17

Textiles for survival

David A Holmes

Faculty of Technology, Department of Textiles, Bolton Institute, Deane Road, Bolton BL3 5AB, UK

17.1 Introduction

The question concerning textile use in this chapter is, surviving what? The main emphasis here is on the preservation of human life. The clothing itself provides the protection rather than an individual textile material, but textile fabric is the critical element in all protective clothing and other protective textile products. As the safety barrier between the wearer and the source of potential injury, it is the characteristics of the fabric that will determine the degree of injury suffered by the victim of an accident.

There has been a large increase in the hazards to which humans are exposed as a result of developments in technology in the workplace and on the battlefield, for example. The need to protect against these agencies is paralleled by the desire to increase protection against natural forces and elements. The dangers are often so specialised that no single type of clothing will be adequate for work outside the normal routine. During the 1980s and 1990s extensive research has been carried out to develop protective clothing for various civilian and military occupations.[1] One such investigation was carried out by the United States Navy Clothing and Textile Research Facility to determine future clothing requirements for sailors exposed to potential and actual hazardous environments.[2] The results indicated that a series of protective clothing ensembles is required for a variety of potential hazards. Woven, knitted and nonwoven fabrics have been designed to suit specific requirements.[1]

In order to be successful, designers need to work closely with quality assurance and production personnel as well as potential customers and users from the earliest stages of development.[3] The types of protective garment specifically mentioned in the literature are:

- tents
- helmets
- gloves (for hand and arm protection)
- sleeping bags
- survival bags and suits

- fire-protective clothing
- heat-resistant garments
- turnout coats
- ballistic-resistant vests
- biological and chemical protective clothing
- blast-proof vests
- antiflash hoods and gloves
- molten metal protective clothing
- flotation vests
- military protective apparel including antihypothermia suits and ducted warm air garments
- submarine survival suits
- immersion suits and dive skins
- life rafts
- diapers
- antiexposure overalls
- arctic survival suits
- ropes and harnesses.

The types of occupation and activities for which protective garments and other products are made specifically mentioned in the literature are:

- police
- security guards
- mountaineering
- caving
- climbing
- skiing
- aircrew (both military and civil)
- soldiers
- sailors
- submariners
- foundry and glass workers
- firefighters
- water sports
- winter sports
- commercial fishing and diving
- offshore oil and gas rig workers
- healthcare
- racing drivers
- astronauts
- coal mining
- cold store workers.

All clothing and other textile products provides some protection. It is a matter of timescale which decides the degree and type of protection required. Hazards to be survived can be divided into two main categories:

- Accidents: these involve short term exposure to extreme conditions.
- Exposure to hazardous environments: this involves long term exposure to milder conditions than those normally associated with accidents or disasters.

Accident protection includes protection from:[2,4–6]

- fire
- explosions including smoke and toxic fumes
- attack by weapons of various types, e.g. ballistic projectiles, nuclear, chemical, biological
- drowning
- hypothermia
- molten metal
- chemical reagents
- toxic vapours.

Long term protection includes protection from:[2,4]

- foul weather
- extreme cold
- rain
- wind
- chemical reagents
- nuclear reagents
- high temperatures
- molten metal splashes
- microbes and dust.

There is obviously no sharp dividing line between short term and long term exposure to hazards and some hazards could fall into either category.

David Rigby Associates has used information from trade sources to estimate the European protective clothing market.[7] The data published focuses on high performance products such as those used by firefighters and other public utilities, the military and medical personnel. It excludes garments for sporting applications and foul weather clothing. The overall total market is over 200 million square metres of fabric. Of this, an increasing proportion is being provided by nonwovens, which was estimated to account for about 60% in 1998. The European protective clothing market is expanding at an attractive rate but most of the expansion is for applications excluding military and public utilities. In rapidly expanding applications such as the medical field, nonwovens are taking more of the market traditionally provided by woven and knitted fabrics as they are better able to match the performance and cost requirements of the customers. It is considered that suppliers of high performance fibres will find greater opportunities in the future in the developing countries as their requirements for protective textiles mirrors the increase in population. Table 17.1 shows the European consumption of fabric in protective clothing during 1996.[7]

17.2 Short term (accident) survival

17.2.1 Drowning and extreme low temperatures

Hypothermia is a condition which is known as the ‘killer of the unprepared’ and occurs when the heat lost from the body exceeds that gained through food, exercise and external sources. The risk increases with exertion or exposure to wet and

Table 17.1 European consumption of fabric in protective clothing during 1996 ($10^6\,m^2$)[7]

Product function	End-use	Public utilities	Military	Medical	Industry, construction, agriculture	Total
Flame-retardant, high temperature	Woven/knit	5	2	–	15	22
	Nonwoven	–	–	–	–	–
	Total	5	2	–	15	22
Dust and particle barrier	Woven/knit	–	–	12	22	34
	Nonwoven	–	–	62	10	72
	Total	–	–	74	32	106
Gas and chemical	Woven/knit	1	1	–	4	6
	Nonwoven	3	–	–	47	50
	Total	4	1	–	51	56
Nuclear, biological, chemical	Woven/knit	–	2	–	–	2
	Nonwoven	–	2	–	–	2
	Total	–	4	–	–	4
Extreme cold	Woven/knit	–	1	–	2	3
	Nonwoven	–	–	–	–	–
	Total	–	1	–	2	3
High visibility	Woven/knit	11	1	–	3	15
	Nonwoven	–	–	–	–	–
	Total	11	1	—	3	15
Totals	Woven/knit	17	7	12	46	82
	Nonwoven	3	2	62	57	124
	Total	20	9	74	103	206

wind conditions. It is a major cause of death in areas where there is a severe climate, such as in Alaska.[8] Over 100 'man overboard' incidents resulting in 30 deaths occurred between 1972 and 1984 in the North Sea oil and gas industry. Immersion times were usually less than 5 min but could be as long as 10 min. In the North Sea the mean sea temperature is below 10 °C for nine months of the year and rarely exceeds 15 °C for the remaining three months. Initial and short term survival is, therefore, the main consideration.[9] Various strategies have been developed for preventing hypothermia, including the use of flotation and thermal protection devices. The United States Navy uses workwear coveralls which provide buoyancy and thermal insulation in case of accidental and emergency immersions in cold water. These provide survival times of 70–85 min in agitated water.[10]

All 140 members of the International Convention for the Safety of Life at Sea (SOCAS) require a thermal protection aid (TPA) to be carried on board vessels as standard equipment in case of shipwreck and the thermal protection required is from cold to prevent hypothermia. The spun bonded polyolefin fibre fabric, Tyvek®, made by Du Pont, when aluminised and made into survival suits[11] and survival bags,[12] satisfies the SOLAS criteria. These suits can also be used in Arctic emergencies.[11] Thermal insulation overalls made from Tyvek are also carried by many Merchant Navy ships and by several airlines flying the polar route in case the aircraft is forced down onto the Arctic ice.[13]

The use of personal water craft for sport is growing at a rate of 40% per year, therefore the demand for specially designed flotation vests has also increased.

Approximately 150000 vests are sold each year.[14] Du Pont claim that their high tenacity yarns can be used in such products and maintain their strength and ultraviolet protection after prolonged exposure to sunlight and ultraviolet radiation. One of the leading manufacturers claims that their flotation products made from such yarn far exceed the United States Coast Guard Standards for protection and durability. Aesthetics are also important for this market and fabrics made from these nylon yarns can be dyed to create products with vivid colours and elaborate designs.[14]

17.2.2 Ballistic protection

Textile fibres are being used very effectively to protect against fragmenting munitions. They are able to absorb large amounts of energy as a consequence of their high tenacity, high modulus of elasticity and low density. Work is being carried out to establish the best fibres and the best constructions. The most commonly used fibres are currently glass fibre, nylon 6.6 and aramid fibre (e.g. Kevlar® and Twaron®). In addition to applications such as flak jackets, these fibres are being used in helmets and, in conjunction with ceramic inserts, provide armour sufficient to stop high velocity rifle bullets.[15]

Blast-proof vests are most frequently made from aramid fibres, such as Kevlar® (DuPont) and Twaron® (AKZO) and Dyneema® (DSM) high tenacity polyethylene fibre. Different fabric constructions are required for protection against low velocity and high velocity ammunition. Yarns made from aramid fibres have the best resilience to ballistic impact owing to their outstanding elasticity and elongation properties. In addition to ballistic resistance it is also important to know the amount of energy that the zone receiving the impact can absorb by way of deformation.

Most traditional ballistic armour used for bullet-resistant vests relies on multiple layers of woven fabric. The number of layers dictates the degree of protection. Neoprene coating or resination are also commonly used.[16]

In general it has been found that plain square weaves are most effective in ballistic protection. Knitting, of course, could offer considerable advantages in terms of cost and in the production of the final design of a contoured armour, but it has not proved successful, probably because of the high degree of interlocking of the yarns that occurs in the knitting process and resulting fabric with too low an initial modulus.

High performance polyolefin fibres such as Dyneema polyethylene are used to make needle punched nonwoven fabric.[17] This is claimed to provide outstanding ballistic protection and outstanding protection against sharp shrapnel fragments by absorbing projectile energy by deformation rather than fibre breakage as is the case with woven and unidirectional fabrics. It is claimed that the fabric is such a light weight, low density and thin construction that ballistic protection vests are hardly noticeable during normal military service. However, considerable care is needed to optimise the felt structure. Ideally the felt needs to have a high degree of entanglement of long staple fibres but with a minimum degree of needling. Excessive needling can produce too much fibre alignment through the structure, which aids the projectile penetration. Felts with very low mass per unit area are probably the most effective materials for ballistic protection, but, as the mass increases, woven textiles are superior to felts in performance.[16]

17.2.3 Protection from fire

The most obvious occupation requiring protection from heat and flame is firefighting. However, the 1992 Survival Conference held at Leeds University[4] noted that there is a growing need for protective apparel for other occupations, such as police and security guards.

Exposure to heat and flames is one of the major potential hazards that offshore oil and gas rig workers face. Protection from elements other than fire is also required and fabrics have been developed which combine fire-resistant characteristics with water and oil repellency (Dale Antiflame, http://www.offshore-technology.com, July, 1997).

Simulated mine explosions, involving coal dust and methane, endure for 2.2–2.6 s and reach maximum heat flux levels from 130–330 $kW\,m^{-2}$. Values from 3–10 s have been quoted for escape through aircraft or vehicle crash fuel spills with heat flux intensities peaking between 167 and 226 $kW\,m^{-2}$. The projected time to second degree burns at a heat flux of 330 $kW\,m^{-2}$ is only 0.07 s. The introduction of a material only 0.5 mm thick increases the protection time significantly to longer than the flashover or explosion time. The danger, however, lies with the parts of the body not covered by clothing, confirmed by statistics showing that 75% of all firefighters' burn injuries in the USA are to the hands and face.[18]

Heat and flame-resistant textiles are used extensively to provide protection from fire and to do so need to prevent flammability, heat conduction, melting and toxic fume emissions.[6] Some of these textiles are made from conventional fibres that are inherently flame retardant (i.e. wool) or fibres that have been flame-retardant finished (principally cellulosic fibres). The newer high performance fibres are also used either alone or in blends. Some of these blends can be a complex mixture of high performance and conventional fibres with a large number of components.[19]

Firesafe Products Corporation has patented a fabric meeting the above criteria. It is woven from inherently non-combustible glass fibre and coated with a series of proprietary water-based polymers. The fabric does not ignite, melt, drip, rot, shrink or stretch and is noted for its low level and toxicity of smoke emissions in a fire. Several versions of the fabric are made for use in furniture barriers, fire and smoke curtains in ships and cargo wraps in aircraft.[20]

Securitex (Turnout Gear Selection, http://www.securitex.com, July, 1997) consider that there is a misconception in the widely held belief that the outer type of shell fibre is the critical factor in determining whether or not a firefighter is injured during flashover conditions and that the use of high performance fibres namely Kevlar and PBI (polybenzimidazole) provide better protection than fabrics made from other fibres. Their tests show that these fibres provide no more thermal protection than any other fabric of equivalent weight. After 10 s exposure to flashover conditions the outer shell was charred and broken up. Under less than flashover conditions, for example, compression bars, it is the type of moisture barrier and water absorption characteristics of the thermal barrier, not the type of outer shell fabric that are the critical factors influencing the type of burn injury.

17.3 Long term survival

Protection from heat, flame, molten metal splashes, severe cold and frost, radiation sources and so on is a prime requirement for both civil and defence applications. The conditions influencing demand depend upon specific environmental hazards, the degree of protection, the level of comfort, the durability of the garments, aesthetics and sociological factors, such as legislation, consumer awareness of possible hazards and so on.[1]

17.3.1 Extreme weather conditions

Events in the industrial field dictate that workers will be required to work and otherwise function in colder and colder temperatures, in weather conditions which hitherto would have been a sufficient excuse to 'down tools and head for the tea hut'. We are asked to provide means for personnel to work and function efficiently in temperatures well below –30 °C in wind, rain and snow, and in the case of military personnel, other hazards. Decisions have been made to send men to drill for oil under ice caps, and to fight in conditions when breathing out is accompanied by icicle formation. These situations are now attracting growing attention among various sectors of the textile and apparel industries.[21] There is also a need for more adequate weatherproof clothing for people who work in less extreme conditions, such as petrol station attendants, surveyors and engineers. Often they use conventionally accepted garments which can be more expensive but far less effective than ones specifically designed for the purpose.[3]

The design of protective military apparel for operating in extreme climates can be complex because of variations in conditions. Requirements for the components in protective apparel sometimes conflict and these demands stimulate interdisciplinary research for new textile materials, equipment and technologies. These disciplines include textile engineering, industrial engineering and design, apparel design, textile science and physiology. Current protection requirements are for normal, combat and emergency survival operations in both peacetime and war. One of the most important current problems is designing apparel that is effective and comfortable.[22]

Price is often synonymous with quality yet this is not always the case in practice. In many cases there is insufficient knowledge of the requirements for high technical performance so that even specialists find difficulty in making judgements on clothing for outdoor pursuits. The design and manufacture of the garment is of considerable importance, particularly the method of seaming for waterproof garments.[23]

Submarine suits must protect the wearer against drowning and hypothermia for long periods under severe weather conditions. The Swedish Division of Naval Medicine of the Swedish Defence Research Establishment has found that survival suits could maintain body temperature for up to 20 hours in cold water simulating winter conditions.[24] Effective survival suits may include a life raft and even diaper material for urine collection. In addition, thermal insulation and buoyancy of the suits are very important. Thermal insulation can be partly provided by an aluminized inner coverall worn over the uniform.[24] It was also concluded that survival suits should be developed consisting of a double layered suit with a life raft, a single layered suit with extra buoyancy and a life raft, or a modified double layered suit with extra buoyancy.[25]

Helly-Hansen, the Norwegian company which specialises in foul weather and survival gear for commercial fishermen, claims a 52% share of the world market. They accept the layering principle and prefer three layers, namely:

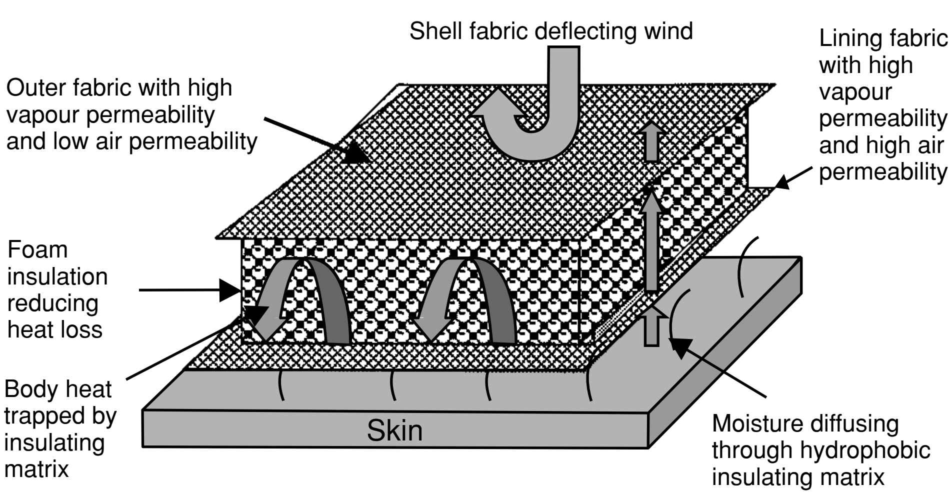
1 an inner layer with good skin contact, not too absorbent
2 an insulating layer trapping large volumes of still air and helping transportation of moisture away from the skin and
3 a wind/ water barrier layer.

Tests have shown that it is not the fibre which is important for insulation value of a fabric, but the construction of the fabric, for example, knitted versus woven, thickness, resistance to compression, weight and so on. This and the design of the garment are key factors and the ability to close the garment at the neck, wrist and ankle are important.[26,27]

Other manufacturers produce multilayer insulation systems for use in clothing for severe weather. Northern Outfitters (Superior Technology Means Superior Performance, http://www.northern.com, July, 1997) use their VÆTREX (Vapour Attenuating and Expelling Thermal Retaining insulation for EXtreme cold weather clothing) to make what they claim to be the warmest clothing and boots in the world. VÆTREX uses special open cell polyurethane foam as the principal insulating medium which has permanent loft and allows the expulsion of perspiration. This is sandwiched between two fabric layers, the outer one which deflects the wind and stabilizes the air in the insulation and the inner one which allows moisture vapour transfer. The construction of VÆTREX is shown in Fig. 17.1.

The hollow viscose fibre, Viloft® (Courtaulds) has been mixed with polyester to give a high bulk, low density material for thermal underwear. It gives high water permeability and water absorbency combined with resilience, strength and shape retention properties of the synthetic fibre. All these properties are essential in thermal underwear and both laboratory and field tests indicated Viloft/polyester had a substantial market potential.[15]

The development of Thinsulate® (3M) has been described.[15] This combines polyester staple with polypropylene microfibre and has undergone extensive tests both in the laboratory and in the field. Examples of the latter include use by postmen, ski centres and survival posts in the northern USA and in underwear for US Navy divers. Excellent results have also been recorded on the recent British winter expedition to Everest.[15]



17.1 Construction of VÆTREX insulation system.[30]

Metallised coatings are frequently used to improve thermal insulation by reflecting heat radiated by the body.[28] An aluminium reflecting surface is very efficient in the part of the spectrum in which the body gives out radiation. It can reflect 95% of the radiant heat back into the body and in addition acts instantly giving fast warm-up in cases of acute suffering from cold. Flectalon is a filling of metallised and shredded plastic film for use in apparel and applications such as survival blankets. The product, besides its ability to reflect thermal radiation, allows diffusion of moisture and retains its reflecting properties when wet and when compressed. Trials have been successfully carried out by coastal rescue and cave rescue organisations, in mountaineering situations, and also for the protection of new born babies. Metallised polyvinyl chloride (PVC) can be used when flame resistance is also important.[15]

Sommer Alibert (UK) Ltd exhibited a novel composite fabric for insulation purposes which consists of a needled acrylic wadding, polyethylene film and aluminium foil, called Sommerflex for use in lightweight and windproof interlinings for anoraks, sleeping bags, gloves, mittens, continental quilts and mountaineering wear.[21]

Temperature-regulating fabric is made from cotton to which poly(ethylene glycol) has been chemically fixed. At high temperatures the fabric absorbs heat as the additive changes to a high energy solid form. At low temperatures the reverse process takes place. Such fabrics have potential in thermal protective clothing such as skiwear.[29] One such product is Outlast™ (Gateway Technologies, Inc). They claim that ski gloves containing Outlast fabric maintain the skin at a higher temperature than conventional gloves ten times thicker by utilizing the energy conserved during exercise. These thinner gloves allow better dexterity.[29,30]

Choice of appropriate fabric is not the only consideration when designing survival wear. The correct design of the suit is very important, particularly with regard to water ingress. Good suits allow less than 5 g of water ingress but many suits allow up to 1 litre. Even this amount of ingressed water would contribute about 50% of the heat loss from the body.[9]

17.3.2 High temperatures and associated hazards

Table 17.2 illustrates occupations where protection from heat and flame are important.[1] In the occupations listed in the table the human skin has to be protected from the following hazards:[1]

- flames (convective heat)
- contact heat
- radiant heat
- sparks and drops of molten metal
- hot gases and vapours.

The main factors that influence burn injury are:[18]

1 the incident heat flux intensity and the way it varies during exposure
2 the duration of exposure (including the time it takes for the temperature of the garment to fall below that which causes injury after the source is removed)
3 the total insulation between source and skin, including outerwear, underwear, and the air gaps between them and the skin
4 the extent of degradation of the garment materials during exposure and the subsequent rearrangement of the clothing/ air insulation

Table 17.2 Hazardous occupations requiring protection against heat and flame[1]

Industry	Flame	Thermal contact	Radiated heat
Foundry (steel manufacture, metal casting, forging, glass manufacture)	*	**	**
Engineering (welding, cutting boiler work)	*	**	*
Oil, gas and chemicals	*	0	0
Munitions and pyrotechnics	0	0	0
Aviation and space	*	0	0
Military	**	*	*
Firefighters	**	*	*

** Very important, * Important, 0 little importance.

5 condensation on the skin of any vapour or pyrolysis products released as the temperature of the fabric rises.

These factors may not be adequately considered when performance specifications are set for materials.

The most serious garment failure for the wearer is hole formation. When the fabric remains intact, its heat flow properties do not change greatly even when the component fibres are degraded, because heat transfer is by conduction and radiation through air in the structure and by conduction through the fibres (which is relatively small). Only when fibres melt or coalesce and displace the air, or when they bubble and form an insulating char, are heat flow properties substantially altered.

Shrinkage or expansion in the plane of the fabric does not substantially change the thermal insulation of the fabric itself. However, the spacing between fabric and skin or between garment layers may alter, with a consequent change in overall insulation. For example if the outer layer shrinks and pulls the garment on to the body, the total insulation is reduced and the heat flow increases.

17.3.2.1 Fibres suitable for protective clothing

These fibres can be divided into two classes:[31]

1 inherently flame-retardant fibres, such as aramids, modacrylic, polybenzimidazole (PBI), semi-carbon (oxidised acrylic) and phenolic (novaloid) in which flame retardancy is introduced during the fibre-forming stage, and
2 chemically modified fibres and fabrics, for example, flame-retardant cotton, wool and synthetics where conventional fibres, yarns or fabrics are after treated.

Flame retardants that are incorporated into fibres or applied as finishes may be classified into three major groups:[31]

1 Flame retardants, based primarily on phosphorus and frequently combined with other products. Phosphorus containing agencies usually operate in the solid phase, frequently with nitrogen showing synergistic effects;
2 Halogenated species (chlorine- or bromine-containing), which are active in the gaseous phase, and in many cases, are applied together with antimony compounds in order to obtain synergistic effects;
3 Compounds, such as alumina hydrate or boron compounds that provide endothermic dehydration reactions, remove heat and aid overall performance of a phosphorous or halogen-based retardant formulation.

Flame-retardant workwear has been available for many years. Inherently flame-retardant fabrics are produced from aramid (e.g. Nomex®), modacrylic (e.g. Velicren FR®, Montefibre), flame-retardant polyester (e.g. Trevira CS®, Hoechst), flame-retardant viscose (e.g. Visil®, Soteri) and other speciality fibres. Some of these fibres have one of a multitude of problems, such as high cost, thermoplastic properties, difficulties in weaving and dyeing, and poor shrinkage properties, which have prevented them from gaining universal acceptance in all industries.

