced from both natural and synthetic fibers or directly from polymers by a variety of techniques that involve web formation and bonding.

Over the past two decades, consumption of nonwoven products has grown at the rate of almost 10% per year (Fig. 16.1). This tremendous growth has been due to their ease of manufacture, higher processing speeds, lower cost of production, and ability to produce fabrics with a range of properties. Unlike traditional textiles, nonwoven fabrics are not manufactured by the conventional processes of weaving or knitting, and converting of fibers to yarns is not required. Both natural and synthetic fibers, organic and inorganic, can be used to produce nonwoven fabrics. The fibers in these structures may be staple or continuous, or may be formed *in situ*, and may be directionally or randomly oriented, depending on the nature of the manufacturing method used.

Nonwoven fabrics demonstrate specific characteristics such as strength, stretch, resilience, absorbency, liquid repellency, softness, flame-retardancy, cushioning, washability, filtering, bacterial barrier and sterility. Nonwoven fabrics can be used in a wide variety of applications, which may be limited life, single-use fabrics as disposable materials or as durable fabrics.[2,3] Demand for nonwoven materials in the USA is expected to increase by 3.9% per year to be nearly $5 billion in 2007. The growth rate in rest of the world is expected to be much higher, in the range of 6–7% per year. This increasing market share will be driven by the strong growth in many key disposable markets such as adult incontinence products, filters, and protective apparel, and key non-disposable markets such as geotextiles and battery separators. The market for disposable products represents the majority of nonwoven demand, accounting for a 64% share in 2002.[4] Disposable consumer products, which primarily include baby diapers, adult incontinence and feminine hygiene products, and wipes, were the largest market for nonwovens in 2002.[5]



16.1 Worldwide nonwoven production data (from ref. 4, with permission from INDA).

Nonwovens are used almost everywhere, in agriculture, construction, military, clothing, home furnishing, travel and leisure, healthcare, personal care, and household applications. Whereas in some areas the nonwovens are replacing traditional fabrics, because of their unique properties, they are finding many new applications as well.

Cotton nonwovens are used as swabs, puffs, wipes, filters, waddings, personal care products such as diapers and feminine hygiene products, semi-durable segments like bedding, household furnishing, pillow fillers, etc. Some of the major uses are listed in Table 16.1. Additional advantages of cotton and other natural fibers include superior wet strength as well as a quick drying surface, notably in wipes. Bleached cotton fibers have high levels of absorbency and are soft to the touch, breathable and biodegradable. One quickly growing area, especially throughout Europe and Japan, is spunlaced cotton used for cosmetic wipes and other disposable products; these trends are likely to spread to other markets as well.

16.2 Production of nonwovens

In most cases, the formation of nonwovens consists of two basic steps, web formation and bonding. The web formation in nonwoven production is a critical contributor of the end-use product performance. Three basic methods are used to form a web: dry laid; wet laid; and polymer laid, the latter of which consists of spun laid and melt blown web formations. Electrospinning,

Table 16.1 Products from cotton nonwovens

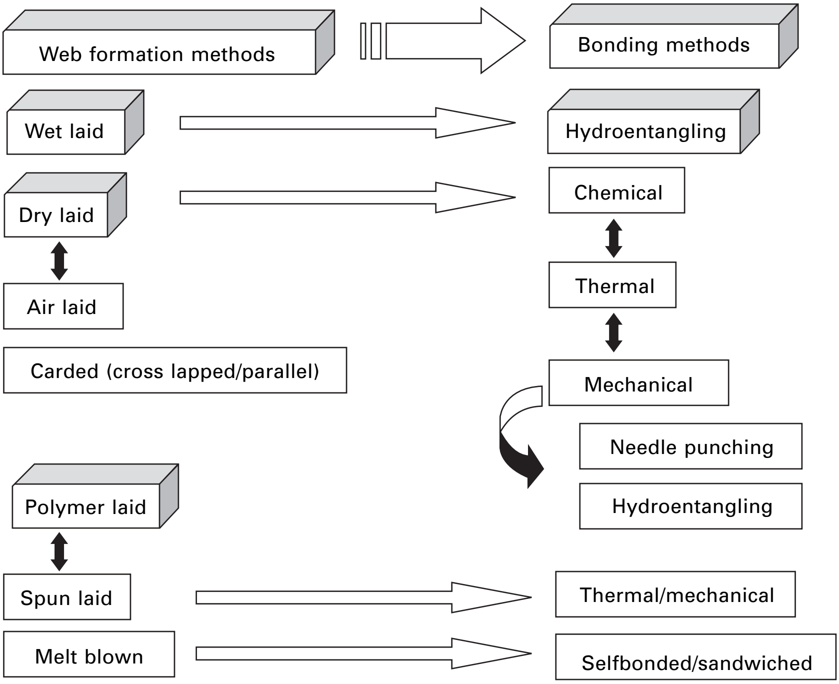
Personal care products
Swabs
Cosmetic pads
Tissues
Medical/dental – wipes, sponges, plugs
Diaper components – coverstock, acquisition layer, cores, back sheet
Feminine hygiene – pads, tampons
Adult continence
Baby and consumer wipes
Durable/semi/durable products
Apparel – clothing, performance wear, outerwear, medical gown and drape, interlinings
Home furnishings – bedding, mattress pads, wall coverings, decorative felts
Industrial products
Filter media
Geotextiles
Protective apparel
Absorbent media – oil and chemical
Insulation – thermal and acoustical
Packaging

an area of continuing research and some commercialization, is also a variation of the polymer laid process. Webs have little strength when they are formed and must therefore be consolidated or bonded in some way. There are three basic types of bonding: chemical, thermal, and mechanical. Whereas cotton webs can be successfully bonded by mechanical process, additional binder polymer or fiber is required to use the chemical or thermal bonding. The nonwoven formation methods used in the industry are summarized in Fig. 16.2.

16.2.1 Web formation

Dry laid

In the dry-laid process, conventional staple fibers are used, which are usually 12 to 100 mm or longer. The fibrous web is prepared using the classical textile carding machine or air laying machine to separate and orient the fiber mechanically. Carding is the most common process to produce nonwoven fabrics from staple fibers. The objective of carding is to separate the fiber stock into individual fibers with minimum fiber breakage. Thus, the carding process consists of opening and blending of different species of fibers

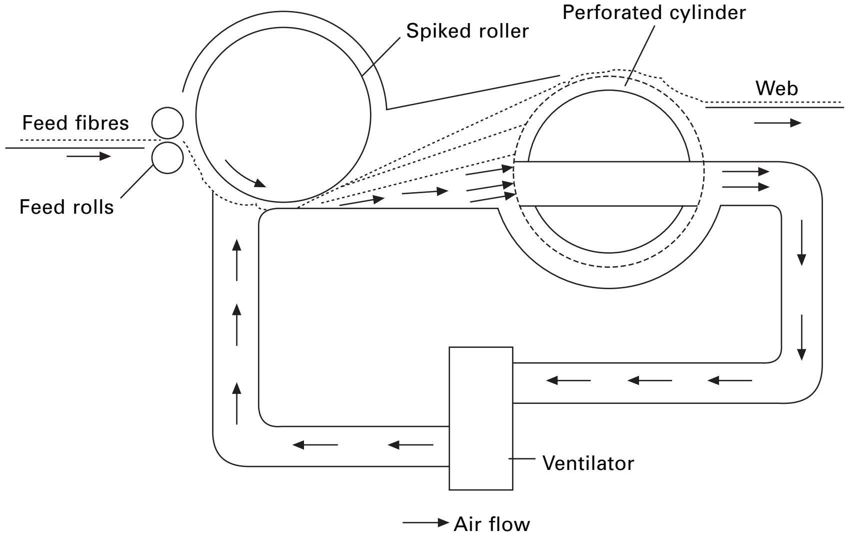


16.2 Nonwoven formation methods.

thoroughly. Carding is performed by the mechanical action in which the fibers are held by one surface while the other surface combs the fibers, causing the separation of individual fibers, as described in earlier chapters. In a normal carding process, the fibers are more oriented along the machine direction than the cross direction. More random web structures can be obtained by cross lapping or a centrifugal dynamic random card system.

