WELLINGTON SEARS
HANDBOOK OF
INDUSTRIAL TEXTILES

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Natural and Man-Made Fibers

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1. INTRODUCTION

Mankind has been fortunate that over the eons, natural materials could be found with suitable fiber properties to fabricate clothing for warmth, comfort and style depending upon the needs at the time. The most important fibers in the world until about 1910 were the protein fibers wool and silk, and the cellulosic fibers cotton and linen. All of these products are produced from agriculture. The production of wool, silk and linen has remained static for the last decade owing to the fact that land and facilities for cultivating these fibers are fixed (and for some they are declining). With the world population growing rapidly and the supply of these fibers either diminishing or fixed, the cost of using these fibers for ordinary textiles is prohibitive. Only cotton is grown in quantities that enable it to continue to be an economical source for textile manufacturing.
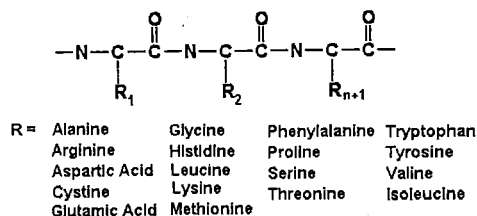
About 1910, discoveries were made which allowed fibers to be spun from special solutions of cellulose as continuous filaments. Unlike the natural products, these fibers could be spun into varying diameters that were essentially the same for every fiber in the bale. Further, the filaments could be cut into any length uniformly unlike that of cotton and linen. Later it was found that they could be made to have cotton-like properties of softness and hand, have ignition, sunlight and rot resistance among other properties that could be built into the fibers as they were being spun. Thus, it was found that the fibers could be engineered to have specific properties depending upon the desired end uses of the product. Today, the number of different genera of fibers that have been produced for textile purposes is quite high.

1.1 Generic Names of Fibers

In addition to the chemical nomenclature (Section 2.1), the Federal Trade Commission (FTC) has defined generic categories of fibers based on chemistry and properties. Each category has been assigned a generic name. Basically, any consumer textile item sold in retail commerce must carry a label declaring the generic name and the percent by weight of all the component fibers in the composition (which exceed 5% of the total). Certain items like luggage, carpet backing, hats, wiping rags, furniture stuffing, and tarps are exempted, as are items intended for industrial applications. A manufacturer may label the fibers with trade names and other information specific to the manufacturer, but the generic names of fibers and the percent composition must always be present. The purpose of a generic name is to provide the consumer with a recognized name with which to associate a set of expected fiber properties. Some fibers find little or no use in consumer textiles, and may not have an established generic name.

Generic names for manmade fibers are defined by the chemistry of the fiber and its physical properties. New names may be added and older ones modified in definition as demanded by technology and developments. When believed required, a manufacturer can petition the FTC for the establishment of a new generic name. In response, the FTC will examine the chemistry of the new fiber as well as its properties, and then decide whether a new name is warranted. Natural fibers are labeled according to their origin. Thus cotton, linen, silk, wool, etc., are legitimate generic names.

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of chemicals, and does not have extensive applications in industrial fabrics. Other hair fibers will differ in size, pigmentation, scale frequency, and harvesting methods. Hair fibers are most often used for apparel and carpeting. A generalized structure of a protein is shown below.

$$-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-$$

R =	Alanine	Glycine	Phenylalanine	Tryptophan
	Arginine	Histidine	Proline	Tyrosine
	Aspartic Acid	Leucine	Serine	Valine
	Cystine	Lysine	Threonine	Isoleucine
	Glutamic Acid	Methionine		

Silk

Silk is a protein fiber like wool but with a much simpler structure. It is an extruded fiber which is chemically and structurally uniform across its diameter. The amino acids have smaller pendant groups than those found in wool, allowing a pleated-sheet structure rather than helical to occur.

$$-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-N-C-\overset{\overset{\displaystyle O}{\|}}{C}-$$

