11
Thermal exposure

The effects of heat on textile products merit a separate chapter, because they are so important in determining whether the material can be regarded as a durable one. Heat is so frequently encountered by fabrics that it is almost automatically considered as an integral part of the list of constraints imposed on a fibre product, no matter what the intended end use.

11.1 Intensity

The actual results of exposure to heat, however, are entirely dependent on the intensity of the thermal source to which the textile material is exposed. These heat sources can include hot air (heated by any of the conventional means, such as electricity, gas, steam pipes, etc.), infrared, microwave or ultrasonic devices. No matter which source is used, though, the effects on the textiles are similar. The differences between the sources are restricted to the way in which the energy reaches the fabric, and the efficiency of conversion to actual usable heat, not to the way in which the heat generated reacts with the material.

11.1.1 Exposure levels

At the lowest level of exposure, no detectable thermally damaging effects can be observed. There must, though, be some molecular modifications occurring, since changes in the fabric do indeed take place, but they are generally regarded as being insignificant in comparison with other changes brought about by exposure to air, moisture or other agents. Heat energy, however, reaches the fabric, increasing the molecular movement, a change that implies the possible modification of some bonds. These are most likely to be in the side chains where, as mentioned earlier, small incident energy first affects the target. The tangible result that we do observe is the phenomenon of thermal insulation. A heat source on one side of the textile emits energy that does not penetrate instantly through the material, so that some of it must be retained within the fibrous structure. The degree of this retention is governed by the actual structure present. Zhang[1] and Bajaj[2] discuss in detail the phenomenon of heat retention in textile materials in their contributions to a book dealing with the development of the new so-called 'smart' textile products.

11.1.2 Insulation

The arrangement of textile material may vary from very open to very closed. We speak of the degree of openness of a structure with reference to open- or closed-cell arrangements. The two are illustrated schematically in Fig. 11.1. In Fig. 11.1(a), it is obvious that there are many passages from one side of the fabric to the other. Thus, air heated on the upper side of the fabric can pass through to the lower side, the rate at which passage takes place being governed by the ease of movement of the air. A very open structure will provide less impedance to flow, so allowing air (and hence heat) to move through relatively rapidly, while a more closed structure will delay the passage more effectively. In the limit, when the structure is extremely close, we reach the point at which there are no passages left through the material, a situation equivalent to the closed-cell structure of Fig. 11.1(b). In this case, the air in a cell near the surface on the upper side of the fabric is heated by the source, but the air contained inside the cell is trapped there and cannot pass on its energy directly across the fabric by convection. Instead, it heats the cell wall, which in turn heats the air on the other side of the cell, so that the next cell also begins to heat up. This process continues until all the cells, from the upper side to the lower side, have been heated. The consequence is a temperature gradient from top to bottom that is much greater than was the case in the open-cell structure.

Two results follow from this fact. The first is that the closed-cell structure produces a much better thermal insulator than the open-cell one. The second is that the energy concentration in the portion of the closed-cell structure near the heat source (which is still receiving energy throughout the slow heat transfer process) will quickly reach a high temperature, one that matches that of the heat source in due course. Thus, if the source temperature is high, the closed-cell structure will be at a much greater risk of suffering damage than the open-cell one if damage is a possible end result of the heating procedure.

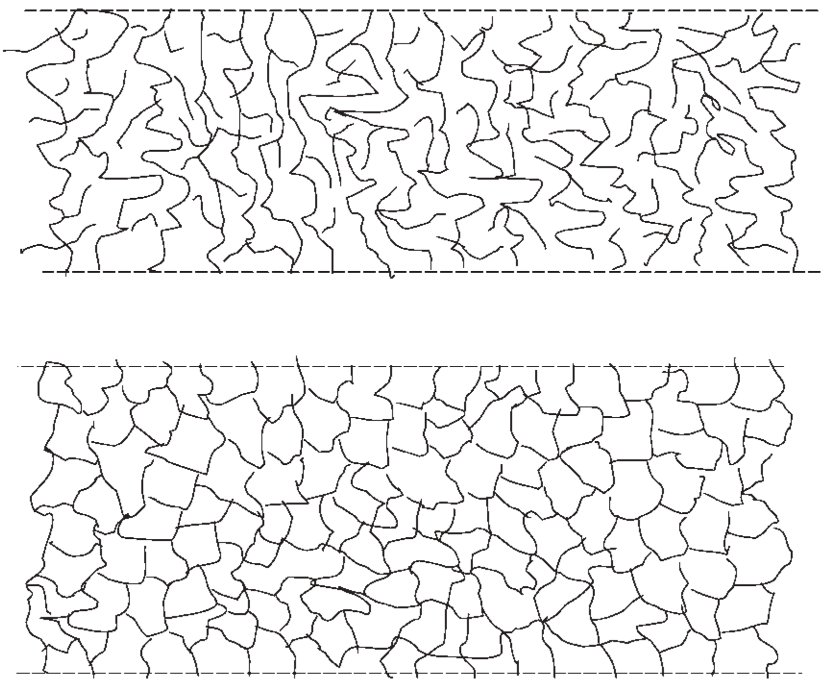
As the amount of heat energy reaching (or retained within) the fabric rises, the potential for damage occurring becomes larger. Perhaps the most familiar case where this risk occurs routinely in the textile industry is in the drying of fabrics. Drying can be used at many other stages in textile processing (notably after washing or scouring of fibres, or dyeing of fibres or yarns) and the factors included here also relate to those alternative places in the production line where drying is incorporated.

11.2 Static drying

Fabric drying can take place in a variety of ways. Historically (and even today in primitive societies) drying was accomplished merely by leaving the fabric exposed outdoors in sunlight. This technique has long been abandoned in Great Britain,

(a)

(b)



11.1 Thermal insulation in open and closed cell structures. (a) Open-cell structure, (b) closed-cell structure.

though the possible advent of a balmy climate may tempt manufacturers to revert to it in an attempt to reduce pollution if global warming creates a desert of the entire northern hemisphere. In other societies, though, the loop or festoon dryer, the drum dryer and the stenter (or tenter) are normally preferred.

In the first of these, cloth is hung from a rack in an enclosed room in which warm air is circulating and is left there until the drying process has been accomplished, an exactly comparable analogy to the drying taking place in front of a fire in homes of a bygone age. The drum dryer, as is implied by its name, uses a heated metal drum, around which the fabric is tightly passed, to remove the water. In a drying oven, where the textile material is exposed to high temperature, it is usual to arrange for the goods to be moving relative to the heat source, either by establishing an airflow around the fabric or (as in the stenter) by drawing the fabric through a heated region of the machine.