The orientation created by carding is improved by capturing fibers on a screen from an air-stream (Fig. 16.3). Starting with a lap or plied card webs fed by a feed roller, the fibers are separated by a licker-in or spiked roller and introduced into an air stream. The total randomization excludes any preferred orientation when the fibers are collected on the condenser screen. The web is delivered to a conveyor for transporting to the bonding area. The length of fibers used in air laying varies from 20 to 60 mm. Shorter fibre lengths allow higher production speeds as they are transported easily in the air stream with larger amount of fibers per unit volume of air and deposited on the collector. Longer fibers require higher air volume, i.e., a lower fiber density to avoid tangling. Problems associated with air laying are speed, web uniformity and weight limitations. Due to uniformity problems across the width due to variation in air and fiber volume, it is not practical to make isotropic webs lighter than 30 g/m^2 by the air laid process.

Some advantages of air laying are the isotropic web structure, that voluminous webs can be produced and that a wide variety of fibers such as natural, synthetic, glass, steel, carbon, etc., can be processed. This will allow the production of webs from blends of cotton with other staple fibers. Some



16.3 Schematic of the air laid process.

of the disadvantages are the low level of opening fiber material by the licker-in, the variation in web structure across the width of layer due to irregular air flow close to walls of the duct and possible entanglement of fibers in the air stream.

The centrifugal dynamic random card forms a web by throwing off fibers from the cylinder onto a doffer with fiber inertia, which is subject to centrifugal force, in proportion to the square of the rotary speed. This is different from the conventional card used in spinning systems, where the fibers are preferentially oriented along the machine direction. The random card can produce a 12 to 50 g/m^2 web with fine fibers of 1.5 den and webs up to 100 g/m^2. Orientation in the web is three-dimensional and is random or isotropic with no preferred orientation of the fibers in any particular direction. Production of the random card is generally about 30 to 50% higher than conventional cards. The machine direction versus the cross-direction strength is better than those produced in the conventional card, but is not as good as that of the air-laid webs.

Nonwovens can be made into the desired structure by the layering of the webs from either the card or garnett. Garnetts are similar to roller top cards, with a group of rolls placed in an order and wire configuration to transport, comb and interlock fibers to form a web. Layering of webs can be accomplished in several ways (i.e., longitudinal, perpendicular or cross) to achieve the desired weight and structure. Carded or air-laid webs usually have basis weights ranging from 30 to 2500 g/m^2. Typical end uses for dry-laid nonwoven fabrics are the fabrics for carpet backing, interlinings for garments, apparel and upholstery backings, filter media, diaper coverstock, wipes, insulation, auto linings, medical fabrics, geotextiles and personal hygiene products.

Wet laid

Wet-laid nonwovens are webs made by a modified papermaking process. First, the fibers are mixed with chemicals and suspended in water to make the slurry. Then, specialized paper machines are used to drain the water off the fibers to form a uniform sheet of material, which is then bonded and dried. Thus, three steps are needed for the wet-laid process, the dispersion of the fiber in water, transporting the suspension onto a continuous traveling screen to form the continuous web, and drying and bonding of the web. Short fibers, which are usually less than 10 mm, are needed for wet-laid processing and the resulting fabric has a basis weight ranging from 10 to 540 g/m^{-2}. The wet-laid process has advantages of high productivity, control of orientation of properties, and high uniformity at low basis weight when compared with the air-laid process. Typical applications for wet-laid nonwovens include tea bags, wipes, surgical gowns and drapes, towels, etc.[6]

Spun laid

Spun laid or spunbonding is a one-step process, which involves polymer melting, filament extrusion, drawing, laydown and bonding of the web to impart strength, cohesiveness and integrity to it.[7] The spinning process is similar to the production of continuous filament yarns and similar extrusion conditions are used for a given polymer. Fibers are formed as the molten polymer exits the spinnerets and are quenched by cool air. Unlike in the typical fiber spinning process, there is no positive take-up, and fibers are directly deposited on a moving collector to form a web. Before deposition on a moving belt or screen, the individual filaments must be attenuated to orient molecular chains within the fibers to increase fiber strength and decrease extensibility by rapidly stretching the plastic fibers immediately after exiting the spinneret either mechanically or pneumatically. Then the web is formed by the pneumatic deposition of the filament bundles onto the moving belt. The fibers have to be distributed on the belt using some type of randomization so that a fairly uniform random web is formed.

The formed webs are bonded either by mechanical, chemical, or thermal methods depending on the ultimate fabric applications. Of the different options, thermal point bonding is the commercially popular method, wherein the bond area is about 15%. At these bond points fiber surfaces are partially melted to form fusion between neighboring fibers, thereby imparting strength to the webs. Today spunbonded fabrics are widely used throughout automobiles as backing for tufted automobile floor carpets, trim parts, trunkliners, interior door panel, and seat covers, etc. For civil engineering applications, spunbond fabrics have been applied for erosion control, revetment protection, railroad bed stabilization, canal and reservoir lining protection, highway and airfield black top cracking prevention, roofing, etc.[18] Spunbonded fabrics have also been widely used in sanitary, medical and packaging industries. Spunbonding is one of the fastest growing processes. Although spunlaying uses thermoplastic polymers and is not suitable for cotton, recently there has been work done to produce cotton containing composites in a spunlay process as will be discussed later.

Melt blown

Melt blowing is one of the most popular processes of making super fine fibers on the micron or sub-micron scale. In a melt-blowing process a thermoplastic polymer is extruded through an extruder die which is rapidly attenuated by the hot air stream to form the extremely fine diameter fibers. The attenuated fibers are then blown by high-velocity air to a collector screen to form a fine-fibered, self-bonded web. The combination of fiber entanglement and fiber-to-fiber bonding generally provides enough web cohesion so that the web can be used without further bonding. Melt-blown fibers generally have diameters in the range of 2 to 7 μm, although they may be as small as 0.1 μm and as large as 30 μm. Due to the large fiber surface area of the melt-blown fabrics, they are used in filtration, insulation and liquid absorption applications. Because of the simplicity of the process, any thermoplastic fiber can be melt blown. However, the polymer should have very low melt viscosity, and it is an energy consuming process. Just like the spun laid process, although melt-blowing uses thermoplastic polymers, composite structures containing cotton fibers can be produced to accomplish unique combination of properties suitable for certain applications.

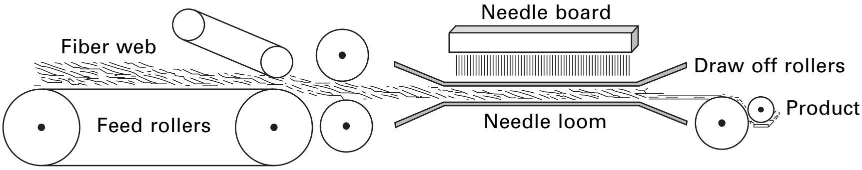
16.2.2 Web-bonding techniques

The web-bonding techniques can be generally classified into three categories, mechanical, chemical, and thermal bonding, depending on the ultimate fabric applications and/or on the web formation method. Sometimes, in order to achieve products with certain properties, a combination of different bonding methods is applied.

Mechanical bonding

Mechanical bonding can be further classified as needle punching, stitching, and spunlacing (hydroentangling). Needle punching is a process of bonding nonwoven web structures by mechanically interlocking the fibers through the web via the barbed needles. A schematic of the needlepunching process is shown in Fig. 16.4. As the unbonded web moves through the needle loom, the web is consolidated and becomes stronger because of fiber interlocking. The level of consolidation is controlled by the needle density. It is the only bonding method suitable for heavyweight nonwoven fabrics. The needle-punched fabrics are extensible, bulky, conformable, distortable and extremely absorbent. Both dry laid and polymer laid webs can be needle punched. Needle-punched fabrics have been used as carpet backing fabrics, automobile carpets and headliners, blankets, and geotextile fabrics.

