WOODHEAD PUBLISHING SERIES IN TEXTILES

Handbook of fire resistant textiles

Edited by F. Selcen Kilinc

The Textile Institute

WP
WOODHEAD PUBLISHING

Woodhead Publishing Series in Textiles: Number 140

Handbook of fire resistant textiles

Edited by
F. Selcen Kilinc

The Textile Institute

WP
WOODHEAD
PUBLISHING

Oxford Cambridge Philadelphia New Delhi

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited, 80 High Street, Sawston, Cambridge CB22 3HJ, UK
www.woodheadpublishing.com
www.woodheadpublishingonline.com

Woodhead Publishing, 1518 Walnut Street, Suite 1100, Philadelphia,
PA 19102–3406, USA

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,
Daryaganj, New Delhi – 110002, India
www.woodheadpublishingindia.com

First published 2013, Woodhead Publishing Limited

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

Library of Congress Control Number: 2013932910

ISBN 978-0-85709-123-9 (print)
ISBN 978-0-85709-893-1 (online)
ISSN 2042-0803 Woodhead Publishing Series in Textiles (print)
ISSN 2042-0811 Woodhead Publishing Series in Textiles (online)

The publisher's 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 elemental chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by Newgen Knowledge Works Pvt Ltd
Printed by MPG Printgroup, UK

Handbook of fire resistant textiles

The Textile Institute and Woodhead Publishing

The Textile Institute is a unique organisation in textiles, clothing and footwear. Incorporated in England by a Royal Charter granted in 1925, the Institute has individual and corporate members in over 90 countries. The aim of the Institute is to facilitate learning, recognise achievement, reward excellence and disseminate information within the global textiles, clothing and footwear industries.

Historically, The Textile Institute has published books of interest to its members and the textile industry. To maintain this policy, the Institute has entered into partnership with Woodhead Publishing Limited to ensure that Institute members and the textile industry continue to have access to high calibre titles on textile science and technology.

Most Woodhead titles on textiles are now published in collaboration with The Textile Institute. Through this arrangement, the Institute provides an Editorial Board which advises Woodhead on appropriate titles for future publication and suggests possible editors and authors for these books. Each book published under this arrangement carries the Institute's logo.

Woodhead books published in collaboration with The Textile Institute are offered to Textile Institute members at a substantial discount. These books, together with those published by The Textile Institute that are still in print, are offered on the Woodhead web site at: www.woodheadpublishing.com. Textile Institute books still in print are also available directly from the Institute's website at: www.textileinstitutebooks.com.

A list of Woodhead books on textile science and technology, most of which have been published in collaboration with The Textile Institute, can be found towards the end of the contents pages.

We are always happy to receive suggestions for new books from potential editors. To enquire about contributing to our Textiles series, please send your name, contact address and details of the topic/s you are interested in to sarah.lynch@woodheadpublishing.com. We look forward to hearing from you.

The team responsible for publishing this book:

Commissioning Editor: Kathryn Picking
Publications Coordinator: Emily Cole
Project Editor: Rachel Cox
Editorial and Production Manager: Mary Campbell
Production Editor: Adam Hooper
Project Manager: Newgen Knowledge Works Pvt Ltd
Copyeditor: Newgen Knowledge Works Pvt Ltd
Proofreader: Newgen Knowledge Works Pvt Ltd
Cover Designer: Terry Callanan

Contributor contact details

(* = main contact)

Editor

Dr F. Selcen Kilinc
National Personal Protective Technology Laboratory (NPPTL)
National Institute for Occupational Safety and Health (NIOSH)
Centers for Disease Control and Prevention (CDC)
626 Cochrans Mill Road, Building 403
P.O. Box 18070
Pittsburgh
PA 15236
USA