11.3 Stenters

11.3.1 Process details

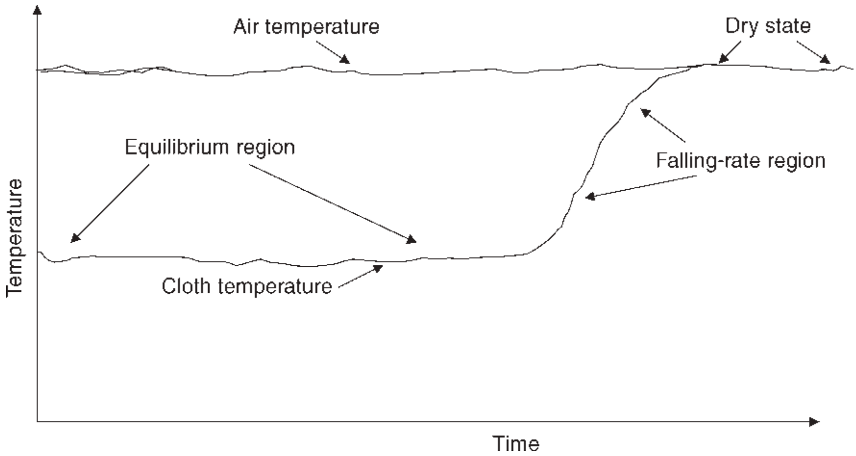
Modern efforts to reduce financial losses and ecological loading have led to research into more efficient dryers. This has focused mainly on the stenter, which is felt to have the most potential for savings to be achieved. In it, the fabric is stretched between pins or clips at either side of the machine and drawn through a box inside which hot air is being blown. If drying is carried out correctly, the only significant change is the fact that water is slowly evaporated from the surface of the fabric, reaching there by a wicking process from deep within the fibrous mass. As a fabric dries, the moisture evaporates from its surface, to be replaced by fresh supplies of water moving from the interior of the cloth, setting up an equilibrium condition as long as there is any water remaining in the material. In this (steady-state) region of the drying process, the cloth remains at a constant temperature, at a fixed interval below that of the air in contact with it. Once loose moisture has been consumed, then bound water from inside the fibre begins to be extracted, and the cloth temperature slowly rises because this water is more difficult to remove. The final stage, in which molecular water is removed from the actual fibre structure, can bring about damage to the cloth in the form of scorching, and a rise in temperature is observed in both air and cloth. The aim of the dryer operative is to ensure that the fabric emerges before this stage is reached, but after all the loose water has been removed. Ideally, the fabric should leave the stenter at its equilibrium regain moisture content to minimise the chance of scorching or cockling, resulting from over- or under-drying, respectively.

11.3.2 Drying equilibrium

Figure 11.2 shows the situation at equilibrium during drying. The air surrounding the cloth (no matter how the air has been heated) has a temperature T_a, while the cloth is at a lower temperature, T_c. The latter temperature remains constant (the so-called wet-bulb temperature) as long as the moisture content at the surface remains constant, fed by the moisture moving to the heated surface from within the cooler depths of the fabric.

As soon as the flow rate falls, depriving the surface of moisture, the same amount of heat energy is no longer required to evaporate the water. Thus, temperature increases and the formerly constant wet-bulb temperature curve changes to one in which the temperature is rising gradually (the so-called falling-rate region of the drying curve). In this region, some of the heat is actually absorbed by the fabric molecules, rather than by the water molecules, so that internal changes in the molecular structure of the textile begin to occur. If the evaporation continues to occur to the point at which all the moisture has been removed before exposure to the thermal source is discontinued, then the fabric temperature rises to that of the heated-air source, as indicated at the right-hand side of Fig. 11.2. The level of this temperature will determine the type of change that can now take place in the textile structure.

Vallier[3] outlines all methods of drying yarns, woven fabrics and non-wovens, comparing warm air with steam transfer in imparting heat to the material, with an examination of systems in which warm gas, warm metal and radiation (infrared or



11.2 Temperature changes during fabric drying.

microwave) dryer types are used. Giessmann[4] describes a high-speed jet dryer for coatings, listing the needs for successful operation as (a) enough fresh air to dilute solvents, (b) controlled recondensation to avoid drips that could mark the coating, (c) controlled air flow to avoid any change in coating conditions, such as coat thickness or strength and (d) a continuously adjustable heat supply to 225°C for better dryer control.

11.3.3 Environmental problems

Each type of dryer system has its particular environmental problems, though many of them are shared in common by all of them. The obvious one universally relevant is the matter of energy use. The heat needed to dry the fabric is not entirely used for this purpose, because a considerable portion of it escapes to the surrounding air. Various attempts to reduce the waste are made; the temperature may be lowered and the fabric left in contact with the heated area for a longer period of time, for example, but the economics of reduced production speed and the inability to prevent heat loss over a long time period both mitigate against taking this ‘solution’ too far. In the stenter, division of the heated box into sections, each at a different temperature, is often used, though there is, of course, no means of accomplishing total isolation of any one area in view of the need for cloth to be allowed to travel between them via open slits.

Cantrell[5] reviews developments in dryer technology, noting that better control of temperature and relative humidity, the key to successful drying, occupies the attention of many manufacturers, together with an increased trend towards automation. Schwartze[6] revives the idea of using superheated steam, first proposed over 40 years ago, to avoid the risk of all water being lost from the fabric. He notes that, at 130 to 150°C and a cloth travel rate of 1 to 1.5 m/s, high and reproducible drying rates can be achieved. The absence of total dryness would eliminate the objections of Hughs and Price,[7] who find that cotton quality is significantly reduced if high-temperature drying on 'dry' (6% moisture content) cotton is carried out, but no ill effects are observed if the initial moisture content is fixed at 18% during the drying. Gogoi *et al.*[8] working with silk, note that deterioration by heat is more rapid if light is present, so it follows that valuable silk articles (such as historic fabrics in museums) should be stored in an enclosed airtight space under controlled temperature conditions.

11.4 New equipment

New equipment also features prominently in literature. Rydergren[9] describes a tumble dryer capable of measuring the moisture content actually in the cloth, not merely in the air, a need reported many years ago (and met) by the author and some of his students.[10–12] Hartmann[13,14] introduces a new stenter design, in which quality and output are both increased while energy consumption is reduced. The same benefits are claimed by an anonymous author[15] with regard to a multilayer stenter, which also occupies less floor space and needs less supervision. Olsen[16] suggests the use of a laser beam for yarn drying, noting that it is capable of heating any fibre type at very high speeds.

11.5 Problems

11.5.1 Emissions

A further common problem is the fact that the heating may cause evolution of harmful agents ***(* A-2, A-3)*** (see Table 1.1 for an explanation of codes) to take place. If the fabric is not completely free of chemical reagents used in a previous stage, for instance, the effect of the heat may bring about some decomposition and toxic material may be emitted. One such example is the production of hydrochloric acid or a cyanide when drying of incompletely removed excess antistatic, flame-retardant or softening compounds occurs.