Stitch bonding is the process of bonding a web by using stitching yarns, filaments, fibers, or just the stitching needles themselves to do the bonding.



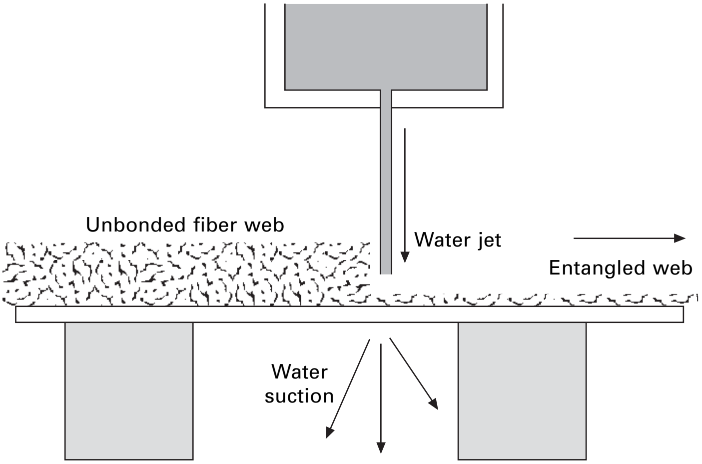
16.4 Schematic of the needle punching process (from ref. 4, with permission from INDA).

Stitch-bonded fabrics have taken the place of woven goods in many applications such as decorative fabrics for home furnishing, shoe fabrics, backing fabrics for artificial leather, etc.

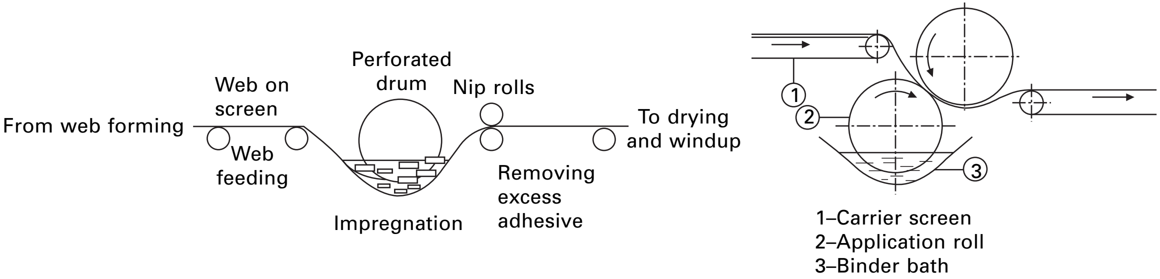
Spunlacing is a process of entangling individual fibers with each other using high-pressure water jets, which cause the fibers to migrate and entangle. As shown in the schematic (Fig. 16.5), water jets push the fibers in the web through the z-direction and the turbulence created causes enough interlocking between fibres to produce strong fabrics. The system requires a good water filtration system as clean water has to go through the fine gauge water jets. Hydroentangled fabrics have more appealing properties than the needle-punched fabrics. Spunlaced fabrics can be used as wipes, medical gowns, dust cloths, etc. Unlike needle punching the spunlace process has no reciprocating mechanical part, which allows faster production speeds to be used.

Chemical bonding

Chemical or resin bonding is a generic term for bonding fibers by the application of a chemical binder. The chemical binders most frequently used to bond fiber webs today are water-borne binders made from vinyl materials, such as polyvinyl acetate, polyvinylchloride, styrene/butadiene resin, butadiene, and polyacrylic, or their combinations. Chemical binders are applied to webs in amounts ranging from about 5% to as much as 60% by weight on fiber. The binder solution is applied to the web and then cured thermally to obtain bonding. Several methods are used to apply binders including saturation bonding, spray bonding, print bonding, and foam bonding, etc. (Fig. 16.6).

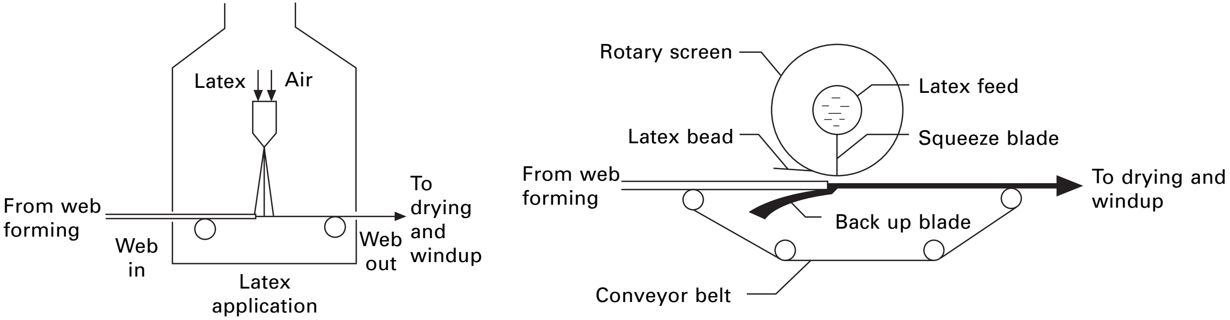


16.5 Schematic of the hydroentangling process.



Saturation bonding

Applicator roll method



Schematic of spray bonding process

Latex printing process

16.6 Various chemical bonding processes (from ref. 4, with permission from INDA).

The type of bonding used depends on the web as well as the type of binder used.

Chemical bonded fabrics have been widely used as wipes and towels, apparel interlinings, automotive trim, filter media, etc. Use of the right chemical binder depending on the fiber and the intended application is important since the binder stays in the fabric. Also, environmental issues while applying or curing of the binders also need to be considered. Chemical bonding allows more room for fabric designs and fiber selections. On the environmental front, increasingly strict regulations and guidelines are driving a trend towards alternative products and technologies. Manufacturers and end-product suppliers alike are seeking ultra-low or formaldehyde-free binders.

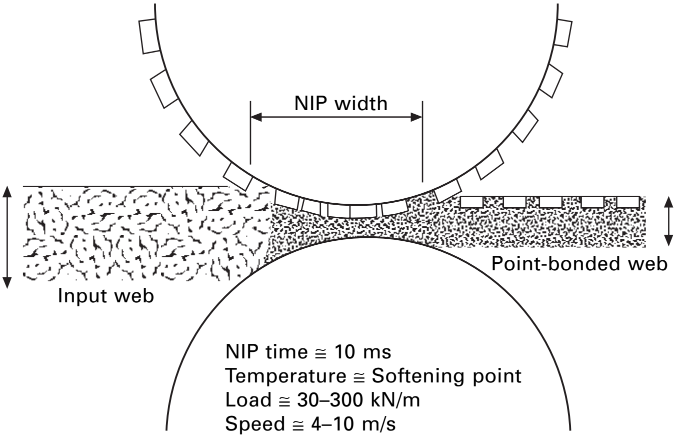
Thermal bonding

Thermal bonding is the process of using heat to bond or stabilize a web structure that contains a thermoplastic binder. It is the most popular method of bonding used in nonwovens, because of the favorable process economics, the absence of chemical binders (that is, environmentally friendly), the availability of new fibers and machinery, and process and product enhancement. The bonding is achieved by the direct action of heat and pressure by a calender, an oven, a radiant heat source, or an ultrasonic wave source. The thermoplastic binder can be in the form of fiber, web, or powder. There are four methods of thermal bonding. They are hot calendering, oven bonding, ultrasonic bonding, and radiant heat bonding. Hot calendering can be further classified as area or point bond hot calendering, and embossing hot calendering.

Among the various types of thermal bonding methods, point bonding using embossing rolls is the most desired method since this produces fabrics with desirable properties at very high speeds. A schematic diagram of the point bonding process is shown in Fig. 16.7. The process employs direct contact, with heat and pressure, to produce localized bonding in a nonwoven. Fabrics have additional softness and flexibility compared with fabrics produced using smooth rolls in area bond hot calendering.

