11

Key issues in testing damaged textile samples

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Abstract: This chapter deals with key issues in testing damaged textile samples. It provides comprehensive information on different types of damage, causes for their occurrence, stages of damage occurrence, practical significance of damage analysis, methods of damage analysis, factors affecting accurate testing, applications of textile damage analysis, and future trends.

Key words: damaged textile, damage occurrence, damage analysis, sample preparation, forensic application.

11.1 Introduction

Textile damage is defined as an injury caused to a textile material. The damage may be caused in the form of abraded portions, change in colour, cuts, harsh cleaning spots, holes, nicks, pitting, scratches, soiling, stains, streaks, tears, etc., which lower the value of an item. Damages are often referred to as faults or defects, which represent some kind of deviation from prescribed requirements that lower the usefulness of goods. Damage is the disadvantage arising from faults, which may be visible on the surface, easily recognizable defects or those hidden inside the structure, and thus damage analysis is a wider-ranging term than analysis of faults.

Textile damage analysis is a special area in testing of textiles and has significant practical relevance as textiles can be damaged at various stages during their manufacture, processing, distribution, transportation and usage. Determining the exact cause of damage can be of great help for all those involved in the manufacture, distribution and usage. It can greatly help in forensic science examination to detect evidence and punish the culprits. Damage analysis demands a wide knowledge of textile fibres, the process of their conversion to yarns and fabrics, chemical treatment, garment production, and typical application of textiles. In addition, it also requires the knowledge of methods of analysis using microscopy, chromatography, infrared spectroscopy, thermal analysis, image analysis, etc. Additional requirements for successful damage analysis are information regarding the

processes and machines used, stages in storage, transportation, conditions of usage, etc.

Analysis of damage to textiles is not usually an exact science although it does use scientific methods. In many cases several different tests are necessary. Their results can sometimes be contradictory. These then have to be evaluated and weighed up against each other very critically, whereby comparison of samples, experience with similar cases and information about the circumstances of the damage can be useful. In many ways this process is similar to a court trial when only circumstantial evidence is available, but fortunately in the laboratory the damage can often be imitated and the evidence thus verified.

The present chapter intends to provide broad information on the importance of textile damage analysis, causes of damage and types of damage to textiles, and the various methods and techniques used to analyse the damages.

11.2 Causes of damage

Inappropriate treatment of textiles during production, distribution and usage can cause chemical, mechanical, thermal and biological damages. Each type of damage has different effects and greatly reduces the serviceability of the textile material. The causes of damage may be attributed to different people, in particular to textile manufacturers, dyers and finishers, garment producers, distributors or consumers. Although there are interrelations between the above causes, it is usual to attribute mechanical damage to the textile manufacturer, chemical damage to the dyer and finisher, and biological damage to the distributor and end user. When a garment or other textile article is damaged in use or in the care process, a determination of the cause can often be made because of the obvious nature of the damage. Once the cause is identified, responsibility can usually be assigned to the consumer, manufacturer or drycleaner (Mahall, 1993).

The manufacturer is responsible for offering a product that will perform satisfactorily for its normal life expectancy when it is refurbished by the care process specified by the care label instructions. Damage such as severe general colour loss and colour bleeding in the care process, shrinkage that makes an item unwearable, colour fade from the decomposition of fluorescent brighteners, and failure of trim and decorations to withstand the care process are examples of manufacturer's responsibility (www.drycleandave.com).

The consumer is responsible for damage that occurs during use and home care. This includes failure to follow care instructions, further complicating a stain by using a home remedy such as water or soda, chemical damage from spillage of alcoholic beverages, medications, perfumes, after-shaves,

hair dyes, perspiration and shrinkage of garments due to improper washing techniques.

It may be difficult to determine responsibility for some types of damage. In cases where the cause of damage is uncertain, a garment can be examined by laboratory methods to analyse the nature of the damage and investigate the probable responsibility.

The various causes of damage are of great importance from the point of forensic science investigations. There are various forms of physical damage which may be found on textiles, for example 'normal wear-and-tear' resulting from normal use of textiles. This usually takes the form of a thinning of the fabric prior to a hole forming, but seams may also come undone, threads can catch and be pulled out from the fabric, or the fabric may even be torn. It must also be remembered that the fabric will probably have been cut in order to make the textile item. In forensic investigations, these forms of 'normal' physical damage must be distinguished from other forms which may be related to the crime.

In a violent scuffle, a fabric may be torn, and the seams often fail; the structure of the fabric may also be distorted. Fabrics may be neatly cut, either with scissors or by slicing with a knife. They may also be punctured by relatively sharp (for example, a screwdriver) or blunt (for example, a hammer) objects, and the nature of the damage will depend on the supporting material (if any) beneath the fabric. The stabbing action of a knife may have features of both puncturing and cutting. Pure tensile failure may occur, especially in ropes and webbing (such as seat belts and slings), although this can often be precipitated by some other form of damage which has weakened the textile.

Abrasive damage, normally considered to be due to 'normal wear and tear', can also be of forensic importance. For instance, a seat belt may fail to protect a passenger in an automobile accident if it has been previously caught in the door and allowed to drag along the road. Damage may also be inflicted by insects, such as moths and carpet beetles, which bite the fibre and digest the fibre pieces internally. Microorganisms, such as some forms of bacteria and fungi, can inject enzymes onto the fibre to break it down.

There are many chemicals which can weaken, modify or completely dissolve some textile fibres. The exact nature of the damage depends on the chemical structure of the fibre and the local conditions, such as temperature and presence of other agents such as oxygen (Johnson, 1991). Textiles may also be damaged by excessive heat, for example in fires or ovens. Heat damage could be localized if inflicted by a cigarette or blow-torch. Thus, when examining a damaged textile item, the textile technologist is usually confronted by a wide range of possible general causes. This range must first be narrowed before any particular scenario can be evaluated.

11.3 Types of damage

Damages in textiles, in general, have been classified into six different classes, namely chemical damage, mechanical damage, thermal damage, biological damage, damage by light and heat, and damage due to presence of defects and contaminants. Each of these damages is described below.

11.3.1 Chemical damage

Chemical damage to textiles can occur when the fibres, yarns, fabrics and garments are exposed to the action of acids, alkalis, oxidizing and reducing agents, solvents, etc. Exhaust gases, especially nitrous gases, can cause yellowing and loss of strength and elasticity for some of the textile fibres. Fibres such as elastane fibres can demonstrate loss of strength and elasticity when they absorb oils and fats such as mineral oil, paraffin wax, unsaturated fatty acids, cosmetic oils and sun protection agents. Hence chemical damage can be discussed with reference to different fibres.

Chemical damage to cotton can occur during the wet processing stages such as desizing, scouring, bleaching and finishing. Cotton is most frequently damaged during bleaching. Reducing agents such as bisulfites can attack the disulfide bonds in wool and cause destabilization of the structure. The cystine links in wool can also be cleaved hydrolytically with hot water, steam and especially alkali. A common damage to silk can occur in the degumming process by the action of alkali. Chemical damage to synthetics is much less frequent than damage to natural fibres because they are more resistant to chemical influences during finishing. The most frequently observed chemical damage to synthetics is acid damage to polyamide and alkaline damage to acetate filaments (Schindler and Finnimore, 2005).

11.3.2 Mechanical damage

Mechanical damage to textiles is generally caused by abrasion during mechanical processing while manufacturing a textile material, resulting in greyed spots and light streaks. The other damage effects are tension breaks and cuts, punctures, setting effects and insect attack. This damage is often only recognized in a later finishing stage when large quantities of material have already been damaged. Natural fibres and cellulose regenerated fibres are more susceptible to mechanical damage than synthetics.

The damage caused by abrasion is usually limited to events which occur to fibres in yarn or fabric. This damage can occur at any stage from spinning to the final product and is often not noted until the final product is examined. Yarn abrasion is sometimes accentuated by an increase in tension as a package is wound, which can lead to patterns of damage visible in fabric.

Abrasion to warp yarns in weaving can occur in drop wires, needle eyes and in the reed. This type of abrasion will cause a line in the fabric which follows a warp yarn. Improper machine settings, damaged guides, dirty machine surfaces and damaged needles can give rise to abrasion of yarns in knitting machines. In garments and other textile end products, damage analysis is often directed at assigning responsibility to manufacturer, consumer or professional launderer or drycleaner (Merkel, 1984).

Tension breaks in fibres usually result in a torn, frayed appearance of the ends of the fibres in contrast to the sharp, clean end of a cut fibre. Cracked selvedges can be caused by excessive tension on filling yarns. This type of damage occurs at a bobbin change and is usually accompanied by an indentation in the selvedge at the site. Holes in knit fabrics are very often associated with excess tension in the yarns during knitting. The excess tension can arise from bad cone winding, improper machine settings, improper operation of positive feed units or tension devices, or dirty yarn guides. Weak places, slubs and knots in yarn can also create holes in fabric during knitting.

Punctures in fabric are often associated with a repeat pattern and may be caused by a rough spot on a metallic roll or a piece of metal embedded in a soft roll. Microscopic examination will reveal cut or crushed fibres at the site. Many finishing plants maintain a list of circumstances of the rolls over which fabric passes so that the source of this type of damage can be easily located.

As previously stated, fabrics may also be punctured by relatively sharp (for example, a screwdriver) or blunt (for example, a hammer) objects, and the nature of the damage will depend on the supporting material (if any) beneath the fabric; the stabbing action of a knife may have features of both puncturing and cutting; pure tensile failure may occur, especially in ropes and webbing. Fabric is not often damaged during processing by tension in the warp direction but set marks can occur in warps made of thermoplastic fibres. A set mark is a line across a fabric parallel to a filling yarn that is caused by secondary creep in the warp yarns which occurs when a loom stops with warp yarns under tension.

11.3.3 Thermal damage

Thermal damage is most frequent in synthetic fibres. It is severe in synthetic fibres having a relatively low melting point. Thermoplastic fibres, which include most synthetic fibres (e.g. polyamide, polyester and polyolefin), change primarily in terms of their physical state as temperature increases (contracting and melting), while chemical degradation (decomposition and burning) occurs only after their melting point has been exceeded (Wąs-Gubała and Krauß, 2006). It results in hardening of handle, yellowing, loss

of strength, uneven fabric appearance (light reflection) and uneven dyeing behaviour (spots, streaks and other types of unevenness such as warp splashes).

Thermal damage can occur at many stages in processing. Examples are texturizing, setting, pressing and sewing. During texturing, the original circular fibre cross-sections are usually flattened to polygons. When setting is at too high a temperature or for too long, the yarns are flattened at the interlacing points and tight spots are formed at a higher texturizing temperature in case of PET and nylon. During singeing of staple fibre blends with cellulosics or wool, protruding synthetic fibres can melt to form small balls, which cause a hard handle and which dye more deeply in exhaust processes (small dark spots, deeper dyeing being caused by the high amorphous content and the decrease in relative surface area) and after continuous dyeing are lighter than the undamaged fibres. Pressing at very high temperatures can cause flattening and bonding of thermally sensitive synthetic fibres. Thermal damage also occurs through friction, impact, striking, cutting or puncturing out during textile production and garment manufacture.

Textiles may lose their original colour and strength when exposed to heat. Prolonged exposure to heat can damage fibres like cotton, wool and silk owing to decomposition reactions. Scorched wool fibres turn yellow or brown and blisters are formed on fibres exposed to high heat. Damage to cotton fibres caused by heat can sometimes be detected by the spiral staining of the primary wall exhibited in the Cango Red test. Most artificial fibres melt when exposed to heat, forming ball-like tips and other distortions typical of partially melted material. Long exposure to slight over temperature can lead to oxidative damage in the fibres.

11.3.4 Biological damage

Biological damage to textiles may be attributed to the attack of fibres, yarns and fabrics by microorganisms. Textiles are particularly susceptible to damage through microorganism growth, a problem very common in textile manufacturing units. Microorganisms will grow on any surface when the temperature, humidity and pH of the environment are suitable and a source of food is present. The organisms grow in colonies that have characteristic appearances and deposit stains on fibres that can be observed in visible and ultraviolet light. Actually, microbes secrete enzymes which cause damage to textiles. Generally, fibres made of naturally occurring polymers are subject to biological attack, and cellulose is damaged more commonly than the protein fibres.

Mould and mildew are the common terms used to identify a whole range of microorganisms that survive on organic materials and cause damage. A

large number of fungi, bacteria, yeast and algae have been identified as surviving on fabrics. Once a microorganism population is established, it alters the pH of the cloth. This alteration may result in a change of colours in the dyes. There can also be a decrease in the strength of the cloth. Associated with a characteristic musty odour, microorganism growth appears as an irregular stain which generally ranges in colour from grey to black, though yellow, orange and red stains are possible. The attack of microorganisms can result in permanent discolouration of the fabric (Conserve O Gram series bulletin, 1993). The factors affecting biological damage are fibre content, environmental conditions, cleanliness of the textile surface, and acidity/alkalinity.

Control of environmental conditions is by far the most effective method of preventing the biological damage to textiles. It is effective not only for the control of microorganisms but for control of other agents of damage such as insects. Microorganism growth will permanently stain a fabric. The resulting damage will remain as a darkened area and only radical treatment procedures will visually diminish such stains.

11.3.5 Damage by light

Damage caused by exposure to light is associated with the breaking of primary valence bonds with formation of functional groups that can be detected by stains or titration. It is difficult to distinguish light damage from other types of chemical damage, but textiles are often tendered by light in a pattern that helps to distinguish from the back, the edges may have been protected, etc. Delustred fibres are more readily damaged by light than are bright fibres. Fabrics printed with white pigments are sometimes damaged to a greater extent in the printed area than in the remainder of the material.

Light damage on many kinds of fibres is oxidative in nature because of the simultaneous exposure of the textile material to atmospheric oxygen. Particularly, when the exposure to light is outdoors (weathering), simultaneous microbial degradation may occur in cellulosic fibres or acid degradation in cellulosic fibres and nylon.

11.3.6 Damage due to presence of defects and contaminants

Textiles are sometimes damaged by the presence of certain types of defects and contaminants. In cotton fibres, the presence of immature fibres is responsible for generation of more neps and higher hairiness in yarns, barre in knitted fabrics, and colour variation in dyed fabrics. The presence of sericin in silk, and grease and suinte in wool, might result in variation in

fineness and other properties of these fibres before and after removal of these impurities. The damage may occur in fabrics due to the presence of non-fibrous content, foreign matter and spun-in-fly in yarns, and oil, grease and paraffin wax deposits. Since these deposits are usually not distributed evenly on the fibres, fabrics contain more or less large stains, spots or streaks. They are one of the most frequent causes of damage. Oils, greases and waxes (e.g. from spin finishes, lubricants, coning oils, sizing waxes and loom oils) which are not removed before dyeing can cause reserving and, as with sizing residues, lead to dyeing unevenness. Precipitated dye or undissolved dye particles cause dye stains. Inappropriate finishes lead to the formation of chalky marks when the fabric is scratched. Typical causes are size residues, printing paste thickeners which have not been washed off, or unevenly distributed finishing agents. Film-like deposits usually cause a somewhat blurry appearance of the surface imprint, for example blurred scale structures in wool. Oligomer and lime deposits result in greying and light stains on dyed and printed fabrics.

Defects in the fabrics such as streaks and bars are another cause of damage occurrence in textiles. They occur in numerous forms, for example parallel or oblique bars in the warp or weft direction, repeat pattern or irregularity, bands, short or long sections of threads, irregular numbers of wales or courses. These defects are caused by irregularities in the yarn in terms of yarn count, twist, diameter, etc. In addition, differences in the yarn tension, hairiness and blend composition can also cause streaks or weft bars in the fabric. Faults during texturization, mercerizing and non-woven manufacture can also introduce objectionable defects in the fabric. The defects arising out of dyeing, printing and finishing such as excessive abrasion in jet dyeing machines, plaiting-down faults, alkali swollen fibres, scums in printing, greasy deposits, etc., can all lead to faulty dyeing and damage the textiles severely (Schindler and Finnimore, 2005).

11.4 Stages of damage occurrence

The damage to textiles can occur at various stages, such as production, processing, storage, transport and distribution, and usage.

11.4.1 Production

Damage may be caused to fibres, yarns, fabrics and garments during their production due to selection of improper processing conditions. Use of improper speeds or tension levels, and poorly maintained machine parts that are worn out, rough, blunt or too sharp will cause damage to textiles in one form or another during their manufacture. The selection of exceedingly high draw ratio and improper temperature during fibre spinning might

cause tensile damage to fibres, rendering them brittle and thermally damaged. The use of suboptimum speeds and settings during opening and carding of fibres will cause mechanical damage to fibres, leading to surface damage and even rupture. Improper carding and drafting conditions are responsible for generation of excess imperfections, which will mar the appearance of the fabric and the garment. Yarn passing at very high speed through rough, rusted and worn-out parts on winding, beaming and weaving machines encourages the occurrence of abraded portions, fuzziness and stains, which are potential causes of damage in the resultant fabrics. Damages such as hole formation and missing stitches are expected in the knitting process if the yarn tension and fibre-to-knitting needle friction are not optimized according to the type of yarn used.

Uncontrolled sewing parameters such as highly varying sewing speed, improper thread tension and worn-out needles, will not only damage fibres in the fabric but also lead to partial fusion of sewing thread, depending upon its fibre composition, and ultimately poor seam formation, which will prove detrimental to the garment during usage. Seam puckering and seam slippage are the most commonly occurring defects in many garments. Appreciable damage to fibres takes place if the suitable shape of needle, barb size and stroke are not used in needle punching, resulting in considerable reduction in strength, extension, thickness and compressional resilience of non-woven fabric.

11.4.2 Storage

Textiles may be unexpectedly damaged during storage if improper conditions of storage are resorted to. Cellulosic based textiles and sized fabrics are prone to attack by moths, mildew and microorganisms if they are stored for extended periods in places with unfavourable conditions of temperature and relative humidity. Insects generally like a warm damp environment. Discolouration of the cotton takes place much more rapidly in a damp environment.

The growth of moulds produces bright stains on fabrics and these stains are extremely difficult to remove, because they are often insoluble. Damage caused by mould attack can be devastating. Moulds digest and break down the materials they feed on. In the process, textiles, paper and wood become weak and eventually crumble away.