11.5.2 Damage

The fabric, too, may decompose if the temperature is too high. The familiar sight and smell of scorched cloth, well known in the above-mentioned bygone homes, is duplicated in industry when an operative uses the wrong heat setting or allows the fabric to travel through the tenter too slowly. The result is a costly one for the environment as well as for the manufacturer's pocket, since all the steps undertaken up to that point, from production of the fibre, are totally wasted if the fabric has to be scrapped. Any attempt to prevent such loss, by only partially drying and allowing the fabric to emerge still wet, may backfire if the damp cloth begins to rot or to cockle as a result of the excess residual moisture. The most risky aspect of this type of problem occurs in heat-setting, where an extremely high temperature is used to 'set' or 'cure' a finish (notably a permanent press one) on the fabric. In such cases, the time of exposure to the intense heat is of the order of seconds, but underexposure may mean that the finish is not properly set and can wash out, while overexposure can bring about destruction of the finish as well as the cloth.

The first indication that changes have occurred is the way in which the fabric becomes harsh to the touch. This brittleness, or denaturing, results from the removal of all or most of the natural moisture normally present in the textile structure. Clearly, if water has been removed, then bonds must have been broken. Some of these will be in the side chains, where substitutional changes have taken place, but others (especially at higher levels of exposure) may well represent side chains that have been broken off from the main chain. As this denaturing becomes more pronounced, the next observable change, one in which colour modification is visible, begins to take place.

The initial symptom is usually a yellowing, on the assumption that a white fabric is the one originally under consideration. This may again represent a change in the structure within a side chain, where specific types of bond are either converted from double to single or vice-versa. The vibrational energy being absorbed is at a different frequency as a consequence, so that absorption in the visible region now takes place, as is evident by the changed appearance.

Further increase in energy brings about still more evidence of destruction. The colour change will now begin to be much more noticeable, being orange, brown and black in turn as increased energy absorption brings about increased destruction of the molecular structure. At the same time, dimensional changes are commonly seen; the fabric shrinks, twists or distorts in a non-reversible manner. These changes represent an exceptionally high level of thermal exposure, with main-chain scission being at least partly responsible for them, and would obviously be the result of a major error in commercial drying. Similar changes can be seen, however, if domestic ironing or drying before an open fire is done without due care.

11.6 Novel approaches

It was partly in an effort to reduce or eliminate these damaging changes that novel techniques for fabric drying were introduced into the textile industry. When fabric drying brings about this much damage, it is not only the environmental harm of discarding the fabric (together with the work carried out, energy used and raw materials or chemicals wasted in all the previous stages of its production) that is of concern, but also the immense financial loss that has been incurred in all these stages. If some safer (i.e. less damaging) way to expose fabrics to thermal energy can be devised, then clearly the margin of error before destruction takes place will become much wider. The earliest heating procedures, using hot air circulating around the tenter, suffered from the fact that a change could not be made rapidly enough to correct the situation if excess heating was taking place. There is a distinct time lag after noticing a harmful situation (and operating the correction control) before the faster-moving fabric can emerge or the air flow shut-off valve can stop hot air from being present in close contact with the cloth.

The earliest simple modification was to use gas or electric heat in close proximity to the cloth as the source of energy. In theory (but not always in practice) these sources can be reduced to a low level at a very fast rate, so minimising the damage brought about in an error situation. Unfortunately, both are relatively expensive sources of energy and tend to heat the air as well as the fabric, leaving a residual high temperature in the vicinity of the cloth that can cause damage as before. For this reason, radiant heating from an infrared source was the next type of energy exposure system tried. This is far superior, especially as the energy is only absorbed when contact with a tangible target (i.e. the fabric) occurs, not during passage through the air. Thus, the surrounding air remains at a relatively low temperature, so preventing cloth damage by exposure to it. Other types of energy sources for drying, investigated subsequently, include microwave and ultrasonic ones.

These last mentioned sources are still, to a certain extent, at an experimental stage of investigation. They appear to be effective (in terms of minimising both cost and cloth damage), but some drawbacks are beginning to emerge. Ultrasonic energy is used elsewhere in the industry, as mentioned earlier, to shred fibre samples for analysis by X-ray spectroscopy, so there must be some potential for mechanical damage to occur if a high level of exposure (as may well be needed for satisfactory drying to take place) is adopted. There has also been the suggestion of some evidence to indicate that the mere presence of microwave radiation (in the vicinity of overhead high-voltage electrical power supply lines, for example) may adversely affect materials in the area, including those of which the human body is composed, so there is reason (but so far no factual evidence) to suspect that textile degradation may also occur as a side product of its use in the drying process.

11.7 Flammability

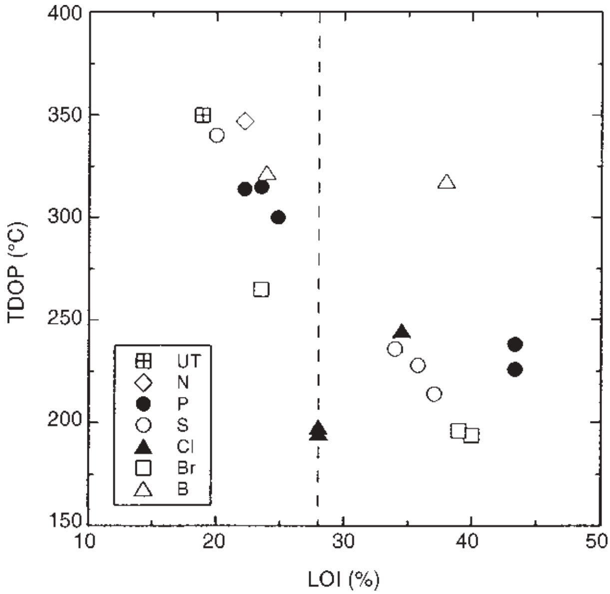
Environmental factors become most noticeable in the most severe application of thermal energy. If the heat applied to certain textile materials is extremely high, they can ignite and burn. The flammability of a textile (on the assumption that no flame-retardant finish or other treatment has been applied to it) is determined in the main by its molecular structure. A fibre that contains large quantities of oxygen, in conjunction with the carbon commonly present, for instance, is in general more likely to ignite and to continue burning after the flame source has been removed than one in which there is little or no oxygen. A fibre in which there are flame-retardant atoms (such as nitrogen, phosphorus or a halogen) inherently present in the structure is less likely to ignite than one in which they are absent. Smith[17] summarises the information needed to judge the ability of a number of fibres to resist high temperatures by providing a table of properties of high-performance and high temperature-resistant fibres.