R = Alanine, Glycine, Serine, or Tyrosine
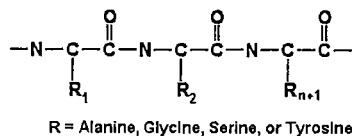
Because no cystine is present, no crosslinking occurs. Silk has no cellular structure, no scales, and no pigment. The silkworm uses the silk to construct a home in which to undergo metamorphosis. A silkworm's cocoon is unwound to produce a natural, continuous filament fiber. Observation of the silkworm at work gave man the idea for extrusion of fibers. Although wool and silk are generally weak, other insects, such as spiders, can produce a very strong protein fiber. Indeed it seems that with a greater understanding of protein structures, a fiber having an optimal choice of physical properties may be designed.

3. MAN-MADE FIBERS

Man-made fibers are those produced by human endeavor. They may be further categorized into regenerated and synthetic classes. Regenerated fibers (such as rayon) are those created from polymeric materials produced in nature. Synthetic fibers have no natural polymeric precursors. Thermoplastic polymers such as nylon or polyester are examples of this category.

Table 2.2 lists common man-made fibers. FTC definition, chemical structure and important properties of the fibers are given below.

3.1 Acetate

"A manufactured fiber in which the fiber-forming substance is cellulose acetate. Where not less than 92% of the hydroxyl groups are acetylated, the term triacetate may be used as a generic description of the fiber." Two varieties of acetate are produced which are secondary cellulose acetate and cellulose triacetate. As the name implies, they describe the approximate number of hydroxyls of the cellulose which are replaced by acetyl groups. These acetyl groups confer new properties to the cellulosic polymeric chains, chief of which is high loss of water absorbency, i.e., the fibers are hydrophobic (water hating) in nature. They are dry spun by spinning solutions of the cellulose derivatives dissolved in low boiling volatile solvents into hot air whereupon the solvent is evaporated resulting in a solid continuous thread of the cellulose acetate polymer.
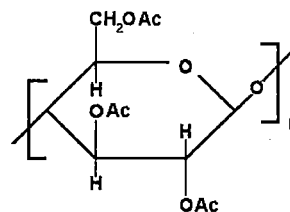
During the fiber extrusion process, either pigments can be added to the spinning dope to color the threads or delustering agents in order to modify (dull) the luster characteristics of the fibers. In addition, other agents can be added to the spin solutions to impart sunlight and ignition resistance to the fibers. The fibers of the yarns can be spun into any denier, cut into any staple length. Further, they are resistant to mildew and insects that damage cellulosic fibers. The fibers are lighter in weight (less dense) than cellulosic fibers (density is 1.32 compared to 1.52 for cotton and rayon).

acrylonitrile units — The term "lastrile" may be used as a generic description for this form of rubber.

$$-[CH_2-CH]_n-CO-[CH_2-CH=CH-CH_2]_n-$$
(with $C\equiv N$ group)
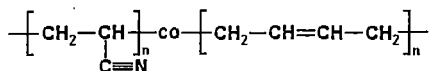
- a manufactured fiber in which the fiber forming substance is a polychloroprene or a copolymer of chloroprene in which at least 35% by weight of the fiber forming substance is composed of chloroprene units ($-CH_2-(Cl)C=CH-CH_2-$).

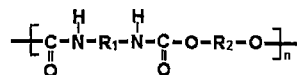$$-[CH_2-C=CH-CH_2]_n-$$
(with Cl group)
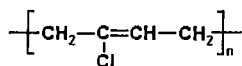
3.17 Saran

"A manufactured fiber in which the fiber forming substance is any long chain synthetic polymer composed of at least 80% by weight of vinylidene chloride units." Saran is usually produced in a specialized monofilament form for flame retardant and chemical resistance applications. The most familiar consumer usage is in film or coating form.

$$-\left[\begin{array}{cc} H & Cl \\ C & C \\ H & Cl \end{array}\right]_n-$$
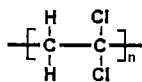
3.18 Spandex