There are myriad insects that can, and will, eat anything edible in our collection. Carpet beetles will feed on a wide variety of materials, of both animal and plant origin (wool, silk, cotton). Clothes moths feed only on proteinaceous materials (wool, silk, leather, feathers) and blends of synthetic and proteinaceous fibres, but will damage synthetic and plant fibres (cotton, linen, canvas) when feeding on sizing, starch, or food spills in the

fabric. Furniture beetles, powder-post beetles and termites will tunnel in and feed on wood.

Synthetic fiber based textiles are prone to soiling by attracting dust and particulate matter if they are stored in open conditions. This phenomenon is often referred to as 'fog marking' and leads to a build-up of quite a large mass of dust on the fabric. Dust absorbs moisture readily, so that areas with a large build-up of dust can have quite high local humidity even when the environment surrounding the object is completely stable at 50% RH.

Particulate matter can be generated within a building in which textiles are stored. In new buildings, concrete and cement can give off very fine dust particles for up to two years after initial pouring. These particles are extremely alkaline and will damage objects they settle on; for example, they will discolour cloth and attack alkali-sensitive materials such as silk and wool.

11.4.3 Transport and distribution

Improper care exercised during transport and distribution will cause severe damage to textiles. For instance, if a truck carrying several bales of cotton in an uncovered condition from a ginning factory to a spinning mill is met with heavy rain, the cotton might be rendered matted, sticky and unprocessable. Similarly, if care is not exercised during transport of dyed and printed goods, there is great risk of discolouration due to exposure to light, rain and dusty weather. Further, improper loading and positioning of goods on a platform can cause damages such as undue abrasion, compressing and deshaping to textile materials. Use of unsuitable packing materials may well damage textile goods during their loading and unloading.

11.4.4 Textile usage

During usage, textiles in various forms may be subjected to unnoticed wear and exposed to sunlight, dirt and particulate matter. All these situations may cause damage to textiles in one way or another. When light and UV radiation fall on a textile object, they deliver a large amount of energy and, as a result, various chemical reactions can take place, depending on the amount of energy delivered. These reactions are called photochemical reactions. It is very easy to see the effects of these reactions, for instance, if a sample of dyed fabric is left in sunlight for just a few hours. The fabric becomes discoloured (yellowed). However, most changes caused by photochemical reactions are not as quick as this nor as obvious; nevertheless their effects can be devastating and highly damaging.

Light causes extreme and irreversible damage to many textiles, most notably organic textile materials. For example, UV radiation and visible

light set off chemical changes in textiles, which weaken and discolour them and cause inks, dyes and pigments to fade, and hence seriously affect the aesthetic quality of many items.

Due to continuous usage, textile materials need to be washed frequently. The use of improper washing conditions, ignoring wash, wear and care instructions, might lead to progressive deterioration of textiles. The use of excessive detergents during washing, inadequate rinsing conditions and prolonged drying will lead to cumulative damage to textile materials.

11.5 Practical significance of damage analysis

The analysis of damage to textiles is a fascinating area of textile testing. It has significant practical relevance and considerable charm but also many difficulties. Determining the exact cause of damage can often be a real challenge. Those who carry out damage analysis need wide-ranging knowledge, imagination and adequate experience, but also intuition and the ability to reason and weigh up evidence like a detective.

It is a common practice in the textile industry that the textile manufacturers quite often dispute with dyers and finishers about the occurrence of faults or damages and questions are simply raised as to who is responsible for the fault and who has to bear the cost of damage. In the case of large lots or continuous production lines, it is often important to locate the cause very quickly to avoid the recurrence of faults as soon as possible. In this respect, damage analysis plays a vital role in quality assurance. In spite of the extensive use of modern process control and optimization techniques, the occurrence of faults cannot be avoided and the costs caused by the damage can be very high. Although some disputes are settled legally by the court, most are resolved through mutual agreement between the producer and the customer. Depending on the importance of the business relationship, fair dealing and price discounts play an important role. In order to investigate the complaints, most of the industries in developed countries have set up their own testing laboratories to carry out the testing of damaged textiles using their own experts in the field, and some companies resolve complaints by simply offering price reductions without carrying out any laboratory investigations. The experts in damage analysis at the fibre, dyestuff and auxiliary agent producers, as well as those at the testing and research institutes, still have their hands full, dealing with many cases of damage where the costs caused by the fault can be quite high (Schindler and Finnimore, 2005).

Determining the exact cause of damage can be of great help for all those involved in the manufacture, distribution and usage of textiles. It can greatly help in forensic science examination to detect evidence and punish the culprits.

Analysis of textile damage is often regarded as a technical service in order to promote and enhance supplier–customer relationships. Its economic importance can be observed from the expenses incurred by the producers of fibres, yarns, fabrics, apparel and dyestuffs and auxiliary selling agents in dealing with complaints and analysing the damage. These expenses sometimes could be very high due to the cost of equipment and the complex procedure involved in analysing a damaged sample. Hence it is highly important to understand the wide-ranging complexity of damage analysis in textiles and the challenges corresponding to the demands made on damage analysis in terms of broadly based, thorough knowledge, great experience and the right combination of logical intuitive approaches depending on the problems (Schindler and Finnimore, 2005).

11.6 Textile damage analysis: sample preparation

Preparation of specimens for textile damage analysis is very interesting and often challenging in nature. Depending upon the nature of damage and the amount of sample available, one has to ingeniously select a specimen of suitable size and the number of specimens to analyse the damage and gather maximum information. As the nature of the damage varies from one type to another, there cannot be a single standard procedure of sample preparation for damage analysis, hence the sample preparation may be very specific to the nature of the damage and the technique employed for damage analysis. Also, there cannot be any established procedure as to exactly how many specimens may be prepared, as this depends upon the size of the damaged textile and its nature. In the event of availability of a large sample, one can resort to the standard procedures highlighted in various test standards as applicable to testing of normal textiles. A standard size of a specimen may be obtained from a larger specimen available, in which for instance the yarns have been subjected to abrasive forces or experienced a surface damage. In addition, an adequate number of specimens, namely up to five, may be chosen in case of availability of sample, for determining the extent of damage caused in different portions of the textile and to gather cumulative knowledge on the causes and severity of the damage. On the other hand, if a textile material has been damaged by a cut or the presence of a hole, it is quite obvious that selection of a standard size of specimen is very difficult as the information regarding the area containing that damage is alone important rather than the standard size of the specimen. In such cases, the person carrying out the damage analysis may opt for selection of an appropriate size and number of samples depending upon the nature of the damage, its shape or size.

Further, besides the selection of a suitable specimen size, some damages require specific preparation of specimens prior to damage analysis. For

instance, analysis of cross-sections of fibres or yarns in a damaged textile requires thorough preparation of the specimen using standard impregnation techniques, image development, photography and analysis. Similarly, other techniques, such as thin-layer chromatography (TLC) and surface imprint techniques, require preparation of specimens using the standard procedure for that type of analysis. The sample preparation procedures for various damage analysis techniques are described in the respective sections below.

11.7 Methods of textile damage analysis

Perception and description of the fault are the first steps in damage analysis. Damage can be perceived visually, macro- and/or microscopically, often only with a specific type of illumination, such as reflected, oblique or transmitted light, or with a specific light source, for example ultraviolet (UV) or polarized light. Some faults are detected by other senses, usually in the form of a handle assessment, or they can be registered by measurements. Examples of the latter are colour measurement, tensile and abrasion strength, extensibility, shrinkage and fastness properties. These technical properties can be supplemented by thermo-physiological comfort properties and care requirements, where significant deviations from the agreed or specified values can be claimed as faults. It is important here to describe the fault as exactly as possible. All the typical characteristics and peculiarities, their frequency and possible regularity have to be noted and also whether they can be localized to individual fibre or thread systems. This makes it easier to determine the cause of the damage.

Unfortunately, there are no hard and fast rules on how to proceed with textile damage analysis. The variety of cases and causes is too great for this. Nevertheless, some companies and institutes use their own preprinted forms with long lists of tests for this purpose. This has the advantage that none of the rare tests is overlooked but also the disadvantage of inflexibility and unnecessary work on certain types of damage. Such preprinted forms may be of help to less experienced testers, but experienced testers tend to have their own specific procedures depending on the case and are often guided by their intuition. As a general rule, preliminary tests are made followed by more painstaking specific tests (Schindler and Finnimore, 2005).

The usual steps involved in an investigation of damage are discussed below:

1. Visual examination of the damage with a description of the type, appearance, distribution and possible causes of occurrence.
2. Microscopic observation of the damage with appropriate magnification.

3. Preliminary tests such as solubility and staining tests.
4. Isolation of the substance causing the stains.
5. Comparison and identification, usually by means of thin-layer chromatography and/or infrared spectroscopy. Comparison is made with the blank sample (extract from unstained areas) and with authentic substances which could have caused the stain. If the stain cannot be extracted, IR spectra from stained and unstained areas can be compared and the spectra subtracted in order to identify the stain substance.
6. Reproduction, if possible, of the damage in order to verify the findings, for example comparison with authentic stain substances on the same textile material, using conditions as close as possible to those used with the damaged sample.
7. Further verification, for example, if possible, by means of consultation with the persons concerned in the stage of production suspected of causing the damage. It is important here to consider alternatives and to test the plausibility of the findings critically.
8. Summary of the findings and discussion of the results. If the cause has not been clearly identified, the results should be formulated carefully and alternatives mentioned.
9. Documentation of findings, including photographs and if possible the sample swatches.

11.7.1 Visual examination

As in any other type of testing, preliminary examination for textile damage analysis is essential and is composed of visual examination and simple tests, carried out in a short time and with little effort, which give the first clues in damage analysis.

It is usual to begin with an exact visual examination, if possible in comparison with an undamaged sample. Notice should be made of any peculiarities in appearance. Sometimes abraded and raised areas, holes, thin places and pressure marks, and changes in colour can be easily recognized without optical aids. With the use of a magnifying glass they can be seen more clearly and in more detail. The same is true for many visible deposits of foreign matter, defects, mildew spots, stains, etc.

As a next step, easily determinable differences between the damaged sample and the undamaged comparison sample can be sought, for example handle assessments, wetting behaviour or pH value. Simple tests of mechanical strength, rubbing fastness and wash fastness also belong to this group.

After marking the damaged area, woven fabrics can be separated into warp and weft threads and knitted fabrics unravelled in order to investigate the isolated threads more thoroughly. The threads from the damaged area are analysed for differences in fibre composition, yarn diameter, twist level

and yarn appearance. Determination of the fibre type, including checking of the stated fibre type, is one of the most important preliminary tests. This may involve quantitative or qualitative analysis. As a part of this, identification of blends consists of dissolving out one fibre component and examining the residual fibre to see which of the fibre components are damaged (Schindler and Finnimore, 2005).

11.7.2 Microscopic examination

Microscopy is certainly the most important method used for damage analysis of textiles. Microscopic examinations are used extensively in the textile industry to investigate certain characteristics of raw materials and product features, to analyse competitors' samples, and to check output quality. Microscopy is indispensable in dealing with complaints concerning damages as well as in repudiating unjustified claims. Microscopy is also of great use in textile damage analysis in the sense that it is essential for analysing the fine structure of fibres in damaged areas, variations in surface, shape and size of damage, and presence and distribution of impurities, contaminants, foreign matter, dyes, auxiliaries, etc. Table 11.1 gives the typical applications of microcopy as applied to textile damage analysis.

Stereo microscope

The microscopic investigation of damage usually begins with a stereo microscope at low magnification (about 5×), which can then be increased to about 100×. If necessary the damaged areas can often be marked and thus distinguished from their intact surroundings. The large distance between sample and objective enables individual threads, foreign fibres or deposits to be easily manipulated. Further advantages of the stereo microscope are the spatial, three-dimensional image obtained and the fact that different types of illumination, in particular reflected light falling obliquely from one side or opposite sides, can be readily used, depending on what is to be examined.

In blends containing cotton and polyester fibres, for example, bundles of fibres which resemble cotton neps when examined superficially may on careful examination reveal the presence of both mature and immature cotton fibres held together by partially melted polyester fibres, which manifests itself like thermal damage (Schindler and Finnimore, 2005).

Optical microscope

More detailed information can be obtained from light microscopes with up to 1000× total magnification. Such microscopes are available with transmit-

Table 11.1 Application of microscopy in textile damage analysis

Production stage	Parameter analysed
Fibre spinning	Cross-sectional shape
	Fineness
	Delustrant
	Drawing
	Core–sheath structure
Yarn manufacture	Fibre identification in yarn
	Fibre distribution in blend yarn
	Yarn twist and hairiness
	Slubs, neps, contaminants
	Yarn structure
Weaving preparation	Increase in neps, hairiness
	Distribution of size, pick-up
Weaving and knitting	Weave/knit pattern
	Fabric faults/damages
	Deposits, contaminants
Pretreatments	Degree of scouring, bleaching
	Mercerization, lustre
Dyeing	Even dyeing, macro- and micro-levelness
	Dye penetration, migration
	Deposits, colour difference
	Bi-colour effects with blends
Printing	Clarity and sharpness of print
	Print penetration
	Distribution of binder
Finishing	Distribution of finish
	Cross-linking
	Mechanical effects
	Fastness

Source: adapted from Schindler and Finnimore (2005)

ted light for single-fibre investigations or thin cross-sections, and with reflected light for non-transparent objects. Bright field illumination is usually used with transmitted light. Dark field illumination allows edge structures such as projecting fibres from yarns, scales on animal hairs and delustrants to be more easily observed. Polarized light is used for the determination of the melting point of synthetic fibres by means of birefringence. Differences in tension and drawing as well as fibres deformed under pressure can be seen more easily between crossed polars. An examination for a pattern in the damage may be very informative. Abraded yarn has more surface fuzz than normal and contains fibres which appear cut, bruised or frayed when examined microscopically (Schindler and Finnimore, 2005).

Fluorescence microscopy

In damage analysis the most important microscopic contrast method is selective staining of structures of interest. If selective staining with fluorescent dyes is successful, fluorescence microscopy can be a useful method of investigation for the analysis of damage to textiles. It is more or less independent of the original dyeing of the textile material and it can create strong contrasts and thus mark substances present in low concentrations. In rare cases the natural fluorescence of the material can be sufficient for the investigation, for example with wool where it occurs in direct relation to 'yellowing'.

Hesse and Pfeifer (1974) described the fluorescent detection of oil stains, the analysis of the distribution of optical brighteners in polyester/cotton blends and the detection of photolytic damage by means of macroscopic and microscopic fluorescence techniques. The damage to fibres arising from different degrees of optical brightening could also be elucidated with the aid of fluorescence microscopy. Using natural fluorescence, many kinds of fungi and biological damage to textiles could be analysed. The distribution of applied spin finishes has been studied with fluorescent staining.

Scanning electron microscopy

In scanning electron microscopy (SEM), because of the very short wavelength of the electrons used, much greater magnification is possible than with light microscopy. More importantly for damage analysis, SEM images have a large focal depth and appear strongly contrasted and spatial. For example, with SEM the examination of surface cracks and damages and the presence of impurities, deposits of silicone, silicates or calcium salts can be easily analysed.

11.7.3 Image analysis

Image analysis is the extraction of useful information from images, mainly from digital images by means of digital image processing techniques. Surface imprints of fibres, yarns and fabrics, textile severance morphology (e.g. knife or scissor cuts), and fabric defects, which are of great importance for damage analysis, are usually not evaluated microscopically. Here digital image analysis, which has now reached a high stage of development, should be used, since it employs high quality images and allows easy evaluation, archiving and distribution of microphotographs. They should show the object of interest as sharply as possible and with high contrast; as a rule they should not be manipulated. Using image analysis, the cut or broken cross-sections of

fibres, yarns and fabrics can be easily processed for fibre identification, fault classification, or estimating the penetration of size materials and dyes into fibres, filaments, yarns and fabrics. Upon analysis of the images of yarns cut mechanically, one can notice a clean, sharp end if they have not been exposed to vigorous handling in subsequent operations. These methods are also used to investigate hollow and multi-component fibres, the build-up, adhesion and evenness of coating layers, and the analysis of other textile composites. Image analysis can also be used for analysing fabric pilling, drape, wrinkle/crease, texture analysis, etc. All of these can be useful for damage analysis.

11.7.4 Thin-layer chromatography

Chromatography comprises an important group of separation methods in which mixtures of substances are separated into their components using a mobile and a stationary phase. With textile damage analysis the possibility of identifying the separated substances by comparing them with authentic samples is often as important as the separation itself. This identification is successful when the separation behaviour in one or preferably more separation systems is the same and when additional findings such as the same staining or reaction behaviour show that the substances are identical. A prerequisite for such chromatographic identification is that the identity of the substance is already suspected so that the relevant substances can be chromatographed at the same time for comparison. An even more fundamental prerequisite is that the substances to be analysed are soluble in the mobile phase.

Of the many chromatographic methods used in analysis, the one preferably used in textile damage analysis is thin-layer chromatography (TLC). The reason for this is that TLC delivers results quickly, simply and cheaply, with usually sufficient accuracy for elucidation of damage cases. Dyestuffs, optical brighteners, soluble textile auxiliaries and fibre finishes are especially suitable for TLC. Many pigments are also sufficiently soluble.

11.7.5 Infrared spectroscopy

Infrared spectroscopy (IRS) is often a useful supplement to TLC, especially in the analysis of insoluble or macromolecular substances, cross-linked finishes, fibres, coatings, etc. However, with mixtures of substances, the superimposed IR spectra are often so complex that they can hardly be interpreted. A previous separation including that with TLC is very useful for IRS.

Table 11.2 Suitability of IR bands for identifying silicone stains in different fibrous materials

Wave number (cm^{-1})	Cotton	Viscose	Wool	Nylon 6,6	Polyester
770–800	++	++	++	++	0 (+)
1020–1120	–	–	+	+	–
1260	+	+	0 (+)	–	–
2965	0 (+)	0	–	–	0 (+)

Note: ++ indicates very good suitability (single, non-overlapping bands); + good suitability; 0 means that because of superimposition silicone can only be detected by the markedly higher intensity of the bands; – means that no increase in intensity of the superimposed bands is recognizable.
Source: adapted from Schindler and Finnimore (2005)

Molecules can be excited by absorption of IR rays to give stretching vibrations (in the direction of the bond) and also the somewhat less energetic bending vibrations with three or more atoms in the molecule. Thus as a rule spectra with many bands and containing a high degree of information are formed. The position and the shape of the IR bands are characteristic of the particular molecular structure which has been excited. IRS in the intermediate IR range from 2.5–25 μm corresponding to 4000–400 cm^{-1} (wave number) enables the identification of functional groups and other structural parts of molecules. If all the essential bands in the IR spectra of the sample and the authentic substance correspond, including those in the so-called fingerprint range of carbon backbone vibrations at about 1500–1000 cm^{-1}, the two substances are identical.