11.7.1 Effects

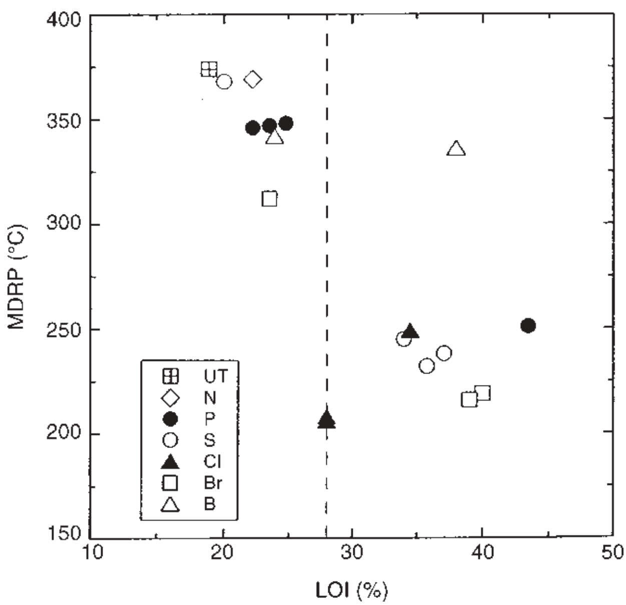
There are many sources of information about flammability; indeed, it is a subject on which vast amounts of literature have been written. For the purpose of this book, it is thus pointless to recount all the details of its many aspects. There is, however, one area that needs to be brought to light, that of the connection between flammability and the environment. The waste involved, the toxic emissions and the environmental cost of treatments are all important factors in the contribution of thermal attack to ecological damage, while the lack of resistance of many textiles to heat also needs to be taken into account. In other words, flammability is one of the instances where there is a two-way relationship between textile products and the environment. Kearns[18] reviews the topic of flammability, giving details of test methods and factors affecting the phenomenon, such as fibre content, fabric construction, oxygen accessibility, weight, dyes and finishes. Indushekar *et al.*[19] investigate the development of finishing treatments that could impart resistance to flame, water and oil to fabrics for chemical warfare protective clothing, but do not give any information to determine how much environmental risk is associated with such treatments. Sicratt Powell[20] reviews the use of phosphorus-based flame-retardant reagents for textiles, without mention of any new compounds that resolve the difficulties.

Flame-resistant treatments have been of major concern as a result of a number of fires that have taken their toll on the life of human beings, especially those in the very young or very old age ranges. These people are unable to react quickly to an emergency, so can be engulfed by fire before they have any chance to escape from or extinguish the flames. It is not usually the flame which is fatal, though, but the toxic gases present as a result of combustion. These gases include carbon monoxide and hydrogen cyanide, so it is hardly surprising that survival times in atmospheres surrounding a fire are not usually too long. There is also a grave risk that anybody in a burning building has to contend with large quantities of smoke, so that clear sight is not usually possible and escape is thus hampered. The shock, too, of being confronted by flames can bring about a heart attack or a bout of panic that can prevent escape from the fire.

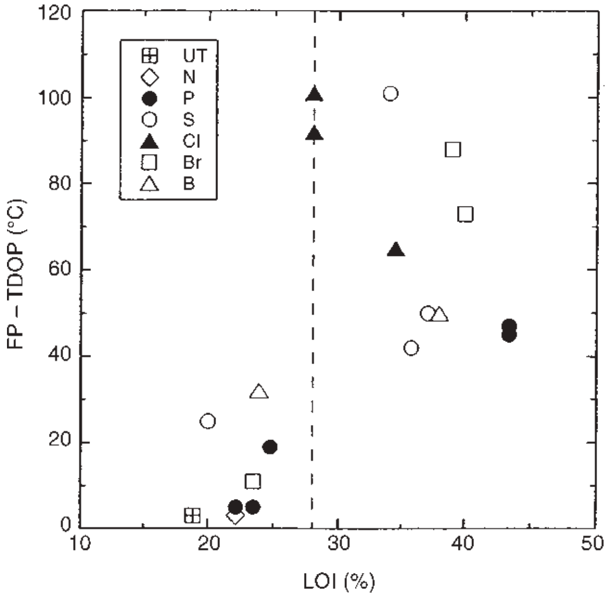
Cantrell[21] and an author from a French organisation[22] independently focus on aspects of the latest developments in treatment of home furnishings against fire, while Nakanishi and Hashimoto[23] compare the effectiveness of compounds of nitrogen, phosphorus, sulphur, halogens and boron, the traditional materials used in this area, singly or in paired combinations. Figures 11.3 to 11.5 show how limiting oxygen index (LOI) and various stages of the drying progress are related.



11.3 Correlation between TDOP and LOI for a cotton fabric (source: ref. 23).



11.4 Correlation between MDRP and LOI for a cotton fabric (source: ref. 23).



11.5 Correlation between the difference (FP–TDOP) and LOI for a cotton fabric (source: ref. 23).

TDOP (thermal degradation onset point), MDRP (maximum degradation rate point) and the difference between TDOP and FP (flash point) are all crucial indicators of thermal changes and their interdependence with limiting oxygen index can readily be seen. An anonymous writer[24] reports a flame-retardant process that reduces the formaldehyde emissions frequently observed in combustion products to 5 ppm, well below the maximum permissible standard of 20 ppm, with no change in fabric qualities.

11.7.2 Textile impact

Flammability can have an enormous impact on textiles, since a flame can destroy a fibrous material completely. When ignition occurs, the molecules begin to undergo a major change, with total destruction of main-chain bonds taking place as combustion continues. Charring, the transformation of a whole piece of fabric into a twisted, black, shapeless lump that has lost all semblance of its original form, is succeeded by the disappearance of part or all of the textile, leaving behind a small mass of ash or a bead of molten residue. In short, flammability utterly destroys a fabric, rendering it totally useless and unfit for any attempt at recovery. Thus, the environment suffers, by having a burnt piece of rubbish discarded into it. In addition, the actual side effect of this burning is the production of substances harmful in themselves to the environment. Combustion of a textile can yield not only carbon dioxide ***(* A-1)***, the obvious product of the oxidation of carbon, but also a whole range of undesirable substances ***(* A-2)***, ranging from simple ones like carbon monoxide or sulphur compounds to more complex (and highly toxic) ones like cyanides or furans. These can bring about all kinds of secondary problems for the ecological health of the planet and the species in it.