E-mail: fselcen@gmail.com

Chapters 1 and 10

D. Price* and A. Richard Horrocks
Fire Chemistry Laboratory
IMRI
University of Bolton
BL3 5AB
UK

E-mail: dp3@bolton.ac.uk; a.r.horrocks@bolton.ac.uk

Chapter 2

Roy M. Broughton* and Idris Cerkez
Department of Polymer and Fiber Engineering
Auburn University
Auburn
Alabama 36849
USA

E-mail: royalb@eng.auburn.edu; brougrm@auburn.edu

Chapter 3

Dr Paul Joseph* and Dr Svetlana Tretsiakova-McNally
School of the Built Environment
The Built Environment Research Institute
University of Ulster
Newtownabbey BT37 0QB
County Antrim
Northern Ireland
UK

E-mail: p.joseph@ulster.ac.uk

Chapter 4

Jenny Alongi*, Alberto Frache, Giulio Malucelli and Giovanni Camino
Dipartimento di Scienza Applicata e Tecnologia
Politecnico di Torino
Italy

E-mail: jenny.alongi@polito.it

Chapter 5

David Loftin
President, David Loftin Consulting, Inc.
629 Andrew Rucker Lane
Nashville
TN 37211
USA

E-mail: davidloftinconsult@att.net

Chapter 6

Marcelo M. Hirschler
GBH International
2 Friars Lane
Mill Valley
CA 94941
USA

E-mail: mhirschler@gbhinternational.com

Chapter 7

Charles Q. Yang
Department of Textiles, Merchandising and Interior
The University of Georgia
Athens
GA 30602
USA

E-mail: cyang@uga.edu

Chapter 8

Tom Burrow
Lenzing Fibers Grimsby Ltd.
Energy Park Way
Grimsby DN31 2TT
UK

E-mail: T.Burrow@lenzing.com

Chapter 9

Jeanette M. Cardamone
U.S. Department of Agriculture
Agricultural Research Service
Eastern Regional Research Center
600 East Mermaid Lane
Wyndmoor
PA 19038
USA

E-mail: Jan.Cardamone@ars.usda.gov

Chapter 11

A. Richard Horrocks* and Baljinder K. Kandola
Fire Chemistry Laboratory
IMRI
University of Bolton
BL3 5AB
UK

E-mail: a.r.horrocks@bolton.ac.uk

Chapter 12

Dr Gajanan S. Bhat
Department of Materials Science and Engineering
Director, Nonwovens Research Laboratory (UTNRL)
The University of Tennessee
Knoxville, TN
USA

E-mail: gbhat@utk.edu

Chapter 13

Dr Anugrah Shaw
Richard Henson Center, Room 2113
University of Maryland Eastern Shore
Princess Anne
MD 21853
USA

E-mail: ashaw@umes.edu

Chapter 14

Jürgen Haase
Consulting office PPE
Fürstenstraße 262
09130 Chemnitz
Germany

E-mail: j.haase@telecolumbus.net

Chapter 15

Dr René M. Rossi
Empa
Laboratory for Protection and Physiology
Lerchenfeldstrasse 5
CH-9014 St.Gallen
Switzerland

E-mail: rene.rossi@empa.ch

Chapter 16

Dr W. Jon Williams
National Personal Protective Technology Laboratory (NPPTL)
National Institute for Occupational Safety and Health (NIOSH)
Center for Disease Control and Prevention (CDC)
Pittsburgh
PA 15236
USA

E-mail: WJWilliams@cdc.gov

Chapter 17

Shonali Nazaré* and Rick D. Davis
Engineering Laboratory
National Institute of Standards and Technology
100 Bureau Drive, MS-8665
Gaithersburg
MD 20899–8665
USA

E-mail: rick.davis@nist.gov

Chapter 18

Shulong Li*, Jack Spoon, J. Travis Greer and James D. Cliver
Milliken Research Corporation
920 Milliken Road, M-405
Spartanburg
South Carolina 29304
USA

E-mail: Shulong.li@milliken.com

Chapter 19

Dr Guowen Song*
Associate Professor
Department of Human Ecology
University of Alberta
Edmonton, AB. T6G 2N1
Canada