"A manufactured fiber in which the fiber-forming substance is a segmented polyurethane." Spandex is an elastomeric fiber used for clothing materials, and finds application in industrial textiles in such places as elastic bands in protective apparel. It is a block copolymer composed of stiff rigid blocks interspersed with soft flexible blocks. In general, the soft blocks have been either aliphatic polyesters or polyethers. A single chemical structure cannot be drawn for Spandex, but a generalized structure is shown below.

$$-\left[C-N-R_1-N-C-O-R_2-O\right]_n-$$
(with O, H, H, O groups)

3.19 Sulfar

"A manufactured fiber in which the fiber-forming material is a long synthetic polysulfide in which at least 85% of the sulfide linkages are attached directly to two aromatic rings." As with other aromatic based fibers, sulfar finds utility from its special stability to environmental challenges. Sulfar is particularly chemically resistant, and finds most of its applications in industrial fabrics.

$$-\left[\bigcirc-S\right]_n-$$
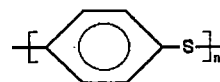
3.20 Vinal

"A manufactured fiber in which the fiber forming substance is any long chain synthetic polymer composed of at least 50% by weight of vinyl alcohol units ($-CH_2-CHOH-$), and in which the total of the vinyl alcohol units and any one or more of the various acetal units is at least 85% by weight of the fiber." Although the polymer is manufactured in large qualities for a variety of glue and coating applications, there is no vinal fiber currently manufactured in the United States. The water solubility of the vinal fiber must be overcome (usually by formaldehyde crosslinking) in order to produce a durable product.

$$-\left[\begin{array}{cc} H & H \\ C & C \\ H & OH \end{array}\right]_n-$$
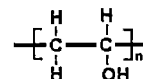
3.21 Vinyon

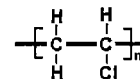"A manufactured fiber in which the fiber forming substance is any long chain synthetic polymer composed of at least 85% by weight of vinyl chloride units." Vinyl (PVC) is almost the universal plastic film, finding application in almost everything, e.g., notebooks, electrical cords, outdoor furniture, and automobile trim.

$$-\left[\begin{array}{cc} H & H \\ C & C \\ H & Cl \end{array}\right]_n-$$

3.1

Manufacture of Man-Made Fibers

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1. INTRODUCTION

Textile fibers are solids with distinct shapes. The primary task in fiber manufacture is to transform solid materials into a fiber configuration. The liquid state is the only condensed state that can easily deform or have its shape changed. In its simplest form, fiber manufacturing processes consist of liquefying a solid polymer, transforming it into the shape of a fiber, and then resolidifying the liquid.

In the 1600s, Robert Hooke and other scientists noted that spiders and silkworms had developed the process of converting solids to liquids, and back to solids, but reshaped as filaments. These early scientists speculated that man would one day be capable of duplicating this natural extrusion process. Early researchers were able to extrude fibers by drawing or pulling liquid threads from solutions of natural gums and resins. An industrialist in Manchester, England, is credited with the design and construction of the first fiber producing machine. However, the materials used in this instrument were not suitable fiber forming polymers. Audemars was awarded a patent for the production of cellulose nitrate fibers in 1855, but the first commercially successful concept of production was not developed until the 1880s. In 1891, Chardonnet's facility began production of regenerated cellulose fibers. This success was followed by the development of the cuprammonium process by Despeisses, which was commercialized in 1897. Cross and Bevan invented the viscose process about 1892, which was further refined to a more practical process by Stearn and Topham between 1895 and 1900. These early pioneers not only had to develop the chemistry necessary to dissolve and resolidify cellulose without severe degradation, they also had to invent the machinery necessary for fiber production. Table 3.1 shows the important events in the history of man-made fibers.