16.2.3 Technology and relative production rate

One of the reasons for the continuing growth of nonwovens is the high production rates that are possible with the new technologies. Typical production rates are listed in Table 16.2. Compared to only a few meters per minute possible with the woven or knitted fabrics, nonwovens can be produced at the rate of a few hundred to thousand meters per minute. This high production rate combined with the fact that the intermediate yarn formation is eliminated helps in keeping the cost of nonwovens very low. This low cost of roll goods production has helped in the tremendous growth of nonwoven products.



16.7 Thermal point bonding process.

Table 16.2 Production rates of different fabric formation processes

Fabric formation process	Production rate, m/min
Weaving	1–6
Knitting	3–16
Nonwovens – web forming:	
• Carding	120–400
• Spunbond	200–2000
• Wet-laid	2000
Nonwovens – bonding	
• Stitchbonding	40
• Needling	30–500
• Calendering	2000
• Hot air bonding	5000

16.3 Fibers used in nonwovens

Manufacturers of nonwoven products can make use of almost any kind of fibers. These include traditional textile fibers, as well as recently developed hi-tech fibers. The selection of raw fibers, to a considerable degree, determines the properties of the final nonwoven products. The selection of fibers also depends on customer requirement, cost, processability, and change of properties because of web formation and consolidation. The fibers can be in the form of filament, staple fiber or even yarn.

Many different fiber types are used in the formation of nonwovens. These include traditional textile fibers such as polyester, polyolefin (PP/PE), nylon, cotton, rayon, wool, lyocell, modacrylic; and advanced fibers, such as aramid (Nomex/Kevlar); conductive nylon; bicomponents (side-by-side, sheath-core, segmented pie, and islands-in-the-sea); melamine (heat and flame resistant); hollow fibers (polyetherketone, polyaniline); Spandex fibers (polyether): fusible co-PET fiber; nylon 6 support/matrix fiber; glass micro-fiber; chlorofibre; antibacterial fiber; stainless steel; rubber thread; poly(tetrafluoroethylene) (PTFE); electrospun polymeric nanofibers.

16.3.1 Cotton fibers for nonwovens

The share of cotton in the nonwoven staple fibre market at present time is insignificant, although the potential for growth is very high. Just about everyone can recognize cotton as a durable, breathable and soft fiber. Whether it is a cotton ball or hand wipe or favorite cotton T-shirt, cotton is well recognized and widely accepted by consumers. Some of the advantages of cotton as well as issues with nonwovens are listed in Table 16.3.[9] A Cotton Incorporated, report, *Cotton Nonwovens: Innovations & Solutions*, sheds light on how powerful the name cotton has become.[10] In 2000, the global nonwovens market used the equivalent of 14.7 million bales of fibers. From 1996–2005, global consumption of bleached cotton fiber rose to 6% of total fiber used in nonwovens, while cotton's current share of the nonwovens market is 7.8% globally and 2.9% in North America. In major consumer markets of North America, Western Europe and Japan, growth of cotton usage in nonwovens is projected to be 3–6% per year for the next few years.

A study,[9] conducted by Cotton Incorporated in six cities across the USA, tested consumers' perceptions of fiber content in nonwoven products and how these perceptions affected purchasing preferences. The study was focused with four product categories: feminine napkins, tampons, baby wipes and disposable diapers. In each category, the Cotton Seal significantly influenced consumers' purchasing preference. Moreover, 66% of consumers perceived personal care products with the cotton seal to be of higher quality. To use the

Table 16.3 Cotton for nonwovens – advantages and issues

Advantages of Cotton	Issues with cotton
• Softness • Absorbency • Excellent wicking • Breathability • Comfort • Biodegradability • Higher wet strength • Low static potential • Dyeable/printable • Chemically modifiable • Sterilizable by all industrial methods	• Cost • Trash content • Color variations • Fiber length variations • Dusting and linting • Nep formation

cotton seal, products must have a minimum cotton content of 15% in some products and a higher level in some other products.

Many of the cotton absorbent products such as surgical sponges, sanitary napkins, tampons and cosmetic pads and puffs can be satisfactorily made from by-product cotton fiber, i.e., gin motes, comber noils and other mill waste. Most of these products use bleached cotton coil (an oversized sliver) that needs little integrity (fiber-to-fiber cohesion). However, roll goods from lightweight webs made by carding or air forming require textile grade fiber. Recommended fiber properties according to Cotton Incorporated and suggested methods of testing are:[11]

- micronaire: greater than or = 4.9
- length: greater than or = 0.95 inches
- uniformity: greater than or = 81.0 percent
- strength: greater than or = 23.0 g/tex
- non-lint content 0.8% maximum (MDTA-3)
- fiber-to-fiber cohesion, 1700 g force maximum (ICI Fiber Cohesion Test)
- fiber openness equal to 100 cc/gram minimum (ITT Test Method)

Fiber length and strength are important in the manufacture of lightweight nonwovens. However, good fabric appearance is more important than fabric strength in certain nonwoven products, and fiber micronaire plays a major role in these items. Nep content is an undesirable component. High micronaire cotton tends to have lower nep content after ginning and is less prone to form additional neps in subsequent processing. A careful investigation[10] of the effect of micronaire showed that substantial increases in neps were noted for the low micronaire cotton during bleaching and nonwoven web formation. There was a dramatic improvement in properties on using higher (> 4.5) micronaire cotton.

Bleached cotton

Many of the cotton nonwoven products that go into hygiene applications require bleached cotton. There is growing capacity to produce bleached fibers targeting nonwovens, due to increasing interest in bleached fibers, among nonwoven manufacturers. Cotton, when bleached, is also more aesthetically pleasing to consumers who appreciate the snow-white quality of bleached cotton. Also, when a natural fiber such as cotton is dyed, the colors tend to be softer and pastel, unlike synthetic fibers that produce much shinier and usually glare-like effects. Cotton fibers give nonwoven fabrics unique characteristics that synthetic fibers cannot duplicate easily. Synthetic fibers are currently being used more in nonwoven fabrics than cotton because of misconceptions regarding cotton's processability. With improved bleaching techniques and the development of new finish applications, cotton can be processed at speeds comparable to that used with synthetics while providing the superior attributes of cotton to the nonwoven.

Colored cotton

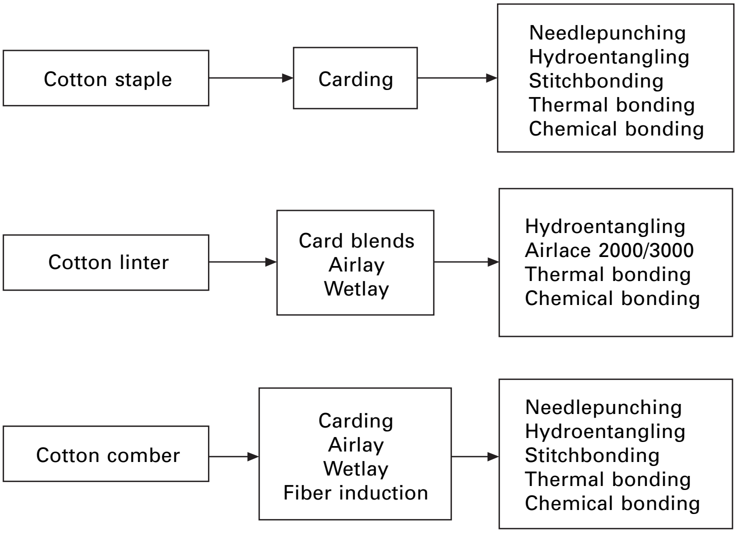
Cotton fiber is often dyed in order to obtain a wide range of colors. Chemical dyes and their finishing demand large amounts of water – so does scouring and bleaching – in turn when these wastes are disposed of they cause soil and water pollution. The negative effects of dyeing can be reduced by naturally colored cotton. Research conducted at USDA has shown that naturally colored cotton performs very well in a needlepunching process.[12] Because naturally colored cotton fibers are shorter and weaker than regular cotton, they do not perform well in spinning, but produce better quality nonwovens than the white cotton, because the nonwoven formation processes are less demanding compared to the conventional textile processes.