11.7.3 Benefits and risks

In a conference report Holme[25] balances the benefits of flame-retardant textiles against their environmental risks. As noted by several speakers, flame retardation saves lives and several of the substances used to retard fire spread, such as oxides of aluminium and antimony, together with various organic compounds, supposedly cause no significant risks to humans. The suggestion is made of using life-cycle analysis, rating the environmental impact from 0 (no impact) to 90 (maximum impact). Application of this principle shows that most compounds are similar in rating. Concerns remain, however; there is some suspicion that the incineration of bromine-containing flame retardants may produce dioxins ***(* A-2)***, though no evidence has been obtained to confirm or refute this hypothesis as yet. A list of acceptable compounds and of ones needing further studies regarding exposure risks is provided. Barton[26] reviews new studies in flame-retardant compounds, pointing out that their toxicity is often lower than had been predicted. She notes, though, that more studies are needed on compounds of antimony or molybdenum, organophosphorus compounds and chlorinated paraffins. She quotes a promising line of research involving intumescent materials, ones that char on ignition and can thus form a barrier against further flame spread. Lin *et al.*[27] investigate the effectiveness of nine new boron flame-retardant compounds, finding the results of their study to be encouraging. They state that the flame retardancy is enhanced by increased amounts of boron, the addition of halogens to the boron compound and the presence of coordinated bonds between boron and phosphorus or nitrogen. The latter factor also enhances wash fastness of the finish.

The effects of exposing textiles to thermal energy range from near-undetectable to the most severe ones, depending on the level of exposure. Though the natural thermal environment, in general, produces little harm in contrast to that brought about by shorter electromagnetic radiation, like light or ultraviolet exposure, we must not forget that, as a consequence of the presence of our species on the planet, higher-than-natural levels of heat are evident at many stages in the life of a textile. The augmented natural environment, changed by human activities, is one in which textile products are forced to exist and to suffer the degradation resulting from their interaction with it. Thermal degradation is indeed a tribulation of tremendous importance to the useful life of a textile material. The only other degradative sources even remotely comparable in their widespread applicability and effects are the chemical and microbiological ones. These will be considered in the next chapter.

References

1 Zhang, X., 'Heat-storage and thermo-regulated textiles and clothing', in Tao, X. (ed), *Smart Fibres, Fabrics and Clothing*, Cambridge, Woodhead, 2001.
2 Bajaj, P., 'Thermally sensitive materials', in Tao, X. (ed), *Smart Fibres, Fabrics and Clothing*, Cambridge, Woodhead, 2001.
3 Vallier, P., *Tinctoria*, 1999, **96**(3), 52–60.
4 Giessmann, H., *Int. Dyer*, 2001, **3**, 26–27.
5 Cantrell, M., *Int. Dyer*, 1999, **184**(4), 28–30.
6 Schwartze, J.P., *Wool Res. Org. NZ Rep.*, 1998, **R 215**, 1–22.
7 Hughs, S.E. and Price, J., *Proceedings 1998 Beltwide Cotton Conference,* San Diego, USA, National Cotton Council of America, Jan 5–9, 1999, pp. 1637–1641.
8 Gogoi, S., Baruah, B. and Sarkar, C.R., *Colourage*, 1999, **46**(2), 23–30.
9 Rydergren, S., *Textile Tech. Int*., 1998, **7**(6), 5.
10 Crow, R.M., Gillespie, T. and Slater, K., *J. Textile Inst*., 1974, **65**, 75–81 and 228–230.
11 Crow, R.M. and Slater, K., *Textile Res. J*., 1974, **44**, 309–378.
12 Chakravarty, R.K. and Slater, K., *J. Textile Inst.,* 1978, **69**, 370–378.
13 Hartmann, W., *Melliand Int.,* 1998, **3**, 206–208.
14 Hartmann, W., *Colourage,* 1998, **45**(7), 49–54.
15 Anon., *Knitting Tech*., 1998, **20**(6), 262–263.
16 Olsen, D.E., *High Perf. Textile*, 1999, February, 6–7.
17 Smith, W.C., *Textile World*, 1998, **148**(10), 53–64.
18 Kearns, C., *Can. Apparel*, 1998, **22**(2), 22–23.
19 Indushekar, R., Abo-Shosha, M.H., El-Iayel, M.Z. and El-Alfy, E., *Man-Made Textiles in India*, 1998, **41/5**, 208–216.
20 Sicratt Powell, C., *Am. Dyestuff Rep*., 1998, **87/9**, 51–53.
21 Cantrell, M., *Int. Dyer*, 1998, **183**(10), 17.
22 Filature de L'Avesnois, *High Perf. Textiles*, 1999, June, 3.
23 Nakanishi, S. and Hashimoto, T., *Textile Res. J.,* 1998, 68, 807–813.
24 Anon., *Textile Month*, 1998, May, 48–49.
25 Holme, I., *Int. Dyer*, 2001, **1**, 34–37.
26 Barton, J., *Int. Dyer*, 2000, **7**, 16–20.
27 Lin, M., Zheng, L., Mao, Z. and Jiang, H., *Can. Textile J.*, 2001, **1**, 71–73.

12

Chemical and microbiological attack

Textile fabrics are often subjected to attack by chemical agents, during both production and use. The effect produced will depend on a range of factors, notably the type of fibre, the type of reagent, the temperature at which contact between the material and the reagent occurs and the concentration of the reagent.

12.1 Reagents

Reagents that can be expected to come into contact with textiles on a regular basis include acids, bases, salts, bleaching agents, other oxidising agents and organic materials such as solvents or more complex molecules. The effects to be expected range from undetectable ones, through colour change and change in handle or dimensions, to partial or complete destruction. Whether the effects are enough to warrant discarding the textile material, thus putting a load on the environment prematurely, depends almost entirely on the type of product involved. A slight change in property (such as a fading of colour or a roughening of the surface) may render unacceptable an evening dress, or one component of a two-piece set or a portion of a carpet faded differentially by light. The same degree of change, though, may not be regarded as critical in an everyday dress or in car upholstery. Even very noticeable changes in appearance, which would cause an everyday garment to be rejected for further use, may be tolerated in working clothing and would certainly not be of any importance whatsoever in an industrial application, such as a tarpaulin, conveyor belt or geotextile. Conversely, a small hole worn in a fabric may be accepted in working clothing, especially if it happened to be in some part of the body where its presence is not obvious, but such a flaw would be very objectionable in, say, protective clothing, because it would allow harmful substances to penetrate to the human skin and cause illness or injury. A small hole would also not be tolerated in a container bag, as it would allow the contents to leak out, or in a conveyor belt, where it could snag and lead to a catastrophic failure, or in a tarpaulin protecting delicate materials from adverse weather conditions.