Energy is required to convert a solid polymer to its liquid state. That energy can be developed either from heat, chemical solvents, or a combination of the two. If heat supplies the energy, the polymer is solidified in fiber shape simply by cooling. If chemical solvents are used, there are two ways of resolidifying the polymer into a fiber shape. The solvent can be evaporated, or the polymer solution can be precipitated by immersion in a non-solvent. The three ways of resolidification are used as a basis to classify fiber extrusion processes (Table 3.2). This rather simple classification scheme does not reveal the true complexity of the processes. Some of the more recently developed polymers require very sophisticated processes. For example, high strength aramid fibers are produced through a wet spinning process, but the polymer solution exists in a liquid crystalline state. High strength polyethylene fibers are created through the extrusion of an ultra high molecular weight melt or gel state. This melt/gel is highly viscous, having some of the characteristics of a solid. Even the viscose process has chemical reactions proceeding during the solidification, so it is not entirely a precipitation.

2. MELT SPINNING (EXTRUSION)

A diagram of the basic melt spinning (extrusion) process is shown in Figure 3.1. Some operations which proceed directly from polymer manufacture to extrusion may use a pump instead of a screw type extruder. All fiber spinning sys-

3.2

Manufacture of Continuous Filament Yarns

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The manufacture of continuous filament yarn is a relatively simple matter of collecting the number of individual filaments necessary to produce the desired yarn size. As manufactured by the fiber producing companies, they are called "producer's yarns." They contain minimum twist, ranging from about zero to 2.5 turns per inch, which is just sufficient to maintain the yarn's integrity.

Most producer's yarn is delivered with a thin resinous finish or size which protects the filaments from damage due to abrasion and snagging. The finish, amounting usually to less than one percent by weight, may or may not be water soluble. Such finishes should not be confused with water soluble sizes such as starch, gelatin, or synthetic resins, which are applied to warp yarns at the mill to give additional protection during weaving. Sometimes a light lubricant is also applied to the yarn by the producer or the mill. This improves running quality by reducing static and friction, and reduces abrasion of the yarn and wear on the textile machinery guides, rollers, etc.

Because of filament uniformity and the complete absence of protruding fiber ends, continuous filament yarns are particularly smooth and lustrous. Such properties are advantageous in the manufacture of many fabrics, but a high degree of filament and yarn uniformity is necessary. Even minor irregularities will be observed as fabric defects due to changes in luster, dye pickup, irregular yarn twist or yarn spacing. Producers must always be on the alert to insure yarn uniformity, both within a package and among packages. Any differences in the amount that the yarn is drawn during manufacture will be manifested as differences in optical and physical properties, for example, dye absorption and residual rupture elongation. Excessive elongation at the beginning or end of the yarn package can result in fabrics with visually obvious defects. Staple yarns, being less uniform, can afford more irregularities, without the danger of the resulting fabrics being considered "defective."

1. THROWING AND TWISTING

There are so many different filament yarn constructions required by textile mills that it is quite impossible for the man-made fiber manufacturer to have all of them available, or make them on order. Instead the fiber producer sells several popular sizes, packaged usually on a standard spool. The textile mill must then arrange to have the producer's yarn converted into the desired yarn of proper weight, twist and ply, properly sized, lubricated, and packaged for subsequent mill operations. These procedures are collectively called "throwing." Throwing may be carried out by the mill which will ultimately weave or otherwise use the yarn, or by a commission "throwster." The term usually applies to the preparation of relatively lightweight yarns, in contrast to "twisting" which pertains to the preparation of heavier yarn constructions. More recently, the term also applies to a company that specializes in texturing yarns.

It is usually impractical to make a heavy yarn by twisting many units or ends of producer's yarn together in the same direction. Such a yarn would be soft, bulky, unstable, and might have low strength. Instead, plied yarns are constructed. Several turns of twist are inserted in one direction into the singles producer's yarn, and then several of these are twisted together, usually in the opposite direction, to make the plied yarn. Several

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4.1

Classification of Fabrics

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A fabric may be defined as a planar assembly of fibers, yarns or combinations of these. There are many different methods of fabric manufacturing, each capable of producing a great variety of structures dependent upon the raw materials used and the setup of control elements within the processes involved. The particular fabric selected for a given application depends on the performance requirements imposed by the end use and/or the desired aesthetic characteristics of the end user with consideration for cost and price. Fabrics are used for many applications such as apparel, home furnishings and industrial. The most commonly used fabric forming methods are interlacing, interlooping, bonding and tufting.