This shows that IRS is a particularly powerful method for damage analysis. With this method, fibres, coatings and other deposits, textile auxiliaries and substances causing stains, and also blend proportion in fibre mixtures can be identified. Table 11.2 shows the suitability of IR bands for identifying silicone stains, depending upon the type of fibre. Chemical damage to fibres can also be detected by means of specific structural changes. All states of matter can be investigated with IR spectroscopy. Thus in damage analysis, the composition of mostly liquid extraction residues is of particular interest (Schindler and Finnimore, 2005).

11.7.6 Thermal analysis

Thermal analysis (TA) is the comprehensive name for a group of analytical methods in which physical or chemical properties of a sample are measured as a function of temperature and time. The sample, contained in a defined

atmosphere (usually air or nitrogen), is subjected to a controlled temperature programme, for example it can be tested isothermally or with a constant rate of heating or cooling. In the area of textiles, TA has increased its importance owing to the fast-growing market segment of technical textiles, for example in quality control and in analysis of products, competitors' samples and damage analysis. In damage analysis using TA, a variety of techniques such as differential scanning calorimetry (DSC), thermo-gravimetric analysis (TGA) and thermo-mechanical analysis (TMA) may be used (Schindler and Finnimore, 2005).

Differential scanning calorimetry

Using differential scanning calorimetry (DSC), the temperature range for melting (T_m) and decomposition (T_d), and during cooling that of crystallization (T_c) can be determined along with the corresponding enthalpies. Furthermore, the characteristic temperature for the amorphous areas, the glass temperature (T_g) and the so-called effective temperature or middle endotherm peak temperature (MEPT) can be determined. The determination of melting point is used as a basis for fibre identification. By comparing the measured heat of fusion with the theoretical value, the purity or content can be determined. Similarly the measured heat of reaction can be compared with the theoretical value in order to calculate the extent of reaction, for example with cross-linking reactions.

For damage analysis of textiles made from polyester, the MEPT is especially interesting because it gives insight into the thermal prehistory of the fibres. The MEPT is the maximum temperature of a small endothermic peak between the small endothermic stage of glass transition and the large endothermic melting peak. The position of this MEPT peak is variable and depends on the temperature of thermal pretreatments (T_p). Its size depends on the intensity, and thus mainly on the duration, of the thermal treatment and also on the tension, for example during setting. The measured MEPT usually lies several degrees above the temperature of a preceding thermal treatment (MEPT > T_p). It gives useful information for damage analysis. For example, it is possible to determine from this temperature whether polyester goods were dyed at the boil (with carrier), under high temperature (HT) conditions or using the thermosol process. Conclusions about setting temperature are also possible, in particular differences in setting conditions can be determined exactly (Schindler and Finnimore, 2005).

DSC is also useful for characterizing bicomponent fibres, film-forming finishes and coatings. For example, with polysiloxane a very low glass temperature (about –120°C) is characteristic, followed by a crystallization peak (at about –100°C) and a large melting peak (–40°C). As a matter of interest

the enthalpies obtained by integration of these peak areas enable the crystalline ratio to be calculated: $(H_m - H_c) : H_m$.

Thermo-gravimetric analysis

With thermo-gravimetric analysis (TGA), the change in weight of the samples on heating is determined (usually possible up to 1000°C). In a nitrogen atmosphere, the decomposition of the sample can thus be studied; in air the ability to be oxidized is additionally determined. In this way fibres modified to be flame-resistant can be distinguished from standard fibres. In fibre composites, for example fibre-reinforced rubber, it is thus possible to determine the proportions of the components with relatively little effort: moisture and softeners in the first stage of weight loss up to about 220°C, then the fibre and rubber components up to 500°C and finally after changing from a nitrogen atmosphere to air the carbon used as a filling burns and above 700°C the non-burnable inorganic filling remains. The first derivative of the weight loss curve, the derivative TG (DTG), enables a more exact determination. By coupling TGA with a mass spectrometer or a FT-IR spectrometer, the decomposition products can be analysed. Because of the higher costs such methods are only used in exceptional cases for textile damage analysis (Schindler and Finnimore, 2005).

Thermo-mechanical analysis

Thermo-mechanical analysis (TMA) investigates the changes in the dimensions of a sample as a function of the temperature, for example shrinkage or extension of fibres. It is easier to work here with filaments than with staple fibres. Fibre composites and other materials are also analysed by dynamic loading. This dynamic mechanical analysis (DMA) enables, for example, the glass temperature of elastomers to be determined exactly.

11.7.7 Physical analysis

Physical analysis includes, for example, identification of fibres in a damaged textile by determining its density, moisture regain, strength, elongation, refractive index, etc. The physical analysis also includes observation of yarn packages, fabrics and garments under suitable illumination for presence of defects or damage.

As regards fibre identification, from the damaged portion fibres in relatively good condition need to be collected and analysed for density using density gradient column, for moisture regain using the environment chamber, and by gravimetric methods. The measurement of strength and extension of fibres, using a single fibre tensile tester, often serves as a

means of fibre identification and thus prediction of conditions of damage. Determination of refractive index or birefringence of fibres using a polarized light method can be of great utility in understanding the extent of structural changes the fibre has undergone during processing or usage *vis-à-vis* the structural characteristics of the original sample. The various methods of physical analysis discussed above are very simple and easy to carry out as compared to other expensive techniques, and thus they may be resorted to quite often in textile damage analysis.

Inspection of cones of yarns or even fabric surface using UV light in a dark room is quite natural in many spinning mills for identification of unintended fibre mixing, presence of contaminants or foreign matter that constitute defects, rendering the packages to be rejected. The physical inspection of knitted fabrics under fluorescent white light is also popular in mills to inspect the presence of barre and explore the causes and remedial measures for its non-recurrence.

11.7.8 Chemical analysis

Chemical analysis of damage to textiles is a broad subject and involves extensive knowledge of chemical testing methods. Technological faults due to using mistaken material or caused by foreign fibres can often be most simply clarified by chemical identification of the fibres. In practical damage analysis, physical methods are often combined with chemical analysis, for example microscopic staining, swelling and dissolution reactions or colour reactions and derivatization in chromatography. IR spectroscopy, a physical method, requires chemical knowledge for the identification of fibres, textile auxiliaries and stains.

Chemical analysis is popularly carried out to determine the extent of acid to cellulosics, nylon, polyester and other fibres. Detection of acid damage with Fehling's solution is very common in case of cellulosic fibres, which are sensitive to acids and can be easily damaged by the acid catalysts used in easy-care, silicone, fluorocarbon and flame-retardant finishes as well as by drops of concentrated acid or faulty dyeing of cellulose/wool blends. Further, chemical analysis includes determination of the extent of molecular damage to fibres, damages caused by chemical weak spots, hydrolytic degradation, analysis of unwanted deposits on textiles, presence of oil, grease, paraffin and wax deposits, analysis of solvent extracts, etc. It is also used for end group analysis and determination of critical dissolution time, etc.

11.8 Further methods of textile damage analysis

There are a large number and variety of methods which can be used for damage analysis of textiles. In addition to the important methods of damage

analysis described above, three further methods will be briefly described here (Schindler and Finnimore, 2005).

11.8.1 Techniques for surface imprints

Imprint techniques have been a proven and important method in damage analysis of textiles for a long period of time. It is often advantageous not to investigate the original object under the microscope but rather the negative imprint of its surface:

- In an imprint, it is often possible to see if a fault in a coloured textile was caused during textile manufacture or during dyeing and finishing. Spinning faults, such as use of different fibre counts or differences in yarn twist, and faults in fabric production, can be seen in the imprint as well as in the original (and in the same location). On the other hand, faults arising from dyeing or printing are eliminated in the imprint.
- The imprint is transparent and the colour of the sample does not interfere. Thus with dark-dyed wool fibres, the cuticle scales can only be easily recognised in the imprint. The same applies to abraded places and other types of mechanical damage to the surface of dark dyeings.
- Since the surface imprint is very thin (about 0.02 mm), the depth of focus is usually much better than in direct microscopy of the uneven, three-dimensional textile surface and possible fibre lustre and transparency do not interfere. In direct microscopy with reflected light, the image is usually not sharp because the fibre interior and the underside of the fibre also reflect light.
- Since the transparent imprints are examined in transmitted light, it is not necessary to have a microscope with reflected light. In addition, the original sample remains unchanged.

There are two different but widely used imprint methods in damage analysis, namely imprints on gelatine-coated plates and on thermoplastic films, usually polypropylene or polystyrene. In Table 11.3, the most

Table 11.3 Comparison of the most important surface imprint methods

Imprint with gelatine-coated plates	Imprint with thermoplastic films
No thermal influence on the sample	No swelling of hydrophilic fibres
No false indication of structural differences, arising from diffusion of grease, oil or wax deposits	Detection of grease, oil or wax deposits possible due to diffusion into and dulling of the film
No special equipment necessary	Special instrument is essential

Source: adapted from Schindler and Finnimore (2005)

important advantages of these complementary imprint methods are compared.

Gelatine-coated plates method

Two grams of gelatine are swollen in 40 ml of distilled water for one hour at about 35°C. One part of this swollen gelatine is diluted with three parts distilled water, and 1020 ml of this solution is sufficient for about 100 cm^2 of glass plate surface. The solution is put evenly on clean glass plates, for example microscope slides, with a pipette. After drying for 24 hours in a dust-free place, the plates are ready for storage or use. Before use they are dipped briefly into water and the adherent water is then removed by shaking. The fabric is then laid on the swollen gelatine and covered with a filter paper and a further glass or metal plate. A weight is added, which should cover the upper plate evenly. For glass plates that have the same size as microscope slides, the weight should be about 500 g. After pressing for 30 min, the textile side is dried briefly with a warm hair dryer and then carefully removed from the imprint. The slides can now be observed under a microscope using appropriate magnification for imprint analysis (Schindler and Finnimore, 2005).

Surface imprints with thermoplastic films

The thickness of the films (usually with polypropylene 30–40 μm or with polystyrene 100–200 μm) depends on the thickness of the individual fibres and yarns or the structure of the fabric. Polystyrene films are preferred for large-scale imprints (up to about 20 × 30 cm) in the Streak Analyser. For small-scale imprints, a piece of film cut to a suitable size is pressed firmly together with the textile sample between two polished metal plates, for example of the size of microscope slides, with two screw clamps. The assembly is placed in a drying oven at 105°C in the case of polypropylene for 30 min and with polystyrene for 45 min. After cooling as rapidly as possible with cold air the sample is separated from the film. The film can then be examined in transmitted light in the microscope without the use of embedding agent (Schindler and Finnimore, 2005).

11.8.2 Extraction methods

Extraction methods using Soxhlet apparatus are quite routine and standard in most textile laboratories. During extraction, substances soluble in organic solvents or water are removed from the textile, then, as a rule, concentrated by distillation, and the extraction residue is analysed qualitatively and/or quantitatively. Examples of extracted substances are stains, fibre spin fin-

ishes, lubricants, residual grease in wool, residues of surfactants and other chemicals such as acids, bases or thickeners, soluble finishes, dyes and optical brighteners, pesticides and other biocides, carriers, heavy metal salts and formaldehyde. Stepwise extraction using solvents of increasing polarity (for example first hexane, then methylene chloride, then absolute alcohol and finally water) can give a first indication of the nature of the extracted substances. Different extraction methods and apparatus can be used. Miniaturized versions of the Soxhlet extractor are preferred for very small samples such as stains. As alternatives to the Soxhlet extractor, automated apparatus computer-aided finish analysers, like the ALFA 200, have been developed.

11.8.3 Determination of average degree of polymerization of fibres

Many types of damage, including biological, chemical, photolytic, thermal and some types of mechanical damage, are based on degradation of the polymer chains in the fibre. Thus determination of the average degree of polymerization (DP) gives a direct scale for assessing the extent of such damage but not its cause. The time and cost of determining DP are, however, so great that whenever possible simpler but less accurate methods are preferred. Examples of these are loss of tensile strength and abrasion resistance or the pinhead reaction. An advantage of DP determination is that it allows quantitative estimation of the damage. For example, Eisenhut (1941) defined a damage factor s for cellulose fibres based on the decrease in DP, which allows comparative assessment of damage for cotton and regenerated cellulose fibres:

$$s = \log[(2000 : P_1) - (2000 : P_2) + 1] : \log 2$$

where P_1 = DP before damage and P_2 = DP after damage.

Damage factors of $s < 0.5$ are said to be acceptable after bleaching treatments, but with $s > 0.75$ the goods are said to be badly damaged. It must be borne in mind that the damage factors are also dependent on the method used; they are higher with the cuoxam method than with the EWNN method (Schindler and Finnimore, 2005).

11.8.4 Detection of streaks and barriness in woven and knitted fabrics

Barre is defined as an 'unintentional, repetitive visual pattern of continuous bars or stripes usually parallel to the filling of woven fabric or to the courses of circular knit fabric'. Streaks and bars are second only to stains as one of

the most common manifestations of damage. They occur in numerous forms, for example:

- Parallel or oblique to the warp or weft direction
- With a repeat pattern or irregularly
- In bands or bars
- Running along short or long sections of thread or across differing numbers of wales or courses.

As a rule, streaks and bars are caused by faults in textile production. Examples of this are:

- Mistaken material, usually use of the wrong yarn
- Differences in yarn count, yarn bulk, yarn twist, thread tension, plying, pile opening, hairiness, inhomogeneous blends
- Faults during texturizing or mercerizing
- With pile fabrics, more deeply incorporated tuft rows or differences in needling
- Wet abrasion and other types of mechanical damage in jet dyeing machines
- Plaiting-down faults in cotton pretreatment: squashed fibres, notches, cracks and splits in the fibres, which occur when the goods, swollen with alkali, are packed down too densely
- Greasy deposits and resinated mineral oil, which have a carrier effect on polyester, leading to deeper dyeing (Schindler and Finnimore, 2005).

The presence of barre can usually be judged by mere inspection of a fabric under proper illumination and careful observation. Barre analysis methods that help to discriminate between physical barre and barre caused by dyeability differences include flat table examination, light source observation, and the Atlas Streak Analyser. The cause of the fault can be readily clarified with the aid of a microscope, fabric dissection and film imprint analysis (www.geocities.com/vijayakumar777/barre.html).

11.9 Factors affecting accurate testing

The accurate testing and analysis of damage to textiles is affected by factors such as limited sample size, sample preparation, presence of contaminants, impurities, etc. As already discussed in Section 11.6, the extent of information gathered from analysis is highly dependent upon the availability of a sample containing the damage and the sample preparation techniques employed. In most cases, adequate and correct information can be obtained if sufficient quantity of sample containing the damage is available. Otherwise,

the availability of limited sample size leads to improper preparation in case of special types of analysis, which ultimately influences the validity of the information gathered.

Further, the presence of impurities might often mislead the scientist carrying out the analysis and offer altogether different information as against the original one. The impurities may subvert the reality and come in the way of drawing inferences. For instance, the presence of titanium dioxide particles in a synthetic textile material used as a window screen may often subvert the fact that the continuous exposure of the screen has rendered it dull and caused surface fading. Also, the presence of impurities in dyes or finishes will influence the characteristics of treated textiles and eventually the causes of damage or deviation from requirements, if any, in the characteristics of such products. Hence one has to be very careful to see the presence of contaminants and/or impurities and their influence on the damage analysis before arriving at appropriate conclusions. In case of difficulty of arriving at appropriate conclusions, one can resort to adopting damage simulation techniques, predictive damage analysis, intuition, practical knowledge and logical thinking. Hence damage analysis demands a wide knowledge of textile fibres, the process of their conversion to yarns, fabrics and garments, chemical treatment, and typical application of textiles, besides the knowledge of various methods of analysis and their utility.

11.10 Applications of textile damage analysis

11.10.1 Forensic applications

Forensic science and its application in criminal investigative technology are used to help clarify criminal cases. Textiles can play an important role here, usually in the form of clothing but also including household and automobile textiles, furnishings and in rare cases also technical textiles, for example strings and ropes used to bind, mangle or hang victims. Textiles used by criminals can also include stocking masks, gloves, bags, sacks and adhesive tapes. Sometimes it is possible to solve cases of murder unequivocally with the aid of a few typical fibre traces transferred from the murderer to the victim and/or vice versa.

Forensic application of textile damage analysis methods will help to extract information from photographs taken at crime scenes using photographic and computer techniques. This can include the matching of items taken from suspects. Analysis can reveal shoeprints in earth, mud, sand or carpet, and hand markings on textile surfaces. This enhances the utility of photographic information and the digital images to match clothing, people, firearms, vehicles, etc. It is also possible to detect prior damage to repaired

surfaces. Extensive literature on forensic analysis is available from Grieve (1990, 1994, 2000) and from www.canesis.com.

11.10.2 Other applications

Damage analysis of textiles is highly useful in determining whether the fibres used in a consignment are made up of particular type of pure polymer or not. It is also of great use in identifying whether the correct proportions of fibres are used in a blend or not and thus in helping to avoid disputes that may arise between the manufacturer and the customer. Damage analysis is often sought to resolve issues concerning whether the right type of chemicals are used on textiles or not and whether they are skin-friendly, eco-friendly, hazardous to the wearer, etc.

Textile damage analysis is helpful in identification of fibre type and thus in detection of happenings of accidents, fire hazards or any other type of risks the wearer of that particular textile was subjected to. Damage analysis of fibres containing blood stains, or any secretions or remnants collected from selected parts of a human body, will help in detection of murders, rape cases, suicides, etc.

A special case of fibre identification involves vehicle accidents with fatal injuries to the occupants. The high pressure of impact causes such a high frictional heat that fibres are embedded in plastic surfaces which are momentarily softened and the fibres are retained there after the plastic cools down. With these traces, known as fusion marks, it is possible to reconstruct where the passengers were sitting and to determine who was driving the vehicle (Schindler and Finnimore, 2005).