12.2 Fibre type

12.2.1 Protein fibres

Thus, the undesirability of the presence of chemical substances, even though their contact with textiles may be inevitable, is dependent on the precise situation. The importance of fibre type should be considered first. In production, for example, acids are regularly used to treat wool in carbonising or scouring and, on occasion, in bleaching, dyeing or finishing. As long as the acid is in dilute form, there is virtually no harm done to the fibres, so the treatments are regarded as highly desirable and safe. In the case of alkalis, though, making the same assumption would be dangerous for a wool fabric. Alkalis are indeed used in the production of wool, as in alkaline scouring, bleaching (notably with hydrogen peroxide), fulling, dyeing or finishing. However, these treatments are always carried out with extreme caution because of the risk of damage. The same is true of bleaching agents, many of which are also harmful to wool. Chlorine bleaches are so damaging that they simply must not be used. Wool is very seldom bleached to a white shade (but is more usually left in a creamy white). Even less severe bleaching agents, such as permanganate or peroxide ones, are potentially able to lower the quality of wool, so must be used with caution. All of these comments, incidentally, are generally true for other hair fibres and silk as well as for wool, though silk is slightly less susceptible to some of the harmful reagent types and more so to others.

12.2.2 Cellulosic fibres

The reverse situation generally holds for cellulosic fibres, such as cotton, linen or viscose. These are relatively immune to alkaline damage, but much more susceptible to harm from contact with acids. Alkaline treatment is used, for instance, to produce mercerised cotton; the sodium hydroxide is applied to the cotton at a very concentrated level (about 38%), yielding a stronger and more lustrous fibre. It is true that, if exposure is prolonged, the fibre can disintegrate, but the time needed for such a drastic change is quite lengthy and does not constitute a real drawback to successful operation of the mercerising step. Acids, though, are so damaging that it is not possible to use acid dyes on cotton without risking harm. Despite this sensitivity, however, acid treatments are sometimes used in special cases. Organdy, for example, is made by treating cotton (usually after dyeing with a colour that will help to resist acid damage) with sulphuric acid at relatively high concentrations to render the fabric partially transparent. The treatment, though, is carried out under split-second timing conditions, the acid is washed off immediately, and the fibre surface is treated with an alkali to ensure that all the remaining acid is neutralised to avoid any lasting continuing reaction.

12.2.3 Synthetic fibres

In the case of synthetic fibres, especially the true synthetic ones, a different set of conditions applies. Most of them are totally impervious to attack by acids, alkalis or bleaching agents. They can be left immersed in quite strong solutions of any of these liquids for prolonged periods of time and will suffer only minimal, if any, damage. On the other hand, some of them (notoriously the acetates) are highly susceptible to the action of certain solvents that leave natural, and many synthetic, fibres totally unharmed. The more robust synthetic materials, such as nylon, polyester or olefin fibres, indeed, are undamaged by any but the most severe treatments with unusual organic compounds.

Exposure to the same classes of compounds also takes place during use, though in this case application of the degradative agent is often not deliberate. Acids potentially able to cause damage can include common household liquids, such as fruit juices, some wines and vinegar, all of which are usually spilt onto clothing only by accident. Acid rain, the ubiquitous by-product of our modern industrial civilisation, can reach clothing or outdoor sporting and industrial fabrics with little note taken of its presence, when fabrics used for tentage, boat sails, geotextile soil stabilisers or coverings for loads are used outdoors. Alkalis coming into contact with fabrics might include baking or washing soda, detergents and garden lime, all of which can easily be spilt accidentally to contaminate clothing, household linens, marquees or garden coverings. Bleaching agents, similarly, can be accidentally scattered when carrying out laundry tasks, or when maintaining a swimming pool, again providing a risk of damage to indoor or outdoor fabrics. Solvents that can come into contact with textile articles might include nail varnish (or its removers), paint thinners, stain removal fluids, tile cement or electronic component cleaning fluids.

In the latter cases, there are more risks than the chance of dissolving the fibres, a risk that is relatively low, given the tolerance of most textile-forming molecules to solvent action. It is more likely in many cases that the fabric will suffer damage because of impurities in the solvent, which will bring about a deposit onto the surface of the textile in the form of a stain so difficult to remove that the article may well be discarded before its useful life is completed, again producing an adverse ecological load. In the same way, salts likely to be encountered by the fabric may include spilt table salt, sodium or calcium chloride used to melt ice in winter road conditions, garden fertilisers or salt spray on a beach. All of these constitute a risk to the textile, simply because, when the liquid in which they are dissolved dries up, they will again leave on a clothing, industrial or sports fabric unsightly stains that cannot easily be removed.

12.3 Planned attack

In many cases reagents of a similar type to all of the above may be applied deliberately to textiles under conditions of normal use. Regular laundering or dry cleaning cycles are necessary by our modern standards and will expose the fabrics to alkalis, bleaching agents or solvents. In industrial applications, the textile product may actually be intended for deliberate exposure to corrosive or otherwise harmful chemicals. Filtration fabrics, for instance, will inevitably be subjected to hot oil, acids and bases or to organic compounds. Even though the filter cloth is made from a fabric especially selected for its resistance to the liquid impinging on it, there is every possibility that degradation will eventually take place, so that the filter must be replaced in due course to avoid its potential failure and as a consequence destruction of the equipment in which it is a vital component.

Textiles can also find application as industrial container linings, included to resist the destruction of the outer container by contact with the liquid contained. Double-bagging of corrosive materials (though usually in solid, rather than liquid, form) is a common practice in many agricultural or environmental situations. In transportation, goods may be wrapped in textiles to prevent contact with harmful liquids, such as acid rain or mud, and the packaging material must be resistant to these contaminants. Textile roofing fabrics and ground-level geotextiles, in the form of erosion or tidal flow control systems, are deliberately exposed to water in the form of rain, polluted effluent or saline solution. In all of these cases, the textile material forms a vital part of the system in which it is used. Its resistance against the chemicals to which it is exposed is the main reason why it is selected in the first place.

Chemical damage, although undesirable, is ever-present and virtually inevitable. Dyestuffs can be affected by the reagent contacting the fabric, or the textile itself may undergo some change in colour, dimension or surface handle. More critical damage, up to and including total destruction, is often a result of chemical exposure but the textile material may also be used to provide protection against such damage to other, more valuable, surfaces which it is designed to cover for this purpose.

12.4 Microbiological attack

Microbiological agents with the potential ability to harm textiles, making them unusable, can be classified into two distinct types, those which are insects (or insect-related) in nature and those which are derived from spores, bacteria or similar minute entities. In general, damage caused by insects tends to be localised and that caused by spores tends to be diffuse.