1. INTERLACING (WEAVING AND BRAIDING)

Weaving—interlacing of a lengthwise yarn system (warp) and a widthwise yarn system (filling) at 90 degrees to one another with fabric flowing from the machine in the warp direction [Figure 4.1(a)].

Braiding—interlacing of two yarn systems such that the paths of the yarns are diagonal to the fabric delivery direction forming either a flat or tubular structure [Figure 4.1(b)].

2. INTERLOOPING (WEFT AND WARP KNITTING)

Knitting—interlooping of one yarn system into vertical columns and horizontal rows of loops called wales and courses respectively with fabric coming out of the machine in the wales direction [Figure 4.1(c) and Figure 4.1(d)].

3. TUFTING

"Sewing" a surface yarn system of loops through a primary backing fabric into vertical columns (rows) and horizontal lines (stitches) forming cut and/or uncut loops (piles) with the fabric coming out of the machine in the rows direction as shown in Figure 4.1(e). Fabric must be back-coated in a later process to secure tufted loops.

4. BONDING (NONWOVENS)

Nonwovens—using either textile, paper, extrusion or some combination of these technologies to form and bond polymers, fibers, filaments, yarns or combination sheet into a flexible, porous structure [Figure 4.1(f)].

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(c) weft knit

(f) nonwoven

(b) braided

(e) tufted
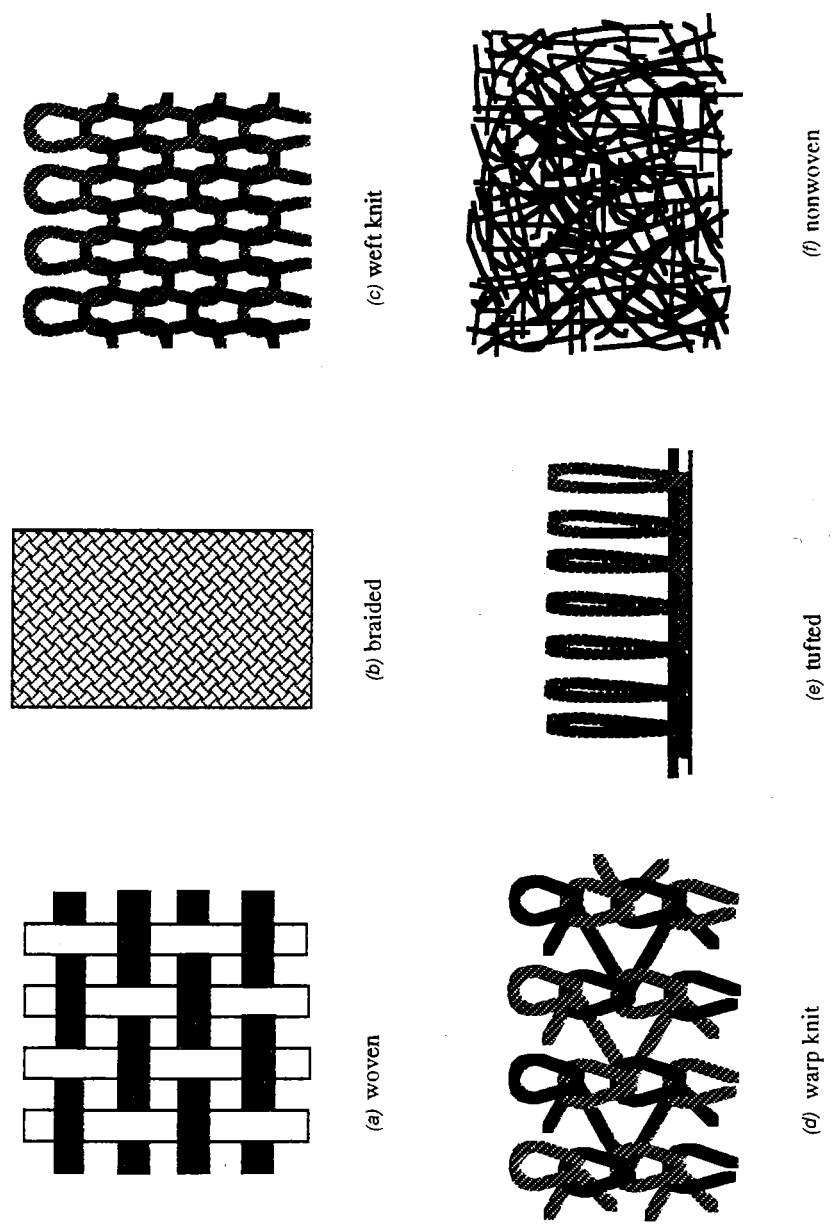
FIGURE 4.1 Types of fabrics.