Durable flame-retardant treated fabrics are composed of natural fibres, such as cotton or wool that have been chemically treated with fire-retardant agents that chemically interact with them or are bound to fibre surfaces.[37]

PBI is claimed to offer improved thermal and flame resistance, durability, chemical resistance, dimensional stability and comfort in comparison with other high performance fibres. Wearer trials have shown that PBI fibre exhibits comfort ratings equivalent to those of 100% cotton. Although PBI is expensive the outstanding combination of thermal and chemical resistance and comfort makes it an ideal fibre for protective clothing applications where a high degree of protection is required, such as firefighting suits, escape suits for astronauts, and aircraft furnishing barrier fabrics for the aircraft industry. PBI is easily processed on all conventional textile equipment and can be readily formed into woven, knit and nonwoven fabrics. PBI's excellent dimensional stability and nonembrittlement characteristics allow fabrics to maintain their integrity even after exposure to extreme conditions. By blending PBI with other high performance fibres, the design engineer can usually improve the performance of currently available protective apparel. PBI offers improved flammability resistance, durability, softness and retained strength after exposure to heat sufficient to damage other flame- and heat-resistant fibres. A 40/60 PBI/ aramid blend ratio has been determined as being optimal for overall fabric performance.[31,32]

Oxidised acrylic fibres have excellent heat resistance and heat stability. They do not burn in air, do not melt and have excellent resistance to molten metal splashes. There is no afterglow and the fabrics remain flexible after exposure to flame. They are ideal where exposure to naked flame is required, are resistant to most common acids and strong alkalis, are very durable and are said to be comfortable to wear. Universal Carbon Fibres markets an anti-riot suit made from oxidised acrylic fibre specifically designed for police and paramilitary forces. The suit is designed to provide protection against both flame and acid and to permit maximum freedom of movement of body and limbs.[34] For lower specification protective clothing, modacrylic fibres are being used successfully. Fibres with improved thermal stability up to 190 °C are available and these can be used alone or in blends for protective clothing.[31] In defence wear-life trials, it has been found that blends of modacrylic and wool can substantially reduce initial cost, reduce maintenance and improve the wear life performance of flame-retardant sweaters.

Wool is regarded as a safe fibre from the point of view of flammability. It may be ignited if subjected to a sufficiently powerful heat source, but will not usually support flame and continues to burn or smoulder for only a short time after the heat source is removed. Wool is particularly advantageous because it has a high ignition temperature, relatively high limiting oxygen index, low heat of combustion, low flame temperature and the material does not drip.[3,15] For foundry workers, who are at risk from being splashed by molten metals such as steel, cast iron, copper, aluminium, zinc, lead, tin and brass, small scale tests using molten iron and copper, verified by large scale tests, showed that wool fabric finished with Zirpro® (IWS) flame retardant offered the best protection. Untreated cotton was found to be second best. Fabric made from glass, asbestos and aramid fibres was considered to be unsuitable for protection against most metals. Molten metal tends to stick to most fabrics allowing time for the skin underneath to reach a high temperature, whereas it runs off wool fabric.[33] Aramid fibres soften and/or melt at around 316 °C and this causes trapping of the molten metal and subsequent excessive heat transfer. Untreated cotton offers good protection against molten aluminium, but the application of some organophosphorous-based flame-retardant compounds makes molten aluminium adhere to the fabric, with excessive heat transfer. This is not the case with some flame retardants based on organobromine compounds. To prevent metal from penetrating the fabric at the point of impact, a relatively heavy and tightly constructed outer fabric is required. In this case, contrary to the case with exposure to the flames, a multilayer approach to garment design is not suitable for protection against molten metal hazards.[34]

Benisek *et al.*[37] have studied the influence of fibre type and fabric construction on protection against molten iron and aluminium splashes. They made the following recommendations for optimum protection:

1 The fibre should not be thermoplastic and should have a low thermal conductivity.
2 The fibre should preferably form a char, which acts as an efficient insulator against heat from molten metal.
3 With increasing weight and density, the fabric should withstand increasing weights of molten aluminium; and
4 Ideally the fabric surface should be smooth to prevent trapping of metal.

Zirpro finished wool meets the above requirements. Decabromodiphenyl oxide/antimony oxide-acrylic resin finished cotton fabrics (Caliban, White Chemical) have also been found to be suitable for workers in the aluminium industry.[31]

Table 17.3 shows the thermal characteristics of protective clothing fabrics made from different types of natural and synthetic fibre.[31]

17.3.2.2 Use of fibre blends in protective clothing

Some aramid fabrics shrink and break open under intense heat, so a fabric blend known as Nomex III® (Du Pont) has been developed by blending regular Nomex with 5% Kevlar®, which itself has much higher resistance to disintegration. Aramid fibres are expensive but cheaper products can be made by blending them with flame-retardant viscose and flame-retardant wool.[31]

Table 17.3 Thermal characteristics of clothing fabrics[34]

Property	Wool	Cotton	FR Cotton	Nomex III	Kevlar
Mass ($g\,m^{-2}$)	240	320	315	250	250
Reaction to thermal exposure	Ignites	Ignites	FR Degrades		Degrades
Degradation temperature (°C)	260	340	320	430	430
Energy to cause thermal failure ($kJ\,m^{-2}$)	437	504	418	749	667
Energy per fabric mass ($kJ\,m^{-2}/g\,m^{-2}$) × 100	1.44	1.25	1.06	2.36	2.13
Mode of failure	Break open	Ignition	Tar deposition		Heat transfer

In France, Kermel®, a fibre with similar chemical structure and performance to Nomex is especially used for firefighters.[31] Its field of use is widening to include both military and civilian occupations in which the risk of fire is higher than usual. Like aramids it has a high price but this may be offset by blending with 10–15% viscose, which also eliminates static electricity generation. Blends of 25–50% Kermel with flame-retardant viscose offer a price advantage and resistance to UV radiation. Blending with 30–40% wool produces more comfortable woven fabrics with enhanced drape. By using blends it is possible to produce garments that are comfortable enough for the wearer to forget that they are wearing protective clothing. In the metal industry where protection from molten metal is needed and the life of a garment is extremely limited, a 50/50 blend gives very good results but a 65/35 Kermel/flame-retardant viscose blend would be preferred. The characteristics of Kermel blends are shown in Table 17.4.[31] Panox® (RK Textiles) is an oxidised acrylic fibre which has been blended with other fibres. Panox/wool blends are suitable for flying suits. In conjunction with aramid fibres, they can be used for military tank crews, where high resistance to abrasion is required. However, fabrics made from the black oxidised acrylic fibre have high thermal conductivity and are non-reflecting. Hence it is essential to have suitable underwear to protect the skin. For this purpose, a 60/40 Panox /modacrylic fibre double jersey fabric and a 60/40 wool/Panox core fabric have been devised. To prevent transfer of radiant heat, Panotex fabrics (containing Panox fibres from Universal Carbon Fibres) generally need to be metallized. An aluminized oxidised acrylic fabric is suitable for fire proximity work but not for fire entry. In some cases, the heat conduction of oxidised acrylic fabric can be an advantage in the construction of covers for aircraft seats. A fabric with Zirpro-treated wool face and Panox back will spread the heat from a localised ignition source and delay ignition of the underlying combustion-modified foam. Another advantage of proofed oxidised acrylic outer fabric is that it sheds burning petrol and can withstand several applications of napalm.[31]

The integrity and flexibility of specific flame-retardant viscose Durvil®, Nomex®, PBI fibre and wool and their blends has been studied. The results are shown in Table 17.5.[34] In all cases except PBI and PBI/viscose, the fabrics are hard and brittle so

Table 17.4 Effect of fabric mass, fibre, and blend ratio on limiting oxygen index[34]

Composition	Mass ($g\,m^{-2}$)	LOI
100% Kermel	250	32.8
100% Kermel	190	31.3
100% FR Viscose	250	29.4
100% FR Viscose	145	28.7
50/50% Kermel/ Viscose	255	32.1
50/50% Kermel/ Viscose	205	29.9

Table 17.5 Thermal convective testing of different fibres and fibre blends[34]

	Time to 2nd degree burn (s)	Exposure energy ($J\,cm^{-2}$)
Durvil	6.5	54.2
Nomex	8.9	73.4
80/20% Durvil/Nomex	4.8	40.3
PBI	7.6	63.4
80/20% Durvil/PBI	6.3	52.9
Wool	10.5	87.8
65/35% Durvil/wool	6.4	53.4
FR Cotton	3.8	31.5

they crack severely and break apart on relatively low flexing. The PBI and PBI/flame-retardant viscose blends can withstand repeated flexing with no effect on fabric integrity. Fabrics of 100% flame-retardant viscose are recommended for overalls and outerwear for military suits, whereas 40/60 viscose wool blends are found to be more suitable for firefighting uniforms. Karvin® (DuPont), a blend of 5% Kevlar, 30% Nomex and 65% Lenzing flame-retardant viscose has been designed for the production of flame-resistant protective clothing. Fabrics made from Karvin have an optimum combination of wear comfort, protection and durability.[31]

Using Dref friction spinning technology, special fibres such as aramid, polyimide, phenol, carbon and preoxidised and other flame-retardant fibres can be simply and economically processed, and special yarn constructions can be created by means of layer techniques.[35] These yarns incorporate the inherently flame-retardant melamine resin fibre, Basofil®.

Multicomponent yarns with cores (e.g. glass filament, metal wire), sheathed with flame-retardant fibre material are increasingly being sought. In the high price sector, which is only implemented when major protection requirements exist, para-aramid or preoxidised stretch broken slivers (up to 40% of yarn as core) are utilised to replace more expensive materials.

The Basofil product description includes the following:

Table 17.6 Characteristics of Basofil fabrics with aluminium coating[38]

Area weight ($g\,m^{-2}$) (without coating)	400	580
Fabric construction	2/2 Twill	Plain weave
Tensile strength (decaN/5 cm)	Warp 250 Weft 150	Warp 135 Weft 50
Convective heat according to EN 367 (s)	7.2	9.4
Radiated heat ($40\,kW\,m^{-2}$) according to EN 366 (s)	150	115
Contact heat 300 °C according to EN 702 (s)	4.4	8.2
Limited flame spread EN 531	Index 3	Index 3

- flame-resistant, temperature-resistant melamine resin, staple fibres
- LOI 31–33%
- 4% moisture regain
- continuous service temperature: approx 200 °C
- hot air shrinkage, 1 hour at 200 °C, <2%
- coatable and dyeable.

Currently, 300 000 tonnes of coarse range Dref yarns are produced annually of which about 15–20% are technical yarns for the protective clothing sector.

Mechanical characteristics are determined by the choice of suitable cores, and heat and fire protection by the sheath material. Owing to this clear functional allocation, the individual components can be matched for the optimisation of the overall system. Two fabrics have proved especially advantageous for medium and heavy-weight fire and heat protection. For additional protection against extreme radiated heat, the outside of the fabric can be coated with aluminium. One fabric has a yarn consisting of a glass core and a sheath comprised of a blend of 80% Basofil and 20% p-aramid. The other fabric has a yarn consisting of a glass core and 100% Basofil sheath. It is claimed that the fabrics have resistance to convective and contact heat twice that of standard fabrics. Typical uses for the fabric are found in foundries and the metal production industry. Table 17.6 shows the characteristics of fabrics made from yarns incorporating Basofil fibre.[35]

17.3.2.3 Fabric constructions for protection

The optimum properties required of fabric intended for protection against heat and flame have been enumerated as:[3]

1 High level of flame retardance: must not contribute to wearers injury
2 Fabric integrity: maintains a barrier to prevent direct exposure to the hazard
3 Low shrinkage: maintains insulating air layer
4 Good thermal insulation: reduces heat transfer to give adequate time for escape before burn damage occurs

5 Easy cleanability and fastness of flame resistance: elimination of flammable contamination (e.g. oily soil) without adverse effect on flame retardance and garment properties
6 Wearer acceptance: lightweight and comfortable
7 Oil repellency: protection from flammable contamination, such as oils and solvents.

The influence of fabric construction and garment manufacture on flammability and thermal protection has been studied extensively.[31] Fabric construction and weight per unit area play an important role in determining suitability for different applications. Different fabric weights have been recommended for thermal protection under various working conditions. For a hot environment in which the fire hazard is principally a direct flame, a lightweight tightly woven construction, such as 150–250 $g\,m^{-2}$ flame-retardant cotton sateen would be most suitable. For full firefighting installations, a flame-retardant cotton drill of about 250–320 $g\,m^{-2}$ is recommended. For work in which the garment is exposed to a continuous shower of sparks and hot fragments as well as a risk of direct flame a heavier fabric is required and a raised twill or velveteen of about 320–400 $g\,m^{-2}$ in flame-retardant cotton could be chosen. With molten metal splashes protection of the wearer from heat flux is important and fabric densities of up to 900 $g\,m^{-2}$ are found useful.

For heat hazards of long duration, protection from conductive heat is required. Heat flow through clothing reaches a steady state and fabric thickness and density are the major considerations, since the insulation depends primarily on the air trapped between the fibres and yarns. Reducing the fabric density for a given thickness increases thermal insulation down to a minimum level of density below which air movement in the fabric increases and reduces insulation. For short duration hazards, increasing the fabric weight increases the heat capacity of the material, which increases protection.[31] In this case of protection against radiant heat, aluminised fabrics are essential. Clean reflective surfaces are very effective in providing heat protection, but aluminised surfaces lose much of their effectiveness when dirty.[31]

Table 17.7 shows the effect of two heat sources on various types of fabric.[19]

Woven and nonwoven fabrics of different masses made from aramid and PBI fibre have been compared[34] and the results are shown in Table 17.8. The original

Table 17.7 Comparison of radiant and convective heat sources[19]

Fabric	Thickness (mm)	Burn threshold (s) at 80 $kW\,m^{-2}$	
		Radiant	Convective
Aluminised glass	0.53	>30	2.6
FR Cotton	0.72	2.2	2.4
Aramid	0.97	2.7	3.1
Zirpro wool	1.16	3.1	4.1
Wool melton	3.64	6.7	8.8
Aramid + cotton interlock	1.77	5.0	5.5
Zirpro wool + cotton interlock	1.96	4.3	6.8
Bare skin		0.5	0.5

Table 17.8 Effect of construction on thermal-protective performance (TPP)[34]

Fibre type	Construction	Mass ($g\,m^{-2}$)	TPP	TPP/mass[a]
PBI	woven	272	17.6	2.2
	nonwoven	296	28.4	3.3
PBI/Kevlar	woven	245	16.2	2.2
	nonwoven	282	26.0	3.1
Nomex	woven	255	16.4	2.2
	nonwoven	238	19.8	2.8

[a] At 84 $kW\,m^{-2}\,s^{-1}$ 50/50 radiant/convective heat exposure.

Table 17.9 Effect of fabric constructional parameters on protection for PBI fabric[34]

Weave (twill)	Mass ($g\,m^{-2}$)	Thickness (mm)	Temperature rise (°C/3 s)	Blister protection (s)
2/1	99	0.19	22.1	2.6
2/1	160	0.29	20.0	3.0
2/1	211	0.39	17.7	3.5
3/3	167	0.31	18.1	3.4

fabric constructional data were published in imperial units and they have been converted to SI units for consistency. Woven fabrics were designed as the outer shell material in firefighters' turnout coats, and the needlefelt nonwoven fabrics could be considered for use as a backing or thermal liner in thermally protective apparel. This work shows that nonwoven fabrics provide consistently better thermal protection than woven fabrics of equivalent mass per unit area.

Table 17.9 shows the effect of fabric constructional parameters on the protection provided by fabric made from PBI fibre.[31] Again the original fabric constructional data were published in imperial units.

There are conflicting requirements of protection and comfort in protective clothing. Fabric thickness is a major factor in determining the protection afforded against radiant and convective heat, but at the same time it impedes removal of metabolic heat from the body by conduction and sweat evaporation. Hence it is necessary to have a suitable garment design to enable body heat to be dissipated.[31] Gore-Tex microporous PTFE (polytetrafluoroethylene) film (Gore Associates) has been developed and used in producing waterproof and windproof fabrics with moisture vapour permeability to provide comfort to the wearer. For this purpose, a three-layer Nomex III/ Gore-Tex/modacrylic fabric has been found to be extremely good.[31]

The high performance aramid fibres such as Kevlar and Nomex have been and are made into both woven and nonwoven fabrics for protection against chemical, thermal and other hazards. As the relatively high cost of Nomex garments precludes their use in limited wear applications, Du Pont has developed Nomex spun-laced fabrics for low cost protective apparel for wear over regular work clothing. Spun-laced technology has also enabled the development of lighter weight turnout coats for firefighters. In the 1990s, Du Pont focused its research and development efforts on improving comfort, dyeing technology and moisture absorption and transmission of Kevlar and Nomex fibres, creating new fibres, reducing fibre linear densities and making permanently antistatic Nomex commercially available.[36]

Cotton textile garments were considered by the US National Aeronautics and Space Administration (NASA) to be suitable for protective apparel for space shuttles on the basis of skin sensitivity, comfort, electrical sensitivity and so on. Chemically treated flame-resistant cotton fabrics for space shuttle apparel were made from a two-ply sateen ($244\,g\,m^{-2}$), a weft sateen ($153\,g\,m^{-2}$), and a two-ply, mercerised, knitted single jersey fabric ($187\,g\,m^{-2}$). A space suit designed for NASA has been developed by combining new technology in fabric moulding with shuttle weaving. The tubular fabric, which is woven on an X-2 Draper shuttle loom from polyester continuous filament yarns is coated and moulded into specific shapes.[31]

A recommendation has been made for the use of an aluminised fabric as a fire blocking layer to encase polyurethane foam in aircraft seating. DuPont has developed lightweight multilayered spunlaced Nomex/Kevlar structures as fire blocking layers in aircraft seat upholstery. Nomex provides fire resistance whereas Kevlar provides added strength.[31]

17.3.2.4 Finishes for heat and flame resistance

The application of various finishes to cellulose fibres has been reviewed by Horrocks.[37] The commercially most successful durable finishes are the *N*-methylol dialkyl phosphonopropionamides (e.g. Pyrovatex®, Ciba; TFRI®, Albright and Wilson) and tetrakis(hydroxymethyl) phosphonium salt condensates (e.g. Proban®, Albright and Wilson).

To fulfil stringent requirements the natural flame-retardant properties of wool can be enhanced by various flame-retardant finishes. Titanium and zirconium complexes are very effective flame retardants for wool and this has led to the development of the IWS Zirpro finish. The Zirpro finish produces an intumescent char, which is beneficial for protective clothing where thermal insulation is a required property of a burning textile. A multipurpose finish incorporating Zirpro and a fluorocarbon in a single bath application makes wool flame retardant as well as oil-, water- and acid-repellent. This is extremely useful for end-uses where the protective clothing could become accidentally or deliberately contaminated with flammables, such as grease and oil and petrol, such as police uniforms where high moisture vapour permeability with low heat transfer and adequate durability are also important. Wool fabric finished with Zirpro flame retardant and a permanent fluorocarbon oil-repellent finish has demonstrated satisfactory performance under laboratory conditions. This combination of finishes is considered to give better overall performance.[3,25] With increasing environmental awareness, the use of such heavy metal-based finishes has been questioned.

Shirts containing 100% cotton, flame-retardant cotton, flame-retardant wool and Nomex aramid fibre have been evaluated for their protective and wear life performance. The greatest protection was provided by flame-retardant cotton and wool fabrics. Nomex fibre fabric gave less protection and untreated cotton the least.[31]

Flame-retardant finishes for synthetic fibres have been developed. Ideally, these should either promote char formation by reducing the thermoplasticity or enhance melt dripping so that the drips can extinguish away from the ignition flame. For protective clothing, char-forming finishes would be desirable. Flame-retardant finishes for nylon 6 or 6.6 do not seem to have had any commercial success.[31,36] Flame retardancy can be imparted to acrylic fibres by incorporating halogen or phosphorus-containing additives.[34] although this never happens in practice because modacrylics yield equivalent and acceptable performance levels.

17.3.2.5 Garment construction

Fireighters fighting a room fire can be exposed to up to 12.5 kW m^{-2} and up to 300 °C temperature for a few minutes. Heat exposure in a fire consists primarily of radiation, but convective and conductive heat (if, for example, molten metal or hot paint falls on a garment) may also be encountered. Under any of these conditions, the garments should not ignite; they should remain intact, that is, not shrink, melt or form brittle chars, and must provide as much insulation against heat as is consistent with not diminishing the wearer's ability to perform their duties. Several garment characteristics are important for protecting the wearer from pain and burn injury.[38] The major protective property is thermal resistance, which is approximately proportional to fabric thickness. Moisture content reduces this resistance. The resistance can be reduced by high temperature, especially if this causes the fibres to shrink, melt or decompose. Curvature decreases the resistance requiring more thickness to protect fingers than large body areas. As stated previously, clean reflective surfaces are very effective in providing heat protection. Surface temperatures of fabrics exposed to radiation are reduced to about half in still air by the use of aluminised surfaces.

Moisture present in a heat protective garment cools the garment, but it may also reduce its thermal resistance and increase the heat stored in it. If the garment gets hot enough, steam may form inside and cause burn injury. In the USA most firefighters turnout coats contain a vapour barrier either on the outside or between the outer shell and inner liner. This prevents moisture and many corrosive liquids from penetrating to the inside, but, on the other hand, it interferes with the escape of moisture from perspiration and increases the heat stress. Some European fire departments omit vapour barriers.

Thermal protective clothing should meet the following requirements:[31]

1 flame resistance (must not continue to burn)
2 integrity (garment should remain intact, i.e. not shrink, melt or form brittle chars which may break open and expose the wearer)
3 insulation (garments must retard heat transfer in order to provide time for the wearer to take evasive action; during combustion they must not deposit tar or other conductive liquids) and
4 liquid repellency (to avoid penetration of oils, solvents, water and other liquids).

The requirements for US firefighting bunker gear are (Turnout Gear Selection, http://www.seritex.com, July, 1997)

1 Those affecting garment life:
   - tear and abrasion resistance
   - resistance to UV degradation (for strength and appearance)
   - thermal damage tolerance (influencing ability to be reused after exposure to high temperatures)
   - resistance to molten metal splatter and burning embers
   - cleanability.

2 Those affecting firefighter safety:
- ice shedding ability
- water absorption on the fire ground
- weight and suppleness
- mobility
- visibility
- thermal protection
- breathability to water vapour.

Bunker gear is made from a three-layer system consisting of (Turnout Gear Selection, http://www.seritex.com, July, 1997) an outer shell, a moisture barrier and a thermal barrier. The outer shell is the first line of defence for the firefighter. It provides flame resistance, thermal resistance and mechanical resistance to cuts, snags, tears and abrasion. There are a variety of outer shell fabrics available each with advantages and disadvantages. Most fabrics have a fibre content of Nomex and Kevlar, a twill or ripstop woven construction and an area density of 200–250 $g\,m^{-2}$.

The moisture barrier is the second line of defence. Its principal function is to increase firefighter comfort and protection by preventing fire ground liquids from reaching the skin. It also provides some burn protection due to its insulation value and ability to block the passage of hot gas and steam. The moisture barrier consists of a film or coating applied to a textile substrate. The substrate is either woven, usually ripstop, or spunlaced nonwoven both with aramid fibre content. The coatings and films can be either breathable or non-breathable.