E-mail: gwsongsgs@gmail.com

Dr Yehu Lu
Protective Clothing Research Centre
Fashion Institute
Donghua University
Shanghai 200051
P. R. China

E-mail: luyehu@gmail.com

Chapter 20

Hugh Hoagland
Consultant, Arcwear.com
Louisville, KY
USA

E-mail: hugh@arcwear.com

Chapter 21

Dr Helena Mäkinen
Finnish Institute of Occupational Health (FIOH)
Work Environment Development
Technical Solutions and Protection
Topeliuksenkatu 41 aA
FI-00250 Helsinki
Finland

E-mail: helena.makinen@ttl.fi

Chapter 22

A. Richard Horrocks
Fire Chemistry Laboratory
IMRI
University of Bolton
BL3 5AB
UK

E-mail: a.r.horrocks@bolton.ac.uk

Chapter 23

Dr Alexander B. Morgan
University of Dayton Research Institute
300 College Park
Dayton
OH 45469–0170
USA

E-mail: alexander.morgan@udri.udayton.edu

Woodhead Publishing Series in Textiles

1 **Watson's textile design and colour Seventh edition**
Edited by Z. Grosicki
2 **Watson's advanced textile design**
Edited by Z. Grosicki
3 **Weaving second edition**
P. R. Lord and M. H. Mohamed
4 **Handbook of textile fibres Volume 1: Natural fibres**
J. Gordon Cook
5 **Handbook of textile fibres Volume 2: Man-made fibres**
J. Gordon Cook
6 **Recycling textile and plastic waste**
Edited by A. R. Horrocks
7 **New fibers second edition**
T. Hongu and G. O. Phillips
8 **Atlas of fibre fracture and damage to textiles second edition**
J. W. S. Hearle, B. Lomas and W. D. Cooke
9 **Ecotextile '98**
Edited by A. R. Horrocks
10 **Physical testing of textiles**
B. P. Saville
11 **Geometric symmetry in patterns and tilings**
C. E. Horne
12 **Handbook of technical textiles**
Edited by A. R. Horrocks and S. C. Anand
13 **Textiles in automotive engineering**
W. Fung and J. M. Hardcastle
14 **Handbook of textile design**
J. Wilson
15 **High-performance fibres**
Edited by J. W. S. Hearle
16 **Knitting technology third edition**
D. J. Spencer
17 **Medical textiles**
Edited by S. C. Anand
18 **Regenerated cellulose fibres**
Edited by C. Woodings
19 **Silk, mohair, cashmere and other luxury fibres**
Edited by R. R. Franck
20 **Smart fibres, fabrics and clothing**
Edited by X. M. Tao
21 **Yarn texturing technology**
J. W. S. Hearle, L. Hollick and D. K. Wilson
22 **Encyclopedia of textile finishing**
H-K. Rouette