11.11 Future trends

Future trends in damage analysis may include the demand for use of sophisticated instruments that can provide quick and accurate information about the damages and their occurrences. One can resort to damage simulation techniques to compare and contrast the real damage with the stages of occurrence and thus find out the causes. Modelling and computational techniques can be increasingly used in stress analysis, predicting structural degradation, impact damage, reduction in strength and other mechanical properties in various textiles and textile-reinforced composites. Online monitoring of various processes, data collection, analysis and storage will be of great use in looking back at the processes to identify the causes of damage. Progressive damage analysis techniques consisting of simulating damage growth, data collection and analysis may find extensive application in damage analysis in the years to come. Use of finite element analysis, digital image analysis, neural network techniques and fuzzy logics, creation

of special test methods, inspection programmes, standard formats of testing, and certification and regulatory actions will make damage analysis much more sound and authentic.

11.12 Sources of further information and advice

In addition to the references cited at the end of this chapter, readers may refer to the following books, websites or sources of literature for further information on testing of damaged textiles and related aspects:

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Caring for Collections Across Australia, Heritage Collections Council, www.amol.org.au

Chemical Testing of Textiles, Qinguo Fan (ed.), Woodhead Publishing Limited, ISBN-13: 978 1 85573 917 8, September 2005.

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Deterioration of textiles, http://www.ashmolean.org/departments/conservation/deterioration#textiles

Environmental Impact of Textiles: Production, Processes and Protection by K Slater, University of Guelph, Canada, ISBN-13: 978 1 85573 541 5, June 2003.

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12

Flammability testing of fabrics

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Abstract: Every application of textile materials has its own textile fire testing method. In some instances flammability standards are mandatory and specific in legislation and regulations, whereas for some applications flammability testing is at the discretion of the manufacturer and/or the user. Moreover, since most standards are assessed and modified every five years or so, we have attempted to highlight key issues of fabric flammability when tested as single layer fabrics or as a part of a composite, flammability measurements in general and the general principles underlying textile flammability test methods and relevant performance requirements when used in various applications. These are illustrated and exemplified by reference to specific test methods where relevant.

Key words: simple ignition test, flame spread, heat release, composite tests, mannequin and flammability standards.

12.1 Introduction

Apart from apparel clothing, the need for textiles requiring defined flammability behaviour for improved safety spans a range of applications that includes furnishing and bedding (domestic and contract), transport, civil engineering, medical and defence. In some instances flammability standards are mandatory and specific in legislation and regulations, whereas for some applications flammability testing is at the discretion of the manufacturer and/or the user. The first UK standards for the flammability testing of textiles appeared in the late 1950s, i.e. the period when around 1000 people died each year in fires with textiles as the first igniting material.[1] These and subsequent standards mainly quantify burning behaviour and flame-resistance of fabrics in terms of ease of ignition and rate of flame spread, and this is true of textile flammability standards introduced worldwide.

The measurement of fabric flammability is primarily based on classification of the burning hazard of self-extinguishing and flammable fabrics. Self-extinguishing fabrics are those which stop burning within an acceptable and defined time before the sample is consumed after removal of an ignition source applied for a defined time. It is generally understood that flammable fabrics are those fabrics which ignite when subjected to a small flame for durations of up to 12 seconds and continue to burn after the source has

been removed. Most of the work on flammable fabrics is therefore concerned and directed towards the observation and measurement of ease of ignition, the rate and extent of flame spread, the duration of flaming, measurement of heat release and heat of combustion and quantitative description of burning debris, such as melt dripping. Rarely if ever does a single test method enable all these parameters to be measured. For self-extinguishing fabrics, such as flame retarded fabrics, test methods include measurement of time of afterflame and afterglow and extent of fire damage in terms of char length, hole size or weakened sample length.

It is beyond the scope of this chapter to describe all the flammability standards and requirements of textiles in different applications. In addition, since most standards are assessed and modified every five years or so, the reader should always contact the major standards authorities (ASTM, BS, EN, ISO, DIN, etc.) in order to be aware of the latest revisions. However, we have attempted to highlight key issues of fabric flammability when tested as single layer fabrics or as a part of a composite, flammability measurements in general and the general principles underlying textile flammability test methods and relevant performance requirements when used in various applications. These will be illustrated and exemplified by reference to specific test methods where relevant.

12.2 Key issues of fabric flammability

Textile materials have very high fibre surface-to-mass ratios and hence tend to ignite easily and burn faster than other materials. Furthermore, because they are thin materials tested in two- and sometimes three-dimensional geometries, textile materials burn differently from other solid and liquid fuels. In addition, other intrinsic differences in material properties include the following:

- The matrix-like, open structure of the textiles which makes it easy for air to circulate between the burning yarns
- Their thermally thin character (see below) which ensures that non-thermoplastic fibrous materials may undergo thermal decomposition or pyrolysis in depth, whereas bulk polymers and solid fuels undergo pyrolysis as surface decomposition–vaporisation processes only
- The presence of fibres protruding well above the yarn-fabric surfaces which often promotes the occurrence of surface ‘flashing’
- The thermoplasticity of some fabrics which may cause shrinkage in one or more directions, curling and deviations from their original plane and, if melting occurs, give rise to often flaming molten drips, which may transfer heat and flame to other materials including the body of a wearer.

While all conventional textile fibres burn, the difference between them is only one of degree. The hazard associated with flammable fabrics is dependent on various fire science-related parameters such as:

- ease of ignition
- rate of flame propagation
- heat transfer mechanisms
- rate of heat release
- total amount of heat released.

These parameters individually and collectively are influenced by characteristics of particular textile material, including:

- chemical composition of fibres present
- interactions of different fibre types if fabric is a blend or composite
- fabric structure (open versus close weave, knitted versus woven versus non-woven structures)
- fabric area density and thickness
- fabric orientation (e.g. horizontal, 45° or vertical)
- point of ignition (e.g. top or bottom of sample, edge or face).

The chemical composition of the fibre is the important fibre characteristic affecting flammability of fabrics. For example, the more thermally stable is the fibrous polymer, the higher is the decomposition temperature as well as the endothermic nature of the decomposition reaction.[2] At a less sensitive level, fabric properties such as area density, construction pattern and surface characteristics also affect flammability. The majority of textile fabrics behave as thermally thin materials with the exception of heavy industrial fabrics, geotextiles and fabrics for thermal insulation which are usually >10 mm thick and have higher densities, often >1 kg/m^2. However, textile fabrics for major conventional end-use applications are thermally thin, with ease of ignition and flame spread rates being of primary importance. The lighter the fabric, the quicker it ignites and the faster it burns compared with a heavier fabric made of the same material.

Besides fabric structural effects, Miller and Goswami[3] analysed the effect of various yarn parameters on the burning behaviour of the fabrics. They found that zero-twist yarns produce higher burning-rate values, whereas yarns with twists from 0 to 1.37 turns per cm decrease the mass burning rate by up to 40%. Wraight *et al*.[4] studied the effect of fabric area density or weight on heat transfer rate. They found that for cotton the heat emission is inversely proportional to the fabric weight, whereas for 100% polyester the heat emission rate varies in the same direction as the fabric weight but to a much lesser degree.

When determining textile flammability, many terms are used to describe different stages of the process. Selected terms used to define flammability

parameters of textile materials described in many British and international standards are given below:

- *Ignition:* flaming of the test specimen for a period of 1 s or more after removal of the igniting flame.
- *Flaming:* combustion in gaseous phase with emission of light.
- *Glowing:* combustion of a material in the solid phase without flame but emission of light from the combustion zone.
- *Smouldering:* combustion of a material with or without emission of light generally evidenced by smoke.
- *Melting:* liquefaction of material when exposed to heat to the extent of forming a hole in its structure, by either shrinking and/or dripping away under the specified test conditions.
- *Flame spread time:* the time taken by a flame on a burning material to travel a specified distance measured from when the igniting flame is applied or after it has been removed.
- *Flaming debris:* materials separating from the specimen during the test procedure and falling below the initial lower edge of the specimen and continuing to flame as they fall.
- *Afterglow time:* the time for which a material continues to glow, under specified test conditions, after cessation of flaming or after removal of the ignition source, ignoring glowing debris.
- *Surface flash:* rapid spread of flame over the surface of a material without ignition of its basic structure.

12.3 Measurement of fabric flammability

Scientifically based measurable flammability characteristics and parameters can be categorised under the following headings:

- Pre-ignition:
  - thermal decomposition (temperature and weight losses)
  - enthalpy changes
  - products of thermal decomposition
  - kinetics of the ignition process.
- Post-ignition:
  - ignition temperature
  - flame temperatures
  - heat release rates during burning
  - flame propagation rates
  - upward mass burning rates
  - extinguishability
  - products of combustion.

However, assessment of the potential flammability hazard of any fabric can only be followed if the source of danger to life and injury is identified at each stage of the burning process. Thus no single laboratory test can determine the complete burning character of a particular textile.[5] Most investigative procedures for assessing textile burning behaviour fall into two groups: the standard test methods and the scientific or research test methods. The research test methods give a fuller picture of burning behaviour and attempt to quantify a number of aspects of the burning process, whereas the standard test methods usually involve 'pass–fail' and/or performance rating criteria.[6] Some of the principal work on development of scientific test methods for measuring flammability of fabrics is discussed in this section.

During the 1970s, the experimental techniques such as Oxygen Index (OI) and flame-temperature methods gained popularity for measurement of flammability of polymeric materials. According to the ASTM,[7] limiting oxygen index (LOI) is defined as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will just support flaming combustion of a material. This technique provides a numerical measure of sample flammability, although it does not explain the burning behaviour of the material. Generally, textiles having LOI values of 21 vol% or less burn rapidly, those having values in the range 21–25 vol% burn slowly, and those with LOI ≥ 26 vol% exhibit some level of flame retardancy in air, which has an oxygen concentration of about 21 vol%. While oxygen index methods have not achieved formal standard status for textile materials, they are included as part of relevant national and international test methods for polymers in general. Horrocks *et al*. reviewed the whole area of oxygen index as it relates to textiles.[5] With respect to textiles, OI tests are mainly used in determining the effects of different flame retardant treatments and finishes, varying the add-on of finishes, or varying synergistic combinations of flame retardant compounds. However, because LOI values may be influenced by many fabric variables for a textile comprising a single fibre type,[5] there are reasons why the test method is rarely used to define fabric performance by regulatory and commercial bodies. OI methods, however, do find applications as research and development tools.

Various flame spread theories were also developed in the 1970s, which formed the basis of standard test methods designed for measuring fabric flame spread.[8,9] The theoretical models to predict flame spread behaviour were developed on the basis of measured burned length using video photography, for example. Some of the ways of measuring fabric flame spread involving different techniques from those above and related theories are briefly discussed below.

One of the ways of measuring vertical flame spread is to weigh the burning sample continuously. This would enable the rate of loss of weight

to be calculated, and from it the vertical flame spread. The details of the apparatus designed for measuring the vertical flame spread on fabrics by the above principle were discussed over 50 years ago by Lawson *et al*.[10] The vertical flame spread was calculated by using the formula

$$v = \frac{rl}{w_1 - w_2}$$

where v = vertical flame spread in m/g
r = constant
w_1 = initial weight
w_2 = weight of carbon residue
l = initial length of specimen.

The authors also examined the minimum length of the specimen required for measuring the maximum rate of flame spread and concluded that this is not reached until a sample of about 127 cm (50 inches) is burned. An alternative method of assessing flammability was to allow the material to burn at various angles to the vertical and to see at which angle the sample is no longer able to support flaming. A simple apparatus was designed by Lawson *et al*.[10] wherein the spread over the sample in a semi-circular track was ignited at one end and the distance to which the flame spread reached was noted. It was found that many materials burned completely round the semi-circular track, and they were differentiated from each other by noting the time taken to burn 21 inches (53.3 cm) of specimen. The authors also derived two empirical mathematical equations for determining flame spread rate and concluded that the vertical flame speed is roughly proportional to the square root of the distance of spread ($V = 1.81d^{0.4}$) and inversely proportional to the time of spread ($V = 1655/T^{1.03}$) for the materials that burn completely (for flammable materials). Both of these sets of experiments were incorporated in early, now obsolete British standards of the 1950–60 period.[5]

Furthermore, heat release measurement is also a significant criterion in assessing textile flammability at the scientific level, although less so in the standard test procedure.[3] A heat release parameter of fabrics is also useful to predict burn injury severity in particular. The rate of heat release is determined by measuring combustion product, gas flow and oxygen depletion, and the rise in temperature of the sample or the rise in temperature of air entrained during burning of the specimen. Initial attempts to measure heat release rate and thus predict burn injury severity differed mainly in the manner in which the specimens were held, the number of sensors and the manner in which they were mounted relative to the specimen and the specimen shape. Of all the early heat release measurement techniques studied, the US Textile Research Institute's (TRI) convection calorimeter gained popularity in the 1970s. Miller *et al*.[11] developed a technique for

continuous monitoring of the heat released when a freely suspended fabric burned under natural convection, using the so-called TRI convection calorimeter. The instrument monitored the rate of heat emission by measuring the airflow rate of convective air. The primary response obtained from these measurements included:

- the maximum rate of heat emission
- the time to reach the maximum rate
- the post-maximum time required for the heat emission rate to subside to one-half its maximum value.

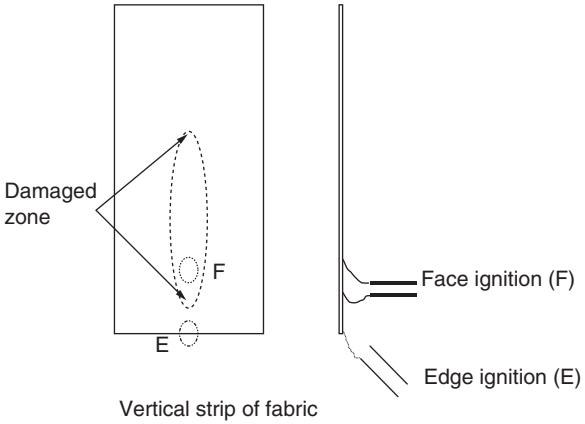
Since the late 1990s, however, heat release rate data have been used as a tool for evaluating the hazard level of a fire system in general and individual combustible materials specifically. Developed by Babrauskas,[12] the cone calorimeter measures the hazard level by measuring the rate and amount of heat released, and smoke and toxic gases generated, and this now standard method (e.g. ISO 5660) is used to define material performance including textiles in a number of applications, notably construction and transport. However, because of its complexity and cost, it is rarely applied to the testing of single fabrics and fabric assemblies.

12.4 Standard testing methods

Ideally, all standard test methods should be designed such that the measurement of flammability parameters, such as time to ignition, rate of flame spread, afterglow times, etc., can be acquired in a reproducible and repeatable manner. The flammability principles on which the standard tests are established should be straightforward and easy to transform into a practically simple and easy-to-use test.[13] Some of the principle test methodologies are discussed below along with illustrative standard method examples.

12.4.1 Simple ignition tests

In standard test methods, fabric ignition is measured in terms of minimum ignition time, i.e. how long a flame needs to be applied to a given material so as to achieve ignition, normally to the nearest second. A simple ignition test includes a vertically oriented fabric subjected to a standard gas flame applied to the face or lower edge (depending on the severity of the test required) of the fabric specimen. Ignition is monitored by visual observations and the time taken to ignite the specimen is recorded. This test is used in many standards including BS 5438, EN ISO 6941, FAR Part 25, etc. A schematic diagram of a typical vertical strip test is shown in Fig. 12.1. For horizontal and inclined fabric orientations (e.g. 45°, 60° etc.), edge ignition is often preferred.



12.1 Schematic representation of a simple vertical strip test.

The minimum flame application times determined using Test 1 of BS 5438:1989[14] for ignition of selected different fabrics are given in Table 12.1. Initial analysis[6] of ignition time data in Table 12.1 suggests that the minimum flame application times are very similar for most of the fabrics in spite of different fibre contents, and that the time to ignition is lower for edge ignition in both warp and weft directions than the respective face ignition times. It is also evident from Table 12.1 that the time to ignition is directly related to area density. All fabrics ignite after 1–4 seconds, indicating their respective ease of ignition. This test method appears to distinguish ignitability of fabrics more on the basis of physical factors (relating to area density and specimen orientation) than on fibre chemistry for the examples listed. This can result in significant change in the ranking order of fabrics if the specifications such as physical form and orientation of fabrics are altered. Therefore, for a fuller understanding of the flame initiation process and the response of a material to it, the authors explored experimental methodology to determine the ignition temperature sensitivity of various fabrics. Details of this study are beyond the scope of this chapter, however, and are discussed elsewhere.[15]

For materials with a dripping tendency, the igniting flame burner can be inclined at 45° so as to avoid flame extinguishment by molten drips from the specimen. Such a test method may include a basket with filter paper placed under the vertically mounted specimen (see Fig. 12.2) to judge the hazard of a material burning with flaming drops.