Breathable films are usually microporous PTFE such as GoreTex and breathable coatings are either microporous or hydrophilic polyurethane. Breathable moisture barriers permit the escape of body perspiration and reduce the incidence of heat stress which is a major cause of death amongst firefighters. The thermal liner blocks the transfer of heat from the firefighting environment to the body of the wearer. It usually consists of a spunlaced, nonwoven felt or batting quilted or laminated to a woven lining fabric. The felt or batting is made from Nomex or Kevlar or a mixture of these two fibres. One manufacturer uses a closed cell foam made from PVC and nitrile rubber to reduce water absorption and increase drying time. The woven lining fabric has usually been made from spun Nomex. Continuous filament Nomex has been used to increase mobility and make it easier to take the garments on and off.

Benisek *et al.* have also described using flame-retardant finished wool in a multilayer approach to garment design.[34] Tightly woven outerwear fabric with a high integrity against flames, and a bulky low density, thick, knitted innerwear fabric, both made from char forming fibres such as Zirpro wool, offer additional insulation against flame exposure, associated with the air trapped in the knitted fabric. As condensation of moisture in the fabric has the effect of increasing both its thermal capacity and its thermal conductivity, it can be seen why a wet outer and a dry inner fabric offer the best protection. In this context, it is surprising to find that garments designed to encourage moisture condensation in the inner layers, by using vapour impermeable barriers, are officially approved for use in fire hazards.

Tables 17.10 to 17.12 show the protection provided by a range of multilayer garments.[31,38]

Table 17.10 shows the effect of total garment mass and thickness for garments containing various fibres and consisting of different numbers of layers.[31] Table 17.11

Table 17.10 Effect of garment mass and thickness on protection index[34]

Garment layer			Total mass ($g\,m^{-2}$)	Total thickness (mm)	Protection index
Outside	Intermediate	Inside			
100% Kermel 250 $g\,m^{-2}$	None	None	250	0.8	15.5
100% Kermel 250 $g\,m^{-2}$	None	Kermel knitted underwear 330 $g\,m^{-2}$	580	3.4	20.5
100% Kermel 250 $g\,m^{-2}$	Kermel knitted underwear 300 $g\,m^{-2}$	Kermel knitted pantihose 200 $g\,m^{-2}$	780	4.8	35
100% Kermel 250 $g\,m^{-2}$	Kermel knitted underwear 330 $g\,m^{-2}$	Cotton knitted underwear 320 $g\,m^{-2}$	900	5.5	43
100% Kermel 250 $g\,m^{-2}$	Kermel knitted underwear 330 $g\,m^{-2}$	Wool sweater 650 $g\,m^{-2}$	1230	7.9	58

Table 17.11 Heat protection characteristics of combinations of shell fabrics, vapour barriers and thermal barriers (84 $kW\,m^{-2}$ flame exposure)[34]

Shell fabric fibre content	Mass ($g\,m^{-2}$)	Vapour barrier	Thermal barrier	Time to burn injury (s)	Total heat after 60 s ($kJ\,m^{-2}$)
Aramid	245	NCN	QN	28	925
		CPCN	QN	31	900
		CPCN	NPN	40	780
		CPCN	FW	38	740
		GN	QN	32	900
		NCNPN		39	745
Coated Aramid	320	none	QN	34	850
Novaloid/Aramid	340	NCNPN		30	980
Aramid blend	255	NCN	QN	30	940
		CPCN	QN	50	590
FR Cotton	440	CPCN	QN	38	855

NCN = Neoprene-coated aramid fabric, 255 $g\,m^{-2}$; CPCN = Coated aramid pyjama check fabric, 265 $g\,m^{-2}$; GN = Gore-Tex-coated nylon base fabric; NCNPN = Neoprene-coated aramid needlepunched fabric, 735 $g\,m^{-2}$; QN = Aramid quilt, consisting of aramid fibre batting with aramid pyjama check fabric attached, 245 $g\,m^{-2}$; NPN = Aramid needlepunched fabric, 245 $g\,m^{-2}$; FW = Wool felt, 430 $g\,m^{-2}$.

shows the range of heat protection properties during an 84 $kW\,m^{-2}$ exposure of US firefighters' turnout coats.[34] The inner thermal barrier is generally a batting or a needlepunched construction with fabric linings on the inside or both sides. The shell fabrics are of aramid fibre, an aramid/novaloid blend, or flame-retardant cotton.

Table 17.12 TPP ratings for protective clothing[42]

Ensembles	Total weight ($g\,m^{-2}$)	Total thickness (mm)	Thermal load (% of $84\,kW\,m^{-2}$)	TTP rating
Nomex III shell; Neoprene polycotton vapour barrier; Nomex quilt liner	766	5.4	50/50 convective/ radiant	38.6
Nomex III shell; Neoprene polycotton vapour barrier; Nomex quilt liner	899	5.6	100 radiant	42.5
Nomex III shell; Gore-Tex vapour barrier; Nomex quilt liner	719	5.4	50/50	46.5
Nomex III shell; Gore-Tex vapour barrier; Nomex quilt liner	726	5.8	100	44.7
Aluminized Nomex I shell	302	0.4	100	67.7
Aluminized Kevlar shell	346	0.5	100	78

Table 17.12 lists representative thermal protective performance (TPP) values for some materials used in structural and proximity clothing.[39] The first two ensembles show the effect of different vapour barriers on the overall thermal performance. The last two materials show the dramatic effect on radiant heat protection of aluminizing the outer shell material.

It has been suggested that standard firefighter's turnout gear or coat should be a multilayer construction with a durable fire-retardant outer shell fabric.[31] The outer shell may or may not be air and water permeable. The turnout coat may or may not incorporate a detachable vapour barrier or insulative liner. The vapour barrier is intended to protect the firefighter from steam and harmful chemicals, but on the other hand, it interferes with the escape of moisture from perspiration and increases the heat stress, which may result in subsequent hazards to health and safety. Hence an inner liner vapour barrier, mostly used in firefighters turnout coats in the United States, is excluded by some European fire departments. Table 17.13 compares the construction of tunics used in a number of European countries up to 1990.[31] In an attempt to produce a normalised EU standard for protective clothing, the current standards relate to clothing performance in general and flame and heat penetration in particular.

The excellent flame protection properties of woven outerwear fabric with bulky knitted underwear has been demonstrated and this combination has formed the basis of many clothing assemblies for protection against heat and flame hazards, for example the racing driver's garment assembly described in Table 17.14.[31] A glass fibre matrix has been used in wool fabric to give integrity to the char. Glass yarn was incorporated into the wool at the spinning stage. The yarn was then plied with all wool yarn and woven alternately with all wool yarn in both warp and weft direc-

Table 17.13 European firefighters tunics[34]

Country	Tunic				
	Mass (kg)	Thickness (mm)	Number of layers	Vapour barrier fibre	Outer fabric content
Austria	1.3	5.7	3	no	Wool/FR viscose/ FR polyester
	0.9	0.7	1	no	Zirpro wool
Belgium	1.9	5.1	3	yes	Coated aramid
Denmark	1.6	2.5	2	no	wool
Finland	2.5	2.3	2	yes	Wool/acrylic
France	2.1	2.3	2	no	Leather
Germany	1.0	1.05	1	no	Zirpro wool
Holland	2.3	3.9	1	no	Wool
	2.1	2.2	3	no	Wool/nylon
	2.2	4.9	3	yes	Aramid
Norway	1.8	1.8	1	no	Wool
Sweden	1.3	5.8	2	no	Zirpro wool
	1.8	2.2	2	no	Wool/FR viscose
	2.2	2.6	2	no	Wool/FR viscose
UK	1.9	4.5	3	no	Wool/nylon
	1.7	3.2	4	no	Aramid

Table 17.14 Specification for racing drivers' garment assembly[34]

Outer Layer		
Fibre content	85/15 wool/glass	
Structure	2/2 twill	
Mass ($g\,m^{-2}$)	350	
Sett (threads/cm)		
warp	17.3	
weft	15.7	
Yarn linear density	R80 tex/2, all wool	Alternately in warp and weft
	R94 tex/2, 70/30 wool/glass	
Inner Layer		
Fibre content	100% wool	
Structure	2 × 2 rib with successive tucks	
Mass ($g\,m^{-2}$)	175	
Loop length (cm)	0.6	
Yarn linear density	R44 tex/2	

tions. Thermal underwear was also developed to offer increased bulk and thickness by incorporating a series of tuck stitches into the 2 × 2 rib construction.

17.3.3 Chemical, microbiological and radiation hazards

Today's user of chemical protective clothing is faced with a formidable task when selecting appropriate clothing. Among many factors that must be considered are cost, construction, style, availability, mode of use (disposable versus reusable). However, the most important factor is the effectiveness of the clothing as a barrier to the chemicals of interest.[40]

Both routine and emergency chemical handling may result in direct exposure to toxic chemicals. Examples of such situations include the following:[41]

1 handling of liquid chemicals during manufacture
2 maintenance and quality control activities for chemical processes
3 acid baths and other treatments in electronics manufacture
4 application of pesticide and agricultural chemicals
5 chemical waste handling
6 emergency chemical response and
7 equipment leaks or failures.

The degree of protection is important, particularly in the chemical industry, in which protective clothing is worn to prevent exposure to chemicals during production, distribution, storage and use. These chemicals may be gases, liquids or solids but, whatever their state, working with them safely means knowing how protective the clothing is or, more specifically, how resistant it is to chemical permeation.[42]

The selection of an appropriate level of protective clothing to be used in any particular situation should be based on a number of objective and subjective factors, including:[41]

- potential effects of skin contact with the chemical (for example, corrosiveness, toxicity, physical damage, allergic reaction)
- exposure period (time of contact)
- body zone of potential contact (for example, hands, feet, arms, legs, face, chest, back)
- permeability or penetration potential of the protective garment (breakthrough time and steady state rate)
- characteristics of potential contact (for example, splash, immersion)
- additive or synergistic effects of other routes of exposure (that is, inhalation and ingestion)
- physical properties required of the protective garment (for example, flexibility, puncture and abrasion resistance, thermal protection)
- cost (that is, based on single or multiple use and acceptable exposure).

Millions of farm workers and pesticide mixers across the world risk contamination by pesticides. Since dermal absorption is the significant route of pesticide entry, any barrier that can be placed between the worker and the chemical to reduce dermal contact can reduce exposure. With the exception of properly filtered air systems in enclosed cabs, the only significant type of barrier available to applicators is protective clothing.[43]

It has been reported[44] that nonwoven fabrics, in general, appear to perform better than most woven fabrics. However, heavy woven fabrics of twill construction, such as denim, have performed quite well in the limited studies completed to date. There is a direct correlation between fabric weight and thickness with pesticide penetration. Fabrics made from synthetic fibres show more wicking of pesticide onto the skin than fabrics containing cotton. Cotton-containing fabric with a durable press finish showed the lowest rate of absorbency and wicking. Fluorocarbon soil-repellent finishes have been found to be excellent barrier finishes against pesticides. Gore-Tex has been found to possess the most effective combination of barrier and thermal comfort properties.

Factors such as fibre content, yarn and fabric geometry and functional textile finish determine the response of a textile to contamination from liquid pesticides.[45] Fluorocarbon polymers alter the surface properties of fabrics so that oil as well as moisture has less tendency to wet the fabric surfaces and wicking is reduced. Liquid soil is partially inhibited from wetting, wicking, or penetrating the fabric. An undergarment layer offers better protection than does a single layer of clothing. The contamination of the second layer is generally less than 1% of the contamination of the outer garment layer; thus, the pesticide is not available for dermal absorption. A tee-shirt undergarment is recommended over other fabrics studied. Spun bonded olefin fabric offers similar protection to the fluorocarbon finish. The use of the disposable spun bonded olefin garments or fluorocarbon finish applied to non-durable-press work clothing has also been recommended. Theoretically, the greatest protection is produced by the use of disposable olefin garments worn during mixing, handling, and application of pesticides, in addition to fluorocarbon finish on the usual work clothing.

Several investigations have been carried out to determine the effectiveness of various types of fabric for protection against pesticides.[46–48] In one investigation two fabrics commonly worn by the agricultural workforce and five potential protective fabrics served as the test fabrics.[46] A 100% cotton 500 $g\,m^{-2}$ denim with Sanforcet finish and a 100% cotton woven chambray shirting weight fabric represented typical clothing used for pesticide application. The five potential protective fabrics included three laminate variations, an uncoated spun bonded 100% olefin, and a 65% polyester/35% cotton 193 $g\,m^{-2}$ coated poplin. Laminate 1 consisted of a microporous membrane of PTFE laminated between a face fabric of 100% nylon ripstop and an inner layer of nylon tricot. Laminate 2 consisted of a microporous membrane of PTFE laminated between an outer fabric of 100% polyester taffeta and an inner fabric of polyester tricot. Laminate 3 was a two-layer laminate with the microporous membrane serving as the face fabric and laminated to a polyester/cotton woven fabric backing. Table 17.15, which lists Duncan's multiple range test results, shows that the fabrics can be divided into three significantly different groupings. The fabrics offering the greatest protection included the three laminate variations and the spun bonded olefin. The second group of fabrics included the 100% cotton denim, the polyester/cotton coated poplin and the 100% spun bonded polyolefin. The fabric offering the least protection was the 100% chambray shirting weight fabric.

Table 17.15 Duncan's multiple range test results for disintegrations per minute (DPM) by fabric[49]

Variable	Mean DPM	Number	Duncan's grouping
Chambray	53 708	36	A
Coated poplin	10 505	36	B
Denim	8 407	36	B
Spunbonded polyolefin	5 914	36	B, C
Laminate 3	52	36	C
Laminate 2	42	36	C
Laminate 1	11	36	C

Lloyd describes four types of fabric selected for suitability for protection from pesticides but does not report any scientific study.[47] In this work, material A was a conventional woven fabric (polyester/cotton) used in work wear for many purposes but relying essentially on absorption for protection against liquids. Material B was a conventional woven fabric (nylon) that had been 'proofed' with a silicone, and thereby was similar to many products used in rainwear with the potential for 'shedding' spray liquids. Material C comprised a three-layer laminate of a microporous PTFE membrane sandwiched between two layers of nylon fabrics (woven and knitted). This product had the potential for resistance to penetration by spray liquids along with improved comfort to the wearer. Material D comprised a woven nylon fabric coated with neoprene. This product is virtually impermeable to air and is used commonly in the construction of general purpose chemical protective clothing.

An evaluation of aerosol spray penetrability of finished and unfinished woven and nonwoven fabrics has also been carried out.[48] The results presented in Table 17.16

Table 17.16 Aerosol protection performance of different types of fabric[51]

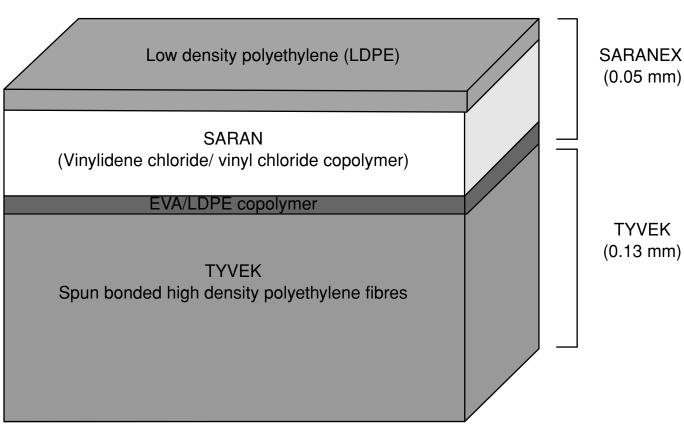
Test fabric	Water	Aerosol spray test performance	
		Water/surfactant	Cottonseed oil/ surfactant
Category I			
Spun-lace polyester, Scotchgard	pass	pass	pass
Spun-lace polyester, commercially finished	pass	pass	pass
Spun-bonded olefin, Scotchgard	pass	pass	pass
Spun-bonded/melt-bonded (90 $g\,m^{-2}$), Scotchgard	pass	pass	pass
Spun-bonded/melt-bonded (50 $g\,m^{-2}$), Scotchgard	pass	pass	pass
Category II			
Commercially finished (Scotchgard) cotton	pass	pass	fail
Cotton, Quarpel	pass	pass	fail
Cotton/polyester, 35/65 Quarpel finished	pass	pass	fail
Category III			
Spun-bonded olefin	pass	fail	fail
Spun-bonded/melt-bonded (90 $g\,m^{-2}$)	pass	fail	fail
Spun-bonded/melt-bonded (50 $g\,m^{-2}$)	pass	fail	fail
Spun-bonded/melt-bonded (50 $g\,m^{-2}$) commercially finished	pass	fail	fail
Category IV			
Denim, unwashed	fail	fail	fail
Denim, 1 wash	fail	fail	fail
Denim, 3 washes	fail	fail	fail
Cotton drill	fail	fail	fail
Spun-lace polyester, unfinished	fail	fail	fail

indicate that the presence of a fluorocarbon finish increases the resistance to aerosol penetration. The woven fabrics tested failed to meet the criterion of being resistant to oil-based spray penetration. The finished nonwoven fabrics, with the exception of the commercially finished spun bonded/melt bonded, passed the spray tests using both the oil-based and water-based solutions. Comparisons of the comfort properties of air permeability, water vapour permeability, and density indicate that the spun lace class of nonwoven fabrics was very similar to the woven fabrics. The spun laced fabrics are denser or more 'clothlike' than many of the spun bonded fabrics.

An alternative need for chemical and microbiological protection is within the hygiene and medical fields. Textiles and fibrous materials may be subjected to various finishing techniques to afford protection of the user against bacteria, yeast, dermotaphytic fungi and other related microorganisms for aesthetic, hygienic or medical purposes.[49] A range of acrylic fibres many of which are phenol derivatives, have been chemically modified in order to fix bacteriostats. Courtaulds have developed a range of bactericidal acrylic fibres marketed under the brand name Courtek M. These fibres contain any of several widely accepted bactericides permanently bound to the fibre at a range of concentrations chosen for specific requirements. Bioactive acrylic polymers are highly effective in both fibre and nonwoven fabric forms. They are for use in the medical, sanitary, personal hygiene, and general patient care areas.

Protection against airborne radioactive particles is a problem in the nuclear industry. Microfilament yarns are densely woven to produce fabrics with maximum pore size of 20–30 μm compared with the 75–300 μm pore size of typical cotton and polyester cotton fabrics for use in the nuclear industry. Incorporation of filaments with a carbon core greatly reduces the attraction of radioactive particulates by static electricity on to the fabric during wear (Protech 2000; The First Protective Clothing Specifically Designed From Fiber to Finished Garment, http://www.wlst.com, July, 1997).

The spun bonded polyolefin fibre fabric Tyvek® while featuring extensively in all types of protective clothing, is claimed to be superior to other fabrics in the nuclear industry in preventing penetration and holding water borne contamination, dry particulate, tritiated water and tritium gas.[50] The fabric can be used uncoated or



17.2 Saranex-coated Tyvek fabric.

laminated with Saranex® (Dow Chemical Co.) depending on the degree of protection required. Saranex-coated Tyvek is a complex fabric. The outer layer is Saranex 23, a coextruded multilayered film 0.05 mm thick. It has an outside layer of high density polyethylene, an inner layer of Saran, a copolymer of vinylidene chloride and vinyl chloride, and the other outside layer of ethyl vinyl acetate (EVA) / low density polyethylene copolymer, which is used for bonding to the Tyvek. Figure 17.2 shows the construction of Saranex-coated Tyvek fabric.[50]

Garments for very specialised applications have to provide protection from a number of agencies, for example military garments for protection against nuclear, biological and chemical weapons (NBC suits). The fabric used to make these garments consists of two layers. The inner layer, usually of nonwoven construction, is impregnated with activated carbon to adsorb the agent particles thus preventing them from reaching the wearers skin. The outer layer is a woven fabric of relatively high porosity to allow the agents to penetrate to the inner layer and to provide mechanical strength, heat and flame-resistance and some weather protection. The heat and flame resistance is achieved by using inherently flame-resistant synthetic fibres.

17.4 Conclusions

As society becomes more safety conscious and has to survive in more arduous conditions in order to provide raw materials, energy and to push the frontiers of knowledge further, there is a need to provide a safe working environment. The modern textile industry plays a part in providing this environment by developing and supplying sophisticated clothing and other products. The degree of sophistication and specialisation is increasing and many products are very highly specified requiring a complex combination of properties. Much has been gained by developing traditional technologies such as, spinning, weaving, knitting and finishing. However the newer technologies appear to be developing at a faster rate. For example, nonwoven technology when it first appeared was seen only as a low cost method of producing fabric for unsophisticated products. Nonwoven fabric is now used extensively in survival products by combining the appropriate fibre content and appropriate method of production with other materials, such as chemical finishes, laminates and coatings.

References

1. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 1.
2. F S ANDRUK, *Protective Clothing for the United States Navy in the 1980s*, Navy Clothing and Textile Research Facility – Natick, Series No. AD-A956 145, 1980.
3. ANON, *Int. Dyer Textile Printer*, 1979 May 389.
4. I HOLME, *Apparel Int.*, 1992 **21**(5) May 31.
5. I HOLME, *Indian Textile J.*, 1992 **102**(9) June 134.
6. M MASRI, *Tech. Textiles Int.*, 1992 June 13.
7. B DAVIES, *Tech. Textiles Int.*, 1998 March 15.
8. J DZUGAN, 'Hypothermia', *Fisheries Safety and Survival Series*, Alaska Sea Grant Coll. Program – Fairbanks, Series No PB92-157937, 1992.
9. I HOLME, *Textile Month*, June 1988 38.
10. J GIBLO, *Thermal Performance of Navy Anti-exposure Coverall to Different Water Exposure Conditions*, Navy Clothing and Textile Res. Facility – Natick, Series No. ADA293950, August, 1993.

11. ANON, Allgemeiner Vliestoff-Report, 1987 **15**(2) 136(E137).
12. ANON, *High Performance Textiles*, 1991 March 10.
13. ANON, *Nonwovens Rep. Int.*, 1987 (194) May 10.
14. ANON, *Du Pont Magazine*, 1996 **90**(2) March/April 18.
15. ANON, *Textile Month*, 1981 June 23.
16. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 65.
17. ANON, *Vliesstoff Nonwoven Int.*, 1994 (6–7) 179.
18. B V HOLCOMBE and B N HOSCHKE, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 327.
19. W G BURCKEL, *Heat Resistant Fiber Blends For Protective Garments*, US Patent Office, Patent No 1 486 997, 1974.
20. S ALEXANDER, *Tech. Textiles Int.*, 1995 **4**(6) July/August 12.
21. T POLFREYMAN, *Textile Month*, 1980 May 19.
22. L A SHANLEY *et al*, *Clothing Textiles Res. J.*, 1993 **11**(3) 55.
23. I HOLME, *Textile Month*, 1987 September 112.
24. A LARSSON *et al*, *Test of Modified Submarine Escape And Immersion Suit*, National Defence Research Establishment, Sundyberg, Sweden, Series No BP92-125624, 1991.
25. M GENNSER *et al*, *Survival Suit for Submarine Personnel*, Swedish Defence Material Administration-Stockholm, Series No PB 93-204634, March, 1993.
26. ANON, *Textile Month*, 1982 July 14.
27. R SPECTOR, *Daily News Record*, 1987 **17**(31) February 22.
Superior Technology Means Superior Performance, http://www.northern.com, July, 1997
28. J BRADSHAW, *Nonwovens Ind.*, 1981, 12, Aug., 18.
29. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 64.
30. M C MAGILL, *Report on Ski Glove Tests*, Outlast, Gateway Technologies, December, 1996.
31. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 9–43.
32. R E BOUCHILLON, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 389.
33. L BENISEK and G K EDMONDSON, *Textile Res. J.*, 1981 **51**(3) March 182.
34. L BENISEK *et al*, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 405.
35. M GSTEU, K OTT and H D EICHHORN, *Textile Horizon*, 1997 **17**(5) October/November 12.
36. H H FORSTEN, *Protective Clothing: An Update on Personal Protection Against Chemical, Thermal and Other Hazards*, Du Pont, May, 1989.
37. A R HORROCKS, *Rev. Prog. Colouration*, 1986 **16**(62).
38. J KRASNY, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 463.
39. J H VEGHTE, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 487.
40. M W SPENCE, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 32.
41. S Z MANSDORF, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 207.
42. N W HENRY, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 51.
43. A P NIELSEN and R W MARASKI, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 95.
44. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 79.
45. J M LAUGHLIN, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 136.
46. H D BRANSON *et al*, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 114.
47. G A LLOYD, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 121.
48. N E HOBBS *et al*, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 151.
49. P A BAJAJ and A K SENGUPTA, *Protective Clothing, Textile Prog.*, 1992 **22**(2/3/4) 75.
50. C E GARLAND *et al*, *Performance of Protective Clothing*, eds. R L Barker and G C Coletta, ASTM Special Technical Publication 900, Philadelphia, 1986, p. 276.