23 **Coated and laminated textiles**
W. Fung
24 **Fancy yarns**
R. H. Gong and R. M. Wright
25 **Wool: science and technology**
Edited by W. S. Simpson and G. Crawshaw
26 **Dictionary of textile finishing**
H-K. Rouette
27 **Environmental impact of textiles**
K. Slater
28 **Handbook of yarn production**
P. R. Lord
29 **Textile processing with enzymes**
Edited by A. Cavaco-Paulo and G. Gübitz
30 **The China and Hong Kong denim industry**
Y. Li, L. Yao and K. W. Yeung
31 **The World Trade Organization and international denim trading**
Y. Li, Y. Shen, L. Yao and E. Newton
32 **Chemical finishing of textiles**
W. D. Schindler and P. J. Hauser
33 **Clothing appearance and fit**
J. Fan, W. Yu and L. Hunter
34 **Handbook of fibre rope technology**
H. A. McKenna, J. W. S. Hearle and N. O'Hear
35 **Structure and mechanics of woven fabrics**
J. Hu
36 **Synthetic fibres: Nylon, polyester, acrylic, polyolefin**
Edited by J. E. McIntyre
37 **Woollen and worsted woven fabric design**
E. G. Gilligan
38 **Analytical electrochemistry in textiles**
P. Westbroek, G. Priniotakis and P. Kiekens
39 **Bast and other plant fibres**
R. R. Franck
40 **Chemical testing of textiles**
Edited by Q. Fan
41 **Design and manufacture of textile composites**
Edited by A. C. Long
42 **Effect of mechanical and physical properties on fabric hand**
Edited by H. M. Behery
43 **New millennium fibers**
T. Hongu, M. Takigami and G. O. Phillips
44 **Textiles for protection**
Edited by R. A. Scott
45 **Textiles in sport**
Edited by R. Shishoo
46 **Wearable electronics and photonics**
Edited by X. M. Tao
47 **Biodegradable and sustainable fibres**
Edited by R. S. Blackburn
48 **Medical textiles and biomaterials for healthcare**
Edited by S. C. Anand, M. Miraftab, S. Rajendran and J. F. Kennedy
49 **Total colour management in textiles**
Edited by J. Xin
50 **Recycling in textiles**
Edited by Y. Wang
51 **Clothing biosensory engineering**
Y. Li and A. S. W. Wong
52 **Biomechanical engineering of textiles and clothing**
Edited by Y. Li and D. X-Q. Dai

53 **Digital printing of textiles**
Edited by H. Ujiie
54 **Intelligent textiles and clothing**
Edited by H. R. Mattila
55 **Innovation and technology of women's intimate apparel**
W. Yu, J. Fan, S. C. Harlock and S. P. Ng
56 **Thermal and moisture transport in fibrous materials**
Edited by N. Pan and P. Gibson
57 **Geosynthetics in civil engineering**
Edited by R. W. Sarsby
58 **Handbook of nonwovens**
Edited by S. Russell
59 **Cotton: Science and technology**
Edited by S. Gordon and Y-L. Hsieh
60 **Ecotextiles**
Edited by M. Miraftab and A. R. Horrocks
61 **Composite forming technologies**
Edited by A. C. Long
62 **Plasma technology for textiles**
Edited by R. Shishoo
63 **Smart textiles for medicine and healthcare**
Edited by L. Van Langenhove
64 **Sizing in clothing**
Edited by S. Ashdown
65 **Shape memory polymers and textiles**
J. Hu
66 **Environmental aspects of textile dyeing**
Edited by R. Christie
67 **Nanofibers and nanotechnology in textiles**
Edited by P. Brown and K. Stevens
68 **Physical properties of textile fibres fourth edition**
W. E. Morton and J. W. S. Hearle
69 **Advances in apparel production**
Edited by C. Fairhurst
70 **Advances in fire retardant materials**
Edited by A. R. Horrocks and D. Price
71 **Polyesters and polyamides**
Edited by B. L. Deopura, R. Alagirusamy, M. Joshi and B. S. Gupta
72 **Advances in wool technology**
Edited by N. A. G. Johnson and I. Russell
73 **Military textiles**
Edited by E. Wilusz
74 **3D fibrous assemblies: Properties, applications and modelling of three-dimensional textile structures**
J. Hu
75 **Medical and healthcare textiles**
Edited by S. C. Anand, J. F. Kennedy, M. Miraftab and S. Rajendran
76 **Fabric testing**
Edited by J. Hu
77 **Biologically inspired textiles**
Edited by A. Abbott and M. Ellison
78 **Friction in textile materials**
Edited by B. S. Gupta
79 **Textile advances in the automotive industry**
Edited by R. Shishoo
80 **Structure and mechanics of textile fibre assemblies**
Edited by P. Schwartz
81 **Engineering textiles: Integrating the design and manufacture of textile products**
Edited by Y. E. El-Mogahzy