Other natural fibers

During the past several years, natural fibers have established a positive and highly regarded name for themselves in numerous nonwoven markets because of their reputation for being soft, durable, breathable, biodegradable and coming from renewable resources.[13] These days, traditional natural fibers, including cotton, hemp, flax and jute have been seeing more demand internationally, while other fibers such as hemp and milkweed are starting to emerge into more nonwovens areas, especially due to their natural origin and biodegradability. Many manufacturers predict that the use of these fibers will grow, as consumers become more aware of their advantages. Obviously cotton is the most used fiber, again due to its popularity in apparel and other fabrics. Jute, kenaf and flax come next, with the rest of the fibers having only a small share. Although cotton is the most attractive fiber for many applications, cost has limited some of its growth, since other manufactured fibers have been cheaper, and for many consumer products cost is a bigger issue. In many cases, blending cotton with other fibers is the best way to achieve good performance per cost.

16.3.2 Processing cotton nonwovens

Processing of cotton into nonwovens follows the general scheme discussed earlier, which involves web formation by carding or air laying and then bonding. Some of the possible production routes suitable for converting cotton fiber into nonwoven goods are shown in Fig. 16.8. As shown, different types/grades of cotton fibers require different processing combinations.[14] Cotton staple fiber, linter and comber, all have differences in length and



16.8 Processing schemes for different cotton fibers.

fineness, which means they cannot be processed using the same set of equipment. Also, properties of cotton fibers grown in different regions have differences in properties, requiring selection of different combination of processing equipment. A few specifics related to processing cotton nonwovens are discussed in this section.

Hydroentanglement

The spunlace, or hydroentanglement, method of web consolidation is highly attractive with cotton because it preserves the pure fiber condition which is conducive to making products with high absorbency. Hydroentangled fabrics have many characteristics that are similar to woven cotton fabrics, i.e., they are easily dyed and finished using conventional textile methods because they have good strength characteristics.[11] To manufacture soft loose nonwovens, partially entangled webs are produced by subjecting cotton webs to low water jet pressures (approx. 300–500 psi). These types of webs can be wet processed in a pad/batch state. Recent introduction of the Jetlace 3000, a spunlace machine by Rieter Perfojet, is a significant advancement over the previous industry standard the Jetlace 2000.[15] It is claimed the Jetlace 3000 will help save energy, reduce cost and is flexible enough to bond wide range of fibers and fiber mixtures and to produce patterns.

The main reason for cotton being suitable for spunlacing is the low wet modulus of the fiber allowing it to easily respond to water jets. Also, the non-round cross-section of cotton fibers results in additional frictional resistance leading to better adhesion and entanglement. There are also advantages in using unbleached cotton as it is cheaper and water jets can remove some of the oils or wax from the fiber. However, the drawback is the need for a better water filtration system.

Needle punching

Needle-punched cotton provides a highly efficient filter media based on the irregular fiber shape and absorption properties. Increased tenacity in the wet condition can be an important advantage for cotton filters. To build strength, scrim materials can be needle punched and used in bed blankets and industrial fabrics. Needles of 36–42 gauges have been found appropriate for the production of cotton needle-punched nonwovens. For very heavy fabrics, use is made of gauge 32 and for finer fabrics 40–42 gauge needles are used. Needle fineness has probably the most effect on fabric properties. Generally with finer needles there is an increase in web density and reduction in air permeability.

Regular length staple cotton should be considered for needle punching since longer fibers perform better. Good length uniformity in a cotton sample provides enough long fiber to form strong fabrics. Fiber finish is critical in needling. Bleached cotton with good lubricity is needed to prevent fiber damage and needle breakage. Raw cotton (unbleached) also needles extremely well with proper needle selection. As discussed earlier, choosing a fiber with a high micronaire allows the production of a stronger needle-punched fabric, providing all other factors remain equal. Recent studies have shown that the H1 needle technology with changes in needle zone contours and profiles help improve the structural features of cotton nonwovens.[16] In addition to the fact that this development allows the production of superior quality nonwovens with relatively less needling, processing speed can be increased resulting in lower production cost.

Stitch bonded nonwovens

Cotton web is stitched as in sewing and the product performance depends on web weight, stitch/cm and type of sewing thread. Arachne and Maliwatt type warp knit machines are used to produce stitchbonded nonwovens. Typically, a filament type yarn is used for stitching purposes, but it has been demonstrated that cotton yarn in counts from 18 to 30 Ne (295–177 denier) are suitable for stitching a cotton web. As with some of the other bonded webs, stitchbonded cotton can be wet processed in fabric form much like conventional textiles.[10]

Chemical bonding

Cotton webs can be bonded using aqueous binders that may be applied by spraying, foaming, gravure roll padding or printing. A wide range of chemical binders are available. Printed patterns provide fabric integrity without imparting objectionable stiffness to the bonded material. Nonwovens for wipes are produced using the print bonding technique.[10]

Thermal bonding

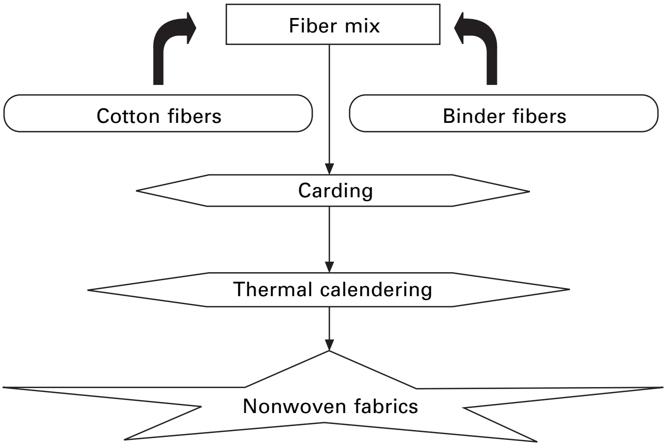
In this process cotton webs with blends of thermoplastic fibers are passed between two hot rollers (calender rollers). The thermoplastic fiber softens/melts and bonds the web. Lightweight fabrics suitable for coverstock, fabric used as a diaper top sheet, can be made by blending cotton with polyolefin, polyester or bicomponent fibers then subjecting the web to heat and pressure using heated calender rolls. The exact bonding conditions are dependent on the melting temperature of the binder fiber and the weight of the web. The calender pressure is increased with fabric weight to get efficient heat transfer. The calender temperatures are close to the melting temperature of the binder fiber. When sheath-core bicomponent binder fibers are used, the temperature is above the melting temperature of the sheath, but well below that of the core polymer. Typically a bonding temperature of about 160 °C is used with polypropylene binder fiber and about 130 °C, for a sheath core fiber with polyethylene sheath. In all the cases, the contact time is in the order of milliseconds, with production speeds of hundreds of m/min.

The strength of the webs varies with the binder fiber composition, as binder fibers are generally stronger and with more binders, there is sufficient to cause melting and flow to form good bond points. Typically 30 to 50% binder fibers with rest cotton produce stronger webs. Whereas a bond area of about 15% is used for the majority of thermoplastic fiber nonwovens, an embossed calender roll with about 30% contact area is needed for blends of cotton and thermoplastic binder fibers to achieve good tensile properties.[10] Alternatively, one can use through air bonding, where the web containing thermoplastic binder is passed through an oven. Here residence time will be in the order of several seconds to minutes for achieving good bonding due to the melting and flow of the binder around the cotton fibers.