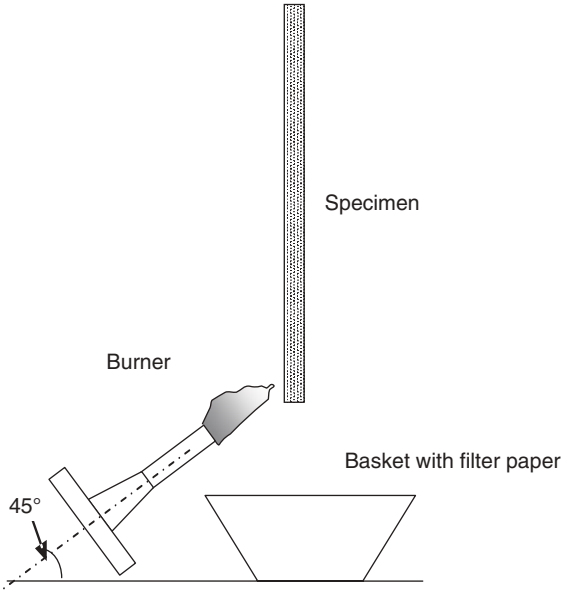
12.4.2 Flame spread

Rate of flame spread is usually calculated by measuring the distance and recording the time taken of the advancing flame front to sever threads

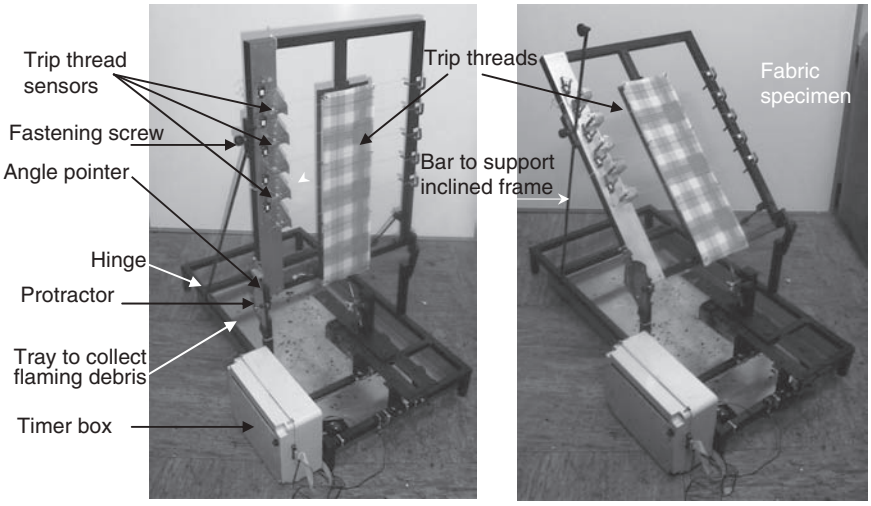
Table 12.1 Minimum ignition times using Test 1 of BS 5438

Fabric sample	Minimum flame application time, s			
	Warp direction		Weft direction	
	Face ignition	Edge ignition	Face ignition	Edge ignition
Light cotton	2	1	2	1
Heavy cotton	4	1	4	1
Poly-cotton (55:45)	3	2	1	1
Poly-cotton (65:35)	2	1	2	1
Polyester	*	*	*	*
Acrylic	2	1	2	1
Light silk	2	2	2	2
Heavy silk	†	3	†	3
Wool	3	3	4	3

*Fabric melted away from the flame.
†Flames extinguished when the flame was moved away.



12.2 Vertical strip test for dripping materials with inclined burner.



12.3 Flame spread test rig: (a) vertical; (b) inclined.

placed at defined distances by the flame front. The flame spread test apparatus is shown in Fig. 12.3. The frame supporting the sample can be hinged (see Fig. 12.3(b)) such that the frame can be moved from the vertical to any other required angle. The frame can be fixed in an inclined position by fastening the screw on the supporting bar.

The upward fire spread is far more rapid than downward and horizontal flame spread and hence is adopted as a better means of measuring the fire hazard of a fabric. Therefore, most standards, including BS 5438:1989, standards for curtains and drapes (see Section 12.5.5) and BS EN ISO 15025:2002, use this type of bench-scale test method for measuring vertical flame spread properties of fabrics in particular.

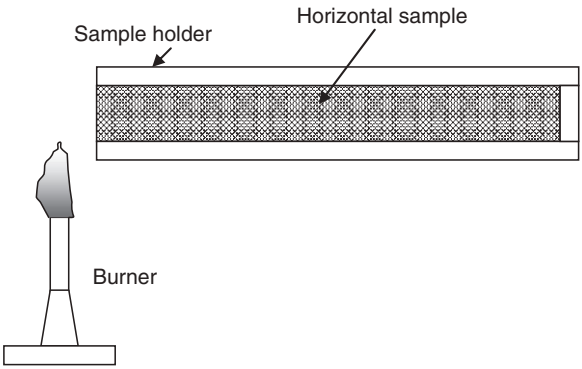
However, fabrics behave differently in different orientations, depending upon their composition and structure. Table 12.2 shows average rate of flame spread for various fabrics at different inclinations. For each fabric, the rate of flame spread decreases as the angle of inclination reduces to 0° as expected. Further analysis[6] of the data in Table 12.2 has shown that the nature and rate of flame spread vary with the angle of sample inclination, area density and fibre content. This is in agreement with theories of flame spread which state that the phenomenon of flame spread is controlled by the mechanism by which heat is transferred ahead of the burning zone, which in turn is strongly influenced by surface geometry and inclination as well as fibre or material type.

The flame spread test in horizontal orientation is relevant for applications where the textile material is used in flooring, ceilings or any other less hazardous horizontal applications. In this test method, the free end of a hori-

Table 12.2 Average rate of flame spread (m/s) for fabrics at different angles of inclination

Fabric sample	90°	60°	45°	30°	15°	0°
Light cotton	57	40	37	30	18	6
Heavy cotton	27	19	18	14	10	3
Polyester:cotton (55:45)	39	30	27	22	19	8
Polyester:cotton (65:35)	37	27	24	21	13	9
Polyester*	–	–	–	–	–	–
Acrylic	23	15	13	11	8	6
Light silk†	–	–	–	–	–	–
Heavy silk	–	–	–	–	–	–
Wool§	23	14	12	10	8	–

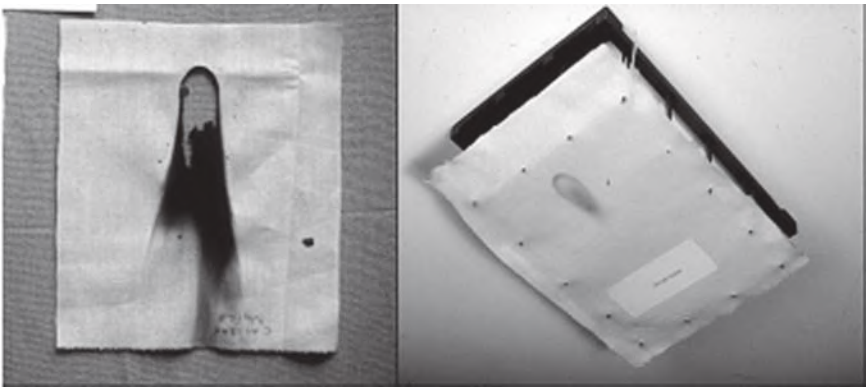
* The fabric did not ignite.
† The flames extinguished on removal of ignition source.
§ The flames extinguished on removal of ignition source in horizontal orientation of specimens.



12.4 Horizontal flame spread test.

zontal sample is exposed to the low-energy flame for times up to 15 s in a combustion chamber (see Fig. 12.4). If the sample ignites, then the time to self-extinguish the flame or the time in which the flame passes a measured distance is recorded. This test method is used in various standards for determining the horizontal burning rate of materials used in the occupant compartment of road vehicles, typified by US standard FMVSS 302, BS AU 169a:1992 and ISO 3795:1989.

In the case of flame retarded textiles which are usually tested in vertical orientations, the flame spread is recorded as extent of damage as a hole, char length or weakened (damaged) length measurement of the specimen, and the test is often termed the limited flame spread test. Figure 12.5 shows a Kevlar® (DuPont) aramid and a flame retarded polyester:cotton (70:30) blend fabric specimen after testing in accordance with Test 2 of BS 5438:1989.



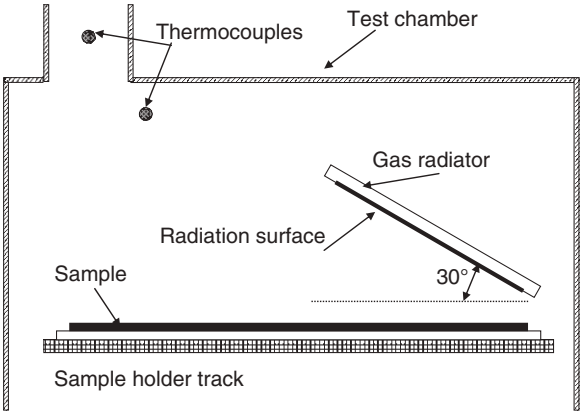
(a) (b)

12.5 (a) Kevlar® aramid fabric and (b) flame-retarded polyester:cotton (70:30) blend fabric.

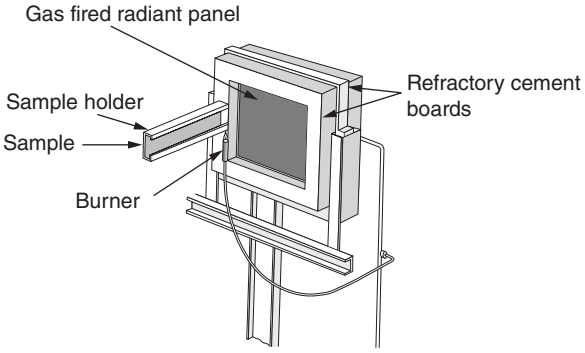
Note that the latter is hardly damaged as expected for such a high performance fibre, while the former has formed a hole and significant char accompanied by sooty smoke deposits.

12.4.3 Flame spread under external heat flux

Measurement of flame spread under external heat flux is necessary where thermal radiation is likely to impinge on the textile materials, for example in the flooring material of a building or in transport vehicles whose upper surfaces are heated by flames or hot gases, or both. This situation is usually encountered in a fully developed fire in an adjacent room or compartment. To simulate this scenario, the radiant panel test typically involves a horizontally mounted test specimen positioned at an angle to the radiant heat source shown in Fig. 12.6. The specimen is exposed to radiant heat from an air- or gas-fuelled radiant panel and the textile fabric specimen is at an angle typically of 30° to the panel face. The mounted specimen is thus exposed to a gradient of heat flux ranging from a maximum of 10 kW/m^2 immediately under the radiant panel to a minimum of 1 kW/m^2 at the far end of the test specimen, remote from the panel. The specimen closest to the panel is often ignited by a small flame and the distance burned until the flame extinguishes is converted into an equivalent critical radiant flux in W/m^2 related to the panel intensity at that point. This test method is the basis of that used by the FAA for assessing flammability of textile composites used in thermal/acoustic insulation materials (FAR 25.856(a)) used in aircraft and has also been included by the EU for fire test approval of floorings such as prEN ISO 9239 and BS ISO 4589-1.



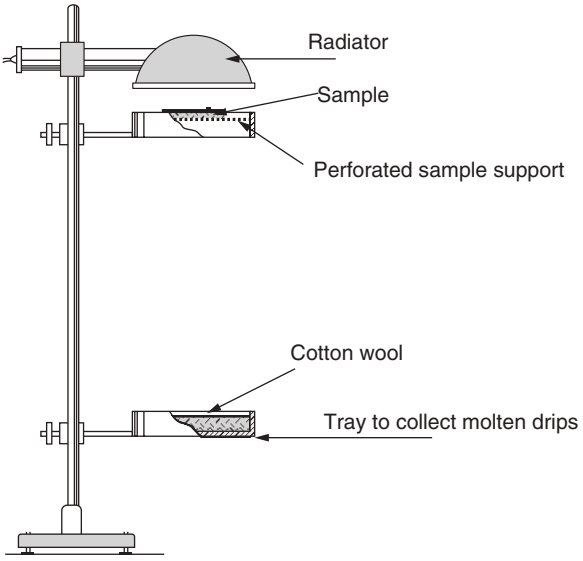
12.6 Schematic of flooring radiant panel test apparatus.



12.7 Radiant panel test for floor coverings as described in BS 476 Part 7.

For textile materials used as interior wall-coverings in UK buildings, including railway carriages, where the fabric could be in a vertical orientation attached to the wall panel, measurement of rate of flame spread under external heat flux is one of the requirements. For such applications, the test method (BS 476 Part 7) essentially requires a vertically oriented specimen (see Fig. 12.7) exposed to a gas-fired radiant panel with incident heat flux of 32.5 kW/m^2 for 10 min. In addition, a pilot flame is applied at the bottom corner of the specimen for 1 min 30 s and rate of flame spread is measured. The same principle is used in the French test for carpets, NF P 92-506.

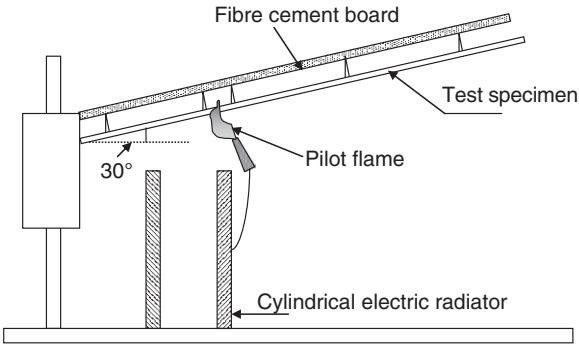
In the French suite of test methods (NF P 92-501–506) for testing building materials, the presence of a radiant panel is a significant test feature.



12.8 Dripping test with radiant heat flux.

Normally if the material shrinks away from the ignition source or away from the vicinity of the radiator without burning, in NF P 92-506, for example, then such materials can be further tested for dripping. The dripping test is defined in NF P 92-505 and is a complementary test to determine burning drops which cannot be assessed in the primary test.[16] The test is shown in Fig. 12.8 and the specimen supported on a horizontal grid is exposed to incident heat flux of 30 kW/m^2. For the specimen to pass the test, the materials should not melt, drip or ignite the cotton wool placed under the specimen holder.

One other particularly important test within this French suite that uses radiant heat flux is the NF P 92-503 Brûleur Electrique or 'M' test for flexible textile materials. The schematic of the test apparatus is shown in Fig. 12.9. The fabric sample is inclined at 30° to the horizontal and is subjected to a radiant heat flux for 5 min and a flaming ignition source is applied to the heated fabric. Time to ignition or time to hole formation, the presence of burning droplets and the length of the damaged specimen are recorded in order to classify materials from M1 to M4, where M1 textiles may be classed as non-flammable, M2 as low flammable, M3 as moderately flammable and M4 as highly flammable. While this test is mainly used in France, Belgium, Spain and Portugal to certify the use of flexible materials in buildings for public use, it affects many UK and other EU manufacturers supplying into EU markets.



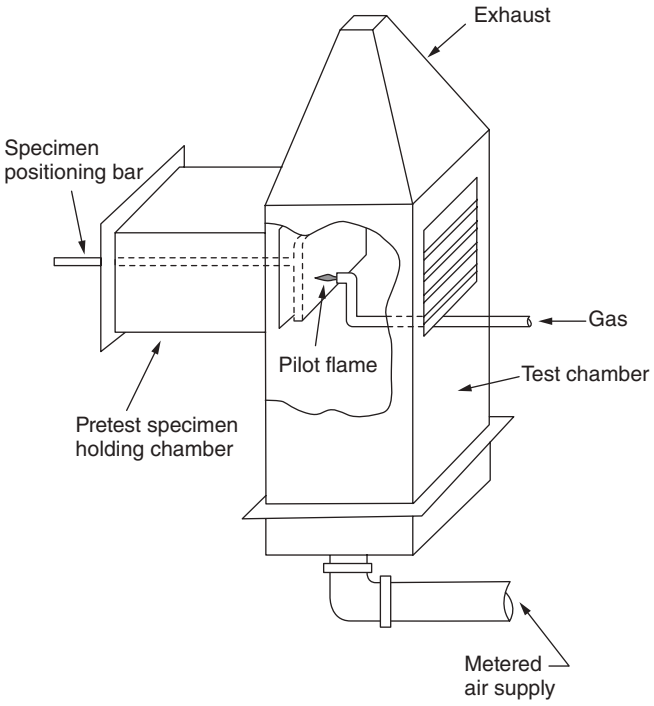
12.9 NF P 92-503 electric burner (brûleur) test.

12.4.4 Heat release tests

When assessing materials for use in buildings and transport, heat release rate is one of the most important parameters characterising the hazard from unwanted fires and is an indicator of:

- rate of fire growth
- size of the fire
- skin injuries from potential fires
- effectiveness of fire suppression agents and their application rates for fire control.

Since textiles may comprise part of a building or transport structure, textile materials, usually part of a building composite, are often subjected to heat release testing. Fire calorimeters to determine the heat release rate during burning of materials operate on a variety of principles, including sensible enthalpy (temperature rise) of the gas stream or enclosure and analysis of the combustion gases for excess carbon dioxide or depleted oxygen.[17] One of the original, successful small-scale calorimeters was the rate of heat release test apparatus developed at Ohio State University (OSU) as shown in Fig. 12.10.[16] The sample is exposed to a heat flux of 35 kW/m^2 generated by silicon carbide heating rods and a pilot flame is applied on the lower end. The rise in the temperature of the fire effluents is measured using thermocouples and the heat release rate is computed from the temperature rise of the air flowing past a 150 mm × 150 mm burning specimen. This apparatus is defined in the aviation standard FAR 25.853 Part IV Appendix F and ASTM E906-1983 for determining the heat release of internal structural materials in commercial aircraft originally in the US and now worldwide. All decorative textiles fixed to wall panels in aircraft must be tested to this standard.

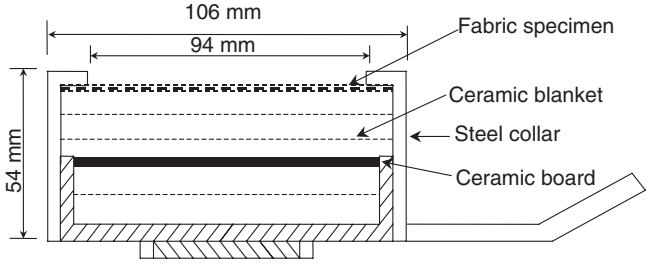


12.10 Schematic of OSU calorimeter.

A more sophisticated bench-scale equipment which measures heat release rate by oxygen consumption is the cone calorimeter (see Fig. 12.11). In this test, the fabric or composite specimen mounted over an insulating ceramic blanket is exposed to an external heat flux (0–75 kW/m^2). The volatiles released from the heated specimen are ignited using a spark igniter and the time taken to ignite the gases is recorded as the time to ignition of the specimen tested. Originally designed to study the fire characteristics of building materials which are physically and hence thermally thick, the cone calorimeter can now be used for thermally thin materials such as fabrics,[6] although not yet as a standard test. It has also been used for characterising furnishing fibres which incorporate the samples in a composite fabric/filling form (for example, an upholstery fabric on top of a polyurethane foam).[18] The sample preparation for the cone calorimetric experiment on fabric specimens is shown in Fig. 12.12.