(a) woven

(d) warp knit

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the traditional weaving machine. These developments include the circular loom and several different multi-phase weaving systems such as warp direction shed waves and weft direction shed waves. These multi-phase concepts offer an advantage in production rate, gained by providing segmented sheds along either the warp or the filling direction of the structure coupled with progressive, simultaneous filling insertions. Although some of these new multi-phase systems and circular looms are being used in limited fabric markets, none of them has challenged traditional weaving machines in major fabric markets so far [5].

4.5

Knitting

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1. INTRODUCTION

As defined earlier, knitting involves the inter-looping of one yarn system into continuously connecting vertical columns (wales) and horizontal rows (courses) of loops to form a knitted fabric structure. There are two basic types of knit structures as shown in Figure 4.1: weft knit and warp knit. Figure 4.46 shows a circular weft knitting machine.

In weft knitting, the yarn loops are formed across the fabric width, i.e., in the course or weft direction of the fabric. In warp knitting, the loops are formed along the fabric length, i.e., in the wale or warp direction of the cloth. In both knitting systems the fabric is delivered in the wale direction. Special needles are used to form the yarn loops as shown in Figure 4.47. The latch needle is the most common type in use for weft knitted fabrics and the compound needle is used mostly in warp knitting. Spring beard needles are becoming obsolete.

The basis of knit fabric construction being the continuing intersecting of loops, any failure of a loop yarn will cause a progressive destruction of the loop sequence and a run occurs. Thus, knitting yarns must be of good quality in order that yarn failures be kept at a minimum. Other important geometrical definitions relating the knit structures are as follows:

- count: total number of wales and courses per unit area of the fabric
- gauge: the number of needles per unit width (the fineness or coarseness of the fabric)
- stitch: the loop formed at each needle

(the basic repeating unit of knit fabric structure)
- technical face: the side of the fabric where the loops are pulled toward the viewer
- technical back: the side of the fabric where the loops are pulled away from the viewer

Industrial application areas of knit structures include medical products such as artificial arteries, bandages, casts, and surgical gauze and flexible composites. Knit fabrics are used as reinforcing base for resins used in cars, boats, and motorcycle helmets.