Research on cotton-based nonwovens has been carried out at The University of Tennessee, Knoxville (UTK) using different kinds of biodegradable thermoplastic binder fibers through carding and thermal calendering processes.[17–20] The main objective is to have fully biodegradable components in the fiber mixtures, thus producing compostable products. Five different kinds of biodegradable binder fibers were used. Cotton fiber was the base fiber, and binder fibers were, ordinary cellulose acetate (OCA), plasticized cellulose acetate (PCA), Eastar *Bio*® copolyester unicomponent (Eastar), and Eastar *Bio*® copolyester bicomponent (Eastar/PP) and polylactic acid (PLA) fibers. These binder fibers have different melting temperatures, resulting in the use of different optimum bonding temperatures, ranging from 110 °C for the copolyester fiber to 230 °C for OCA. All these fibers showed good bonding with cotton. The nonwoven fabrics in this research were produced by first carding of cotton and the binder fiber and then thermally bonding the carded webs, as shown in Fig. 16.9.

The tensile strength of the nonwoven fabric made with a cotton/cellulose acetate nonwoven blend is quite low and is not suitable for consumer applications when it is processed at the temperatures associated with cellulose acetate's softening temperature (180–205 °C). Solvent treatment has been introduced in order to modify the softening temperature of cellulose acetate fiber and to lower the calendering temperature, while maintaining enhanced tensile properties. The results showed that these solvent treatments can decrease the softening temperature of cellulose acetate fiber and produce comparatively stronger webs.

From the point of energy concern, it is better to make the whole process as simple as possible. So a plasticized cellulose acetate fiber, wherein an internal plasticizer was added during fiber manufacture to lower the softening temperature of ordinary cellulose acetate and further lower the bonding temperature during the thermal calendering process was investigated. It was clearly seen that fabric strength was improved by using PCA instead of OCA. A newly introduced Eastar *Bio* GP copolyester unicomponent (Eastar) fiber, which has a relatively low softening temperature (~80 °C), was further selected as a binder fiber instead of cellulose acetate fiber.[21–22] Because of the low softening temperature of the binder fiber (T_s: ~80 °C), the bonding temperatures used are lower.

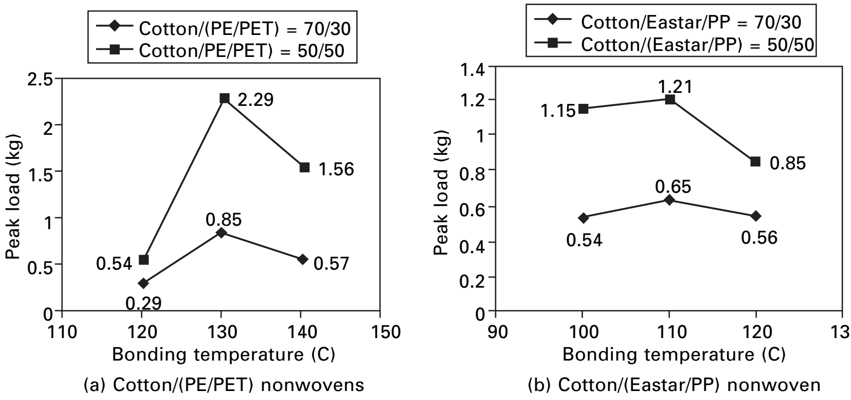


16.9 Production scheme for cotton-based thermal bonded nonwovens.

The tensile properties of cotton and two different bicomponent binder fibers with temperature and binder composition are shown in Fig. 16.10. Both the biodegradable (Eastar/PP) and the PET/PP bicomponent binder fibers show the trend of tensile strength initially increasing with bonding temperature and then dropping off after an optimum value. Actual strength values were much higher for the PET/PP bicomponent fiber compared to Eastar/PP. The SEM photographs of bond points of both blends are shown in Fig. 16.11. This indicates that bonding is comparable with both the binders, but the strength difference is due to the strength values of the binder fibers. Also, the bonding area, where there is contact between the embossed roll and the smooth roll of the calenders, in this study was only 15% compared to the 25 to 30% area that is desirable for cotton-based nonwovens. Further studies have shown that PLA can be a very good binder for cotton-based nonwovens. With the production of PLA in large volumes, the cost is supposed to come down and it is supposed to be comparable to that of or cheaper than bleached cotton, making it an attractive binder fiber. Additional advantages of PLA are that it is from a renewable resource, and is biodegradable.

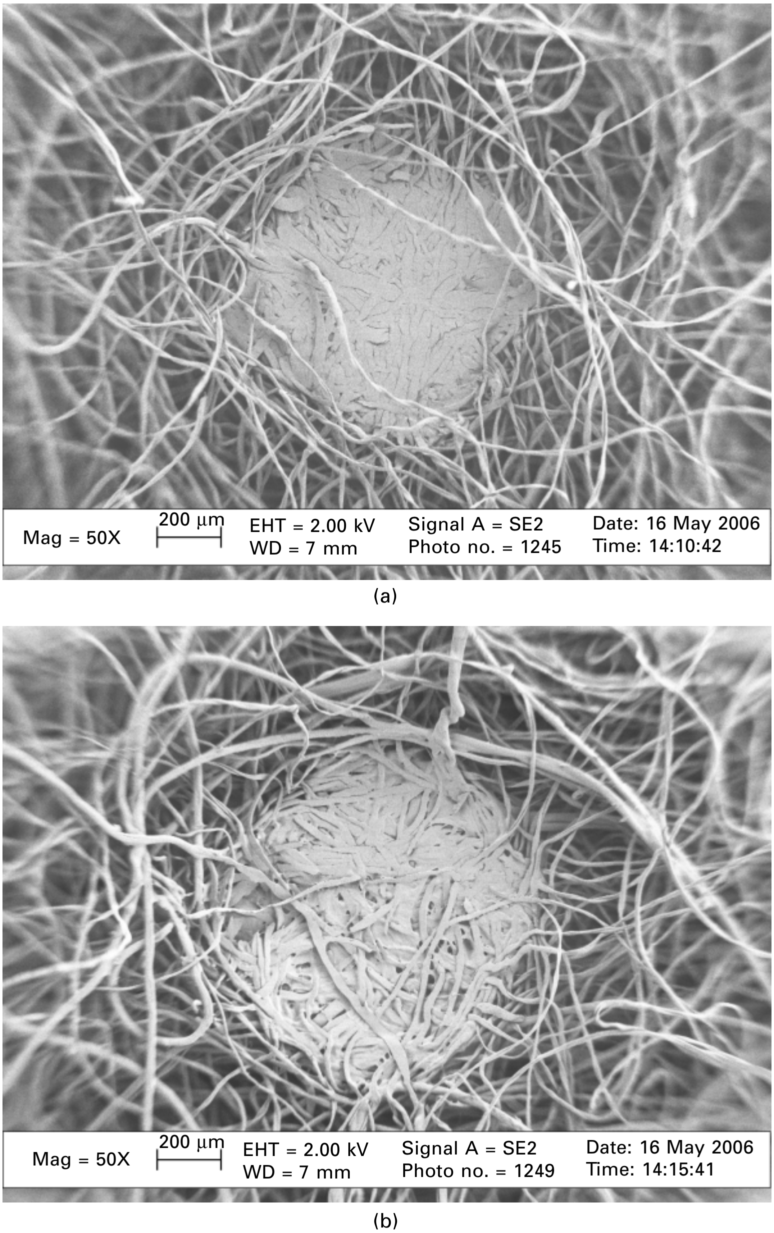
16.3.3 Laminated cotton nonwovens

Cotton surfaced and cotton core nonwovens with polypropylene spunbonded fabrics have been produced with cotton content varying from 40 to 75%.[23,24] A schematic showing the introduction of a cotton/PP carded web with a spun laid fabric to produce thermally bonded composite webs during the thermal bonding process is shown in Fig. 16.12. For achieving cotton surface on both sides, another carded web is introduced from below, and for cotton core nonwovens, another spun laid web is combined from the top. The thermally bonded two or three layered laminates are soft but strong, and have a hand