82 **Polyolefin fibres: Industrial and medical applications**
Edited by S. C. O. Ugbolue
83 **Smart clothes and wearable technology**
Edited by J. McCann and D. Bryson
84 **Identification of textile fibres**
Edited by M. Houck
85 **Advanced textiles for wound care**
Edited by S. Rajendran
86 **Fatigue failure of textile fibres**
Edited by M. Miraftab
87 **Advances in carpet technology**
Edited by K. Goswami
88 **Handbook of textile fibre structure Volume 1 and Volume 2**
Edited by S. J. Eichhorn, J. W. S. Hearle, M. Jaffe and T. Kikutani
89 **Advances in knitting technology**
Edited by K-F. Au
90 **Smart textile coatings and laminates**
Edited by W. C. Smith
91 **Handbook of tensile properties of textile and technical fibres**
Edited by A. R. Bunsell
92 **Interior textiles: Design and developments**
Edited by T. Rowe
93 **Textiles for cold weather apparel**
Edited by J. T. Williams
94 **Modelling and predicting textile behaviour**
Edited by X. Chen
95 **Textiles, polymers and composites for buildings**
Edited by G. Pohl
96 **Engineering apparel fabrics and garments**
J. Fan and L. Hunter
97 **Surface modification of textiles**
Edited by Q. Wei
98 **Sustainable textiles**
Edited by R. S. Blackburn
99 **Advances in yarn spinning technology**
Edited by C. A. Lawrence
100 **Handbook of medical textiles**
Edited by V. T. Bartels
101 **Technical textile yarns**
Edited by R. Alagirusamy and A. Das
102 **Applications of nonwovens in technical textiles**
Edited by R. A. Chapman
103 **Colour measurement: Principles, advances and industrial applications**
Edited by M. L. Gulrajani
104 **Fibrous and composite materials for civil engineering applications**
Edited by R. Fangueiro
105 **New product development in textiles: Innovation and production**
Edited by L.Horne
106 **Improving comfort in clothing**
Edited by G. Song
107 **Advances in textile biotechnology**
Edited by V. A. Nierstrasz and A. Cavaco-Paulo
108 **Textiles for hygiene and infection control**
Edited by B. McCarthy
109 **Nanofunctional textiles**
Edited by Y. Li
110 **Joining textiles: Principles and applications**
Edited by I. Jones and G. Stylios
111 **Soft computing in textile engineering**
Edited by A. Majumdar

112 **Textile design**
Edited by A. Briggs-Goode and K. Townsend
113 **Biotextiles as medical implants**
Edited by M. King and B. Gupta
114 **Textile thermal bioengineering**
Edited by Y. Li
115 **Woven textile structure**
B. K. Behera and P. K. Hari
116 **Handbook of textile and industrial dyeing. Volume 1: Principles, processes and types of dyes**
Edited by M. Clark
117 **Handbook of textile and industrial dyeing. Volume 2: Applications of dyes**
Edited by M. Clark
118 **Handbook of natural fibres. Volume 1: Types, properties and factors affecting breeding and cultivation**
Edited by R. Kozłowski
119 **Handbook of natural fibres. Volume 2: Processing and applications**
Edited by R. Kozłowski
120 **Functional textiles for improved performance, protection and health**
Edited by N. Pan and G. Sun
121 **Computer technology for textiles and apparel**
Edited by J. Hu
122 **Advances in military textiles and personal equipment**
Edited by E. Sparks
123 **Specialist yarn and fabric structures**
Edited by R. H. Gong
124 **Handbook of sustainable textile production**
M. I. Tobler-Rohr
125 **Woven textiles: Principles, developments and applications**
Edited by K. Gandhi
126 **Textiles and fashion: Materials design and technology**
Edited by R. Sinclair
127 **Industrial cutting of textile materials**
I. Vi umsone-Nemes
128 **Colour design: Theories and applications**
Edited by J. Best
129 **False twist textured yarns**
C. Atkinson
130 **Modelling, simulation and control of the dyeing process**
R. Shamey and X. Zhao
131 **Process control in textile manufacturing**
Edited by A. Majumdar, A. Das, R. Alagirusamy and V. K. Kothari
132 **Understanding and improving the durability of textiles**
Edited by P. A. Annis
133 **Smart textiles for protection**
Edited by R. A. Chapman
134 **Functional nanofibers and applications**
Edited by Q. Wei
135 **The global textile and clothing industry: Technological advances and future challenges**
Edited by R. Shishoo
136 **Simulation in textile technology: Theory and applications**
Edited by D. Veit
137 **Pattern cutting for clothing using CAD: How to use Lectra Modaris pattern cutting software**
M. Stott
138 **Advances in the dyeing and finishing of technical textiles**
Edited by M. L. Gulrajani
139 **Multidisciplinary know-how for smart textiles developers**
Edited by T. Kirstein