2. WEFT KNITTING

Weft knit goods are made by feeding a multiple number of ends into the machine. Each loop is progressively made by the needle or needles. Figure 4.48 shows the loop forming process with a latch needle. The previously formed yarn loop actually becomes an element of the knitting process with the latch needle. This is why the latch needle is referred to as the "self-acting" needle. As the needle is caused to slide through the previous yarn loop, the loop causes the swiveled latch to open, exposing the open hook (head) of the needle. The newly selected yarn can now be guided and fed to the needle. If a simple knitted loop is to be formed, the previous loop (the one which opened the latch) must slide to a point on the needle stem allowing it to clear the latch. Having the needle reach this clearing position allows a reversal of the sliding action which
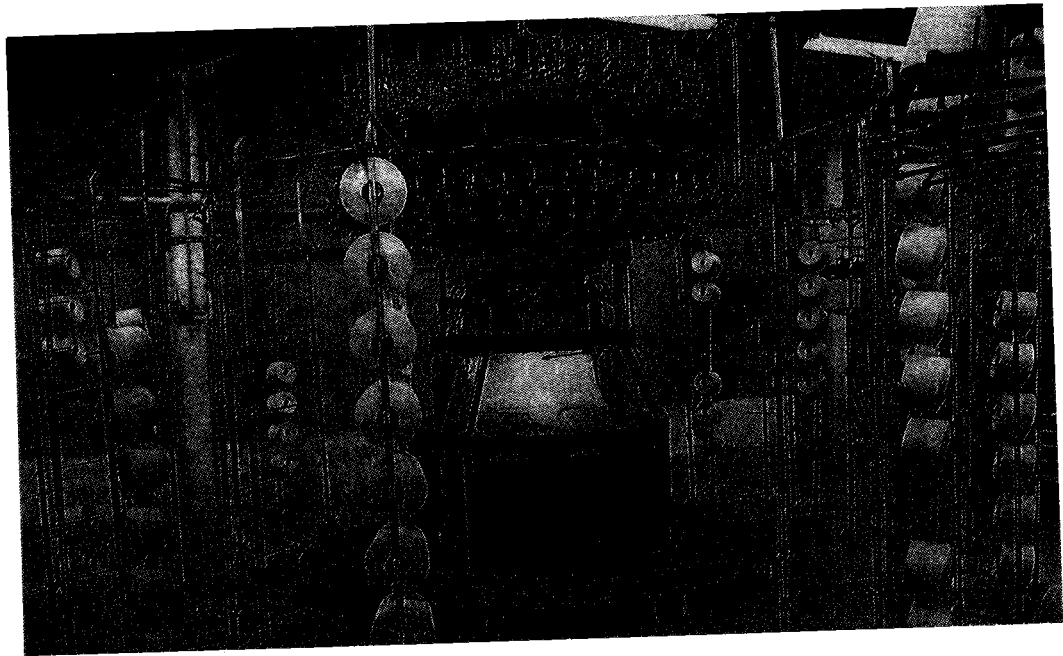
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FIGURE 4.46 Circular weft knitting machine.

in turn pulls down on the new yarn and uses the previous yarn loop to close the latch trapping the new yarn inside the hook. The previous loop is now in a position to ride over the outside of the latch and be cast off the needle head, thus becoming a part of the fabric while the new yarn loop is pulled through the previous loop.

Depending on the structure in weft knitting, several types of knitting stitches are used includ-

ing plain [Figure 4.1(c)], tuck, purl (reverse), and float (miss) stitch which are shown in Figure 4.49. The plain stitch fabric has all of its loops drawn through to the same side of the fabric. The plain fabric has a very smooth face and a rough back. Other stitches produce different effects depending on the arrangement of the loops. Special stitches are also available to prevent runs.

Weft knitting machines may be either flat or
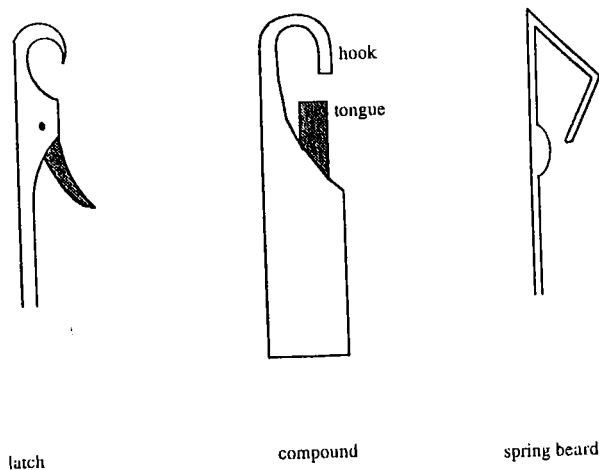