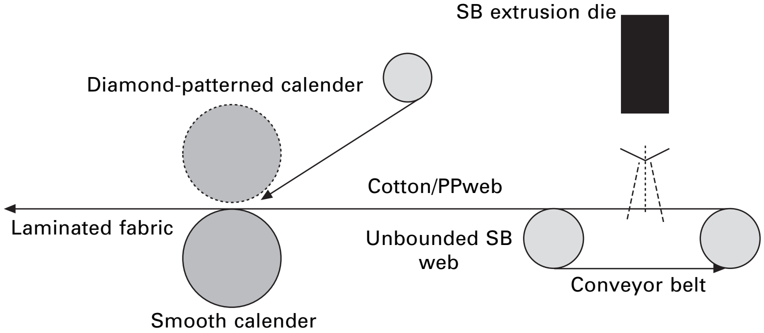
(a) Cotton/(PE/PET) nonwovens (b) Cotton/(Eastar/PP) nonwoven

16.10 Effect of bonding temperature on (MD) strength of cotton-based nonwovens.



16.11 SEM photograph of bond points of thermal bonded cotton nonwovens; (a) (cotton – PE/PET), (b) (cotton-Eastar/PP).

similar to that of cotton knits or hydroentangled fabrics. The fabrics also have excellent wetting, wicking rates, water absorption and water retention properties. Most of these properties come close to that of traditionally used woven fabrics, but provide better production and are produced at a much



16.12 Cotton surface nonwoven formation using a spunbonding machine (from ref. 23, with permission from INDA).

lower cost. These fabrics exhibit minimum linting characteristics, and can be finished to impart stretchability. This study shows how cotton fibers/webs can be combined with other synthetic fiber webs to produce nonwovens with a unique combination of properties.

16.3.4 Cotton containing nonwovens for molded products

The natural feel of cotton, biodegradability and good adhesion to binder fibers, makes it a suitable candidate for molded composites. Molding of preformed nonwoven web simply using heat and pressure is a simple and practical approach to produce shaped products. Natural fiber composites containing flax/kenaf are extensively used for many automotive molded products. These show good thermal and acoustical insulation properties as well. Cotton has properties comparable to these fibers and is a suitable candidate except for its relatively high price. Recent studies by Kamath *et al.*[25–26] have shown that cotton when combined with flax or kenaf produces good molded products that have acceptable physical properties and acoustical insulation properties. In these studies waste or low quality cotton was used, and there was no need for bleaching, thus keeping the fiber cost low. Also, this is another good outlet for low-quality cotton fibers. Another advantage was that using suitable biodegradable thermoplastic binders such as PLA, fully biodegradable/compostable products could be produced. Also, these can be fabricated with other fibers without need for any modification of the process. These molded composites can be good insulating materials in automobiles as well as appliances. The acoustic measurements have demonstrated that natural fiber-based nonwoven composites contribute to the absorptive properties of the components, and are effective for noise reduction.[27–28]

16.4 Finishing and treatment of cotton nonwovens

Finishing of nonwoven bonded fabrics can be classified in different ways, such as chemical, mechanical, or thermal-mechanical. Chemical finishing involves the application of chemical agents such as coatings to fabric surfaces or the impregnation of fabrics with chemical additives or fillers. Mechanical finishing involves altering the texture of fabric surfaces by physically reorienting or shaping fibers on or near the fabric surface. Thermal-mechanical finishing involves altering fabric dimensions or physical properties using heat and pressure. Generally, finishing of nonwoven bonded fabrics is classified as dry finishing or wet finishing. The majority of finishing operations are applicable to nonwovens. Some of the possible treatments given to cotton nonwovens to enhance their performance are:

- flame resistance
- antibacterial
- water repellency
- resistance to biodegradation
- dyeing/printing
- cross linking for durability to washing
- increased resiliency.

Cotton nonwovens can be treated like other cotton fabrics for many applications to achieve desired properties or to enhance performance. The nonwoven fabric finishing is carried out either in tandem with web formation and consolidation or off-line as a separate operation. There are many examples of particular methods and types of finishing equipment being used for both kinds of fabrics. Nonwovens may be given one or more of a variety of finishing processes as a means of enhancing fabric performance or aesthetic properties. Performance properties include functional characteristics such as moisture regain and transport, absorbency, or repellency; flame retardancy; electrical response; resistance; and frictional behavior. Aesthetic properties include various attributes such as appearance, surface texture, color, and odor. The specific property requirement is dependent on the application as they vary widely from one product to another.

A significant amount of research on nonwoven fabric finishes is being conducted at USDA laboratory in New Orleans, LA.[29] One such example of the research was to carry out single-bath chemical finishing of perpendicular-laid (P-laid) high lofts to afford the composites' improved flame resistance (FR) and physical resiliency. High loft nonwovens are low density fabrics characterized by a high ratio of thickness to weight per unit area, which means that high lofts contain considerable void volume. They are usually made of synthetic fibers. The major problems with using cotton in high lofts are cotton's high flammability and lack of resiliency. Parikh *et al.* have developed finishing formulations containing the flame retardants (i) diammonium phosphate (DAP)/urea, and (ii) DAP and cyclic phosphonate ester along with the crosslinking agent dimethyloldihydroxyethyleneurea DMDHEU.[30] Both the formulations imparted flame resistance to the highly flammable high lofts, protecting them completely. However, the formulation containing DAP/urea is preferred because it is of lower cost. The crosslinking agent was effective in improving compressional resistance and recovery. So, the finishing treatment produced P-laid cotton blend highlofts that were both FR and resilient. This is important for cotton fibers that are used in mattresses that have good resiliency as well as flame retardancy to resist the open flame.

For many wound dressings, there is a need for high absorbency and ability to retain moisture. Carboxy methylation was shown to be very effective in producing a highly swellable, water retentive cotton fiber without any strength loss. The carboxymethylation was accomplished by treating the nonwoven in alcoholic caustic and monochloroacetic acid using 90/10 ethanol water. Such a treated cotton nonwoven product is sterilizable and suitable for moist dressings, especially on burn wounds. Such a product is cheaper and competitive with the traditionally used calcium/sodium alginate dressing. Also, cotton dressings can be easily modified to improve healing of chronic wounds.[31] In addition to some of these finishings, cotton nonwovens can be used as substrates for coated/laminated products as well.

Another category of finishing is the conversion of roll goods into final products. This involves cutting, slitting, folding, application of various chemicals/agents, and packaging. Some of the conversions can include thermal fusing, welding and sewing. For some products, such as premoistened wipes, nonwovens are impregnated with lotions after folding in packaging. Medical and surgical products are sterilized after the conversion of products. The sterilization could be radiation type or the one using ethylene oxide and steam. Unlike many other types of nonwovens, cotton nonwovens are easy to handle in many finishing operations.

16.5 Future trends

Cotton fiber nonwovens are already used in a variety of applications, but the potential for growth is very high. Consumer demands for cotton are well documented, but because nonwovens are not required to list fiber content in products, consumers often do not know what they are purchasing. There is definitely an opportunity to increase market share by adding cotton to the fiber content since there is a consumer preference for cotton-containing products.[11] Some of the recent developments leading to increased use of cotton in nonwovens are:

- Cotton linters replacing the traditional 100% wood pulp fibers for producing absorbent cores for disposable diapers and famine pads, as this improves some properties as well as consumer appeal.[32]

- Cotton is being blended with kenaf fibers to improve the softness and hand.[33]
- Buckeye Technologies has developed 100% natural cotton for tampon manufacture.[34]
- Development of a ‘flexible cotton decontamination wipe’ for human and sensitive equipment decontamination at Texas Tech University.[35] The purpose here is to use the natural fiber that is comfortable to use on the body, but at the same time can be incorporated with decontaminant additives such as activated carbon and metal oxides.

Wipes are one of the largest application areas for cotton nonwovens. Because of its high absorbency, a good fabric-like structure, low linting tendency and high wet strength, spunlaced cotton nonwovens are highly suitable for hospital, medical, consumer, cosmetic and wet wipes. These are also suitable for special applications in the computer industry for cleaning lithographic plates, etc.