18

Textiles in transportation

Walter Fung

Collins and Aikman, PO Box 29, Manchester Road, Walkden,
Manchester M28 3WG, UK

18.1 Introduction

Transportation is the largest user of technical textiles. Textiles provide a means of decoration and a warm soft touch to surfaces that are necessary features for human well being and comfort, but textiles are also essential components of the more functional parts of all road vehicles, trains, aircraft and sea vessels.

Textiles in transportation are classed as technical because of the very high performance specifications and special properties required. Seat coverings, for example, are not easily removable for cleaning and indeed in automobiles they are fixed in place and must last the lifetime of the car without ever being put in a washing machine. In trains, aircraft and passenger vessels they are exposed to much more rigorous use than domestic furniture. In addition they have to withstand much higher exposure to daylight and damaging ultraviolet radiation (UV) and because they are for public use they must satisfy stringent safety requirements such as flame retardancy.

In more functional applications, textiles are used in articles as diverse as tyres, heater hoses, battery separators, brake and clutch linings, air filters, parts of the suspension, gears, drive belts, gaskets and crash helmets. They are present in all forms of transport and, apart from tyres, are in applications of which the non-technical person is not even aware. Fibre/plastic composites are replacing metallic components and more traditional materials with considerable benefits, especially savings in weight. The most significant growth area in transportation textiles is expected in composites that straddle the textile and plastics industries. Volumes of the more traditional applications of textiles such as clothing and furnishing are not expected to grow substantially in the developed countries of Western Europe, North America and Japan. The largest growth will be in technical applications and a 40% increase on 1996 figures is expected by the year 2000 for fibre composites.

The most familiar technical textile in transportation is car seat fabric which is amongst the largest in volume and is growing annually in the developing world of the Pacific rim, Eastern Europe and South America (see Table 18.1). Car seat fabric

Table 18.1 World car sales ($\times 10^3$ units)

	1996	1997	1998	1999	2000	2001
Western Europe	12829	13030	13366	13698	14087	14134
Germany	3497	3522	3583	3779	3954	3846
Italy	1744	1899	1917	1854	1950	2089
France	2132	1889	2064	2202	2243	2218
UK	2025	2117	2054	1973	1960	2013
Spain	914	1000	1023	1055	1111	1128
East Europe	1637	1695	1861	1964	2132	2277
North America	9366	9320	8853	8637	9383	9813
USA	8527	8339	7826	7563	8210	8652
Canada	661	715	700	694	738	758
Mexico	179	266	327	380	434	403
Latin America	1761	1874	1825	1811	1830	1918
Japan	4643	4471	4842	4879	4932	4988
Asia Pacific	2912	3149	3562	3947	4287	4518
TOTAL	37566	38061	39311	40023	42055	43715

Source: J D Power-LMC Automotive Services/Automotive International March, 1997.

requires considerable technical input to produce both the aesthetic and also the very demanding durability requirements. The processes developed for car seat fabric and the technical specifications provide some indication of the requirements for seat materials in other transport applications.

In all transportation applications certain important factors recur, like comfort, safety and weight saving. In public transportation situations as far as textiles are concerned safety means reduced flammability. Environmental factors have also become important and these have influenced the transportation textile industry in a number of ways including design, choice of materials and manufacturing methods. Conservation of world resources by using less fuel, not to mention reduced atmospheric pollution by reduced exhaust emissions, is now a concern for world governments.

Reduced flammability properties are understandable considering the restrictions on escape routes especially in the air and at sea. Flame-retardancy (FR) requirements of private cars are not especially high but are stringent for passenger trains and standards are increasing for passenger coaches. Transportation disasters which become headline news are frequently the impetus for increased FR standards and improvements in public safety, for example, the Salt Lake City air disaster of 1965, the Manchester Airport fire of 1985 and more recently the Channel Tunnel fire.

The whole area of transportation is growing with increasing trade between all the nations of the world generating higher volumes both in freight and also commercial passenger travel. Leisure travel is also increasing dramatically with larger disposable incomes, increased leisure time and increased interest in foreign cultures; the largest growths are expected in air travel.

The stresses of modern living require transportation interiors to be more pleasing and mentally relaxing, to ease travelling and to make journeys more enjoyable. Indeed the various forms of transport now compete with each other for passengers.

For many national internal journeys the travelling times and costs of, say, air and rail are very similar from city centre to city centre.

A further recurring requirement of textiles involving passenger transport is cleanability. The only opportunity for servicing is at the end of a journey and just before the start of the next one. Expensive items of equipment such as jumbo jets must earn their keep by being on the move as much as possible and indeed jumbo jets are in the air 22 hours a day. Being out of service for lengthy overhauls or cleaning is money wasted and so cleaning must be done as quickly as possible. Easy care and maintenance are very important requirements; dirty carpets or seats would deter passengers.

Technical textiles are important, especially for the developed countries of the world, because they generally rely less on labour costs and are more dependent on technical know-how. However, even with technical textiles the manufacturer is facing new challenges to reduce costs even further still. To a certain extent this is being achieved by rationalisation, consolidation of production, transfer of production to developing countries, company mergers and joint ventures; but at the end of the day, much depends on the innovative technologist to devise new and more effective materials and production methods at lower cost and with increased performance as well!

Technical textiles are relative newcomers to the textile industry, which is probably one of the world's oldest industries, but there are still opportunities to learn from more traditional methods and from 'synergies' with other industries; for example, the film industry developed a process for producing novel film properties on a piece of apparatus that is essentially a textile stenter.

Although textiles have been used in some car seats since the invention of the car, widespread use has only occurred since the mid-1970s. The technology and manufacturing methods are still on the 'learning curve' compared to other sectors of the textile industry. Fabric car seats could still benefit from certain developments and processes that have been available to the garment and finishing industry for many years, for example advanced finishing techniques providing softer handle and touch, antistatic finishes, antimicrobial finishes, encapsulated chemicals, specialist yarns and techniques for improved thermal comfort.

18.1.1 Fibre requirements

For seat coverings the main technical requirements are resistance to sunlight (both colour fading and fabric degradation by UV), abrasion resistance[1–5] and, for public transport vehicles, reduced flammability (see Table 18.2). Seats frequently get damp from contact with wet clothing and, in the case of seats in public transport, subject to abuse by vandals and other irresponsible individuals.[6] The fabrics need to be resistant to mildew, hard wearing and strong with high tear strength. Soil resistance and easy cleanability are also necessary. Other requirements will become evident later in the chapter.

18.1.1.1 Resistance to sunlight and UV degradation

Resistance to sunlight is perhaps the most important property a fabric must have. Choice of the wrong fabric can lead to breakdown of the seat cover within weeks, depending on the intensity and spectral distribution of the sunlight. Spectral distribution of sunlight varies with geographical location, cloud cover and even the

Table 18.2 Properties of fibres used in transportation[a]

	Density ($g\,cm^{-3}$)	Melting point[b] (°C)	Tenacity ($g\,den^{-1}$)	Stiffness (flexural rigidity) ($g\,den^{-1}$)	LO1 (% oxygen)	Abrasion resistance	Resistance to sunlight
Acrylic	1.12–1.19	150d[b]	2.0–5.0	5.0–8.0	18	Moderate	Excellent
Modacrylic	1.37	150d[b]	(HT)	3.8	27	Moderate	Excellent
Nylon 6	1.13	215	2.0–3.5 4.3–8.8	17–48	20	Very good	Poor–good (stabilised)
Nylon 6.6	1.14	260	(HT)	5.0–57	20	Very good	Poor–good (stabilised)
Polyester	1.40	260	4.3–8.8 (HT)	10–30	21	Very good	Good–excellent (stabilised)
Polypropylene	0.90	165	4.2–7.5 (HT) 4.0–8.5 (HT)	20–30	18	Good	Poor–good (stabilised)
Wool	1.15–1.30	132d[b]	1.0–1.7	4.5	25–30 (Zirpro)	Moderate	Moderate
Cotton	1.51	150d[b]	3.2	60–70	18	Moderate	Moderate
UHM							
Polyethylene	0.97	144	30	1400–2000	19		
Aramid	1.38–1.45	427–482d[b]	5.3–22	500–1000	29–33		
Carbon	1.79–1.86	3500d[b]	9.8–19.1+	350–1500	64+		
Glass	2.5–2.7	700	6.3–11.7	310–380	–		
PBI	1.30	450d[b]	–	9–12	41		
Inidex	1.50	–	1.2	–	40		
Panox	1.40	200–900d[b]	–	–	55		
Steel	7.90	1500	2.5–3.2	167–213	–	–	–
Aluminium	2.70	660	–	–	–	–	–

LOI, limiting oxygen index; HT, high tenacity; UHM, ultra high modulus; PBI, polybenzimidazole.
[a] Data compiled from several sources and intended only as a guide.
[b] d, does not melt but starts to degrade.

time of day. Because glass windows are being placed more at an angle, the temperature within a vehicle can exceed 100 °C and during the course of a day relative humidity can vary from 0–100%. These factors, combined with sunlight, contribute to breakdown of seat fabric. Glass filters out a section of the sunlight spectrum including part of the UV area, which is most damaging to most fibres and in particular polyester. Hence polyester exposed behind glass exhibits much better performance compared to polyester exposed directly to sunlight. This factor is a major reason why polyester has emerged as the most used fibre for car upholstery (see Table 18.3).

Actual degradation by UV radiation is influenced by the thickness of the yarn, the thicker the better because less radiation will penetrate into the centre. This is particularly the case for nylon yarns. Matt or delustred yarn often breaks down the fastest because the titanium dioxide delustrant may photosensitise degradation and the lower specific surface area reduces the rate of photo-oxidative attack. UV degradation will therefore also be influenced by cross-section, the poorest again being those presenting the greater surface area for a given linear density.

Table 18.3 Light durability (in Florida) of some natural and synthetic fibres exposed simultaneously (months required to reach loss in strength indicated)

	Initial tenacity (g denier^{-1})	Outdoors (direct sunlight)		Behind glass	
		50% Loss	80% Loss	50% Loss	80% Loss
Acrylic semidull	2.1	13.6	36 (72%)[a]	19	36 (63%)[a]
Polyester bright	4.2	3.7	7.9	24	36 (75%)[a]
Polyester semidull	3.1 (spun)	4.0	9.1	36	36 (49%)[a]
Polyester dull	4.2	3.6	8.0	20	36 (79%)[a]
Nylon bright	5.3	9.5	17.0	10.3	20.7
Nylon semidull	5.4	3.2	6.5	4.5	8.2
Nylon dull	5.1	3.1	5.1	4.1	7.7
Rayon bright	1.6	2.6	6.3	3.0	14.2
Acetate bright	1.0	5.1	11.8	8.1	27
Cotton deltapine	1.8	2.9	5.8	4.9	14.0
Flax Irish	3.5	0.9	2.5	4.5	5.0
Wool worsted	0.7	2.3	3.2	4.5	7.6
Silk	4.2	–	–	0.8	3.9

[a] Loss per cent indicated after 36 months.
Source: B F Faris (DuPont), in *Automotive Textiles*, ed. M Ravnitzky, SAE PT-51 1995, p. 23. Copyright held by Society of Automotive Engineers, Inc. Warrendale PA. Reprinted with permission.

Significant improvements in UV resistance can be obtained by addition of certain chemicals that are UV absorbers[7,8] and these are used extensively with polyester, nylon and polypropylene for transportation applications. UV absorbers in nylon are usually added to delustred yarns which deactivate the sensitising effects of the titanium dioxide present.

18.1.1.2 Abrasion resistance

Seating fabric needs to be of the highest standard of abrasion resistance. Only polyester, nylon and polypropylene are generally acceptable, although wool is used in some more expensive vehicles because of its aesthetics and comfort. Wool has other specialist properties such as non-melting and reduced flammability which, as will be seen, make it suitable for aircraft seats. Fabric abrasion is influenced by yarn thickness, texture, cross-section and whether spun or continuous filament. Those factors that result in larger surface area or provide points of frictional stress reduce abrasion resistance. Fabric construction and weight have an effect on abrasion, not to mention fabric finishes and processing variables. Reproducing damage by accelerated testing is well known to cause problems. The simulation of UV degradation,[9–12] abrasion damage and the associated problem of pilling that occurs in actual use with accelerated laboratory tests is therefore not straightforward and has been the subject of much research.[13–15] All fabric property requirements are demanding and need to be of general 'contract' standard[16] or higher.

18.1.1.3 Reduced flammability

Reduced flammability testing[17–20] has become much more sophisticated as the mechanisms of fire disasters and the causes of fatalities are analysed. Thus it is now important to test for toxicity of smoke generated (see Tables 18.4–18.6) and its effect on

Table 18.4 Composition of off-gases of Kevlar and other fibres under poor combustion conditions[a]

	Combustion products of sample (mg g^{-1})									
	CO_2	CO	C_2H_4	C_2H_2	CH_4	N_2O	HCN	NH_3	HCl	SO_2
Kevlar	1850	50	–	1	–	10	14	0.5	–	–
Acrylic	1300	170	5	2	17	45	40	3	–	–
Acrylic/modacrylic (70/30)	1100	110	10	1	18	17	50	5	20	–
6.6 Nylon	1200	250	50	5	25	20	30	–	–	–
Wool	1100	120	7	1	10	30	17	–	–	3
Polyester	1000	300	6	5	10	–	–	–	–	–

[a] The sample is placed in a quartz tube through which air is drawn at a controlled flow and heated externally with a hand-held gas–oxygen torch. Air flow and heating are varied to give a condition of poor combustion (i.e. deficiency of oxygen). Combustion products are collected in an evacuated tube and analysed by infrared.
Source: KEVLAR Technical Guide (H-46267) 12/92 Table II-8 (DuPont), December 1992.

Table 18.5 Combustion products and their physiological effects

Product	Sources	Physiological effects		
Oxygen depletion	All fires	21%	=	Normal concentration
		12–15%	=	Headache, dizziness, fatigue, loss of coordination
		<6%	=	Death in 6–8 min
Carbon monoxide	All fires (incomplete combustion)	1000 ppm	=	Death after 2 hours
		5000 ppm	=	Death within 5 min
Carbon dioxide	All fires	250 ppm	=	Normal concentration
		5%	=	Headache, dizziness, nausea, sweating
		12%	=	Death within 5 min
Hydrogen cyanide	Nitrogen-containing polymers (nylon, wool, modacrylics etc.)	50 ppm	=	Death in up to 1 hour
		180 ppm	=	Death after 10 min
Hydrogen chloride	PVC, PVDC fibres, neoprene coatings	10 ppm	=	Irritation
		100 ppm	=	Death within 5 min
Oxyfluoro compounds	PTFE membranes	50 ppm	=	Irritation
		100 ppm	=	Death within 1 hour
Acrolein	Polyolefins, Cellulosics (cotton)	1 ppm	=	Severe irritation
		150 ppm	=	Death in 10 min
Antimony compounds	Some modacrylics some rubber coatings, tentage	>0.5 mg m^{-2}	=	Pulmonary and gastrointestinal problems

PVC = polyvinyl chloride, PVDC = polyvinylidene chloride, PTFE = polytetrafluoroethylene.
Source: see footnote to Table 18.6.

Table 18.6 Heat release rate (HRR), total heat release rate (THRR) and time to peak of heat release (T_p) for a variety of fabrics

Fabric	HRR ($kW m^{-2}$)	THRR ($kW min m^{-2}$)	T_p (s)
Cotton/polyester	170	53	33
Wool	117	39	24
Modacrylic	83	28	27
Zirpro wool	64	24	25
Panox	27	15	30
Meta-aramid	13	6	40

Source: M Masri, 'Survival under extreme conditions', in *Technical Textiles Int.*, 1992 June.

visibility as well as for ignitability and rate of propagation. Heat generated has also been identified as important and tests have been developed to measure this. Testing of whole assemblies such as seats is now carried out in addition to testing of the individual components.

For comfort, foam materials are used beneath the covering fabric. Despite much development, which has significantly reduced the foam flammability,[21,22] 'fireblocker' materials have been introduced between the face fabric and the foam. Fireblockers, first used on aircraft seats, are textile fabrics made from fibres with a very high level of inherent flame retardancy and heat stability,[23,24] for example Panox (Lantor Universal Carbon Fibres), Inidex (Courtaulds) and aramid. They are being used increasingly on trains, buses and coaches.

18.1.2 Fibre/plastic composites

Composites can be regarded as a macroscopic combination of two or more materials to produce special properties that are not present in the separate components. How composites function can be explained by the analogy of the use of straw in clay bricks by the ancient Egyptians. A strong brick was obtained because the straw reduced and controlled the occurrence of cracks in the hard but brittle clay. Glass fibres have a very high tensile strength but are brittle because of their extreme sensitivity to cracks and surface defects. When incorporated in a plastic matrix, the tensile properties of the fibres define that of the composite to which the plastic is added. The plastic protects their surface thus preventing crack developments; this results in a strong composite material.[25]

Glass reinforced plastics (GRP) date from the 1920s and combine high strength and stiffness with light weight. From the early 1960s more advanced fibres became available (e.g. carbon, aramid, boron and ceramic fibres), which are all very strong and many times stiffer than glass. Carbon fibre properties vary enormously depending on the conditions of manufacture. Nomex and Kevlar (DuPont), the first aramid fibres,[26] offer high thermal stability and very high strength at relatively low weight. Their density is about $1.45 g cm^{-3}$ compared to about $2.5 g cm^{-3}$ for glass and $7.9 g cm^{-3}$ for steel.

18.1.2.1 Advantage of composites

Composites have made very significant advances because of their high strength and stiffness combined with low weight and, in many cases, less bulk. These properties are especially suited to transport applications offering fuel savings and more useful space within the aircraft, vessel or vehicle. A man-powered aircraft, 'Gossamer Albatross' weighing 32 kg, flew across the English Channel.[27] This would have been impossible without Kevlar as a structural reinforcement. In many cases several metal parts joined together can be replaced by a single composite component.[28] Life-cycle analyses on composites show that, although they can be more expensive to produce, they are generally more environmentally friendly because they consume less fuel during their lifetime compared to the heavier metallic items they replace. Yet composite technology is still in its infancy compared to the use of metals, which has centuries of accumulated know-how. More significant innovations can be expected, however; carbon fibres are already used extensively in aircraft, trains, some buses and racing cars. The use of carbon fibre is predicted eventually in volume passenger cars. Carbon fibre growth is estimated to be at about 10% annually to the year 2001, although not all of it will be in transportation.[29]

More advanced fabric structures are being developed (e.g. three-dimensional knitting and weaving, multiaxial knitting, cartesian braiding, 'noobing' and so on). These are extending the scope of composites for all industrial applications, including transportation.[30–32] A UK Civil Aviation Authority project is developing composite material involving 20 layers of fabric capable of containing terrorist bomb explosions on board aircraft.

18.1.2.2 Tyres

The tyre, a rubber/textile composite (approximately 10% w/w of textile) dates from 1888 when canvas was the reinforcement used in Dunlop's first tyre. Continuous filament rayon began to be used in the 1930s. Research subsequently led to high tenacity variants and much needed improvements in fibre/rubber adhesion. Nylon, offering toughness at a lighter weight, was introduced into aircraft tyres during World War II. Once again, fibre/rubber adhesion limitations needed to be overcome and nylon 6 was claimed to have better adhesion than nylon 6.6. 'Flat spotting', probably caused by low nylon elasticity when hot, restricted the growth of nylon in tyres for cars but nylon tyres were used extensively on trucks and farm vehicles where heat generation during use is less of a problem. Use of rayon declined from the mid-1950s owing to competition from polyester, which like its predecessors required improvement in its adhesion to rubber[33] and from steel cords, which were cheaper to produce. Tyre cord development continues with new yarn variants, for example high modulus low shrink 'DSP'™ (dimensionally stable polyester) (Allied Signal) and novel means of improving fibre adhesion to rubber.[34] Aramids, offering high strength to weight ratios and high temperature resistance, find use in high performance car and aircraft tyres.

18.2 Textiles in passenger cars

Car interiors have become increasingly important for a variety of reasons. People spend more time in cars generally with increased daily commuter distances to and from work, increased traffic density and because more people are working away from home and travelling long distances by car at weekends. The car has become a place of work for sales representatives, sales engineers and businessmen who are now also able to communicate with the office and customers by mobile telephone. The general public has more leisure time and larger disposable incomes and so travel more on days out, on holidays, and make more journeys to the supermarket and out of town shopping centres. The car has become not just an office and a living room on wheels but also a 'shopping bag' on wheels.

This increased time spent inside the confined space of a car, plus the stresses of modern living, not to mention the frustrations of gridlocks and roadworks, has produced a need for more pleasant, comfortable and relaxing interiors. Comfort in all its forms reduces stress and fatigue and, therefore, contributes to road safety. The buying public has become more discerning and demands more value for money and this is coupled with more choice from an increasing number of competing vehicle manufacturers. The increasing numbers of female car buyers means that they have more influence in the area of family car purchase than before.

With the importance of fuel economy all cars must be aerodynamic and because exterior shapes of models from different manufacturers can look generally similar, greater emphasis must be put upon interiors to compete effectively. From the manufacturers' point of view, changing the car interior via a 'facelift', is an economical way of revamping and relaunching a model that is not selling well quickly or prolonging the life of a model (see Fig. 18.1).

18.2.1 Interior design

The colour, texture and overall appearance of the car interior, especially the seat, has become extremely important in attracting a potential buyer's attention. There is only one opportunity to make a first impression. The textile designer must be able

18.1 Computer-assisted design plays an important role in modern automobile seat cover design.

to produce innovative interior appearances which reflect or even set current fashion trends, social and economic moods and customer lifestyles,[35] whilst at the same time being compatible with the exterior colour and car shape. The design must be aimed at the market sector at which the particular model is aimed and also be in the particular car company's chosen overall style.

New designs originate from the fabric producers who submit several ideas for each car model to the vehicle producer. These are developed and fine tuned until eventually a single selection is decided upon. European designers are considered world leaders. Lead times for new car models are currently about two years, so the designer must be able to forecast future trends. The logistics of availability of materials, attainable colours and fabric performance limitations also have to be considered carefully.