Since textile fabrics are dimensionally as well as thermally thin materials, a number of refractory ceramic blankets are used to form a 13 mm thick layer to separate the lower sample surface and/or backing material from the bottom of the sample holder. However, testing single layer textile materials does pose a major challenge. This is because the fabrics are very light-

12.11 Cone calorimeter apparatus.

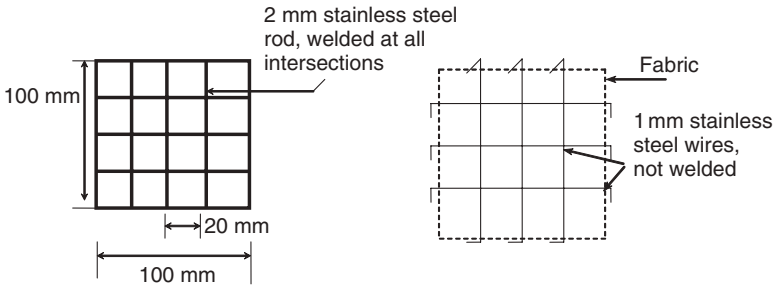


12.12 Sample holder for cone calorimeter.

weight and physically thin, and often tend to shrink and even melt during the course of burning. Even for non-thermoplastic fibres, this shrinkage is estimated[19] at a maximum of 15% of the original surface area and is often accompanied by a distortion of the specimen in the vertical plane. A 3×3 stainless steel (rod diameter 1 mm) crosswire assembly (see Fig. 12.13) can be used for maximising specimen reproducibility, especially in the case of the single-layered specimens.[6]

The cone calorimeter measures the following parameters during a test:

- Sample mass
- Time to ignition
- Flow rate and temperature of the exhaust gases
- Oxygen and carbon oxides (CO and CO_2) in the exhaust gases
- Smoke density.



12.13 Sample preparation for cone calorimeter.

By using the above information, calculations are performed to produce the following:

- Heat release rate (HRR)
- Total heat released (THR)
- Mass loss rate (MLR)
- Specific extinction area (SEA), i.e., the amount of smoke produced per unit mass of sample consumed
- Carbon oxides (CO and CO_2) consumed for unit mass of sample.

12.4.5 Mannequin (or manikin) tests

The major means of determining the fabric burn hazard of textiles, and more particularly clothing assemblies, has been by the use of sensored mannequins. Sensor systems used on mannequins have ranked from paper which turns black at certain temperatures[20] to sophisticated sensor systems which indicate the depth of burn.[21,22] The history and development of mannequin tests has very recently been reviewed by Camenzind *et al*.[23] A typical mannequin is equipped with 100–122 individual heat-flux sensors distributed over the surface of the body. The test garment is placed on the mannequin at ambient temperature conditions and exposed to intense fire or flash fire simulation sources with controlled heat flux, duration and flame distribution. The sensors measure incident heat flux upon the underlying mannequin surface during and after exposure. The changing temperature of the mannequin surface temperature simulates damage to human tissue at two skin thicknesses, one representing a second degree burn injury point and the other a third degree burn injury point.[24] The computerised data acquisition system also calculates surface heat fluxes, skin temperature distribution histories and predicted skin burn damage for each sensor location.

These tests offer a more analytical means of assessing apparel burning hazards and predict potential skin burn hazards of garments. They are

useful in research but are very expensive and complex for use in standard test procedures,[25] although a new draft standard ISO/DIN 13506.3 is currently being assessed. A major problem has been poor reproducibility, because a major variable is correct clothing assembly fit over the mannequin's torso, even when garment sizes are identical. This is particularly the case in firefighters' clothing where the overlap between top coat and trousers may present a thermal weakness during flame exposure. However, improved reproducibility is being achieved at a level sufficient to enable the test method to be included within the overall performance requirements of firefighter turnout suits within the near future.[23] Notwithstanding these problems, mannequins are considered to be important in simulating the burn injury severity in real-life accidents.

12.4.6 Full product or composite tests

Furniture is a complex product comprising many different materials, including the cover material which is often a textile, a filling or cushioning material which is often polyurethane foam, and the supporting metal or wooden frame. When in contact with an igniting source, for example a smouldering cigarette or a small match flame, the covering fabric can char, melt or catch fire. If the fabric forms a smouldering char, this may generate considerable heat accumulation over a period and subsequently spread into the filling material. The covering fabrics may also melt away from the ignition source, thereby exposing the underlying cushioning foam or filling. Smouldering may have two consequences as it penetrates into the filling: either the intensity of the ignition source can be reduced and oxygen presence diminished thus extinguishing the fire, or the filling material can catch fire and the whole assembly burst into flames. In case of an open flame, if the cover fabric catches fire, it can act as a high-intensity secondary ignition source leading to ignition of the underlying materials. Thus the burning behaviour of the whole composite system depends on the burning behaviour of individual components as well as the interaction between two components, namely the covering material and the filler material.[26]

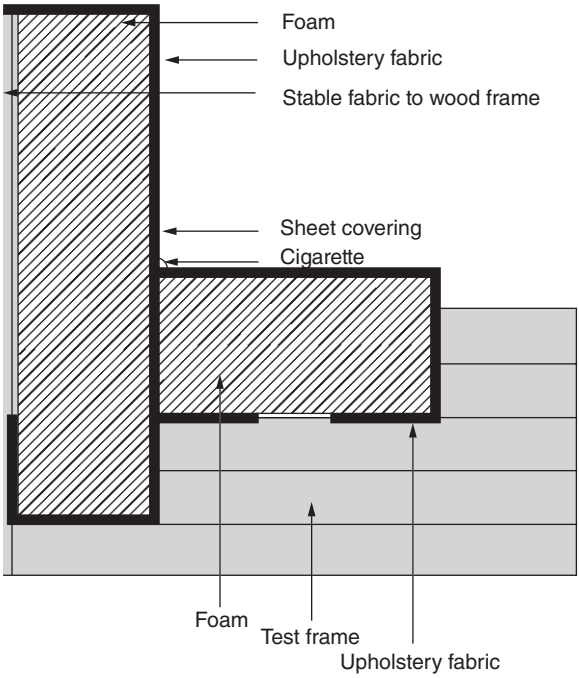
Bench-scale laboratory tests for individual components are suitable for screening new materials and for quality control purposes in the manufacturing industry and, more importantly, for establishing regulatory performance. However, these component tests cannot assess the fire hazard posed by the upholstered composites, and hence composite flammability tests are essential to measure the fire performance under end-use conditions. Small-scale composite tests present a clearer picture of the now well-established BS 5852 (and its subsequent ISO and EN versions), and small-scale testing for furnishing composites is a prime example.

Table 12.3 Flammability and heat transfer test methods for firefighter's clothing, BS EN 469:1995

Property tested	Standard	Principal performance specifications
Flame spread	BS EN ISO 15025:2002	No flame extending to top or edge, no hole formation, and after-flaming and after-glow times of ≤2 s
Heat transfer (flame)	BS EN 367:1992 (ISO 9151)	HTI_{24} ≥13 s
Heat transfer (radiant)	BS EN ISO 6942:2002 at 40 kW/m^2	$RHTI_{24}$ ≥22 s
Residual strength	ISO 5081 after BS EN ISO 6942 Method A at 10 kW/m^2	Tensile strength ≥450 N
Heat resistance	BS EN 469:1995 Annex A	No melting, dripping or ignition
Dimensional change	ISO 5077	≤3%
Contact heat transfer	BS EN 702:1995 (ISO 12127)	Defined by manufacturer/ consumer
Mannequin (optional)	ISO/DIS 12127	Defined by manufacturer/ consumer

Flammability tests for upholstered furniture using various ignition sources were first developed in 1979 as British Standard BS 5852: Parts 1 and 2 in the United Kingdom. Source 0 is a smouldering cigarette and Source 1 a small butane flame which simulates a lighted match. Sources 2 and 3 are more intense flame sources (see Table 12.9). The test specimen is a composite specimen consisting of fabric and filling material as shown in Fig. 12.14. A similar composite specimen assembly is used in the US standard Cal TB 116 for testing flame retardance of upholstered furniture. In addition to the smouldering cigarette ignition source, BS 5852:1979 and its subsequent variants define the use of a variety of pinewood cribs (Sources 4–7) which match the calorific outputs of increasing numbers of full-size newspaper sheets. Figure 12.15 shows composite test specimens with wooden crib Source 5 as ignition source.

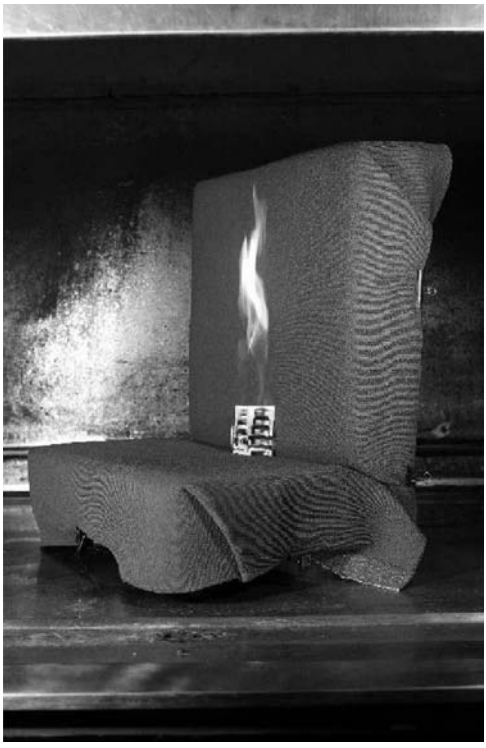
Development of BS 5852 as a small-scale composite test was a breakthrough in realistic model testing that cheaply and accurately indicated the ignition behaviour of full-scale products of a complex nature.[27] Good reproducibility, cost-effectiveness and easy to use features of BS 5852 have led to the establishment of the concept, which was further employed for flam-



12.14 Composite specimen assembly for flammability test of upholstered furniture.

mability testing of bedding and mattresses.[13] The presence of bedcovers, including sheets, blankets, bedspreads, valances and quilts, together with pillows and pillow cases, introduces many interacting variables that affect the fire behaviour of mattresses. Therefore, the test methods developed for determining the ignition resistance of mattresses are composite tests including bed sheets. Assessment of ignitability of mattresses is generally carried out with cigarettes on the bare mattress and sandwiched between two cotton sheets over the mattress. For the mattress to pass the test, flaming combustion should not occur and the char development should typically not be more than 50 mm in any direction from the cigarette. Specific flammability test methods for bedding mattresses are described in Section 12.5.7.

Other textile products that require composite flammability testing are protective clothing assemblies including firefighters' suits, military flight suits, etc. The test methods specific to the flammability of protective garments will be discussed below. The major performance requirement of such clothing demands protection from high-heat flux thermal exposures. Flammability standards and test methods for textile components in protective clothing have been discussed by Bajaj[28] and very recently by



12.15 Composite specimen with wooden crib as ignition source.

Horrocks.[29] Their reviews suggest that standard bench-scale tests for separate determination of flame resistance, thermal insulation/protection and heat resistance may be undertaken on a single fabric or a composite form in a manner that reflects a real application or product requirement. Nowadays, the trend is to provide an overall set of performance specifications for a given type of protective clothing item or assembly. For instance, the performance of firefighters' clothing defined in BS EN 469:1995 (updated 2005) is a composite of tests which measure the different hazards of open flame, hot surface or radiant heat exposure and also offers an optional mannequin test. These are listed in Table 12.3. A similar performance standard exists for protective clothing and other occupations such as workers exposed to heat, BS EN 531:1995.

12.5 Textile flammability standards

Test methods defined in early standards were widely used for general fabrics until 1970 when it was realised that different end-uses required different

test methods. Nearly every country had its own set of textile fire testing standard methods. Fabric flammability regulations in different countries are often similar in spirit, but they differ in detail. Since 1990, within the EU in particular, some degree of rationalisation has been underway as 'normalisation' of individual EU member states' testing methods in order to avoid differences in the national standards which could lead to technical barriers to trade. The development of European Standards is thus binding on all community members. The European Committee for Standardisation (CEN) is responsible for publishing European Standards, prefixed by the letters EN which are intended to replace national standards within the European Union, e.g. BS EN, NF EN, DIN EN. Within the US, ASTM is still the overarching standards organisation but increasingly ASTM, ISO and EN standards are becoming similar, if not equivalent, for certain test methods.

12.5.1 Nightwear and apparel

In-depth analysis[6,15,30] of clothing-related fire statistics in the UK show that nightwear is more likely to cause deaths than any other clothing item in spite of the UK Nightwear (Safety) Regulations, 1985.[31] In 1945, legislation regarding flammability of fabrics was brought into force for the first time in California. During the past three decades, governments of the US, Canada, the UK, Australia and several European countries have enacted legislation aimed at reducing the hazards of burning apparel fabrics. Fabric flammability standards and test methods in different countries are summarised in Table 12.4. The Dutch and French standards in Table 12.4 are derived from an ISO standard (ISO 6941) which determines flame spread properties and ISO 6940 which determines ease of ignition. The Swedish and Norwegian regulations are based on the American ASTM 1230 standard test method for flammability of clothing textiles.

This issue of garment flammability has been recognised in the UK since the 1960s when regulations, revised in 1985, were first applied to children's and subsequently to all nightwear.[31] The subsequent UK Nightwear (Safety) Regulations 1985 require the testing of all nightwear, including pyjamas and dressing gowns, and demand that adult and children's nightwear carry a permanent label showing whether or not each item meets the requirements of BS 5722:1984[32] (which uses Test 3 of BS 5438:1976). This latter performance standard defines a maximum permissible burning rate of a vertically oriented fabric. However, it fails to regulate the fabrics according to their heat release properties, which are considered to be more realistic when the burning hazard is to be correlated with the burn injury severity.[33]

In the EU, a new standard that addresses the fire safety hazards associated with children's nightwear has been issued.[34] The flammability testing methods required by EN 14878:2007 are based upon EN 1103 which

Table 12.4 Selected test standards for nightwear (safety) regulations

Country	Test standard	Testing					
		Face (F)/ edge (E)	Flame height, mm	Type of test	Ignition time, s	Frame V = vertical	Label
Germany, France	EN ISO 6940	F-E	40	Ignitability	0–20	ISO, V	–
Germany, France	EN ISO 6941	F-E	40	Flame spread	10	ISO, V	–
	EN1103	F	40	Flame spread Flash Flaming debris	10	ISO, V	–
Ireland	IS 148	F	45	Flame spread	10	BS, V	Yes
UK	BS 5722 method 2	F	45	Limited flame spread	10	BS, V	Yes
UK	BS 5722 method 3	F	45	Flame spread	10	BS, V	Yes
Australia	AS 2755/2	F-E	40	Flame spread	5–15	ISO, V	Yes
Denmark, Finland, Iceland, Norway, Sweden	NT FIRE 029	F	16	Flame spread	1–20	45°	–
Germany	Dutch convenant	F	40	Flame spread Flash Flaming debris	5 spread 1 flash	ISO	Yes
USA, Norway, Sweden	ASTM D1230	F	16	Flame spread	1	45°	–

describes a detailed procedure to determine the burning behaviour of textile fabrics for apparel. The standard covers all types of nightwear, including nightdresses, nightshirts, pyjamas, dressing gowns and bath robes. It also places responsibility on the manufacturer to ensure that any flame retardant chemicals used are effective throughout the life of the garment and do not present a health hazard.

12.5.2 Textiles for protective clothing

As discussed above, tests for specific hazards such as ignition resistance and thermal exposure are well defined individually but may also be grouped together within a single end-use-related performance specification such as BS EN 469 for firefighters' clothing (see Table 12.3). The individual test methods for protective clothing in general are largely based on assessing the resistance of a fabric when tested in a specific geometry (e.g., horizontal, 45° or vertical) and subjected to a small flame igniting source, which usually is a small gas flame applied to the lower edge or face close to the edge of the sample. Parameters measured include time to ignition, rate of flame spread, afterflame and afterglow following a prescribed ignition time (e.g. 10 s), extent of damaged/char or burnt fabric length, or a combination of these. Some of the standards for protective clothing are briefly summarised in Table 12.5. In addition to those in Table 12.3 defined within BS EN 469:1995, an additional example of such an overall performance requirement is the US NFPA 2112 standard for protection of personnel against flash fires. This is presented in Table 12.6.

The most important aspect of protective clothing testing is the evaluation of burn injury protection and thermal characteristics of clothing systems. Skin burn injury evaluation and subsequent modelling has been studied extensively[35–37] and has been recently reviewed by Song.[38] An overall fire resistance determined under realistic real-fire exposure conditions may be undertaken using an instrumented mannequin (see Section 12.4.4) yielding information regarding a complete clothing system's ability to resist heat flux and protect areas of the torso to first, second or third degree burn injury as described earlier. Resistance to heat transfer by convective flame, radiant energy or plasma energy sources is quantified in terms of thermal protective index (TPI), often related to the time taken for an underlying skin sample with or without an insulating air gap to achieve a minimum temperature or energy condition sufficient to generate a second degree burn (see Tables 12.3 and 12.6).

To evaluate flame and thermal protective performance of a fabric or assembly at a heat flux simulating defined thermal hazards, for example battlefield flame, methods which determine a thermal protective performance or TPP exist.[29] The instrument measures the time for a thermocouple

Table 12.5 Standards and performance requirements for protective clothing

Standard code	Standard title	Property measured	Performance requirement
ISO 2801:1998	Clothing for protection against heat and flame – General recommendations for selection, care and use of protective clothing	–	–
BS EN ISO 6942: 2002 at 40 kW/m^2	Protective clothing – protection against heat and fire. Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat	Heat transfer (radiant)	$RHTI_{24}$* ≥22 s
ISO 9151:1995 BS EN 367:1992	Protective clothing against heat and flame – Determination of heat transmission on exposure to flame	Heat transfer (flame)	$HTI_{24}^{\dagger}$ ≥13 s
ISO 11612:1998 BS EN 469:2005	Clothing for protection against heat and flame – Test method and performance requirements for heat-protective clothing	Heat resistance	No melting, dripping ignition
ISO/DIS 12127:1996 (BS EN 702:1995)	Clothing for protection against heat and flame – Determination of contact heat transmission through protective clothing or constituent materials	Contact heat transfer, manikin (optional)	Defined by manufacturer/ customer
ISO 17492:2003 Cor 1:2004	Clothing for protection against heat and flame – Determination of heat transmission on exposure to both flame and radiant heat	–	–

BS EN ISO 15025:2002	Protective clothing – Protection against heat and flame – Test method for limited flame spread	Flame spread	No flame extending to top or edge, no hole formation, and after-flaming and after-glow times ≤2 s
ISO 17493:2000	Clothing and equipment for protection against heat – Test method for convective heat resistance using a hot air circulating oven	–	–
ISO 5081 after BS EN ISO 6942 Method A at 10 kW/m^2	The determination of the breaking strength and elongation at break of woven textile fabrics (except woven elastic fabrics)	Residual strength	Tensile strength ≥ 450 N
NFPA 2112	Standard on flame-resistant garments for protection of industrial personnel against flash fire	–	–
ASTM F 1930, ISO/DIS 13506	Test method for evaluation of flame resistant clothing for protection against flash fire simulations using an instrumented mannequin	Burn injury prediction	–

* RHTI = radiant heat transfer index.
† HTI = heat transfer index.