12.4.1 Insects

Of the insects, the most familiar are moths and carpet beetles. The clothes moth is a much smaller creature than the moths seen flying freely around outside the home, being only about half a centimetre in size, with a greyish-yellow or brown body and darker brown spots on the fore-wings. It lays eggs in dark places, as the larvae that hatch from them cannot tolerate exposure to sunlight. One convenient dark place is, of course, the inside of a storage area where textile garments are located. When the eggs hatch, the larvae eat enormous amounts and are easily able to digest wool. In general, it is the cystine or disulphide linkages that provide food for the larvae and, as these are eaten, the integrity of the wool structure is destroyed. As a result, the fibre disintegrates, with the resulting familiar holes that ruin the appearance of the article and render it unwearable. If necessary, though, the larvae will eat (but not always digest) other materials. Thus, in order to reach the supply of food represented by a tasty wool snack, the larvae will eat their way through other fibres in a blend, or through an outer layer that protects an inner (wool) one.

The carpet beetle behaves in a similar manner. It is about twice the size of the clothes moth, distinctively coloured with black, red and white markings on its back and white scales on the underside. Once again, it is the larvae, hatching from eggs laid in floor cracks under the carpet, that actually eat the wool. The larvae are spindle-shaped, with tufts of stiff bristles along the sides and ends of their bodies, but are less fussy about their diet than are clothes moths. The carpet beetle larvae, in fact, will eat a wider range of materials of animal origin, including meat proteins from (say) spilt gravy, as well as keratin from the hair of other animals than sheep, such as domestic pets. The damage tends to be characterised by long slits, rather than round holes, as the beetle larvae follow the line of the threads in a carpet instead of simply eating their way through the material from one surface to the opposite one, as the clothes moth larvae do. Barton[1] claims that carpets are the most critical area in which to apply mothproofing agents, since a colony of moths can form there easily and can subsequently spread to less accessible sites, such as closets or drawers. She notes that research is in progress on means of lowering environmental contamination by increasing fixation levels, improving containment of finish chemicals and reducing water use.

12.4.2 Moulds and fungi

The second type of microbiological agent, classified together under the name of mould or fungus, is actually represented by a wide range of creatures. Schatz[2] states that mould and mildew not only cause unpleasant odours, but can also leave stains on fabrics and bring about problems, such as discolouration, strength loss, reduced elasticity and tensile strength, which can shorten the life of the fabric, or lung problems such as allergies or diseases harmful to the user. He notes that washing is often unable to remove these defects and describes a finish that is effective and that is not incompatible with either human skin or the environment. He then demonstrates the importance of antimicrobial protection by giving a comparison between protected and unprotected fabrics.

Fungi in general obtain their nutrient supply by direct absorption, rather than by oral consumption, in a process of assimilation aided by the secretion of enzymes excreted by the fungi. There are over 100 000 types of fungi, of which several hundred may be active in causing damage in textile goods. They spread either by airborne distribution, by transmission on the bodies of animals or by a creeping process from a parent mass. When attack by enzyme-assisted absorption occurs, food in the form of carbohydrates is usually sought and textile fibres (especially cellulosic ones) can act as a rich source of this nutrient. The remaining portion of the textile is a fragile residual mass of the destroyed molecules with the carbohydrate removed. It often has an unpleasant odour resulting from the end products of decomposition. The transfer process is also aided by moisture, so that decay is accelerated in damp conditions. Many fungi are present in the soil, a fact that explains why goods such as tents or other sporting equipment are prime candidates for the rotting produced. Other chemical substances, such as nitrogen, sulphur or phosphorus, may also be the target of a fungal search for food, so that other fibres, like wool, silk or even nylon, may also suffer damage from this form of attack.

12.4.3 Bacteria

The final type of microbiological agent that can cause problems for textile goods is the bacterial one. Bacteria are again of a wide variety, though the number causing destruction of textiles is smaller than in the case of fungi. They occur in virtually all parts of the Earth, but especially (in the context of this book) in soil, in the human body and even in air or water. The problematic ones are capable of decomposing molecules into their constituent atoms, leaving behind virtually nothing tangible if the process of damage is allowed to continue unabated. This activity is the reason why very few textile samples are available from antiquity, or even from relatively recent times, and why textiles disappear totally after periods of time of immersion in the soil. The need of water for the survival of bacteria is illustrated by the fact that we do actually have a few representative textile samples from Ancient Egypt. The arid climate there and the fact that the fabrics have been buried away from light have allowed the materials to survive because bacterial growth has been inhibited under these dry and dark conditions. There are also textile grave goods from Scandinavian burials of the first few centuries that have survived to the present time, simply because they have been immersed in peat and the conditions produced by the peat (acidic, dark and moist) have prevented bacteria from growing and have preserved the wool samples virtually intact.

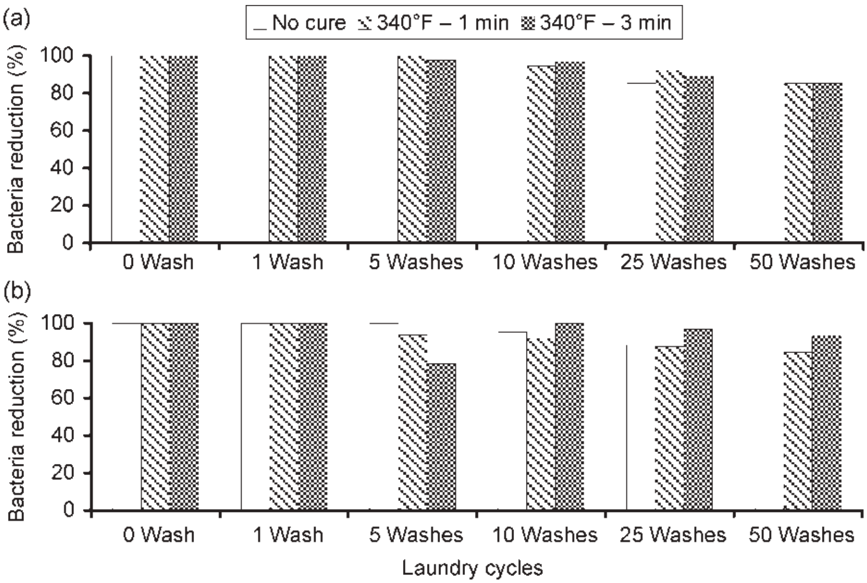
Soil bacteria are not the only ones likely to damage textiles. The bacteria present in the human body, excreted in such host habitats as perspiration, urine or other secretions, are a ready source of microbiological agents that can bring about damage. Clothing can often be seen to disintegrate into holes in areas where excretions of this type have taken place. Tendering into a weak region is quite common in such places as the underarm or crotch portions of the body. Again, darkness and moisture, both of which are characteristic of these regions, allow bacteria to thrive and multiply there in the absence of any preservative conditions (such as the acidic content of peat soil that prevents wool from rotting, as just described), thus making them a significant source of harm for the cotton clothing worn over the area.