Modern designers have access to computers that allow designs to be created and viewed in three-dimensional simulation on actual car seats within a car without any actual fabric being made. Colours and other variants can be varied at the touch of a keyboard and usually national preferences exist for interior colours and texture. Flat woven fabrics account for about half of car seat fabric in Europe but only about a quarter in the USA and Japan. Woven velours are the most important type in the USA, and tricot knit the most important in Japan.

Circular knits are increasing in Europe, and woven velours increasing further in the USA. Worldwide, designs are becoming more sophisticated with increased use of more colours and Jacquard-type designs.[36] In Japan printing on to tricot knit has been attributed to a need for a more economical alternative to Jacquard equipment, which is in short supply in Japan. Printers in the USA and Europe are developing the technology, but some manufacturers hold the view that printing may not be necessary because adequate Jacquard equipment is readily available in these areas. Car models increasingly must have global appeal which cuts across national boundaries and is suited to different cultures on different continents. Lead times are also shortening in an increasingly competitive marketplace.

18.2.2 General requirements

Interior textiles must generally last the life of the vehicle and show no significant signs of wear for at least 2–3 years to maintain a good resale value of the car. If the seats look worn, buyers will assume the engine is worn. Car interiors are subjected to the full range of temperatures (–20 to 100+ °C) and relative humidities (0–100%). In addition, the car seat occupants' clothes may be wet and rough in texture and so the seat fabric must always appear uncreased and without noticeable colour fading or soiling.

18.2.2.1 Fibre selection

The two most important factors governing the selection of fabrics for car seat covers are resistance to light (UV radiation) and abrasion. Several fibres were initially used as replacements for the widely used PVC (polyvinyl chloride) in the late 1960s and early 1970s, namely nylon 6 and nylon 6.6, acrylic, wool and polyester. Nylon, especially nylon 6, suffers rapid sunlight degradation, which has made car seat makers still cautious about its use. Abrasion of acrylic is limited and wool is relatively expensive. These factors have resulted in polyester emerging as the predominant fibre now accounting for about 90% of all textile seat covers worldwide.

Manufacturers of polypropylene strive to have their fibre more widely accepted as seat material[37] but disadvantages like low melting point, low yarn extensibility, and limitations in colour spun dyeable at present outweigh the advantages, which are significantly lower density 0.90 $g\,cm^{-3}$ compared with 1.38 $g\,cm^{-3}$ for polyester, cheaper cost, and easier recyclability. Polypropylene is, however, used in nonwovens in headliners, floor coverings and parcel shelves. Addition of light stabilisers has improved the stability of polypropylene fibre to light and thermal degradation.[8]

18.2.2.2 Yarn types

Fabrics are generally produced from bulked continuous filament (BCF) textured polyester yarns; false twist, knit de knit and air texturising are common, although the latter method is the most used. Courtaulds Textiles Automotive Products[38] were the first company in Europe to use 100% air textured for car seats in the late 1970s. Staple spun yarns are less common because of their limited abrasion resistance in flat woven constructions. They are used, however, in woven velvets where the abrasion or wear is on the tips of the yarn rather than across its width.

The multinational fibre producers such as Hoechst, DuPont and Rhone Poulenc supply flat continuous filament yarns, and sometimes partially orientated yarn to yarn (POY) texturisers, for example Neckelmann, Autofil. These 'feedstock' yarns are doubled, tripled or even quadrupled during the texturising process. Special effects can be produced by mixing the yarns or by applying significant overfeed of one component to produce core and effect yarns. Here the overfeed yarn (the 'effect' yarn) may hang loosely around the core yarn. In flat woven fabrics, these yarns produce a certain amount of surface texture and give a more pleasant touch.

Typical yarns for weaving are 167 dtex/48 filaments primary feedstock yarn which when quadrupled produces 668 dtex/192 filaments and 835 dtex/240 filaments yarn made from five ends of a primary yarn. Heavy duty yarns over 3000 dtex with 550 filaments are used for heavy goods vehicles (HGVs) or for special effects. Knitting yarns are lighter up to say 300 dtex.

18.2.2.3 Fabric structure

The main fabric types with typical weight ranges are: flat woven fabric (200–400 $g\,m^{-2}$), flat woven velvet (360–450 $g\,m^{-2}$), warp knit tricot (generally pile surface, 160–340 $g\,m^{-2}$), raschel double needle bar knitted (pile surface, 280–370 $g\,m^{-2}$) and circular knits (generally pile surface, 160–230 $g\,m^{-2}$). Fabrics in nylon tend to be towards the lower weight range. Woven fabrics have been produced for many years using mechanical Jacquard systems and while they once offered the greatest design potential, knits have now caught up with them with the introduction of computer-controlled knitting machines. The growth of automotive fabrics, especially knitted, has been the subject of several papers.[39–48]

Woven fabrics have limited stretch, which sometimes restricts their use in deep drawer moulding applications for door casings. Some polybutylterephthalate (PBT) yarns, which have increased stretch, are being used in certain instances, but they are significantly more expensive than regular polyester even though they are more easily dyeable. However, woven fabrics, even with PBT yarns, cannot compare with the stretch capabilities of knitted fabrics.

Flat woven velvet fabrics are the most expensive to produce but are considered top of the range in quality. Knitted fabrics with raised surfaces are more softer to the touch than flat wovens. Modern weft knitting machines equipped with advanced electronics that allow intricate design patterns offer considerable potential. These utilise yarn packages, compared with warp beams where yarn preparation is necessary in both weaving and warp knitting. Thus machine setup is much quicker and production volumes are much more flexible. Both of these factors are ideally suited to the shorter lead times and sometimes unpredictable production programmes required by car companies.

18.2.3 Composition of car seat covers

Whatever the construction of the fabric, it is usually made into a trilaminate consisting of face fabric and polyurethane foam with a scrim lining on the back.[49] The foam backing ensures that the fabric never creases or bags during the life of the car. It also produces attractive deep contoured sew lines in the seat cover, imparts a soft touch to the seat surface and contributes to seat comfort. The polyurethane foam density is usually between 26–45 $kg\,m^{-3}$, anything from 2–20 mm thick and can be either polyester polyurethane or polyether polyurethane, the latter being more hydrolysis resistant and is necessary for humid climates. Foam can be either standard or flame retardant, the test method being FMVSS302, although car companies each have their own performance specifications.

The scrim fabric lining is usually warp knitted nylon or polyester 30–90 $g\,m^{-2}$ in weight. This fabric acts as a 'slide aid' when the seat cover is sewn and when it is pulled over the foam seat body. It also contributes to seam strength, helps prevent strike through of liquid foam in 'pour in' techniques and can, by choice of construction, assist laminate dimensional stability by controlling excessive stretch. Nonwovens are sometimes used when only a slide aid property is required. Exact specification of cover components depends on where in the car the laminate will be used, that is, seat centre panel, bolster or back. Matching door panels are frequently made from the same material as the seats.

18.2.4 Manufacturing processes

18.2.4.1 Dyeing and finishing

Polyester yarn is package dyed usually with a UV light absorbing agent such as Fadex F (Clariant). This improves the lightfastness of disperse dyes and also contributes to yarn UV degradation resistance. Similar products are available for polyamide yarn, which is dyed mainly with 1:2 premetallised dyes. Higher lightfastness of certain shades is possible compared to aqueous dyeing by melt (also referred to as dope, solution or spun) dyeing during yarn manufacture. The drawback here is that it is not economical to produce small amounts of yarn in this way, which is a serious restriction in a commercial world where flexibility is an important advantage. Dyeing and finishing procedures have been published.[50–53] Flocked yarns and space dyed yarns are also used.

Processing routes for the production of woven and knitted fabric can be summarised as follows:

- Yarn, texturise, package dye, warp/beam, **weave**, scour, stenter/finish, laminate, cut/sew, fit to seat;

- yarn, texturise, warp/beam, **warp/knit**, brush/crop, stenter preset, scour/dye, stenter, brush, stenter finish, laminate, cut/sew, fit to seat;
- yarn, texturise, package dye, cone, **weft knit**, shear, scour, stenter/finish, laminate, cut/sew, fit to seat;
- yarn, texturise, package dye, cone, **three-dimensional knit**, heat stabilise, fit so seat.

When spun dyed yarns are used, the dyeing stage is, of course, omitted. The sequence of brushing, stentering and dyeing can be varied according to the particular warp-knit product. Piece dyeing has the advantage of colour flexibility because the fabric can be dyed to the required colour at the last minute. Some woven fabrics are coated with acrylic or polyurethane resin to confer reduced flammability properties and to improve abrasion. Woven velvets, however, must be coated to improve pile pull-out properties. Compared to the apparel and domestic furnishings industry, relatively few finishes are used on automotive fabrics. Antistatic and antisoil finish are applied either by padding or by foam processing on to the face of the fabric. Any finish must be carefully tested not only for effectiveness but also for any harmful side effects such as catalytic fading or discolouration of the dye, fogging, unpleasant odours or waxy or white deposits developing on the car seat during use. Some finishes, especially silicone-based ones, have a harmful effect on adhesion during lamination and should be avoided. The fabric must be stentered to provide a stable, flat, tension free substrate for lamination and eventual seat fabrication.

18.2.4.2 Printing

This is a relatively new development in Europe and the USA for automotive fabrics, although it has been carried out in Japan since the late 1980s.[54–56] The initial problems of dye penetration and sublimation of UV absorbers during the printing process are now being overcome. Printing offers a means of producing almost unlimited design options on both wovens and warp knits and quicker setup than either piece dyeing or the yarn dyed route. The constraints of weaving or knitting are absent and the design decision can be made closer to the launch date of the car, thus enabling the design to be right up-to-date. Another significant advantage is the cost saving gained by not having to put a new printed fabric through the full testing and acceptance procedure if a different print is put on to an existing and already approved base fabric.

18.2.4.3 Lamination

Most automotive fabric worldwide is flame laminated to foam. This is a quick economical process whereby all three components are fed into the laminator and the triple laminate emerges at speeds up to and exceeding 25–40 m min^{-1}. The process depends on a gas flame licking moving foam to melt the surface of the foam, which acts as the adhesive. The flame lamination process, which produces potentially toxic emissions, has come under environmental scrutiny[57,58] and alternative methods of lamination have been developed using hot melt adhesives.[59–62] However, very few major laminations of automotive fabric have changed to the hot melt route, but some have installed improved methods of controlling emissions, such as carbon filter absorption.

Also on environmental grounds, alternatives to polyurethane foam have been sought. The triple laminate comprising polyester face fabric, polyurethane foam and nylon or polyester scrim is made from two or three dissimilar materials which are joined together and cannot be easily separated for recycling. Polyester nonwovens have been evaluated as alternatives to the foam,[63–64] as have three-dimensional knitted structures such as spacer fabric (Karl Mayer) and fleece materials such as 'Kunit' and 'Multiknit'.[65,66] All, however, lose thickness during use, especially at the higher temperatures that sometimes prevail inside the car. Nevertheless some car companies have replaced the laminate foam with wool or wool/polyester non-woven material.

Some nonwoven fabrics made from recycled polyester have been used.[67–72] Attempts are being made to replace the foam in the seat squab (back) and cushion (bottom) both with nonwoven material and also rubberised natural products such as coconut hair, horse hair and pigs' hair which are considered recyclable. 'BREATH AIR'™ (Toyobo), random continuous loops of a thermoplastic elastomer are claimed to offer improved thermal comfort and recylability, amongst other benefits.

18.2.4.4 Quality control and testing

Fabric laminate testing is carried out for two main reasons, first to determine suitability for further processing so the processes will be right first time every time and second, to simulate actual wear conditions during the life of the car. Accelerated ageing and wear tests are applied.

The actual tests and performance required depend where in the car the fabric laminate will be used, for example, seat centre panel, bolster, seat back, door casing, headliner, parcel shelf. Each car maker has its own test methods and performance specifications.

For seat make-up, panels must first be cut accurately and invariably several layers are cut together. It is important that the material lies flat and does not change its dimensions due to residual fabric shrinkage or tensions introduced during lamination. Fabrics dyed in different dyebaths or even different dye works may come together in the same car seat set and there must not be any noticeable differences in shade.

Lightfastness testing of textiles is not easy. The objective is to reproduce several years of simulated exposure in conditions of actual use within a short test period. This is especially difficult for automotive fabrics, where the damaging effect of sunlight inside a car means the combined effect of light and UV radiation, heat and varying relative humidity (and dampness). In addition, the test substrate itself, chemical finishes, processing conditions and possibly industrial and traffic fumes can all influence results. There are different types of test equipment, and although most car makers now use xenon arc, some Japanese require the carbon arc as a source. In Europe DIN 75202, the FAKRA method of continuous exposure is widely used. The American method of SAE J1885 includes an intermittent exposure, that is, a period with the light switched off. Performance requirements vary, but values around blue wool scale 6 is the required lightfastness rating necessary for seating fabric. Some US manufacturers were considering raising their present lightfastness standards substantially by the year 2000.

Abrasion is carried out using the Martindale, Taber or Schopper machines, again each car manufacturer specifying their own method and performance requirements. The related fabric wear phenomena of pilling and snagging are also assessed. Typical requirements are around 50000 Martindale rubs for seating fabric.

Other tests carried out on fabric laminates include the following:

- Peel bond adhesion (face fabric-to-foam and scrim-to-foam) including testing wet, after heat ageing tests and treatment with solvents and cleaning fluids
- Cleanability after soiling with items such as chocolate, hair lacquer, lipstick, coffee, ball point pen ink and engine oil. Some vehicle manufacturers also include tests for 'minking' (loose hair deposits on the seat from fur coats) and 'linting' (white fibrous deposits)
- Dye fastness to perspiration
- Dye fastness to crocking (both dry and wet)
- Dimensional stability
- Flammability
- Tear/tensile strength
- Sewing seam strength
- Bursting strength
- Stretch and set
- Fogging (see below).

Although vehicle manufacturers detail their own preferred test method, many are based on national and international specifications. Table 18.7 lists many of these tests. Details of actual test methods are generally confidential between customer and supplier and performance specifications are stringent, and typically of 'contract' standard.[16]

'Fogging' is a mist-like deposit on car windscreens which reduces visibility.[73–79] It is caused by volatile materials vaporising from interior trim components and probably is aggravated by other materials introduced from outside the car or even from other areas of the car, for example ducting in the ventilation system.

Attempts are being made by the car companies and their suppliers to harmonise test methods.[80] The Transportation Division of the Industrial Fabrics Association International in the USA is especially active in this exercise. A 'data bank' has been proposed by one of the American technical journals and contributors have been requested.[81] Thus testing could become simpler and require fewer items of expensive test equipment, thereby releasing time and effort that could be directed towards development of new products, increasing efficiency and reducing costs.

18.2.5 Other parts of the car interior

Headliners used to be simple items in warp-knitted nylon, or PVC, sometimes 'slung' that is, held in place only at certain points. Modern headliners are multilayer materials[82] that have become a structural part of the car roof supporting accessories, such as sun visors, interior lights, assist handles, electrical components and some even contain brake lights. They are engineered to give sound insulation and sound absorbing properties. The majority of headliner face fabrics in Japan and Europe are nonwovens, but in the USA most are still warp-knitted nylon or polyester.

Warp knits have better abrasion and pilling resistance and mould better because of their superior stretch properties. However, nonwovens have the advantage of non-recovery after moulding. Nonwoven headliners are typically made from fine denier polyester or polypropylene fibre for maximum cover at low weight, about 200 $g\,m^{-2}$, with an antiabrasion finish. Rotary screen-printed needle-punched polyester and malifleece headliners are used in some European cars.

Table 18.7 Summary of test methods applied to automotive seating fabrics

	British Standard test methods	Selected related test methods
Colour fastness	BS 1006: 1990 (1996) Methods for determining colour fastness to about 70 different agencies BS 1006 Grey scales for assessing changes in colour AO2 BS 1006 Grey scales for assessing staining A03 BA 1006 B01 Blue wool standards	ASTM methods ASTM evaluation procedures DIN 54022 (fastness to hot pressing) DIN 54020 (rub fastness)
Crocking (wet and dry)	BS 1006: 1990 (1996)	SAE J861 Jan 94 AATCC TM8 DIN 54021
Light fastness	BS 1006: 1990 (1996)	SAE J1885 Mar 92 Water cooled Xenon-arc SAE J2212 Nov 93 Air cooled Xenon-arc DIN 75202 FAKRA 7/91
Abrasion	BS 5690: 1991 (Martindale) NB: Sometimes tested after UV exposure	SAE J365 Aug 1994 Scuff resistance (Taber) ASTM 3884 (Taber) DIN 53 863 3/4 (Martindale) DIN 53 863/2 (Schopper) DIN 53528 (Frank Hauser, loss in mass for coated fabrics) DIN 53 754 (Taber)
Pilling	BS 5811: 1986 pill box	ASTM D3511-82 (Brush) ASTM D3512-82 (Tumble) DIN 53863/3 (Modified Martindale) DIN 53865 (Modified Martindale)
Snagging		SAE J748 ASTM D5362-93 (Bean bag) ASTM-D3939-93 (Mace Test)
Tear strength	BS 4303: 1968 (1995) Wing tear BS 3424 pt5: 1982 (for coated fabrics) BS 4443 pt6 Method 15 (for foam laminates)	ASTM D2261: 96 (Tongue tear) ASTM D1117-95 (Trapezoidal tear) DIN 1424-96 Elmdorf tear apparatus DIN 53 356 (Tear propagation)
Tensile strength/ breaking and elongation	BS 3424: 1982 Method 6 (coated fabric) BS 2576: 1986 (Woven fabric/ strip method) BS 4443 pt6 1980 Method 15 cellular foam (laminates)	ASTM D5034:95 (Grab method) ASTM D1682 (Grab method) DIN 53857 (Nonwovens) DIN 53571 (Tensile and elongation) ASTM D-751 (Test for coated fabrics)
Stretch and set	BS 3424 pt 21: 1987 (for coated fabrics) but BS 3424 pt 24 1973 (still in use)	SAE J855 Jan 94 DIN 53853 DIN 53857

Table 18.7 *Continued*

	British Standard test methods	Selected related test methods
Stretch and recovery	BS 4952: 1992 (for elastic fabrics–replaces BS 4294: 1968)	
Bursting strength	BS 4768: 1972 (1997) Bursting strength and distension	DIN 53861
Dimensional stability	BS 4736: 1996 (cold water)	SAE J883 Jan 94 Cold water SAE J315A DIN 53894
Stiffness	BS 3356: 1990 bending length and flexural rigidity	D1338-96
Drape	BS 5058 1973 (1997)	DIN 53350 (bendability)
Crease recovery	BS EN 22313: 1992	
Steam strength		ASTM D1683 for woven fabrics SAE J1531
Peel bond	BS 3424 Pt 7 1982 Method 9 (coating adhesion)	ASTM D-751 ASTM D-903 DIN 53357
Compression (For foam/ laminates)	BS 4443 Pt 1 Method 5A stress strain characteristics BS 4443 Pt 1 Method 6A compression set	ASTM D2406-73 Method B DIN 53 572 Compression set DIN 53 577 Stress strain characteristics
Air permeability	BS 5636: 1978 for fabrics now BS EN ISO 9237: 1995 BS 4443 Pt 6 1980 Method 16 (For foam laminates) BS 6538 Pt 3 1987 (Gurley method)	ASTM D737 DIN 53 887
Surface resistivity (antistatic)	BS 6524: 1984 (Surface resistivity)	DIN 53282 (Surface resistivity) ASTM F365-73 Charge decay Federal Method 101C – 4046 (Charge decay) BTTG Body voltage chair test
Cleanability		AATCC Method 118 – 1983
Stain repellency	BS 4948: 1994 Soiling by body contact	
Fogging		SAE J1756: 1994 ASTM D5393 DIN 75201
Flammability resistance		FMVSS302 DIN 75200 SAE J369 ASTM D2859-70
Water wicking		SAE J913

Table 18.7 *Continued*

	British Standard test methods	Selected related test methods
Accelerated ageing methods	BS 3424: 1996 Pt 12 for coated fabrics BS 4443 Pt 4 Method 11 for cellular materials (foam) humidity and elevated temperatures BS 4443 Pt 6 Method 12 (heat ageing)	ASTM D2406-73 DIN 53 378 'Environmental cycles' of individual manufacturers as pretreatments for further testing, e.g. peel bond, dimensional stability and effect on appearance. Sometimes includes cooling to as low as –40 °C and heating to as high as 120 °C
Resistance to microorganisms		AATCC Method 30 resistance to mildew and rot AATCC Method 100 resistance to bacteria AATCC Method 174 bacteria resistance for carpets Federal test method standard 191 Method 5750 mildew resistance, mixed culture method

Parcel trays, being just beneath the slanting rear window, demand the highest resistance to sunlight, for example 450 kJ compared to 150 kJ for a headliner. They are made by a press lamination technique or by direct pouring of the polymer on to the back of a polyester or polypropylene nonwoven. Many of the decorative interior nonwovens are needle punched in the usual manner, but increasing numbers are formed using the Dilour technique to produce a velour-type material with deep draw mouldability.

18.2.5.1 Nonwoven applications

Nonwovens are used under the bonnet to reinforce acoustic insulation material. A novel material, Colback (Akzo), made from a bicomponent yarn/nylon 6 sheath over a polyester core/provides very high strength with light weight.

With increasing awareness of air quality within cars, air filters are being installed as standard equipment. Nonwovens with an effective surface area of about 0.3 m^2 are required to filter out solid particles with diameters as small as 3 μm. Development is being carried out to improve performance and up to 0.5 m^2 of nonwoven material may be required with activated carbon and antibacterial chemicals to remove malodours.[83,84]

Textile battery separators experienced substantial growth in the late 1970s to early 1980s when woven and nonwoven polyesters, impregnated with specially selected acrylic resins, replaced many of the PVC type. Batteries are used in all transportation vehicles, especially in electric powered vehicles such as golf carts, road sweepers, milk floats and forklift trucks and represent an increasing market.

Needlefelt nonwoven carpets are increasingly popular in Europe especially those comprising polypropylene, which offers savings both in weight and cost and is claimed to be better for recycling. More expensive cars generally use tufted carpets in nylon, however recyclability of automobile carpets is becoming an important issue and both nonwoven polypropylene and tufted nylon carpets are ideal in principle. In practice, the presence of dirt (up to 1 kg m^{-2}) is a major problem.

18.2.5.2 Flocked fibre

Surfaces such as window seals and dashboard components have textile flocked surfaces. The flock is usually polyester or nylon 6.6, but viscose and acrylic fibre are also used. Flock is useful in eliminating rattles and squeaks in the car as well as contributing to the overall aesthetics.[85,86] Flocked yarns are sometimes used for seating and door panel fabric. Novartis (Rhone Poulenc) are targeting automotives with their improved flock technology and they claim enhanced seat thermal comfort together with a velour-type appearance at an economical price.

18.2.5.3 Seat belts

Seat belts are multiple layer woven narrow fabrics in twill or satin construction from high tenacity polyester yarns, typically 320 ends of 1100 dtex or 260 ends of 1670 dtex yarn. These constructions allow maximum yarn packing within a given area for maximum strength and the trend is to use coarser yarns for better abrasion resistance. For comfort they need to be softer and more flexible along the length, but rigidity is required across the width to enable them to slide easily between buckles and to retract smoothly into housings. Edges need to be scuff resistant but not unpleasantly hard and the fabric must be resistant to microorganisms. Nylon was used in some early seat belts but because of its better UV degradation resistance, polyester is now used almost exclusively worldwide.