Table 12.6 Test methods and performance requirements for flame-resistant garments meeting requirements of NFPA 2112

Property tested	Test method	Application of test method	Performance requirements
Thermal protective performance	152 × 152 mm of specimen is exposed to heat and flame source with heat flux of 84 kW/m^2. The amount of heat transferred through the specimen is measured using a copper calorimeter. The test measures the time taken to transfer amount of heat sufficient to cause second degree burn. This time multiplied by the incident heat flux gives TPP rating.	This test is used to measure the thermal insulation provided by garment materials. The TPP test uses an exposure heat flux that is representative of a flash fire environment.	TPP rating of 3 or more when tested in 'contact', simulating direct contact with skin, and 6 or more when measured 'spaced', simulating an air gap of 6.35 mm between the skin and the garment material.
Flame resistance	76 × 30 mm specimen is held vertically over a small flame for 12 s. After-flame time, char length and length of tear along the burn line are measured. Melting and dripping are also observed.	This test is used to determine ease of ignition and ease of flame spread.	After-flame time ≤2 s, char length ≤102 mm, no melting or dripping.
Thermal shrinkage resistance	381 mm^2 fabric specimen is suspended in a forced air-circulating oven at 260°C for 5 min to determine amount of shrinkage. The specimen is examined for evidence of melting, dripping, separation or ignition.	The test measures resistance to shrinkage of a fabric when exposed to heat, since this property is considered important in minimising the effects of a flash fire.	Shrinkage ≤10%.

Heat resistance	Same as above.	The test measures how garment fabrics and components react to the high heat that could occur during a flash fire.	The specimen should not melt, ignite or separate when exposed to heat.
Mannequin testing	Standardised coverall design placed on an instrumented mannequin wearing cotton underwear is subjected to an overall heat and flame exposure averaging 84 kW/m^2 for 3 s. Sensors embedded in the manikin's skin predict occurrence of second or third degree burns. Percentage of body sustaining second or third degree burns is determined using computer program.	This test provides an overall evaluation of how the fabric performs in a standardised coverall design.	Body burn rating ≤50%. Lower body burn ratings indicate greater protection provided by the fabric.
Thread melting resistance	The test involves soaking of the thread used in stitching FR garment in an organic solvent to extract substances that would interfere with the melting of thread. Melting temperature is determined by slowly heating the thread.	Measures the melting temperature of the thread used in flame-resistant garments.	Thread fails the test if melting temperature <260°C.
Label legibility	Sample labels containing product information are subjected to 100 wash/dry cycles and then examined for legibility.	This requirement checks for label durability.	Label must remain legible from 0.3 metres.

placed behind a fabric or assembly to reach a critical temperature equivalent to that causing a radiant energy source.

For fabrics used in flame-resistant garments, a thermal protective performance (TPP) of 3 s or more is required when tested in the 'contact' condition, simulating direct contact with skin, whereas a TPP value of 6 s or more is required when tested in a 'spaced' condition, simulating an air gap of 6.35 mm (0.25 in) between the skin and the garment material.

A similar bench-scale experimental setup is used for test methods described in EN ISO 6942 and EN 367:1992 (see Tables 12.3 and 12.5) for measuring radiant heat transfer index (RHTI) and convective heat transfer index (HTI) respectively. RHTI values of ≥22 s and HTI values of ≥13 s are required for materials used in protective clothing.

Early full-scale fire-testing of flame-resistant garments initially used a fully dressed mannequin exposed to open-pit fuel fires. However, nowadays, as stated in Section 12.4.4, the military uses a state-of-the-art instrumented mannequin and an environmentally controlled chamber. In the ISO/DIS 13506 standard[23] method for protective clothing, a dressed mannequin is subjected to a full flame exposure with gas burner flames of about 800°C and heat flux of about 80 kW/m^2 for 8 s. The mannequin test method in ASTM F1930 for flash fire resistance requires exposure of a fully dressed mannequin to a heat flux of 84 kW/m^2 for 3 s. According to the NFPA 2112 standard (see Table 12.6), the performance requirement for the materials to be used in flash fire-resistant garments is that the body burn rating should be ≤50% when tested in accordance with ASTM F1930. This test method is being recommended for adoption as the new military standard to evaluate military flame-protective materials and clothing systems.

12.5.3 Structural fabrics

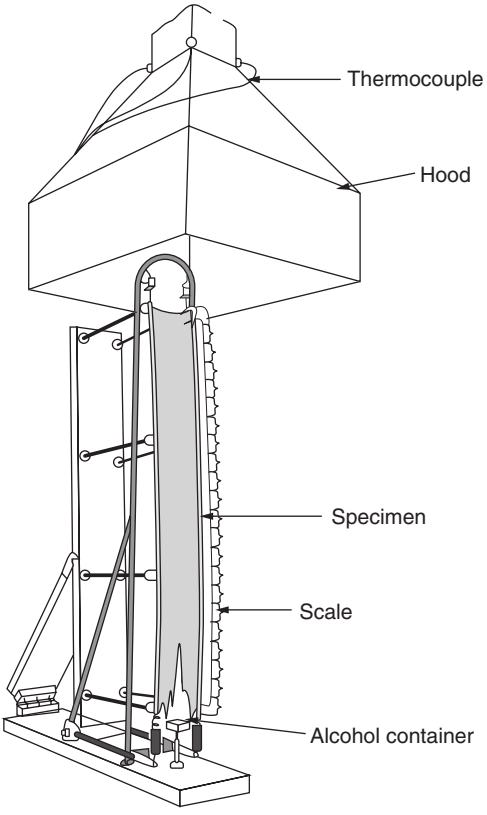
Tents and marquees are intended to accommodate large numbers of people and, therefore, the fabrics used for such structures must be flame retardant. The primary requirement for the fabrics to be used in tented structures is that they do not readily ignite or produce flaming debris. In the UK the fabrics used for such purposes should either be inherently flame retardant or have a durable flame retardant treatment. The early British standards (BS 6341:1983) for tented structures required the fabrics to be tested in a vertical orientation with bottom edge-ignition as shown in Fig. 12.1. The subsequently modified standard BS 7837:1996 specified mandatory water soaking of the fabric specimen prior to testing. The test method was similar to the one described in BS 6341 except for the addition of filter paper under the test apparatus to catch any flaming debris (see Fig. 12.2).

More stringent standards (BS 7157:1989) use the range of pinewood cribs of various dimensions as ignition sources previously mentioned in Section 12.4.6 and listed in Table 12.9. The fabric specimen is mounted on the test frame in the form of a mini-tent with sloping roof, three side walls, an open front and no flooring element. Depending on the end-use, the ignition source (Sources 4 to 7 as described in BS 5852:1979 Part 2) is placed in one of the corners of the mini-tent at floor level. The test records the progress of combustion and formation of flaming drips. The most recent standard for tented structures, BS EN 14115:2002,[39] requires exposure of the test specimens (600 mm × 180 mm) to radiative heat. Additional hot gases are blown over the surface of the specimen to encourage any spread or propagation of the flame, thus making the test even more stringent. A flame is used to ignite any emitted gases. The effects of ignition and hot flowing gases on the extent of damage are measured.

Nordic countries have specific test procedures for testing fabrics used in the construction of tents. Swedish standard SIS 65 00 82 specifies a test method for testing the ignitability of fabrics for such constructions. The test method is a simple vertical ignition test (see Fig. 12.1) using a diffusion flame of length 38 mm.

In the US, the building code agencies use standards defined by ASTM and NFPA to evaluate the fire-performance characteristics of structural fabrics. The NFPA-701[40] test method is based on the ease of ignition test described earlier (see Section 12.4.1). For the fabric to pass the test, it must self-extinguish within 2 s after removing the flame. The ASTM E84[41] tunnel test evaluates the flammability of a membrane fabric on the underside when in the horizontal position, as would exist for the roof area. The rate of flame spread and smoke formation during a 10 min fire exposure is measured by visual observations. The ASTM E108 test method[42] evaluates the flammability of a membrane fabric and its resistance to penetration by fire on the outer surface. Fabrics for membrane structures also need to be classed as non-combustible materials according to the ASTM E136 test method,[43] which measures flaming, temperature rise and weight loss in a vertical tube furnace at 750°C.

Australian standard AS 1530.2 for flammability of fabrics used as building materials uses the flammability apparatus shown in Fig. 12.16.[44] The test method is quite comprehensive as it measures ignitability, rate of flame spread (expressed as speed factor), temperature of fire gases (expressed as heat factor) and finally the flammability index, which is computed from speed and heat factors. The sample holder is a slightly convex frame inclined at 3–4° to the vertical and the sample is ignited by burning 100 ml pure alcohol in a copper container placed 13 mm below the sample. The temperature of the fire gases is measured by thermocouples positioned in the exhaust hood, and the temperature of combustion gases versus time curve



12.16 AS 1530.2 flammability test apparatus for fabrics and films.

is plotted. The average area between the recorded temperature curve and the ambient temperature curve over a period of 180 s is determined to compute the heat factor *H*.

12.5.4 Floor covering textiles

Flammability tests for carpets used in residential as well as commercial buildings are intended to assess the ease with which the textile floor covering will ignite if a burning cigarette, hot coal or similar source of ignition is dropped on the flooring material. To simulate such a phenomenon, the primary UK test for carpets as described in BS 6307:1982[45] uses a methanamine tablet of 6 mm diameter and 150 ± 5 mg weight as ignition source, which models a small flame source such as a lighted match. The tablet is placed in the centre of the specimen and ignited. The damaged zone is measured and the flaming and/or afterglow time is also recorded. This test is carried out in controlled laboratory conditions.

The ease of ignitability test for carpets described in BS 4790:1987[46] uses a 30 g hexagonal hot metal nut to model a burning ember ejected by a domestic coal/solid fuel fire as a source of ignition. A stainless steel nut is heated to 900 ± 20°C in a furnace and placed on a specimen in an enclosed chamber. The times of flaming and of afterglow as well as the greatest radius of the effects of ignition from the point of application of the nut are measured. The radius of the affected area should not be greater than 75 mm. The methanamine tablet test is preferred as an acceptance criterion in industry and is also used in the ISO standard (ISO 6925:1982) for textile floor coverings due to the greater consistency of the ignition source. These tests, however, do not give an overall indication of the potential fire hazard under actual conditions of use.

The US ASTM E648[47] and NFPA 253[48] standards for floor covering textile materials are mainly applicable in the construction industry. These standards use the radiant panel test described in Section 12.4.2 to evaluate the tendency of a flooring system to spread flame when exposed to the radiant heat flux. The test method determines a material's critical radiant flux (measured in W/cm^2), i.e. the minimum energy necessary to sustain flame propagation. Various test methods for textile flooring materials defined in standards of different countries are summarised in Table 12.7.

Carpets are used also in many transportation applications including automobiles, buses, rapid transit vehicles, aircraft and marine vessels. In these applications, carpet is not subject to the traditional carpet test methods described above, but subject to the rules and requirements of respective transportation departments or agencies.[49]

For floor coverings in motor vehicles the BS ISO 3795:1989 as well as FMVSS 302 published by the US Office of Vehicle Safety Compliance of the National Highway Traffic Safety Administration describes a test method which measures horizontal rate of flame spread as described in Section 12.4.2. To comply with these standards, the material must not have a burn rate of more than 102 mm/min (4 in/min).

The flammability regulations for carpets in passenger aircraft and ships are probably the most stringent for any interior textile application. In addition to a radiant panel test, the Federal Aviation Regulation (FAR) 14CFR25 (Airworthiness Standards: Transport Category Airplanes) describes a vertical flame test whereby a carpet sample is suspended vertically in a chamber. A propane/butane flame is applied to the lower edge of the specimen for 12 s. After removal of the flame, the after-flame time, burn length, and any flaming drippings are measured and recorded. The minimum requirements under FAR 25.853(b) for crew or passenger compartments require average flaming and glowing times which are listed in Table 12.8. The IMO (International Maritime Organization) Fire Test Procedures

Table 12.7 Test specifications for textile floor coverings

Country	Standard	Sample size, mm	Replicates	Orientation	Ignition source	Flame application time	Test duration	Performance criteria
Germany	DIN 54332	340 × 104 × original thickness	5	Vertical	Small flame burner (20 mm), inclined at 45°	15 and alternatively for 5 s.	20 s	
Germany	DIN-4102-14, EN ISO 9239-1	230 × 1050 × original thickness	3	Horizontal	Gas heated radiation panel, inclined at 30° to horizontal		600 s if no ignition occurs, 1800 s max	
USA	ASTM D 2859-96, 16 CFR, Part 1630.4, ISO 6925:1982, BS 6307:1982	230 × 230	8	Horizontal	Methanamine tablet (0.15 g)	–	Until flame extinguishes or reaches edge of the steel frame	Damaged area should be <25 mm from the steel frame

USA	ASTM 648-99, NFPA 253	254 × 1070 × original thickness	3	Horizontal	Gas heated radiation panel, inclined at 30° to horizontal	300 s	900 s including 300 s preheating
Austria	ÖNORM B 3810	200 × 800	3	Horizontal	Gas heated radiation panel, inclined at 60° to horizontal	Swivelling pilot flame for 120 s	≤1200 s
France	NF P 92-506	400 × 95 × 55 (max)	3	Vertical, Perpendicular to the radiating panel	Gas heated radiation panel, 850°C + gas pilot flame	600 s for radiation	Until extinction of specimen
UK	BS 4790:1987				Hexagonal hot metal nut, 900 ± 20°C		

Table 12.8 Flammability tests for components inside the fuselage

Test	Acceptance criteria						
	Burn length	Rate of flame spread, mm/min	After-glow time, s	Weight loss, %	Heat release rate, kW/m^2	Self-extinguishing time, s	Drip extinguishing time, s
Vertical Bunsen burner	≤203 cm	–	–	–	–	≤15	≤5
	≤152 cm	–	–	–	–	≤15	≤3
45° Bunsen burner			≤3			≤15	
60° Bunsen burner	≤76 cm					≤30	≤3
Horizontal Bunsen burner	–	64	–	–	–	–	–
OSU heat release	–	–	–	–	≤65; total heat release in first 2 min ≤65 kW-min/m^2		
Seat cushion oil burner	≤432 cm	–	–	≤10	–	–	–
Insulation blanket radiant panel	≤52 cm	–	–	–	–	≤3	–

(FTP) for testing flammability of carpets (46CFR72.05-55) also use the radiant panel test method described in Section 12.4.2.

12.5.5 Fabrics for curtains and drapes

Curtains and drapes are the vertically oriented fabrics used in interior furnishings and hence flammability testing of such fabrics is often carried out by mounting the specimen vertically on the testing rig. The principal UK flammability test uses Test Method 3 described in BS 5438:1976[14] for curtains and drapes, which measures the rate of flame spread of a vertically oriented fabric specimen. For curtains and drapes used for domestic usage, the flame application time is typically 10 s, whereas for curtains used in contract furnishing, the test is more severe with a longer flame application time of 15 s. The flammability test is even more stringent for the curtains and drapes used in more hazardous applications such as hospitals, prisons, etc. For these applications the fabric has to be tested with four flame application times of 5, 15, 20 and 30 s. The flammability requirements for curtains and drapes employed for various applications are given in BS 5867:Part 2:1980[50] which also mentions that 'the fabric complying with the requirements of the present standard may not always withstand exposure to large sources of heat, but it should have some resistance to flame spread following accidental contact with small sources of ignition'. Furthermore, the UK fire statistics[51] have shown that curtains are often ignited by flame spread from other sources such as a fire started in an armchair by a discarded cigarette. In order to address this issue, a test method devised is defined in BS EN 13772:2003,[52] which specifies a method for the measurement of flame spread of vertically oriented textile fabrics using a large ignition source. A heat flux of a defined energy is applied to a specified area of the lower part of the vertical specimen for 30 s. A small propane flame is then applied for 10 s to a small piece of cotton fabric fixed around the bottom edge of the specimen. Flame spread is measured through severance of marker threads.

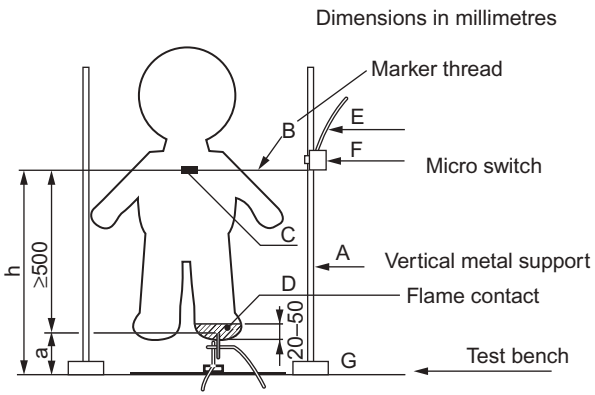
In the US, the NFPA 701 fire test for flame resistant textiles and films is used for curtains and drapes including all the decorations and trimmings. The test apparatus for measuring flammability of single as well as multilayer fabric assemblies of less than 700 g/m^2 uses a freely hanging test specimen. A methane gas burner is used as the ignition source, which is applied to the bottom edge of a vertically held specimen (150 mm × 400 mm) for the duration of 45 s. Average weight loss and burning time of flaming fragments for 10 replicates are recorded. The National Building Code of Canada (NBC), ULC-S 109, uses a test method which in principle is similar to NFPA 701, except that the intensity of the igniting flame is different. The ULC-S 109 test method also suggests the possibility of applying the ignition flame at an angle of 25° to the vertical. Application of a Bunsen burner flame at

an angle would thus prevent flame extinguishment due to molten drips from a dripping specimen.