Spunlaced cottons are also used as semi-durable bed sheets, napkins and table cloths. These can be washed 6–8 times without any problem.[36] The products obtained have the appearance and feel of linen and can be dyed and printed for special effects. Cotton blankets, carpets and rugs also have been produced from needlepunched nonwovens. Thermal bonded nonwovens are suitable for cover stock and other healthcare products therefore cotton nonwovens find application in many areas. The challenge is to make them economically competitive by appropriate selection of fibers and manufacturing methods.

16.6 Conclusions

Although the current share of cotton in nonwovens is small, cotton has a bright future in this growing sector of fabrics. Hygiene and other absorbent products are the major markets for bleached cotton fibers. Raw cotton can be used for many products such as moldable composites, furniture and bedding pads, and for several products produced through the hydroentangling process. Absorbency, wet strength and breathability of cotton give natural advantages to many products. The biodegradability of the fiber as well as its renewable resource makes it an environmentally safe product to use. Cotton nonwovens can be recycled, reused or disposed of by natural degradation conditions. Cotton is a readily renewable resource with long-term supply assurance. Extensive research to improve the bleaching process and nonwoven fabrication processes such as needling and hydroentangling make cotton nonwovens more economical. The share of cotton in nonwovens will continue to increase as cotton-containing items are preferred by consumers. Innovation is the key to produce competitive products with superior performance to increase the share of cotton in the growing nonwovens industry.

16.7 References

1. http://www.inda.org/category/nwn_index.html
2. G. S. Bhat, 'Future of Nonwoven Fabrics', *Speculations in Science and Technology*, Vol. 19, 149–155 (1996).
3. S. K. Batra and F. L. Cook, *The Nonwoven Fabrics Handbook* 1992.
4. *Nonwovens Handbook*, ed. Butler, I., INDA Publications, Cary, NC (2004).
5. http://www.the-infoshop.com/study/fd16116_nonwovens.html
6. S. M. Hansen, *Nonwoven Engineering Principles, Nonwovens – Theory, Process, Performance and Testing*, Edited by A. F. Turbak, TAPPI Press, Atlanta, GA, 1993.
7. G. S. Bhat and S. R. Malkan, 'Extruded Continuous Filament Nonwovens: Advances in Scientific Aspects', *J. of Appl. Polym. Sci.*, Vol. 83, 572–585 (2002).
8. R. L. Smorada, *Encyclopedia of polymer science and engineering*, New York, 227–253.
9. G. S. Bhat, 'Overview of Cotton-Based Nonwovens', *Beltwide Conference Proceedings*, New Orleans, LA, January 2005.
10. *Cotton for Nonwovens: A Technical Guide*, Cotton Incorporated, http://www.cottoninc.com/Nonwovens
11. http://www.cottoninc.com/Nonwovens/CottonNonwovens/?S=Nonwovens&Sort=0
12. L. Kimmel, C. Delhom, W.R. Goynes, V.G. Yachmenev and T.A. Calmari Jr., 'Superior Nonwovens made from Naturally Colored Cottons', *Proceedings of the Beltwide Cotton Conferences*, Anaheim, CA, January 2001.
13. G. Bhat and H. Rong, 'Biodegradable Nonwovens', in *Biodegradable and Sustainable Fibers*, ed. by R. S. Blackburn, Woodhead Publishing Limited, Cambridge, UK, (2005) 310–342.
14. E. M. McLean, 'Cotton Nonwoven Innovations', *Proceedings of the Beltwide Cotton Conferences*, Anaheim, CA, January 2001.
15. http://www.expresstextile.com/20031009/productportfolio02.shtml
16. S. Ramkumar and A. P. S. Sawhney, 'Production of Cotton Nonwoven Fabrics using H1 Technology Needleloom', *Proceedings of the 2001 Beltwide Cotton Conferences*, 1, 674–676 (2001).
17. H. Suh, K. E. Duckett and G. S. Bhat, 'Biodegradable and Tensile Properties of Cotton/Cellulose Acetate Nonwovens', *Textile Research Journal*, 66(4) 230–237 (1996).
18. G. S. Bhat, K. E. Duckett, G. M. Heismeyer, X. Gao and Mac McLean, 'Processing and Properties of Cotton-Based Nonwovens', *Proceedings of the 9th TANDEC Conference*, Knoxville, TN (1999).
19. K. E. Duckett, G. S. Bhat and Hagen Suh, 'Compostable/Biodegradable Nonwovens', U.S. Patent 5,783,505 (issued July 21, 1998).
20. X. Gao, K. E. Duckett, G. S. Bhat and H. Rong, 'Effects of water Treatment on Processing and properties of Cotton/Cellulose Acetate Nonwovens', *International Nonwovens Journal* 10(2), 21–25 (2001).
21. G. S. Bhat, H. M. Rong, and M. Mclean, 'Biodegradable/Compostable Nonwovens from Cotton-based Compositions', *INTC 2003 Proceedings*, Baltimore, Maryland, September 15–18, 2003.
22. H. M. Rong and G. S. Bhat, 'Preparation and Properties of Cotton-Eastar Nonwovens', *Int. Nonwovens J.*, 12(2), 53–57, 2003.
23. L. C. Wadsworth, H. Suh and H. C. Allen, 'Cotton Surfaced Nonwovens for Short-Wear-Cycle Apparel', *International Nonwovens Journal*, Summer 2000, pp. 13–17.

24. L. C. Wadsworth, *Proceedings of the Beltwide Cotton Conferences*, Anaheim, CA, January 2001.
25. M. G. Kamath, G. S. Bhat, D. V. Parikh and D. Mueller, ‘Cotton Fiber Nonwovens For Automotive Composites’, *International Nonwovens Journal*, pp 34–40 (Spring 2005).
26. M. G. Kamath, G. S. Bhat, D. V. Parikh and D. Mueller, ‘Biodegradable/Compostable Composites From Ligno-Cellulosic Fibers for Automotive Applications’, *SAE Proceedings*, October 2005.
27. D. V. Parikh, T. A. Calamari, ‘Performance of Nonwoven Cellulosic Composites For Automotive Interiors’, *Int. Nonwovens J.*, 9(2), 83–85, 2000.
28. Yachmenev, V. G., Parikh, D. V. and Calamari, T. A. Jr., ‘Thermal Insulation Properties of Biodegradable, Cellulosic-based Nonwoven Composites for Automotive Application’, *Journal of Industrial Textiles* (2002), 31(4), 283–296.
29. T. A. Calamari and D. V. Parikh, ‘Cotton Nonwovens Research at the Southern Regional Research Center’, *Proceedings of the 2001 Beltwide Cotton Conferences*, (2001).
30. D. V. Parikh and T. A. Calamari, ‘Flameretardant Highlofts Containing Cotton’, *Proceedings of the 2001 Beltwide Cotton Conferences* (2006).
31. J. V. Edwards, ‘Design, Preparation and Activity of Cotton-based Wound Dressings for Chronic Wounds’, *Proceedings of the 2001 Beltwide Cotton Conferences*, 1, 674–676 (2006).
32. H. C. Allen, ‘Cotton in Absorbent Cores’, *Nonwovens World*, Aug.–Sept 1999, pp. 71–78.
33. P. Bel-bieger *et al.*, ‘Textile Technology, Cotton/Kenaf Fabrics’, *The Journal of Cotton Science*, 3, 60–70 (1999).
34. ‘Readers Service, Natural Cotton Fiber’, *Nonwovens Industry*, Jan. 1999, 74.
35. http://www.cotton.org/foundation/2005-06/Projects/gen-new-products.cfm
36. D. Gillespie, ‘Nonwovens and Lifestyle’, *Proceedings of the 2001 Beltwide Cotton Conferences*, Anaheim, CA, Jan. 9–13 (2001).

INDEX