Melt-dyed yarns are used, but other colours are obtainable by pad thermosol dyeing with dyes selected for the highest resistance to light and UV degradation and excellent wet rub and perspiration fastness. Fabric is about 50 g/linear metre (about 5 cm wide) loomstate but about 60 g/linear metre after finishing. This is because shrinkage is induced in the finishing process to improve the energy absorption properties. Controlled, limited non-recoverable (i.e. not elastic) stretch reduces deceleration forces on the body in a collision.[87,88]

Performance standards (e.g. BS 3254) typically require a belt to restrain a passenger weighing 90 kg involved in a collision at 50 km h^{-1} (about 30 mph) into a fixed object. Straight pull tensile strength should be at least 30 kN/50 mm. Other tests include accelerated ageing and, in the made up form, resistance to fastening and unfastening 10 000 times. The seat belt must last the lifetime of the car without significant deterioration.

Studies in the 1970s concluded that seat belts could reduce fatal and serious injuries by 50%, consequently front seat belts became compulsory in the UK in January 1983 and are now compulsory in many countries of the world. Many US drivers, however, still refuse to wear them and rely only on the air bag. Because of this the US front seat air bag is larger than those used in Europe where air bags are used in conjunction with seat belts.

About 14 m of seat belt fabric weighing about 0.8 kg are present in every new car and total usage is about 32 000 tonnes per annum. Recycling of seat belts is feasible because they are very easily removed and are of uniform composition.[89] Belts are mainly black in Europe, light grey in the USA and Japan, but this is changing to coordinate more with interior colours.

18.2.5.4 The airbag

Airbags were first introduced in the late 1960s, but it is only in the 1990s that their use has grown spectacularly and is set to grow even further. This justifies the considerable research and development still being conducted on design, deployment and base fabric material.

A triggering device sets off explosive chemicals when it senses an accident above $35\,km\,h^{-1}$ is about to occur. These chemicals inflate the bag to restrain and cushion the car occupant from impact with harder objects.[90] The fabric from which the bag is made must be capable of withstanding the force of the propellant chemicals. More important, the hot gases must not penetrate the fabric and burn the skin of the car occupant. The earliest airbags were Neoprene (DuPont)-coated, woven nylon 6.6, but lighter and thinner silicone-coated versions soon followed.[91] Later, however, uncoated fabrics have appeared.

There are advantages and disadvantages for each type; coated fabrics are easier to cut and sew with edges less likely to fray and air porosity can be better controlled, whilst uncoated bags are lighter, softer, less bulky and easier to recycle.[92] Airbags vary in size and configuration depending on in which car they are to be used. In addition driver side airbags (from 35 litre capacity upwards) are smaller than for the front passengers, from about 65 litres capacity upwards.

Airbags are typically made from high tenacity multifilament nylon 6.6 in yarn quality finenesses from 210, 420 to 840 denier although some polyester and even some nylon 6 is used.[93] Nylon 6 is said to minimise skin abrasion because it is softer. Airbag fabric is not dyed but has to be scoured to remove impurities which could encourage mildew or cause other problems. It needs to have high tear strength, high antiseam slippage, controlled air permeability[94] (about $10\,l\,m^{-2}\,min^{-1}$) and be capable of being folded up into a confined space for over 10 years without deterioration. Some tests require 75% property retention after 4000 hours at 90–120 °C, the equivalent of 10 years UV exposure and also cold crack resistance down to –40 °C. A new fibre nylon 4.6 (Akzo) with a melting point of 285 °C has been introduced especially for airbags.

In the USA, FMVSS 208 requires all passenger cars sold during 1997 to have airbags both for the driver and front seat passenger.[95] Worldwide production of airbags was about 43 million units in 1997 and this was expected to grow to 120–200 million units (up to 50 000 kg of mainly woven nylon) by the year 2000.[96] Production could be much more with the development of head protection via inflatable tubular structures (ITS), side airbags, rear seat airbags, even knee and foot well airbags have been mentioned.[97–99] Indeed, in the USA, FMVSS 201 has required that by May 1999 10% of cars must be fitted with some kind of head protection. This requirement will rise to 100% by May 2003. BMW has introduced a side impact airbag and an ITS for head protection in their 1997 '7 series' to be extended later to their '5 and 3 series'. A BMW 'concept car' features 12 airbags![100] Future airbags are likely to be smaller, lighter and more compactable.

Whilst airbags undoubtedly save lives they can also cause serious injury. Following the deaths of children in accidents under 20 mph, the design of airbags in the USA has come under considerable scrutiny. The search is on for a reliable 'smart' airbag which can sense the size of the passenger or even if the seat is unoccupied and react accordingly. Furthermore, integrated safety systems combining the seat belt and other safety items are under development especially for child passengers.

18.2.6 Seating developments

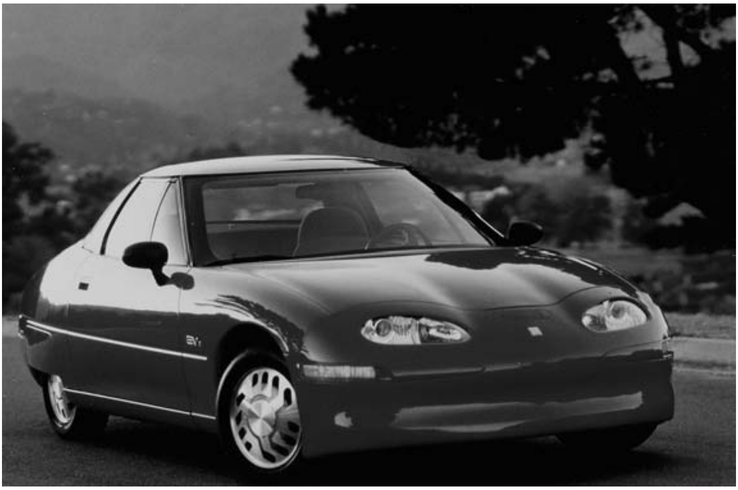
18.2.6.1 Three-dimensional knitting of car seats

This novel development originated from garment research at Courtaulds, Research laboratories in Derby. The objective was to knit garments in one piece, thus eliminating panel cutting and making up along with the associated cutting waste of up to 30%. The potential benefits to the automotive industry were soon recognised and General Motors became involved.

Initial progress was hampered by the mechanical flat bed weft-knitting machine controls and its Jacquard card needle selection mechanisms, but these limitations were overcome with the appearance of the computer.[101–103] With computer assistance, each needle can be individually controlled enabling almost infinite colour combinations and design patterns and car seat covers can now be knitted in just one piece with accurate placement of logos if necessary. This single item includes all flaps, tubes and tie downs necessary for direct fitting. The stages of panel cutting and sewing together of up to seventeen pieces of fabric are reduced to just one or two with no cutting waste.

Other benefits include rapid setup and dramatically reduced stock holding especially end of model surplus.[104,105] A new design can be produced simply by changing the yarns and inserting a new floppy disk, so that within minutes a different seat cover becomes available for fitting. Design themes can cover two or more seats and can even include the door panel.

Three-dimensional seat covers made their European debut in the Vauxhall Rascal van and in the 1993 Chevrolet Indy Pace car in the USA. They are being used in the General Motors electric car EVI (see Fig. 18.2) and in the GM car GEO Prizm.[106] Research work however continues with a variety of different yarns to develop the aesthetics and handle further. Although the 25 or so worldwide patents relevant to automobile application are held by GM of the USA, the original inventors are mainly British and continue their work at Derby.



18.2 New generation of environmentally friendly vehicles. The EVI contains many novel features including three-dimensional knitted car seat covers.

18.2.6.2 New seat technology

The traditional way of seat making, involving cutting and sewing panels into a cover that is then pulled over the squab (seat back) and cushion (seat bottom), is time consuming and cumbersome in the modern age. Efforts have been made to develop alternative quicker and more efficient methods. Three-dimensional knitting is an option but this has had only limited usage so far.

'Pour in foam' techniques for small items such as head rests and arm rests are carried out, but the preparation of whole seats by this method on a large scale by one car manufacturer in the early 1990s was discontinued. A barrier film was needed to allow vacuum to be applied and to prevent liquid foam penetration before solidification. The barrier films, however, affected seat comfort. For small items, the laminate foam itself is sufficient to prevent this 'weeping through' of liquid foam.

The latest techniques involve bonding the seat cover laminate to the squab/cushion using a vacuum technique and a hot-melt adhesive film. The cover and film are held together by vacuum, the moulded squab/cushion is placed on top and the adhesive film activated by hot air or by steam in some variations of the process.[107] Many seats are made in the USA by this method. It is especially suited to increasingly curvaceous seat contours and could reduce the need for thick cover laminate foam. Because of the adhesive layer, seat breathability and comfort may be affected, but the seat makers are aware of this.

DuPont have developed polyester nonwoven fibre 'clusters', which can be formed into seat cushions and squabs in place of polyurethane foam. Benefits claimed include 20% reduced weight and increased comfort through improved breathability and recyclability. With polyester-based material used as webbing and a polyester fabric covering and scrim, the whole seat in just one material becomes easily recycled.[108,109]

In an entirely different approach, cushion foam or springs are replaced by woven fabric with the correct stretchability. Two systems Sisiara (Pirelli) and Dymetrol (DuPont)[110] have appeared in production cars. Benefits include savings in both weight and space. Developments of the same concept using elastomeric materials have appeared.[107]

18.2.6.3 Artificial leather and suede

A leather shortage is forecast in the near future and at the same time designers anticipate an increased demand in cars, especially for leather/textile combinations. Leather is universally regarded as the ultimate in seat luxury. The shortfall is likely to be filled by artificial products and the manufacturers, almost entirely Japanese, have expansion plans. Toray estimate an increased production of artificial suede from 16 million m^2 in 1995 to 25 million m^2 by 2005 with a significant part going into European cars.[111] The base material is polyester microfibres approximately 68% by weight (32% polyurethane). Automotive grades are backed by polyester/cotton or knitted nylon scrim fabric. The best known product in Europe is Alcantara, made in Italy since 1975 in a Toray/Enichen joint venture. At present about 1 million metres are used in cars, mainly of Italian manufacture.[112]

A new artificial leather, Lorica, which was launched in Italy in 1994 by Enichen,[113] has several advantages over natural leather, including increased elongation and tear strength, mouldability and high frequency microwave weldability. It is produced from polyamide microfibres and polyurethane and is available in a variety of colours. Artificial leathers and suedes have the advantage over natural products in uniformity of quality and thickness and availability in roll form which facilitates production planning and minimises waste. Significant improvements in the quality have been achieved by microfibres and the latest Japanese products use ultra fine filaments of 0.001–0.003 dtex. While Alcantara and other successful suedes are produced by a solvent coagulation process, attempts have been made to develop more environmentally friendly aqueous methods.[114]

18.2.7 Aspects of management

A revolution is taking place within the car industry. Car makers, 'original equipment manufacturers' (OEMs) have become assemblers of components, making few individual items themselves. As competition intensifies, OEMs have to manufacture and sell worldwide and their immediate suppliers, the Tier 1 level suppliers have had to follow suit. In turn, suppliers to Tier 1, that is Tier 2, also need to have a global presence. Global strategies are now vital for global products[115] and the QS-9000 quality standard (based on ISO 9001 and specific to the automotive industry), is becoming required increasingly.

OEMs are continually applying pressure to cut costs, indeed some required 3–6% annual cuts to the year 2000, that is, 20% compounded.[116] To meet the challenge 'Tier 1s' are integrating interior components and assuming responsibility for design and specification and because of this in some ways the design and specification control of interiors is moving away from the OEMs. Lear Corporation is buying up interior component companies with the declared intention of eventually being able to offer entire interiors of cars at an agreed price.[117,118]

The trend for OEMs and others is to reduce the number of suppliers to simplify administration and reduce cost. They expect more from the select few, requiring supply 'just-in-time' at the required quality. These companies are in almost minute-by-minute contact with their customers. In such a fast moving environment, the successful textile technologist must know his/her subject and all the downstream processes inside out to be able to identify and solve problems quickly. However, all involved must provide all relevant information without hesitation. The cooperative culture must be created and fostered. OEMs rarely rely on a single supplier and a supplier who has developed a new product may be required to hand over all details to a competitor for them to become a second supplier.

18.2.8 Recycling

The car seat laminate comprising up to three different chemical types, polyester face fabric, polyurethane foam and nylon scrim cannot be easily recycled, although use of polyester scrim reduces the number to two. Chemical hydrolysis can break the three polymers down into simpler chemicals, which can be repolymerised but this is not commercially feasible at present. Use of nonwoven polyester, both in the seat cover laminate and in the seat cushion/squab, has already been mentioned. Replacing the laminate foam with a polyester nonwoven may not solve the problem if the adhesive joining the two polyester components (i.e. face fabric and non woven) is chemically dissimilar.

Fibre manufacturers Hoechst and EMS have shown the possibility of recycling polyester face fabric into nonwoven material. Shredded face fabric mixed with 30% of virgin polyester polymer has been re-extruded into polyester nonwoven fibre.

Nonwovens, notably from Wellman produced from recycled polyester bottles, are already being used commercially.

A key factor is the time taken for disassembly. The 'dirt factor' for carpets has already been mentioned and this must also be a factor for car seat fabric and adds to the case for better cleanability. The impetus for recycling arose within the last six years and it is only relatively recently that cars are actually being designed for disassembly. Possibly in the future a second (recycled) use for a material could be decided in advance and influence the initial choice. Recycling has been and is the subject of much research[119–124] some of it funded by the European Union (through Brite Euram programmes), which has also funded efforts to make the car lighter. Choice of materials are now influenced by 'cradle to grave' (life cycle) analyses of the various options and commonisation of materials.[125]

18.2.8.1 Voluntary action by the industry

About eight million 'end of life vehicles' (ELVs) are scrapped annually in the European Union. Early in the 1990s voluntary accords were set up. Amongst them are the Automotive Consortium on Recycling and Disposal (ACORD)[126] in the UK and PRAVDA[127] in Germany to provide national frameworks for economic break-even for recovery systems, to reduce waste disposal from ELVs and to ensure by 1998 that all were properly collected. CARE (Consortium for Automotive Recycling)[128] was set up in the UK in 1996. Composed of ten car manufacturers and a number of car dismantlers, it works with government bodies and others to obtain specific results from practical work by helping individual companies. Since 1993 Recytex (a subsidiary of Viktor Achter, the car upholstery manufacturer) has processed textile waste from its parent company and others.[129]

18.2.8.2 European legislation

Proposed European Directive DGX1 (Environment) targets 80% of the car to be recycled by the year 2002 with not more than 15% by weight going to landfill. This will be decreased to 5% by 2015 with 90% recycled.[130] Already landfill fees in the UK and elsewhere have risen substantially. The draft directive also requires a system of collection and treatment to be created with the responsibility for reuse, recovery and recycling of the ELVs to rest with the automotive sector's 'economic operators'. This can be interpreted as meaning everyone involved with the vehicle. The European Car Industry considers these measures unreasonable because the car is already recycled 75% by weight and actual waste, the industry claims, represents only 0.2% of all European industrial waste. The EU however considers ELVs a priority.[131] These issues are very likely to affect the textile industry eventually, because fabric and fabric laminates are major components of vehicle interiors. In addition, the EC directive also proposes to scrutinize the use of PVC – if replacement is recommended, textiles are likely to replace at least some of it.

18.2.9 Future development in automotive textiles

Car production is expected to remain generally static up to 2005 in the developed world, but is likely to expand considerably in the developing nations. Globally there are excellent opportunities for the multinational OEMs and their suppliers, especially those with the imagination and will to innovate new products and design features that will make car journeys more comfortable, safe and pleasant. The following paragraphs discuss the possibilities that are believed to exist.

The largest growth area in automotive textiles will be in air bags as they become standard equipment in more cars. Development is needed to improve their safe functioning, however, legislation may spur on such developments in a similar way to the USA. The latest system is an air bag that deploys outwards from the occupant's seat belt. Possible new applications for textiles within the car include the dashboard, sunvisor and seat pockets and circular knitted fabrics may be especially suited to these outlets.

Increased hygiene awareness, already present in Japan, may lead to greater use of antimicrobial finishes on car seats and carpets and perhaps the use of fibres with built in permanent protection, such as Bactekiller (Kanebo) and Diolen (Akzo), both polyesters, and Amicor (Courtaulds' acrylic fibre). This may be hastened by more food being consumed in cars, particularly in recreational vehicles (RVs) and multipurpose vehicles (MPVs). Improved cleanability or more durable soil-resistant finishes may also be necessary, especially with increased Jacquard designs and brighter colours. The quest for cleaner air is leading to more air filters being installed as standard features and existing ones being improved. One novel development, which does not appear to have been widely adopted in the USA or Europe, is the Japanese invention of odour-absorbing backcoatings on seat fabric.[132]

Engineered fabrics can contribute to comfort, making journeys less stressful and therefore safer. Fabrics can be designed to improve seat thermal comfort[133–137] by absorbing and transporting moisture away from the body. Softer touch and more pleasing handle would make car seats more comfortable as many car seat covers are rough compared to domestic furniture and of particular note is that clothing today is significantly softer than it was say in the mid 1980s. Much research, possibly assisted by the Kawabata objective measurement of fabric handle and touch,[138,139] has resulted in the soft and smooth surface to touch of modern clothing. Some attempt has been made to apply the Kawabata technique to automotive fabric.[140] The very high abrasion resistance requirements, however, restrict progress. Additionally, textiles could possibly contribute more to the control of noise in the car,[141–143] which after alcohol is believed to be one of the main causes of accidents, because it contributes to driver fatigue.

The layout of car seats is becoming more flexible with, for example, some individual seats able to be turned through 180° for family meals or for conferences. They can even be removed altogether in the latest vehicles and so increase load carrying capacity. Could this lead to renewable seats? Will car seats be changed in a similar way to renewing easy chairs in the living room? Renewable items may not need the extremely high durability requirements and this could open the door to many new developments not possible at present, such as use and introduction of significantly softer fabrics. Another possibility is that people will keep their vehicles for longer, which will push performance specifications even higher. DuPont have developed 'Xtra-life' nylon in anticipation of this and US OEMs are believed to favour significantly increased light-resistance properties. Generally higher durability requirements are anticipated in the USA, because of the growing market in pick-up trucks (a 'robust' product, treated accordingly!) and increased vehicle leasing. In the latter case, the vehicle's 'private life' begins when it is already 2–3 years old. The developed countries will see a larger retired population. People who have retired younger and are living longer, with reduced incomes, may not wish to change their cars as frequently as before.

'Mass customization' is expected in the garment industry. Garment scientists working with retailers are developing a 'body scan' which instantly measures a person's dimensions. The information will enable a garment to be made quickly in any colour and design of the customer's own choosing. Could this concept spread to car interiors? Younger persons and others seek designs to suit their individual lifestyle and so it is possible, if not probable, that this will occur.

Environmental issues already influence car design and manufacture. Chlorofluorocarbon (CFC)-expanded foams have disappeared, but the antimony/halogen synergy combinations are still used in flame retardants in textile coatings and these are currently giving concerns on ecotoxological grounds in Europe. Will the environmental laws of the future prohibit their use? Alternative FR chemicals are being developed, but so far are less effective weight for weight. Will it become necessary to recycle car seat covers? At present they consist of dissimilar materials joined together. However, the new technique of joining the seat cover directly to the cushion and squab would appear to make recycling more difficult.

Will a 'green car' sell better? Consumer research in the USA suggests that the public may well be prepared to pay more for environmentally friendly items. One of the simplest ways to make the car greener is to reduce fuel consumption by building it lighter. Already several parts have been replaced with lighter plastic composites and eventually carbon fibres are likely to appear in mass-produced cars. Some attempts are being made to make seat cover fabrics lighter by using finer yarns and reduced construction densities but this lowers abrasion resistance and other properties. Fewer fabrics are now backcoated to save both weight and cost. In Germany, the objective is to produce the 'three-litre car'[144] in other words a car which will cover 100 km on 3 litres of petrol, equivalent to 94 mpg.

New generations of specialist yarns based on established fibres are appearing, for example high tenacity low shrink polyester (for tyres) and nylon variants exclusively for air bags. Teijin have developed 'soft feeling' polyester yarns specifically for velvet pile fabric and a type that is resistant against pile crush.[145] The Japanese fibre companies have developed many yarns with novel cross-sections and ever finer microfibres to produce new generations of apparel fabrics (e.g. 'Shin-Goshen' fabrics). Courtaulds (working with Gateway Inc.) and DuPont are developing smart acrylic yarns for clothing which respond to body temperature, that is, provide warming when cold and cooling when hot.[146,147] In addition there are several modified yarns designed to improve thermal comfort of clothing.[148,149] These yarns may be adaptable for automotive seating, but they are likely to cost more and have lower abrasion resistance. As global volumes increase it may become economically feasible to develop speciality yarns for automotive seating, perhaps offering some novel feature of texture or appearance or with enhanced abrasion and light fastness durability.

The control of static electricity in cars in being studied carefully[150] because, whilst static shocks may be unpleasant, concern is being expressed that they present a safety hazard by interfering with the electronic management systems within the car. Fabric finishes wear off eventually and may not be fully effective if the car seat is not earthed. New solutions may be possible using conductive yarns.

Opportunities for textile innovation exist, but projects developing new products which are likely to add to the cost of a car must be scrutinized very carefully because

OEMs, at present, are mainly concerned with cost reduction. This is understandable in an intensely competitive industry, but it can be discouraging to their supplier's research and development staff who strive to produce the innovative features the industry needs.

Factors other than those directly concerned with textiles could significantly influence fabric development in the not too distant future, like better UV and other radiation screening glass or new lighting systems via fibre optics. The former factor may well lead to cooler interiors in sunlight and possibly eventually remove some of the restrictions on fibre type and attainable shades.

18.3 Textiles in other road vehicles

18.3.1 Heavy goods vehicles (HGV)

More use of textiles is even being made in HGV interiors, which are becoming more comfortable with livelier colouring, softer more rounder shapes and surfaces. In the USA there is a reported shortage of drivers and comfort and appearance are important factors in attracting and retaining employees. In addition there are a growing number of husband and wife teams in the industry.[151,152]

Composite materials are being used to replace bulky space dividers and doors to create more cab storage space. More cabs have sleeping quarters with beds, curtaining, carpets and textile wall coverings. Seating fabric requirements are very similar to automobiles except heavier fabrics about 430 $g\,m^{-2}$ using yarns up to 3000 dtex are sometimes used and the performance requirements of the flame retardant test, FMVSS 302, are generally higher.

18.3.1.1 Tarpaulins

HGVs are a major user of tarpaulins, which are made from PVC plasticol-coated nylon and polyester, usually Panama and plain woven from high tenacity yarns.[153,154] Base fabrics vary from about 100 $g\,m^{-2}$ to over 250 $g\,m^{-2}$ and are coated with up to 600 $g\,m^{-2}$ or more of PVC plastisol applied in several layers. The more up-market products, for example Complan–Trevira (Isoplan–Trevira in the USA) are coated on both sides with the face side lacquered with an acrylic or polyurethane resin to improve UV degradation resistance, abrasion resistance and antisoil properties and also to reduce plastisol migration. Tarpaulins must also pass flexing resistance, cold cracking, reduced flammability, coating adhesion, waterproofness and tear and tensile tests. They must be dimensionally stable over a wide range of temperatures and relative humidities and be resistant to common chemicals, oils and engine fuels. However, if the coating is damaged, microorganisms can migrate via moisture into the material. Both Hoechst (Trevira HT Type 711) and Akzo (Diolen 174 SLC) have developed special variants of polyester to prevent this.