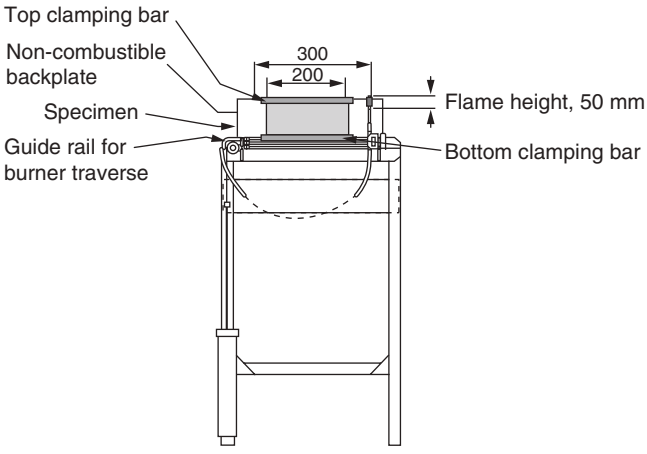
12.5.6 Pile and fur fabrics

Fancy fabrics, including pile and fur fabrics, are often used in manufacturing filled soft toys, 'fancy dress' or disguise costumes including beards, moustaches, wigs, etc. Flammability testing of toys using hair or protruding fibres is in accordance with BS EN 71-2:2003,[53] which specifies a test method to determine flammability of toys under particular test conditions. The test rig is as shown in Fig. 12.17. The test method uses a butane/propane gas flame (flame height 20 ± 2 mm) as an ignition source. The flame is usually applied for 2 ± 0.5 s to the lower edge of a representative sample. For products with hair and fibres protruding more than 50 mm from the surface, the test flame is applied either vertically or at an angle of 45°. If ignition occurs, the duration of flaming is measured and the length of specimen damaged by flames is noted. For certain types of toys, the rate of flame spread is also measured through severing of marker threads.

In the UK, BS 4569:1983 describes a test method to determine whether or not the pile of pile fabrics and simulated fur fabrics promotes rapid flame spread. The test method in BS 4569:1983 has also been used as the basis for the EN 14878 standard for flammability of children's nightwear as mentioned in Section 12.5.1. The test method is also applicable to assemblies having a pile on the surface. The flammability testing rig for pile fabrics is shown in Fig. 12.18. The test specimen is held vertically in a draught-free enclosure and a flame is moved across the surface of the pile at a known speed to determine whether flame from the ignition source flashes over the



12.17 BS EN 71-2:2003 test setup for measuring flammability of fur toys.



12.18 BS EN 4569:1983 flammability test rig for pile fabrics.

surface of the pile. If there is no surface flash on either side of the test specimen, the fabric is considered to have passed the test.

12.5.7 Upholstery and bedding fabrics

Upholstered seating furniture

Flammability testing of upholstered furniture including mattresses is a complex process and fully reviewing the history, development and detail of these test methods is beyond the scope of this chapter. Section 12.4.5 has discussed the general principles behind the current composite testing methodologies used, and work on the development of standards, test procedures and reproducibility of test methods has been published in abundance.[2,54–56] Post-ignition flaming behaviour of full-scale upholstered furniture in general can be classified into four main phases: flame spread, burn through, pool fire and burnout. Among these processes, flame spread occurs mainly through the fabric component of the furniture and ends when the fabric from the underside of the seat cushion has fully burnt out.

The majority of upholstered furniture fires result from ignition by smoking materials with a strong emphasis on cigarettes[54,55] and hence most flammability tests for upholstered furniture use a smouldering cigarette as the primary ignition source, defined as ignition Source 0 in BS 5852 (see Table 12.3 and Section 12.4.5), for example. To simulate the open flame of a burning match, a butane gas flame (gas flow rate of 45 ml/min, applied for 20 s), referred to as ignition Source 1 in BS 5852, is designed to give a similar calorific value. However, in the UK, the upholstered furniture used in contract environments, for example public buildings, restaurants, hospitals,

prison cells, etc., is not covered by the Furniture and Furnishings (Fire) (safety) Regulations but is required to meet requirements of the performance standard BS 7176:1995.[57] Requirements of this performance standard are classified for four categories of hazards depending on the type of building in which the furniture is used. For buildings with very high hazard levels, combinations of ignition sources are required to be used for evaluating fire performance of upholstered furniture. For example, upholstered furniture in sleeping accommodation in certain hospital wards and offshore installations has to be tested using three different ignition sources: the smouldering cigarette (Source 0), the match flame equivalent (Source 1) and the pinewood crib (Source 7). The small-scale UK and EN composite test method for upholstered seating is briefly described in Section 12.4.5 and elsewhere.[13]

In California, the Cal TB 133 test method uses oxygen depletion calorimetry for testing flammability of seating used in public occupancies such as public auditoriums, hotels, hospitals, etc. This test method uses a 250 mm^2 tube burner with heat generating capacity of 18 kW. The burner is placed on the seating area for 80 s. This full-scale furniture item is tested in a room and the pass/fail criteria depend on the measurements used, i.e., temperature increase at the ceiling thermocouple or peak heat release rate.

In 2006, the US Consumer Product Safety Commission (CPSC) revised draft standards for performance tests for major upholstery materials.[58] The revised standards include requirements for cigarette and small open flame (SOF) ignition performance of fire barriers and filling materials. The open flame ignition test is not mandatory for the fabrics in upholstered furniture unless the fabric is part of the composite in the end-product test and could contribute to mass loss. All fabric materials, however, have to pass the cigarette test.

Mattresses

Bedding materials have traditionally been combustible materials. Requirements of comfort, convenience and cost will continue to demand the substantial use of textile materials. Fire behaviour of bedding materials has been thoroughly reviewed by Hilado.[59] The California Test Bulletin CAL TB 106 test method for testing ignition resistance of mattresses uses a burning cigarette, whereas in the Cal TB 603 test method the mattress is exposed to large open flames from a gas burner to replicate localised heat flux from burning bedclothes. Two burners with heat flux of 19 kW each are placed on top of the mattress for 70 s and the side burner with 10 kW heat flux is applied for 50 s. The performance criterion is based on peak heat release with maximum allowable peak heat release

Table 12.9 Types of ignition sources specified in BS 5852

Source number	Ignition source	Description	Energy input, kWh	Combustion type	Time of application	Time limits for flaming of composites
0	Cigarette	–	–	Smouldering	Throughout the test	No ignition or progressive smouldering
1	Burner	45 ml/min	0.001	Flaming	20 s	After-flame time up to 120 s
2	Burner	160 ml/min	0.004	Flaming	40 s	After-flame time up to 120 s
3	Burner	350 ml/min	0.016	Flaming	70 s	After-flame time up to 120 s
4	Crib	8.5 g	0.04	Flaming	Throughout the test	Total flaming time up to 10 min
5	Crib	17 g	0.08	Flaming	Throughout the test	Total flaming time up to 10 min
6	Crib	60 g	0.28	Flaming	Throughout the test	Total flaming time up to 13 min
7	Crib	126 g	0.59	Flaming	Throughout the test	Total flaming time up to 13 min

of 200 kW and total heat release rate of 25 MJ for 10 min from the start of the test.[60] In the UK, the standard BS 6807:1996 is used to assess ignitability of mattresses and uses ignition sources specified in BS 5852 (listed in Table 12.9), while BS 7177:1995 specifies various combinations of ignition sources for four different hazard classifications: low, medium, high and very high. The 0/NS (cigarette plus non-smouldering insulation) ignition source is also described in Annex B of BS 7177:1996 to provide guidance for users on the ignitability behaviour of mattresses when covered with bedding. These test methods are not mandatory except in contract furnishings, but they are used for quality control in industry or for development of new products.

12.5.8 Textiles in transportation

Fire and heat resistant textiles find applications in the transportation industry (e.g., seat coverings in commercial aircraft) and do so without sacrificing aesthetic and comfort properties. Despite no-smoking regulations, smouldering fires in transport vehicles often occur as a result of carelessly discarded matches or cigarettes in bins, apertures or hidden spaces.

Upholstered fabrics used in seating of public transport are often the first item to ignite. The risk of fire incidents and hence the flammability standards for textile materials used in road, rail, air and water transport vehicles are discussed in this section. Specific flammability test methods and performance requirements are also mentioned in brief. Most of the textile materials used in mass transport vehicles may also be regulated for smoke and toxic gases but this topic is beyond the scope of this chapter.

Motor vehicles

The flammability testing of fabrics used in motor vehicles has not yet been made mandatory due to the fact that fire incidents in motor vehicles are rare and, moreover, such fire spreads relatively slowly. Flammability standards for textiles used in motor vehicles are usually governed by individual countries, although with globalisation of the automotive industry, major manufacturers subject internal textile materials such as seating covers and carpets to the US FMVSS 302 tests described previously in Section 12.4.2. The Federal Motor Vehicle Safety Standard (FMVSS 302) was brought into force in the US in 1972 and specifies a simple horizontal flame spread test as described in Section 12.4.2. It measures rate of flame spread over a horizontally placed specimen subjected to a Bunsen burner flame for 15 s. This test method has also been adopted by the German (DIN 75 200), British, Australian (BS AU 169) and Japanese (JIS D 1201) automotive standards.

In 1982, specific technical fire protection requirements for motor coaches with more than 16 passengers were introduced in France.[61] The Specification Technique ST 18-502 specifies that the materials used for curtains and blinds must be tested in a vertical orientation to the specifications described in ISO 6940. ST 18-502 also defines a dripping test for the head lining material in coaches to be tested in accordance with NF P 92-505. The test apparatus (see Fig. 12.8) specified in NF P 92-505 uses an electric burner test as described in Section 12.4.2.

The European Union directive 95/28/EC, defining requirements for the fire behaviour of upholstery of seats including the driver's seat, interior lining material and any textile material used for thermal and/or acoustic insulation in certain categories of motor vehicles, was released in 1995. Appendix IV of the directive 95/28/EC describes a test method to determine the horizontal burn rate of the materials and is similar to the FMVSS 302 test method. The lining material is tested for burning drips using the test apparatus described in French standard NF P 92-505 (see Fig. 12.8). For curtains and blinds and/or any other hanging materials in the motor vehicle, a test method similar to ISO 6941 to measure the vertical burn rate is specified.

Rail vehicles

Textile flammability standards are extremely severe because fires in railways can spread very quickly and can result in significant losses. Besides fires caused by technical defects, passenger-induced hazards are also very common.[62] In European countries the Union Internationale des Chemins de Fer (UIC) Code, Sheet 564.2, harmonises test procedures and performance criteria for flammability and smoke production. The Annex of UIC 564.2 describes a test method for textiles in particular. The test measures after-flame time, extent of charred surface and observed dripping when a fabric specimen inclined at 45° is exposed to a Bunsen burner flame for 30 s. Flooring textiles are tested using a fishtail burner with a 42–48 mm flame width. In the UK, the standard for flooring textiles in railways uses the radiant panel test described in BS ISO 4589-1.

Furnishing fabrics used in railway seatings are tested as a complete assembly with a 100 g paper cushion used as an ignition source (Annex of UIC 564.2). In the US, complete seat assemblies are tested according to ASTM E 1537-98. In the UK, ceiling lining materials are tested according to the test method described in Part 6 of BS 476 (see Section 12.4.2, Fig. 12.8). This fire propagation test, described in Section 12.4.2, measures the contribution of the lining material to the growth of fire. If textiles are used as lining materials for walls and ceilings of a passenger car, the flame spread along the surface of the specimen is tested according to Part 7 of BS 476 with the radiant panel described in Section 12.4.3 employed to measure the rate of flame spread (see Fig. 12.7).

Aircraft

Approximately 900 kg of combustible textile material in the form of seat upholstery, decorative textiles, wall coverings, carpeting, tapestries, blankets, curtains and seat belts are used in a modern commercial passenger aircraft. Flammability testing of such textile materials has been regulated by the US Federal Aviation Administration (FAA) under Federal Aviation Regulations (FAR) and these latter extend to all commercial airliners operating across the world internationally.

Test methods for measuring ignitability and flammability of fabrics used in aircraft are, in principle, similar to the ones already described in Section 12.4 of this chapter. However, the performance criteria are often more stringent than for other applications. Tests involving a small ignition source simulate the start of fire in the cockpit or cabin due to electrical faults or overheating during the flight. However, catastrophic fires occur as a consequence of crash landings or crashes when taking off. All textiles present in an aircraft have to pass the test requirements defined in FAR 25.253(b) in

which a 10 mm diameter Bunsen burner flame impinges upon the bottom edge of a vertically oriented 75 mm (3 in) wide by 305 mm (12 in) long sample for either 12 or 60 s depending on the requirement. Maximum permeable flame-out and melt drip times are defined following removal of the ignition source, e.g. ≤5 s for flameout after 12 or 60 s ignition and ≤3 s or ≤5 s drip times respectively. Average burn lengths should not exceed 152 mm (6 in) for 12 s and 203 mm (8 in) for 60 s ignition times. Textiles required to be subjected to 12 s ignition include carpets, curtains, upholstery outer fabrics, seat cushions, padding, blankets, coated leather fabrics and galley furnishings. Textiles are required to be subjected to the 60 s condition only if they are part of a composite such as interior wall panels, ceilings, partitions, etc.

For textiles used in seat harnesses and webbings, the above test is used with the sample held in a horizontal orientation and with a 15 s flame application time. The above vertical strip test is used as a prior requirement of any textile used in a composite or product requiring a subsequent, more intense flammability requirement. In this respect, measurement of ease of ignition under high heat flux and post-ignition behaviour of textile materials may be of crucial importance. For example, the oil burner test for seat cushions described in FAR 25.853(a) Appendix F Part II uses a kerosene burner calibrated to produce a heat of 12 kW/m^2 at the seat surface and with flame temperature of around 1000°C. The flame is applied to the complete seat assembly as shown in Fig. 12.19. The flame is applied for 2 min and average percentage weight loss is measured. The pass requirements are that the total average weight loss is 10% or less and average burn lengths of the cushions do not exceed 43 cm. For textiles attached to internal wall and ceiling panels or partitions, they are tested as a composite for heat

12.19 FAR 25.853(a) Appendix F Part II kerosene burner test for aircraft seating.

release using the OSU calorimeters as defined in ASTM E 906-1983 which specifies the test method for measurement of ease of ignition and associated heat release of textiles used in commercial aircraft when exposed to high heat flux (see Section 12.4.3). The overall method is contained within FAA 25.853 Part IV Appendix F in which the vertically oriented composite is exposed to a heat flux of 35 kW/m^2. A maximum peak heat release rate of ≤65 kW/m^2 and average heat release rate over the first 2 minutes of the test not exceeding 65 kW/m^2 are required for a textile composite to achieve a pass. For more detailed information, the reader is directed to the recent review by Lyon.[63]

Ships

Flammability standards and tests for furnishing fabrics, bedding and draperies used in ships and submarines have been developed by the International Maritime Organisation (IMO) and the National Fire Protection Association (NFPA) and include Safety of Life at Sea (SOLAS), High Speed Craft (HSC) and Fire Test Procedures (FTP) codes. The Fire Test Procedures (FTP) code describes the flammability tests and performance criteria for combustible materials[64] and Sorathia has recently reviewed this area.[65]

The surface flammability of interior finish materials used in bulkheads, overheads and decks is evaluated through either the IMO Resolution A.653(16) test method or the NFPA 25/ASTM E84 tests, which in principle measure the rate of flame spread under a radiant heat flux (see Section 12.4.2). The performance criteria for textile wall coverings demand a flame spread index (FSI) of ≤75 and a smoke developed index (SDI) of ≤450. In addition to this, materials to be used as deck overlay and finishes are required to be tested in a vertical orientation and should not produce more than 10 flaming droplets. Decking materials also must not have jetting combustion in the presence of adhesives or bonding agents.

Upholstery fabrics used in passenger ships must be tested in accordance with the IMO Resolution A.652(16) test method. The upholstered part of the furniture is placed on the back and bottom on the test seat fame and exposed to cigarette and butane flame for 1 h. The sample fails if any progressive flaming or smouldering is observed during the test period. In addition, the upholstered furniture (one chair) must meet the limited heat release criteria such that when tested in accordance with NFPA 266,[66] the maximum heat released must not be more than 80 kW, and when tested in accordance with ASTM E1537[67] and UL 1056,[68] the total heat released during the first 10 minutes should be less than 25 MJ.

Bedding components, including mattresses, pillows, blankets, quilts and bedspreads, used in ships are tested in accordance with IMO Resolution

A.688(17) according to the SOLAS and HSC Code, whereas NFPA 301 requires mattresses and mattress pads to comply with the NFPA 267,[69] ASTM E1590[70] and 16 CFR 1632[71] test methods. When tested according to the IMO Resolution A.688(17), the bedding should not ignite readily or exhibit progressive smouldering when subjected to smouldering or flaming ignition.

The SOLAS and HSC Code for materials used in hanging drapes specify that they have to meet flammability requirements when tested in accordance with IMO Resolution A.563(14). The test method includes a small swatch of material exposed to a small flame either at the bottom of the swatch or in the centre. The sample must not continue to burn for more than 5 s after application of the flame. In addition to this, the sample must not burn through the edges and should not have a char length of more than 150 mm.

12.6 Future trends

Bench-scale flammability tests are useful in that several material fire properties can be derived and data can be used for relative ranking of textiles. The tests are fairly cost-effective and can be employed for screening of new materials. The data derived from bench-scale tests can also be used for predicting large-scale fire behaviour using mathematical models. It is essential that future bench-scale tests should therefore be scientifically sound and should be a good indicator of large-scale end-use performance.

Computer models can be used to simulate real-scale fire tests using data obtained from bench-scale tests. However, this approach has its own limitation since the results will be applicable to a specific textile or composite geometry with a particular ignition scenario. Modelling of furniture fires and thermal burn injury have been developed by simplifying the problem and overlooking some important details of the burning item, and so cannot replace real testing methods. Reaction-to-fire tests such as the cone calorimeter are more robust and scientific and have greater applicability to realistic end-use applications and fire scenarios. However, they are too complex and expensive for everyday textile testing.

It is most likely, therefore, that future testing methods will be based on simple but increasingly scientifically sound principles, will be normalised across trading areas (e.g. the EU) and consequently will be cost-effective in application. Increased instrumentation will occur, as evidenced by the development of mannequin-type tests, providing costs of purchase, servicing and use remain affordable. At the present time predictive testing has too many unquantifiable variables and so will remain a research tool only, for at least the next 10 years.

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