Bacteria can also exist in food or drink. Normally, textile fabrics are not left in contact with foodstuffs for any length of time, but occasionally (as, for instance, when a cloth used to wipe up milk spills or to protect cheese from drying out is lost behind a sink or under a refrigerator) fabrics that are in contact with bacteria may be overlooked. A problem may also occur if a house is empty for some time and a piece of cloth has accidentally been left in contact with some kind of beverage; when the householders return, an unpleasant odour arising from a rotted cloth is likely to greet them at the door.

However, the bacterial problem is slowly being overcome, thanks to new finishes being introduced into textile production (as described briefly in Chapter 7). An anonymous author[3] introduces the topic of antimicrobial fabrics, with effective elimination of microbiological agents for the life of a garment, that can be used for underwear and socks. Ibrahim *et al.*[4] introduce antibacterial activity into cellulose-containing fabrics in conjunction with an easy care finish and a range of treatments that then combine to make the fabrics rotproof as well as providing other desirable properties. Yang *et al.*[5] carry out work intended to increase the durability of antibacterial treatments, examining four methods with fabrics of cotton, polyester, acrylic and other fibre types present in hosiery. All the agents they test use the controlled release mechanism, although they recognise that other methods (such as renewal by laundering and the bonding of cationic substances to fibres) also exist. They use two common bacteria, *Staphylococcus aureus* and *E. coli*, as challenges and assess the influence of various conditions of application on the effectiveness of their test substances. As shown in Fig. 12.1, increased concentrations of antibacterial agent above a critical level and different curing times have no effect on the bactericidal activity, and this activity remains potent for at least 50 launderings.

There are, though, still drawbacks to be overcome. Mansfield[6] discusses antimicrobial agents, noting that traditional ones are an environmental hazard. In modern agents there are three different types of operational mode: (a) those functioning by controlled release, (b) those in which regeneration by a chlorine bleach reactivates their effectiveness and (c) those forming a barrier. He notes that hydrophobic fibres, such as polypropylene, polyester and nylon, only need surface protection, while hydrophilic ones, such as cotton, rayon or lyocell, have to be protected in all regions of the textile where water can come into contact with the fibres. The requirements of a good antimicrobial agent include safety (i.e. low toxicity to people or the environment and a non-allergenic, non-irritant nature), compatibility (i.e. having no negative impact on textile properties or processing) and durability to multiple launderings.

In addition to the destruction of bonds, there are also instances where bacterial or fungal action can bring about discolouration of the fabric. Even textile fibres that are immune to attack by microbiological agents, such as the synthetics, can suffer



12.1 Bactericidal activity of cotton fabrics finished with 2% (a) and 4% (b) PHMB against *S. aureus*. The number of laundry cycles in each group (left to right) is 0, 1, 5, 10, 25 and 50, respectively (source: *Textile Chemist and Colorist & American Dyestuff Reporter*, Vol. **32**, No 4, April 2000, pp 44–49; reprinted with permission from AATCC).

visual damage that makes them unacceptable. The usual cause of this is the death or decay of some of the microbiological agent on the cloth surface, leaving residual stains that cannot be removed by normal maintenance procedures. In such cases, laundering and dry cleaning are ineffective. The only possible means of solving the problem is by resorting to chemical treatment with a bleaching agent or an acid that can destroy the invasive entity, although even these are sometimes ineffective. When this is the case, there is no alternative but to discard the article, with the end result of an adverse ecological load.

New work is abundant in trying to devise more environmentally friendly alternatives. Sun and Xu[7] note that durable finishes for antibacterial activity without adverse effect on fabric properties are indeed available and explain[8] antibacterial action in simple terms. Benisek[9] reports on a conference devoted to the topic, extending also to combating fungi, static electricity and ultraviolet radiation. Vigo *et al.*[10] suggest the use of various magnesium compounds with hydrogen peroxide as antibacterial agents and show various fibre types before and after treatment with antibacterial agents and laundering. Lin and Wong[11] prefer to recommend quaternary ammonium compounds because they are non-toxic and not carcinogenic. Anonymous authors in two journals mention finishes effective against bacteria plus either fungi[12] or static electricity,[13] respectively. Lee *et al.*[14]

report a finish using chitosan and fluoropolymers that makes fabrics resistant to blood, as well as bacteria. Another worker[15] provides details of an unusual antibacterial treatment based on pure metallic silver dyed into nylon yarns. Toray Industries[16] report a finish that can withstand industrial washing and is effective against many different types of bacteria.

No matter which of the microbiological agents discussed above is responsible for attacking the textiles, the final result is the same. The fabric is made useless by weakening, by staining or by actually disintegrating into holes. The tendency for this to happen with insects is much lower than it used to be, thanks to the modern methods of approaching the problem already discussed, but the omnipresent nature of the smaller agents, mould, fungi and bacteria, make it difficult to guard against damage from these sources. Careful maintenance can help, but it is necessary to keep a continual watch for the presence of these harmful substances and to prevent them from thriving if textile preservation is required.

References

1 Barton, J., *Int. Dyer*, 2000, **9**, 14–16.
2 Schatz, K., *Int. Dyer*, 2001, **6**, 17–19.
3 Anon., *Int. Dyer*, 2001, **6**, 28.
4 Ibrahim, N.A., Abo-Shosha, M.H. and Gaffer, M.A., *Colourage*, 1998, **45**(7), 13–19 and 30.
5 Yang, Y., Corcoran, L., Vorlicek, K. and Li, S., *Textile Chem. Colorist*, 2000, **4**, 44–49.
6 Mansfield, R.G., *Textile World*, 2002, **152**(2), 42–45.
7 Sun, G. and Xu, X., *Textile Chem. Colorist,* 1999, **31**(1), 21–24.
8 Sun, G. and Xu, X., *Textile Chem. Colorist*, 1999, **31**(5), 31–35.
9 Benisek, L., *Textile Month*, 1998, December, 12–17.
10 Vigo, T.C., Danna, G.F. and Goynes, W.R., *Textile Chem. Colorist*, 1999, **31**(1), 29–33.
11 Lin, M.Y. and Wong, W.W., *J. China Textile Inst*., 1999, **9**(3), 285–294.
12 Anon., *Int. Dyer*, 1999, **184**(2), 36–38.
13 Anon., *Knitting Int*., 1999, **106/1257**, 46.
14 Lee, S., Cho, J-S. and Cho, G., *Textile Res. J.,* 1999, **69**, 104–112.
15 Anon., *Med. Textile*, 1999, March, 2.
16 Toray Industries Inc., *Med. Textile*, 1999, January, 3–4.