Environmental pressure groups, especially Greenpeace, maintain that PVC is harmful to the environment, especially during manufacture and disposal. The PVC industry has countered such claims, but tarpaulins using other coatings such as polyethylene have appeared. Tarpaulins are secured with high tenacity polyester narrow fabric which must also be tested carefully for strength and UV resistance.

18.3.1.2 Spray guards

A European Community directive requires HGVs to be fitted with guards to reduce road spray. Suitable products have been produced from polyester monofilament yarn knitted in a spacer fabric construction about 12 mm thick. Textile guards are substantially lighter than ones produced in plastic and about six guards are required for the average HGV.[155]

18.3.1.3 Flexible intermediate bulk container

Flexible intermediate bulk containers are used for transporting materials such as powders and so may be considered as an adjunct to HGVs. They are woven from polypropylene tape yarn with a specially formulated coating. Because of the danger of static explosions when being filled or emptied they need to be carefully earthed with metal wire in the fabric. It has been possible to replace the wire with Negastat, DuPont's antistatic yarn that functions without the need to earth.

18.3.2 Buses and coaches

These vehicles cater for the general public and therefore require the highest standards of safety and durability. Seating fabric is typically 780 $g\,m^{-2}$ after coating with acrylic latex and is generally in conservative designs. Wool or wool/nylon woven moquettes are very common with high standards of abrasion (80 000 Martindale rubs), light fastness (to at least wool blue scale 6), fastness to perspiration, crocking, tear strength, soil resistance and cleanability by shampooing all being important requirements. The life of seating fabric varies from less than 6 years in some commuter public transport vehicles to 10 years or more in luxury coaches. High flammability performance requirements are becoming more stringent. BS5852 ignition source 5 is necessary and 'fireblocker' materials similar to those used in aircraft (see below) are being used increasingly. Consideration is also being given to smoke opacity and toxicity and heat flux. Following a number of coach disasters, both in the UK and Europe, safety standards are being studied and the use of seat belts for passengers may become compulsory in the near future. In some cities of the world, vandalism and graffiti is a serious problem in public transport. Fabrics have been designed to minimise these effects, like fabrics with pile that stands up so that if slashed with a knife it will not show readily.[155,156]

Textile-reinforced rigid composites are being used increasingly in buses and coaches to reduce weight and therefore conserve fuel. A prototype bus was unveiled in California that included three structural composites to replace 250 parts in a conventional bus. The 'stealth bus', nicknamed after the stealth bomber, has an expected life of 25 years compared to 8–12 years for ordinary buses and, being over 4000 kg lighter, will allow very considerable savings on fuel.[157]

18.4 Rail applications

The railways went through a period of contraction in the early 1960s in the UK and, more recently, reorganisation into different companies. This may lead to more varied textile designs in seating fabric. Railways in Europe have a key role to play in an integrated transport system[158] and several primary routes using high speed trains are being developed, some of which include the Channel Tunnel. A plan envisaging

30 000 km of new and improved lines was presented to the European Union in January 1989. The railway is probably the most environmentally friendly mode of passenger travel, both for long distance and commuter traffic. Traffic congestion, both on the road and in the air, plus concerns over the environment, strengthens the case for rail travel. The development of high speed trains allows rail to compete effectively with airlines. Interior decor and comfort are key factors in winning passengers away from other forms of transport. The decor of wall panels, seats and carpets cannot be changed every year and so designs must be neutral and not driven by fashion or fad.[159] The major technical issue concerning textiles is reduced flammability. Seat upholstery, loose coverings, carpets curtains and bedding must all pass stringent tests.[160] The materials must also have the correct aesthetics and durability must be in line with planned maintenance schedules.

18.4.1 Seating

Woven moquette weighing about 800 $g\,m^{-2}$ in 85% wool/15% nylon has been the standard fabric for many years.[161] To withstand high volumes of passengers, the fabric must satisfy high burst strength and breaking load tests and abrasion resistance must be in the order of 80 000 Martindale rubs. It must meet light fastness standard 6 (blue wool scale), be dimensionally stable and not change in appearance after shampooing. Polyesters, especially FR grades such as Trevira CS and FR have gained acceptance especially in Europe. Designs are generally conservative in dark colours to mask soiling but this may change with the privatisation of British Rail and the formation of several companies who may develop corporate colours.

The overall FR standard aspired to is BS6853 1987 '*Code of Practice for Fire Precautions in Design and Construction of Railway Passenger and Rolling Stock*'. This document includes requirements for smoke and toxic fumes assessment. Materials are not only tested singly but complete seats are evaluated according to BS5852 ignition source 7.[162] Fire blocker materials are being used increasingly for rail seats. Control of toxic fumes and smoke, which reduces visibility, is of especial importance for trains that pass through tunnels or are used in underground railways. Halogen-containing materials, such as PVC, and any other materials that have high toxicity indices (modacrylic fibre) are excluded from passenger coaches.[163] The building of the Channel Tunnel has influenced regulations and all international passenger trains must comply with the International Union of Railways specification UIC 574-2 DR. The French standard NF F 16-101, which contains a very structured procedure for the testing of individual materials for flammability and both smoke opacity and toxicity, is also sometimes required. Generally, however, the FR standards across Europe are quite diverse. In addition some local authority vehicles have graffiti-proof fabric and metal wire beneath face fabrics to minimise vandal damage by knife slashing.

18.4.2 Other textiles uses

Sleeping car textiles, such as bed sheets and blankets, generally require high standards of performance and durability and some FR properties. Carpets are important in helping to create an attractive relaxing appearance, but they must be extremely hard wearing to cope with the volume of foot traffic sometimes for up to 20 hours a day.[164] Wool and nylon are the fibres most used in FR qualities with smoke emission, toxicity of fumes and heat release carefully assessed. BS476 Part 7 *Spread* *of flame* is used, but ASTM E 648 *Critical heat flux* is applied in addition for certain cases. Nylon carpet is reported to be better than wool for cleanability and stain resistance but wool is preferred for flammability resistance. Durable antistatic properties are sometimes accomplished with the use of small amounts of conductive fibres in the carpet, such as Resistat (BASF) or Antron P140 (DuPont).

With the advent of the high speed train to compete with aircraft, weight is becoming more sensitive and metal and other traditional material parts of trains have been replaced with composite materials to reduce weight. The French TGV train capable of above $300\,km\,h^{-1}$ contains significant amounts of carbon fibre/epoxy composites.

18.5 Textiles in aircraft

As the 21st century dawns, more effort is being put into design of aircraft interiors to make them more passenger 'friendly'. This means more head room and rounder and softer surfaces to give the impression of spaciousness.[165–167] Increased safety is also being researched to make seats stronger and bulk head airbags may soon appear in passenger aircraft.

The main technical challenges for the textile technologist are safety (mainly with respect to flame retardancy) and weight saving. It is estimated that for every 1 kg of weight saved in an aircraft, £150 a year is saved in fuel costs, whilst a 100 kg lighter load can increase the range by 100 km. Reduced flammability is vital and statistics show that fire accounts for over 25% of deaths in aircraft accidents.

About 500–600 large passenger airliners are constructed each year, almost entirely in the USA (75%) and Europe (25%). A further 250 smaller passenger aircraft, 1300 light aircraft and about 1500 helicopters for civil use are built every year.[167] Aircraft have a lifespan of about 30 years, so the numbers in service are increasing steadily. Of all the forms of transport, air, especially air freight, is the biggest growth area.[168] Furnishings and equipment are refurbished regularly or when signs of wear are evident.

18.5.1 Furnishing fabrics

Furnishing fabrics include seat covers, curtaining, carpets and on long distance flights, blankets and pillows. Designs are generally in the livery colours of the particular airline, sometimes with company logos appearing in prominent positions. The article requiring most technical attention is the seat cover assembly on top of polyurethane foam. The fabric itself is generally made from woven wool or wool/nylon blends (nylon in the warp) of $350–450\,g\,m^{-2}$ weight. Before acceptance by the airline it is tested for colour fastness, crocking, cleanability, pilling, snag resistance and dimensional stability. Some woven polyester covers are now being used, giving saving in weight and improved easy care. The wool is generally Zirpro (IWS) treated for the highest FR performance and the polyester must have FR properties that are durable in washing. Seat covers are usually fully laundered every three months and life expectancy is about three years. Cleaning must be accomplished during the restricted 'turn around' times in between flights. The materials must therefore have soil-release properties and cleanability is evaluated by test staining with items such as lipstick, coffee, ball point ink, mayonnaise and other oils. After cleaning, the effect of residual stains or colour change is assessed, sometimes with the use of grey scales. There is an increasing interest in antistatic properties for all aircraft textiles both for comfort and also for non-interference with electronic equipment.

All textile furnishings must pass stringent vertical burn tests such as BS3119 or DIN 53906. An internationally accepted test is (USA) FAR 25.853b which limits burning time to 15s after removal of the source and a char length no greater than 20cm. However vertical fabric strip tests on individual items are not sufficient for seating that contains foam. The whole seat assembly must satisfy the FAR 25.853c test procedure in which a paraffin burner delivering flame at 1038°C is applied to the seat cushion for 2min. The average weight loss must not exceed 10% and the char length must not exceed 17 inches (43cm). All seats in all passenger aircraft have had to satisfy this test[169] from 1st July 1987. To pass this test, 'fireblockers' were introduced under the face fabric to encapsulate the polyurethane foam in the seat and shield it from flame.[23,24] Fireblockers are made from preoxidised acrylic fibre, for example Panox (Lantor Universal Carbon Fibres), aramid fibres (Nomex, Kevlar – DuPont) Zirpro (IWS) treated wool, Inidex (Courtaulds), PBI (Celanese – Hoechst) fibre or combinations of these materials. Fabric weight needs to be considered; amongst the heaviest fireblockers is 60% wool/40% Panox, and the lightest but amongst the most expensive is 100% aramid.

FR grades of foam are used, but the higher FR grades can compromise comfort and tend to crumble. Research to improve both foams and fireblockers continues to produce improved effectiveness at lower weight and cost.[21,22] Amongst the materials being developed is Visil (formerly Kemira, now Sateri Fibres, Finland) a modified viscose fibre[170] that may offer benefits in comfort.

Study of aviation fires showed that victims were overcome by smoke or toxic fumes rather than direct contact with flame. Disorientation or incapacitation caused by the products of combustion prevented them evacuating the aircraft. Airbus Industrie standard ATS 1000.001 controls smoke opacity and the concentration of toxic gases such as CO, HCl and HCN. Wool and aramids have especially low toxic emissions from combustion (see Tables 18.4 and 18.5), but PVC and modified acrylic fibres have high levels.

Tests to measure heat release have come into force, for example the Ohio State University test, OSU 65/65. This test requires that interior components larger than 10×10 inches square (25.4×25.4 cm) on new aircraft (i.e. those built from 1990 onwards) must not release more than 65 kW m^{-2} min^{-1} heat during 5 min of flame exposure and the heat must not peak at more than 65 kW m^{-2} at any time during the test.[171] Table 18.6 provides data on various fabrics. Fabrics must pass all the tests that are designed in anticipation that passengers can evacuate the aircraft in 1.5min should a small fire start.

18.5.2 Fibre-reinforced composites

Fibre-reinforced composites are used extensively in all parts of the aircraft resulting in very significant savings in weight, for instance, about 1350kg of composites are used in the Airbus A310 and approximately 690kg are used in the Boeing 737-300 representing about 6% of the entire weight of the planes.[168] Actual weight savings in the parts replaced by composite materials are between 20–30%. Internal dividing structures are mainly glass fibre in phenolic resin. They must comply with the flammability standards and also those regulations governing smoke and toxic gases. Knitted fabrics are used for compound contours, woven fabrics for flat parts. Phenolic resin is widely used because of its fire-resistant properties, low smoke and low toxic gas emissions.[172]

Advanced composites such as boron, silicon carbide and ceramic fibres are used in miliary aircraft for functional reasons not restricted by cost. The NASA space vehicle, Challenger, uses composites in many areas. Composites can only be used for radomes, (radio and radar equipment protective covers) because radiowaves would be shielded by metal. Composites are used extensively in helicopters and the rotor blades are made from carbon fibres.

18.5.3 Technical fabrics

Each passenger seat has a safety belt and in emergencies there is a life jacket under every seat. The life jacket is generally coated nylon of total weight about 265 $g\,m^{-2}$. A hot-melt polyurethane layer is applied to woven nylon usually primed first with either a solvent or a water-based base layer of polyurethane. The seat belt is a lap-type only, usually in woven polyester. Some consideration is being given to making these more like car seat belts with three anchoring points that would more than double the present volume of material required.

Carpets are usually woven loop pile wool with a polypropylene backing to save weight and coated with FR neoprene foam. Aisle carpets which need to withstand food and drink trolleys are changed around every 3 months whilst carpet in other areas is changed much less frequently.[173] Needless to say, the carpet has to meet high FR standards (e.g. FAR 25 8536) and smoke emission tests and has to be easily cleaned and maintained. Typically, they must be under 2000 $g\,m^{-2}$ in weight and contain conductive fibres together with a conductive backcoating for permanent antistatic properties. Some airlines require a maximum generated voltage of 1000 V in a static body voltage generation test. Carpets or any items aboard the aircraft must not contain any material that could give rise to corrosive chemicals, which could cause deterioration of the aircraft's metal structure.

In large aircraft there are life rafts and escape chutes generally made from coated woven nylon or polyester fabric. The coatings are usually polyurethane or a synthetic rubber; PVC is avoided because of toxic emissions if it is set alight.

18.6 Marine applications

As in other areas of transportation, fibres are used in functional applications and more overtly in decorative applications. Again safety, like flame retardancy, is crucial and weight savings are also important requirements, especially in racing craft. Many safety requirements for furnishings and standards are set by the International Maritime Organisation such as the IMO Resolution A471 (XII) for fire resistance.[174] As in other forms of transport, comfort, design and appearance are important in providing passengers with a relaxing atmosphere.

18.6.1 Furnishing fabrics

Cruise ships can be regarded as 'floating hotels'[175] and, therefore, textile properties requirements must be of 'contract standard'.[16] Flame retardancy standards need to be high because of escape restrictions at sea and also because narrow corridors and low ceilings in many vessels make panic more likely in the event of a fire.[176] Fires in hotels and cruise ships are frequently caused by carelessness on the part of smokers. Furnishing fabrics must have durable high standards of flame retardancy and more use is therefore being made of inherently FR textiles. Standards required include DIN 4102 class B and BS476 paragraph 6.[177]

Carpets are especially important on passenger vessels because of their noise and vibration absorbing properties. They are more pleasant to walk upon than a hard surface and help to reduce physical stress and to provide a calmer and quieter atmosphere. Dyes used must be fast to light, rubbing and salt water. Durability is important because some areas of vessels are in use 24 hours a day and cleaning is done to rigorous schedules. Some ferries in Scandinavia have a million passengers a year; the heavy duty carpet is expected to last over 7 years.[178] Flame retardancy is important and wool carpets are generally Zirpro (IWS) treated. Durable antistatic properties are also generally required, imparted sometimes by the use of conductive fibres which are more durable than chemical finishes.

18.6.2 Functional applications

Fibre composites of glass reinforced plastic are used extensively in small vessels, patrol boats and pleasure craft.[179,180] Polyester fibre is being used to replace some of the heavier and more costly glass fibre in the composite. The advantages are easy handling, corrosion resistance and low maintenance. Kevlar (DuPont) is also used, sometimes in combination with glass fibre. Examples of specific cases where metal cannot be used are minesweepers, sonar domes and in corrosive-cargo carriers. Composites are being increasingly used for navigational aids such as buoys so that no damage results to the craft in the event of an accidental collision.[181]

Coated fabrics are used for life rafts buoyancy tubes, canopies and life jackets.[153] The base fabric for life rafts is generally woven polyamide with butyl or natural rubber, polychloroprene or thermoplastic polyurethane coatings. The total weight of the material varies from 230 $g\,m^{-2}$ up to 685 $g\,m^{-2}$. Quality tests include air porosity, coating adhesion and breaking and tear strength both in the warp and weft direction, flexing and waterproofness measured by hydrostatic head test methods. The canopies used on life rafts are made from much lighter coated fabrics. Natural rubber, polyurethane or SBR (styrene butadiene rubber) coated on to woven polyamide fabric give a total weight of between 145–175 $g\,m^{-2}$. Life jackets are generally made from woven polyamide coated with butyl or polychloroprene rubber to give total weights of about 230–290 $g\,m^{-2}$. Performance specifications include polymer adhesion, tensile strength, flex cracking and elongation-at-break, including testing after immersion in water for 24 hours. Performance standards for life jackets and life rafts are usually subject to government departmental controls and specifications.

18.6.3 Sails

Natural fibres in sails were first replaced by nylon and polyester, which are lighter, more rot resistant, have lower water absorption and, in the case of polyester, higher sunlight resistance. Sail development has progressed to some lighter laminated types where film is bonded to the fabric. Thus the fabric does not form the surface of the sail, only the reinforcing structure. For racing yachts, where weight is crucial, aramids which provide high strength with light weight, began to be used for the reinforcing structure. However, aramids degrade in sunlight, so that the ultra high modulus polyethylene yarns Spectra (Allied Signal) and Dyneema (DSM) and carbon fibres are now used.[182] The new polyethylene yarn has also found application in heavy duty ropes.

18.7 Future prospects for transportation textiles

Probably the most important challenge facing the transportation industry is its effect on the environment. Greenpeace warn that transportation at present accounts for 30% of carbon dioxide production, the main global warming gas, from burning fossil fuels. Yet the industry continues to grow and growth is inevitable for the forseeable future as the economies of the developing nations and those of the Third World progress. International trade is essential for a prosperous world society. Tourism, now the largest single industry in the world, is an important leisure pursuit but it also builds bridges and spreads understanding between the nations of the world.

As transportation volumes increase, the environmental issues are likely to be addressed with more efficient and lighter aircraft, trains, road vehicles and sea vessels. The 'three-litre' car is likely to become a reality and greater use of fibre-reinforced composites will result in savings of large quantities of fuel. The 'stealth' bus will become common place and it is probably only a matter of time before we see 'stealth' trains and private cars as well. Spurred on by government legislation, high levels of recycling of vehicles will occur assisted by design for recycling from the outset and by 'commonisation' of materials.

At the same time, more welcoming and pleasing transportation interiors, as well as enhanced comfort and safety can be expected as competition intensifies, not only between individual car companies, train companies, airlines and passenger shipping lines, but also between the different modes of transport.

All these improvements and advances are likely to be assisted by the invention of novel processes and more specialist materials, both as new fibres and in the form of composites. Within the last thirty five years up to 2000, an extremely short period in the history of humanity, significant discoveries bringing tremendous benefits have been made with the introduction of carbon, aramid and other specialist fibres, the most recent being the ultra high modulus polyolefin fibres. More 'breakthroughs' can be expected in future years.

Society is now taking a broader view of issues and a whole generation is growing up educated in environmental affairs. Research and development teams are much better equipped than ever before, benefiting from synergy enhancing instant communication via fax machines, e-mail and the Internet. There are exciting times ahead. For every problem there is an opportunity for those with the energy, imagination and determination to build a better world.

Acknowledgements

Thanks are due to colleagues past and present for their help in compiling this chapter and to the directors of Courtaulds Textiles Automotive Products for their permission to publish it. Special thanks are due to the following: Ian Leigh (Mydrin), Walter Duncan (Synthomer), David Dykes (British Vita), Neil Saville (LUCF), Mike Smith (Duflot), Jim Rowan (Courtaulds Aerospace), Tony Morris (Courtaulds Chemicals), Gerald Day (Delphi), Simon Beeley (Holdsworth), Roy Kettlewell (IWS), Lara Creasey (Automotive & Transportation Interiors), Mick Dyer (DuPont), and the staff of Hoechst (Frankfurt), Boeing (Seattle), Autoliv (Birmingham), DuPont (Wilmington and Geneva) and to John Gannon (for translation from French and German) and to Melanie Wray who typed the manuscript.

Thanks are also due to General Motors for the photograph of the Electric car, EV1 and to the following for permission to reproduce tables: LMC Automotive Services (Table 18.1), The Society of Automotive Engineers; SAE (Table 18.3), DuPont (Table 18.4), and International Newsletters (Tables 18.5 and 18.6).

References

1. J PARK, 'The technology and production of fabrics for the automotive industry', *Rev. Prog. Coloration*, 1981 **11** 19–24.
2. B MILLIGAN, 'The degradation of automotive upholstery fabrics by light and heat', *Rev. Prog. Coloration*, 1986 **16** 1–7.
3. A HORSFALL, 'One big technical headache on wheels', *J. Soc. Dyers Colorists*, May/June 1992 **108** 243–246.
4. M A PARSONS (Rover), 'Fabric requirements for automotive use', *Autotech*, *Seminar 9*, NEC Birmingham 1991.
5. T L SMITH, 'Taking the heat', *Auto Transp. Interiors*, June 1996 32–35.
6. C DOIREAU, 'Specific requirements for urban transport and future trends', *Techtextil*, lecture 314, Frankfurt 1991.
7. G REINERT (CIBA), 'Coloration of automotive textiles using stabilisers', *IMMFC*, Dornbirn, 22–24 September 1993.
8. R V TODESCO, R DIEMUNSCH and T FRANZ (CIBA), 'New developments in the stabilisation of polypropylene fibres for automotive applications', *IMMFC*, Dornbirn, 20–23 September 1993.
9. R D WAGNER, R C LESLIE and F SCHLAEPPI, 'Test methods for determining colourfastness to light', *Textile Chemist Colourist*, February 1985 **17**(2) 17–27.
10. J PARK, 'Assessment of fastness properties', *Rev. Prog. Coloration*, 1979 **10** 20–24.
11. J PARK, 'Colour fastness assessment of textile materials', *Rev. Prog. Coloration*, 1975 **6** 71–78.
12. Midwest AATCC Section Committee, 'Accelerated lightfastness testing of disperse dyes on polyester automotive fabrics', *Textile Chemist Colourist*, December 1993 **25**(12) 25–32.
13. G FRANCKE and A HENKEL, 'Friction wear on car upholstery materials causes and possibilities of avoiding it', *Textiles in Automobiles*, VDI Congress, Dusseldorf, 14–15 October 1992.
14. J HURTEN, 'How pilling in polyester weaves can be controlled in the finishing process', *Textil Praxis Int.*, 1978 **33** 823–836.
15. M BOSCH, 'Pilling on textiles, fundamentals, extent of influence and test procedures', *Textiles in Automobiles*, VDI Congress, Dusseldorf, 14–15 October 1992.
16. M O'SHEA, 'Interior Furnishings', *Textile Prog.*, 1981 **11**(1) 1–68.
17. A R HORROCKS, 'Flame retardant finishing of textiles', *Rev. Prog. Coloration*, 1986 **16** 62–101.
18. D L ROBERTS, M E HALL and A R HORROCKS, 'Environmental aspects of flame retardant textiles – an overview', *Rev. Prog. Coloration*, 1992 **22** 48–57.
19. A J G SAGER, 'Protection against flame and heat using man-made fibres', *Textiles*, 1986 **15**(1) 2–9.
20. J BAGNALL, 'Testing the reaction of textiles to fire', *Textiles Magazine***,** 1995 (4) 12–17.
21. K T PAUL, 'Flame retardant polyurethane foam furniture testing and specification', *Rev. Prog. Coloration*, 1990 **20** 53–69.
22. R HURD, 'Flame retardant foams', *J Cellular Polym.*, 1989 (4) 277–295.
23. N SAVILLE and M SQUIRES, 'Latest developments in fire resistant textiles', *Textile Month*, 1990 May 47–52.
24. G KEIL, 'Fire-blockers – a protection for passengers', *Tech. Usage Textiles*, 1991 **4**(2) 46–47.
25. KIRK OTHMER, 'Composite Materials–Survey', *Encyclopaedia of Chemical Technology*, 4th edition, John Wiley, New York, 1993.
26. P M EATON, 'Aramid fibres', *Textiles*', 1983 **12**(3) 58–65.
27. P M EATON, 'Fibre reinforced composites', *Textiles*, 1986 **15**(2) 35–38.
28. Modern Plastics Magazine, *Encyclopaedia Handbook*, McGraw Hill, USA 1994, pp. 124–136.