140 **Handbook of fire resistant textiles**
Edited by F. Selcen Kilinc
141 **Handbook of footwear design and manufacture**
Edited by A. Luximon
142 **Textile-led design for the active ageing population**
Edited by J. McCann and D. Bryson
143 **Optimizing decision making in the apparel supply chain using artificial intelligence (AI): From production to retail**
W. K. Wong, Z. X. Guo and S. Y. S. Leung
144 **Mechanisms of flat weaving technology**
V. Choogin, P. Bandara and E. Chepelyuk
145 **Innovative jacquard textile design using digital technologies**
F. Ng and J. Zhou
146 **Advances in shape memory polymers**
J. Hu
147 **Clothing manufacture management: A systematic approach to planning, scheduling and control**
J. Gersak
148 **Anthropometry, apparel sizing and design**
D. Gupta and N. Zakaria
149 **Silk: Processing, properties and applications**
K. Murugesh Babu
150 **Advances in filament spinning**
D. Zhang

To my dear parents.

Introduction

Fire resistant textiles are one of the fastest growing sectors in industrial textiles. Military personnel, police officers, firefighters, healthcare workers, and those who work in various industrial settings rely on clothing and other equipment for protection against bullets, flames, hazardous chemical splashes, punctures, etc. The purpose of this book is to provide an update on the considerable advances that have occurred in the field of fire resistant textiles in recent years. It is based on the work of numerous researchers and scientists who have devoted the majority of their time and effort towards the advancement of knowledge in the field of fire resistant textiles. The book is intended both for readers in industry, from fiber and fabric manufacturers to garment designers, manufacturers and safety professionals, as well as academic readers, from researchers to students in universities and colleges.

This book is organized into four parts. Part I provides an overview of fire resistant textiles. In this overview, burning and combustion mechanisms of textile fibers, chemical modification of natural and synthetic fibers to improve flame retardancy, multi-component flame resistant coating techniques for textiles, and care and maintenance of fire resistant textiles are discussed along with the safety, health, and environmental aspects of flame retardants. Part II covers different types of fire resistant fibers and fabrics, including flame retardant cotton, manmade cellulosics, wool, ceramic fibers and blends, composites and nonwovens. Part III reviews aspects of testing and regulation. It starts with the selection criteria for fire resistant protective clothing and then focuses on the testing, standards, and regulation of fire resistant clothing and soft furnishings. Part IV deals with case studies that detail six major applications of fire resistant textiles. Throughout this book, the terms 'fire resistant' and 'flame resistant' are used interchangeably.

Materials such as textiles used in everyday life consist of mainly organic polymers, which are flammable. Flame retardants have been developed to reduce the risk of fire either by inhibiting the possibility of the material igniting or reducing the rate of flame spread in the event that it does. In Chapter 1 of this book, D. Price and A. R. Horrocks of the University of Bolton review the current knowledge of the processes involved in the combustion behaviour of textiles and approaches to their flame retardant