29. ANON, 'Toray expanding PAN-based carbon fibres', *Japan Textile News (Japanese)* 1996 September 107.
30. ANON, 'Technical textiles', *Knitting Int.*, June 1996 **103**(1227) 38–39.
31. J W S HEARLE, 'Textiles for composites', *Textile Horizons*, December 1994 **14**(6) 12–15 and February 1995 **15**(1) 11–15.
32. N KHOKAR, 'An experimental uniaxial "Noobing" device', *Textiles Magazine*, 1996 **3** 12–14.
33. KIRK OTHMER, 'Tire Cords', *Encyclopaedia of Chemical Technology*, 4th edition, Vol 24, John Wiley, New York, 1997.
34. M O WEBER and D SCHILO, 'Surface activation of polyester and aramid to improve adhesion', *J. Coated Fabrics*, October 1996 **26** 131–136.
35. J WATERSON, 'Global trends in colour and trim', *Auto Interior Int. Directory*, 1996 16–18.
36. B TEN HOEVAL, 'Worldwide trends in automotive textiles', *Auto Interior Int. Directory*, 1996 16–18.
37. C GARNER, 'Polyolefin and the 10 year automobile', *America's Textiles Int.*, 1996 February 75–78.
38. D WARD, 'Car textiles – Courtaulds makes up for lost time', *Textile Month* 1980 December 30–32.
39. D WARD, 'Car makers realising merits of textiles', *Textile Month*, 1981 January 21–23.
40. G REINERT, 'Textiles as interior furnishing fabrics in vehicles', *IMMFC*, Dornbirn, 22–24 September 1993.
41. C WILKENS, 'Automotive Fabrics', *Knitting Int.*, August 1995 **102**(1218) 50–55.
42. J MILLINGTON, 'The rise, rise and prospective further growth of knitted fabrics in automotive applications', *Knitting International*, December 1992 **99**(1188) 13–17.
43. J MILLINGTON, 'Automotive fabrics-the role of warp knitting', *Knitting Int.*, January 1993 **100**(1189) 13–18.
44. J MILLINGTON, 'Prospective growth of knitted fabrics in automotive applications', *Knitting Int.*, February 1993 **100**(1190) 13–18.
45. W R SCHMIDT (Eybl), 'The application of circular knitted fabrics in the motor industry', *IMMFC*, Dornbirn, 22–24 September 1993.
46. S ANAND, 'Knitted fabrics take the lead in automotive market', *Textile Month*, 1993 September 41–42.
47. ANON, 'Guildford Automotive knows the business', *America's Textiles Int.*, 1995 June 44–52.
48. W C SMITH, 'Automotives – a major textiles market', *Textile World*, 1993 September 68–73.
49. M KAWALSKI, 'Automotive textile presentation', *Autotech* NEC Birmingham 1991, Seminar 9.
50. T D FULMER, 'Dyeing textiles for automotive interiors', *America's Textiles Int.*, 1993 December 88–90; B KRAMRISCH (Oldham S-Ciba), 'Dyeing of automotive fabrics', *Int. Dyer Printer*, 1986 December 28; P OSMAN (Ford), 'Dyestuff selection and colour control for the car industry', *Int. Dyer Printer*, June 1985 **170** 7–8.
51. J R ASPLAND, 'Disperse dyes and their application to polyester', *Textile Chemist Colourist*, December 1992 **24**(12) 18–25.
52. D J PEARSON (Guildford), 'The finishing of automotive textiles', *J. Soc. Dyers Colorists*, December 1993 388–390.
53. M KOWALSKI, 'Automotive textiles update', *Textiles*, 1991 (2) 10–12.
54. J KATH, H P HARRI, P JOHNSON, L MCGARRIE and R ROMMEL (CIBA), 'Printing on automotive textiles', *IMMFC*, 20–22 September 1995 Dornbirn.
55. T L SMITH, 'Printed fabrics make their mark on US interiors', *Auto Transp. Interiors*, 1994 October 34–35.
56. T L SMITH, 'Rotary screen printing offers possibility for colour variety, speed of production', *Auto Transp. Interiors*, 1996 May 74–76.
57. C GARNER, 'The low down on laminating', *Inside Automotives*, 1995 May/June 23–25, 47.
58. R GARNER, 'Flame or dry? The debate is on', *Auto Transp. Interiors*, 1994 May 52–54.
59. D C MILES (Dermil), 'Dry powder bonding adhesives in automotive trim laminates', *J. Coated Fabrics*, April 1991 **20** 229–239.
60. J HOPKINS (Nordson), 'A comparative analysis of laminating automotive textiles to foam', *J. Coated Fabrics*, 1995 January 250–267.
61. F WOODRUFF (Web Processing), 'Environmentally friendly coating and laminating; new processes and techniques', *J. Coated Fabrics*, April 1992 **21** 240–259.
62. J HALBMAIER (Bostik), 'Overview of hot melt adhesives application equipment for coating and laminating full-width fabric', *J. Coated Fabric*s, April 1992 **21** 301–310.
63. S KMITTA (Fehrer), 'Use of polyester fibre padding in shaped upholstery for car seating', *Textiles in Automobiles*, VDI Conference, Dusseldorf, 14–15 October 1992.
64. S KMITTA (Fehrer), 'Polyester nonwovens – an alternative material for car seats', *IMMFC*, Dornbirn, 20–22 September 1995.
65. C WILKENS, 'Raschel knitted spacer fabrics', *Melliand English*, 1993 (10) E348–E349.
66. KARL MEYER/MALIMO Technical information leaflet, 'Manufacture of fabrics for automotive interiors using warp knitting and stitch bonding', We 75/1/8/93.
67. G SCHMIDT and P BOTTCHER, 'Laminating non woven fabrics made from or containing secondary or recycled fibres for use in automotive manufacture', Index Conference, 1993.

68. H FUCHS and P BOTTCHER, 'Textile waste materials in motor cars-potential and limitations', *Textil Praxis Int.*, 1994 April (4) II–IV.
69. H HIRSCHEK, 'Recycling of automotive textiles', *IMMFC*, Dornbirn, 22–24 September 1993.
70. M COSTES (Rhone-Poulenc), 'Use of textiles in vehicles and recycling; state of the art and outlook', *IMMFC*, Dornbirn, 22–24 September 1993.
71. B KIEFER, A BORNHOFF, P EHRLERN, H KINGENBERGER and H SCHREIBER, 'Assessing second hand automotive textiles for use in new vehicles', *IMMFC*, Dornbirn, 20–22 September 1995.
72. E EISSLER, H NONNER and G SCHMIDT, 'Use of textiles in the Mercedes-Benz S Class', *Textiles in Automobiles*, VDI Conference, Dusseldorf, 30–31 October 1991.
73. E BAETENS and E ALBRECHT, 'Fogging characteristics of automotive textiles' *Techtextil*, Frankfurt, May 13–16 1991, lecture 336.
74. E BAETENS and E ALBRECHT, 'Reducing the fogging effect in cars', *Technical Usage Textiles*, 1992 **4** 42–44.
75. P HARDT, 'Estimation of the amounts of volatile substances as applicable to stenter frames for automotive fogging,' *IMMFC*, Dornbirn, 22–24 September 1993.
76. W BEHRENS and T LAMPE (VW), 'Fogging behaviour of textile materials', *Textiles in Automobiles*, VDI Congress, Dusseldorf 30–31 October 1991.
77. P EHLER, H SCHREIBER and S HALLER, 'Emissions from textiles in vehicle interior trim causes and assessment of short term and long term fogging', *IMMFC*, Dornbirn, 22–24 September 1993.
78. J B MCCALLUM, 'Ford Motor Co develops its own test method for predicting light-scattering window film', *Textile Chemist Colourist*, December 1989, **21**(12) 13–15.
79. W BEHRENS, 'Fogging behaviour of car interiors', *Technische Textilen*, March 1993 **36** E25–E27.
80. G S RINK (Opel), 'Harmonisation of textile testing in the German automotive industry', *IMMFC*, Dornbirn, 20–22 September 1995.
81. T L SMITH, 'There's no time to re-invent the wheel-or the seat cover', *Auto Transp. Interiors*, 1996 November 40–41.
82. C GARDNER, 'Headliners rising to the occasion', *Inside Automobiles*, 1994 December 19–23.
83. ANON, *Edana Automotive Non-wovens Newsletter*, (4) 1993 and (5) 1996.
84. A CASHIN, 'Preserving the environment', *Auto Interior Int.*, Autumn 1995 **4**(4) 16–21.
85. A WEHLOW, 'Flocked parts for car interiors', *IMMFC*, Dornbirn, 22–24 September 1993; J P BIANCHI (Novalis), 'Flock technology for car interiors', *IMMFC*, Dornbirn, 17–19 September 1997.
86. S W BOLGEN, 'Flocking technology', *J. Coated Fabrics*, October 1991 **21** 123–131.
87. W J MORRIS, 'Seat Belts', *Textiles*, 1988 **17**(1) 15–21.
88. C ROCHE, 'The seat belt remains essential', *Technical Usage Textiles*, 1992 (3) 63–64.
89. W KRUMMHEUR (Akzo), 'Recycling of used automotive seat belts,' *IMMFC*, Dornbirn, 22–24 September 1993.
90. A DAVIDSON, 'Growing opportunities for airbags', *Tech. Textiles Int.*, 1992 May 10–12.
91. F BOHIN and M LADREYT, 'Silicone elastomers for airbag coatings', *Auto Interior Int.*, Winter 1996/7 **5**(4) 66–71.
92. T L SMITH, 'Tough stuff', *Auto Transp. Interiors*, 1996 August 30–32; H R ROSS (AlliedSignal), 'New future trends in airbag fabrics', *IMMFC*, Dornbirn, 17–19 September 1997.
93. DUPONT Automotive TI leaflets H-48030 and H-48032 (USA); V SIEJAK (Akzo), 'New yarns for lighterweight airbag fabrics', *IMMFC*, Dornbirn, 17–19 September 1997.
94. J A BARNES, J PARTRIDGE and S MUKHOPADHYAY, 'Air permeability of nylon 66 airbag fabrics', *Yarn & Fibre Conference*, Textile Institute, Manchester 2–3 December 1996.
95. T L SMITH, 'Airbags and seat belts; fabric's role in safety restraint systems', *Auto Transp. Interiors*, 1995 December 53–54.
96. J BRAUNSTEIN, '2001 and beyond, a safety odessey', *Auto Transp. Interiors*, 1996 April 27–29.
97. K N CRIGHTON, 'Tubular side airbag technology takes another shape', *Auto Transp. Interiors*, 1995 April 16.
98. ANON, 'New head impact rules spur research', *Auto Transp. Interiors*, 1996 April 28–29.
99. P SONDERSTROM, 'Side impact airbags, the next step', *Inside Automotives*, 1996 May/June 12–15.
100. H MOUND, 'BMW gives a boost to hyperinflation', *The Times*, 12 April 1997.
101. ANON, 'Knitted car upholstery', *Knitting Int.*, June 1993 **100**(1194) 34.
102. F ROBINSON and S ASHTON, 'Knitting in the third dimension', *Textile Horizons*, 1994 December 22–24.
103. C GARDNER, 'CAD and CAE, balancing new technology with traditional design', *Inside Automotives*, 1994 June 17–20.
104. T L SMITH, '3-D knitting adds new dimension to interiors', *Auto Transp. Interiors*, 1994 November 42–45.
105. ANON, 'Technical textiles', *Knitting Int.*, June 1996 **103**(1227) 38–39.
106. M JONES and W GIRARD, '3-D knitting', *Auto Interior Int.*, 1995 Autumn 24–30.
107. J BRAUNSTEIN, 'Whole lot goin' on underneath', *Auto Transp. Interiors*, 1997 April 22–32; R BORROFF, 'Rubber soul', *Automotive Seating Review 1997 (Auto Interior International)*, 1997 22–26.
108. I ADCOCK, 'The inside track', *European Plastic News*, 1996 December 37.

109. C GARDNER, 'Interior industry's one stop shop-Dupont automotive', *Inside Automotives*, 1995 March/April 40–45.
110. J GRETZINGER, 'Dymetrol seating supports for automotive applications', *Automotive Textiles* Symposium, Greenville, S. Carolina, October 1991. Also J Gretzinger and R L Rackley US Patent No 4,469,739.
111. C BORRI, 'Comfort for car interiors-Alcantara-features and advantages of a unique product', *IMMFC*, Dornbirn, 22–24 September 1993.
112. ANON, 'Man-made leather grows in product and demand', *JTN* (*Japanese*), 1997 June 66–73.
113. G BAGNOLI and G POLETTE, 'The revolutionary high-tech leather, Lorica, for automotive interiors', *IMMFC*, Dornbirn, 22–24 September 1993.
114. J HEMMRICH, J FIKKERT and M VAN DER BERG (Stahl), 'Porous structured forms resulting from aggregate modification in polyurethane dispersions by means of isothermic foam coagulation', *J. Coated Fabrics*, 1993 April 268–278.
115. H MILLER SIR, 'Global strategies imperative to supplier success', *Auto Transp. Interiors*, 1995 August 52.
116. A LORENZ, 'Ford slam the brake on parts prices', *Sunday Times Business*, 22 October 1995.
117. L E SULLIVAN, 'System integration; the race is on', *Auto Transp. Interiors*, 1997 June 20–23.
118. ANON, 'Life in the fast lane', *Non-wovens Rep Int.*, 1997 (311) March 23.
119. A WEBER, 'Potential for recycling plastics from scrap cars', *Plastics Rubber Weekly*, 1990 14 April 13.
120. 'Recyclable moulded parts made from Grilene needled mats', *Techtextil telegramm*, 26E 10 December 1992.
121. D WARD, 'There's nothing new about recycling', *Textile Month*, 1995 June 30–32.
122. ANON, 'Opel undertakes comprehensive review of its automotive plastics usage', *Plastics Rubber Weekly*, 9 May 1992, p 10.
123. ANON. 'Recycling becomes a key', *Plastics Rubber Weekly*, 1993 23 October 18–19.
124. R ROWAND, 'Polyester may replace PU', *Urethanes Tech.*, 1995 October/November 34–36.
125. ANON, 'Common materials to cut costs from manufacture', *Automotive Int.*, 1997 March 20.
126. ANON, 'ACORD deal agreed', *Materials Recycling Weekly*, 1997 18 July 3.
127. ANON, 'PRAVDA-the moment of truth?', *European Plastic News*, 1991 September 58–59.
128. B JAMES, 'Rover takes CARE to meet European goals', *Plastics Rubber Weekly*, 1997 7 February 7.
129. ANON, 'Automotive textiles', *Kettenwirk-Praxis*, 1995 (3) E30–E32.
130. S EMINTO, 'Vehicle recycling-UK to take voluntary route', *Materials Recycling Weekly*, 1997 31 January 12–14.
131. ANON, 'ELV recovery', *Automotive Textiles Newsletter*, Rhone Poulenc Setila/Mavel, 1997 April 4.
132. Y YAMADA, 'Holding the odours', *Auto Interior Int.*, 1992/3 Winter 52–58.
133. H BOLLINGER and K R DUWEL, 'New concepts in seating', *Textiles in Automobiles*, VDI Congress, Dusseldorf, 30–31 October 1991.
134. G T KNOZINGER, H THEYSOHN and H VOGT, 'Physiology of seat comfort', *Textiles in Automobiles*, VDI Congress, Dusseldorf, 30–31 October 1991.
135. M JARRIGEON, 'Sensorial and thermal comfort', *Techtextil*, Frankfurt, May 13–16 1991, lecture 335; S E HANEL, T DARTMAN and R SHISHOO, 'A new method for measuring mechanical and physiological comfort in car seats', *IMMFC*, Dornbirn, 20–22 September 1995.
136. W FUNG and K C PARSONS, 'Some investigations into the relationship between car seat cover materials and thermal comfort using human subjects', *J. Coated Fabrics*, October 1996 **26** 147–176.
137. W FUNG, 'How to improve thermal comfort of the car seat', *Vehicle Comfort and Ergonomics*, ATA (Italy), Bologna 6–7 October 1997; V T BARTELS and K H UMBACH, 'Laboratory tests of thermophysiological seat comfort', *Vehicle Comfort and Ergonomics*, ATA (Italy), Bologna 6–7 October 1997.
138. S KAWABATA and M NIWA, 'Fabric performance in clothing and clothing manufacture', *J. Textile Inst.*, 1989 **80**(1) 19–50.
139. J W S HEARLE, 'Can fabric hand enter the dataspace?' Part 1, *Textile Horizons*, April 1993 **13**(2) 14–16 and Part 2, *Textile Horizons*, June 1993 **13**(3) 16–20.
140. C J KIM, 'The Kawabata system use in the fabric hand evaluation of automotive textiles', *Automotive Test Procedures*, IFAI Transportation Division, Atlanta, 7–8 October 1992.
141. R WHITE, 'Fabrics for acoustic control', *Tech. Textiles Int.*, 1993 April 26–29; Y SHOSHANI, 'Studies of textile assemblies used for accoustic control', *Tech. Textiles Int.*, 1993 April 32–34.
142. B RIEDEL, 'Sound-insulating materials for cars based on chemical recycling of PUR flexible foams from car seats', *IMMFC*, Dornbirn, 20–22 September 1995.
143. J DIJKEMA 'Acoustic protection for cars', *Technical Usage Textiles*, 1992 **4**(6) 47–49; J LASER, 'Moulded automotive carpets-influence on the interior noise level', *IMMFC*, Dornbirn, 17–19 September 1997.
144. K GRACE, 'Polymers are crucial for the motor industry to meet its aspirations', *British Plastics Rubber*, 1996 November 26–30.
145. T MATSUI (Teijin), 'Development of polyester fibres for car seats', *IMMFC*, Dornbirn, 22–24 September 1993.

146. A P ANEJA (DuPont), 'New fibre technology for thermal comfort in performance apparel', *Textiles Sports Sportswear*, Huddersfield, 1995 11 April.
147. ANON, 'Coating produces dynamic insulation', *America's Textiles Int.*, 1995 June 6–8.
148. A DOCKERY, 'New process lets polyester breath', *America's Textiles Int.*, 1993 October 12–13.
149. T I DUPONT sheet, *CoolMax*, H-53717 December 1993.
150. P HALL, 'Triboelectronics', *Saturday Telegraph*, 14 May 1994; J CHUBB, 'Testing how well materials dissipate static electricity', *British Plastics Rubber*, 1995 May 8–10.
151. M HENRICKS, 'Truck interiors become home from home', *Auto Transp. Interiors*, 1994 October 16–19.
152. M HENRICKS, 'Works like a truck, rides like a car', *Auto Transp. Interiors*, 1996 March 22–25.
153. P BAJAJ and A K SENGUPTA, 'Industrial applications of textiles for filtration and coated fabrics', *Textile Prog.*, 1982 **14**(1) 15–17 and 25–26; M WILKINSON, 'A review of industrial coated fabric substrates', *J. Coated Fabrics*, October 1996 **26** 87–106.
154. T I HOECHST sheet, *Trevira in focus – Complan*, 12687/98e.
155. C WILKENS, 'Raschel knitted spacer fabrics', *Melliand English*, 1993 (10) E348–E349.
156. L MOORE, 'Bus interior components softer, more flexible', *Auto Transp. Interiors*, 1994 April 26–29.
157. J A GRAND, 'High tech bus draws heavily on aerospace technologies', *Modern Plastics Int.*, February 1997 **27**(2) 30.
158. H-J FRANK (Deutsche Bank), 'The development of transport until the year 2000', *Techtextil*, Frankfurt, May 13–16 1991, lecture 311.
159. C B SUMMERS, 'Transit agencies position for the inside track', *Auto Trans. Interiors*, 1995 April 36.
160. J TROITZSCH, *International Plastics Flammability Handbook*, 2nd edition, Hanser, New York, 1989, 299–310.
161. E J LOWE, 'Textiles in railways', *Textiles*, February 1972 **1**(1) 8–11.
162. H R JONES, 'Textiles in the railway passenger environment', *Flammability*, BTTG, Britannia Hotel, London, 1–2 December 1993.
163. J BAKER-COUNSELL, 'Testing for fire safety on London underground', *Plastics Rubber Weekly*, 1988 30 January 8–9.
164. IWS TI leaflet, *Wool contract carpets for rail passenger vehicles.*
165. R GARNER, 'Aircraft interiors feel the pressure', *Auto Transp. Interiors*, 1996 February 12–22.
166. T L SMITH, 'Fabrics and fibres review; aircraft designers go corporate', *Auto Transp. Interiors*, 1995 March 28–32.
167. M HENRICKS, 'Return of the pampered passenger?', *Auto Transp. Interiors*, 1996 April 48–50.
168. H LAURENT, 'Fabrics used in transport vehicles', *Techtextil*, Frankfurt May 13–16 1991, lecture 312.
169. C C BARROW, 'Standards for textiles used in commercial aircraft', *Textile Horizons*, 1992 April/May 30–34.
170. S GARVEY, 'Visil-the hybrid viscose fibre', *Textiles Magazine*, 1996 (3) 21–24.
171. J BUCHER, 'Regulations, economics limit plastics choice in aircraft', *Auto Transp. Interiors*, 1995 September 48–50.
172. J M ANGLIN, 'Aircraft applications (of composites)', *Engineered Materials Handbook*, Vol 1, ASM Metal Park, Ohio, 1987, 801–809.
173. IWS TI leaflet, '*Wool contract carpets for passenger aircraft*'.
174. International Maritime Organisation, '*Fire Test Procedures*', 2nd edition IMO 844E, London 1993.
175. U GIRRBACH (Hoechst), 'Decorating ship interiors with flame retardant fabrics', *Textile Month*, 1995 April 25.
176. J TROITZSCH, '*International Plastics Flammability Handbook*, 2nd edition, Hanser Publications, New York, 1990, 322–323.
177. P LEWIS, 'Polyester "safety fibres" for a fast-growing market', *Textile Month*, 1997 April 39–40.
178. IWS TI leaflet, *Wool contract carpets for passenger ships'.*
179. J G KAREGEANNES, 'Discovering and exploiting new markets for a fibre', *Tech. Textiles Int.*, 1992 May 14–17.
180. R F PINZELLI, 'Use of composites in maritime structures', *Techtextil*, Frankfurt May 13–16 1991, lecture 323.
181. J SUMMERSCALES, 'Marine applications (of composites), *Engineered Materials Handbook*, Vol 1, ASM Metal Park Ohio, 1987, 837–844.
182. G BELGRANO and C O'CONNELL, 'Carbon sails to the front', *Tech. Textiles Int.*, 1992 May 28–31.
NB. *IMMFC* = International Man-Made Fibres Congress held annually at Dornbirn, Austria organised by Osterreichisches Chemiefaser-Institut Tagungsburo Dornbirn.