latch   compound   spring beard

FIGURE 4.47 Needle types used in knitting.
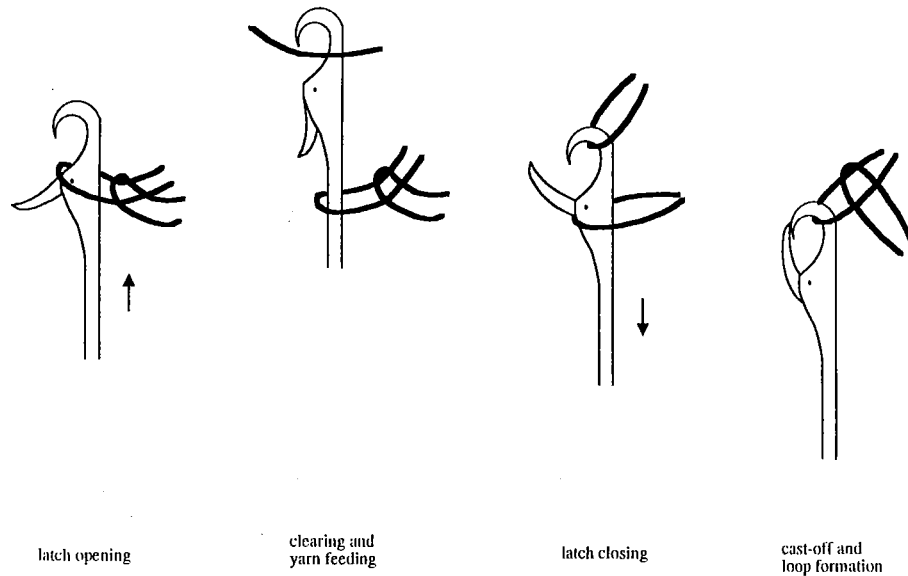
FIGURE 4.48 Loop forming on a latch needle.

circular, the former knitting a flat single layer of fabric, the latter knitting a continuous tube. No matter which machine configuration is used, weft knit manufacturing involves the same fundamental functions:

- yarn selection and feeding
- needle knitting action
- fabric control during knitting
- needle selection
- fabric take-up and collection

There are several devices added to weft knitting machinery for improving quality of the product and/or operation of the process. A partial list of these added features includes:

- yarn break sensors
- fabric hole detectors
- needle "closed latch" sensors
- air blowing systems to keep needles clear of lint
- centralized lubrication dispensing unit
- computer interfaces for production monitoring
- computer interfaces for pattern entry
- computer aided design systems

Knit fabrics can be classified as single knits and double knits. Single weft knits have one layer of loops formed with one yarn system. Three major types of single weft knits are jersey, rib and purl structures. Double knits have two insepa-

FIGURE 4.49 Types of stitching in weft knitting.

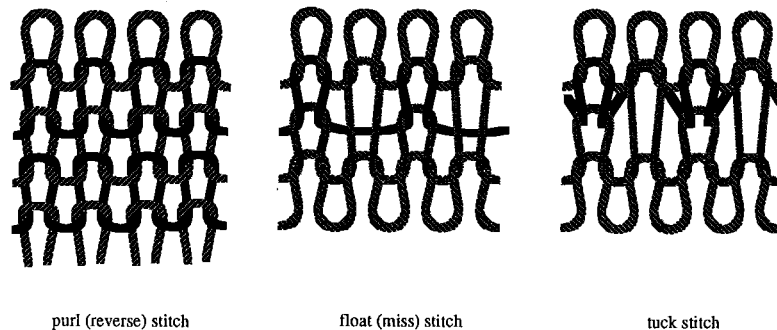rable layers of loops. Each yarn forms loops that appear on both faces of the fabric. Two major types of double knits are rib double knit and interlock double knit.

The major characteristics of weft knit fabrics are as follows:

- can be either manufactured as net-shape or cut to shape and sewn
- form a run the wale direction if a yarn breaks
- have good stretch especially in the course direction
- do not ravel
- do not wrinkle easily and have good recovery from wrinkling and folding

3. WARP KNITTING

Warp knit fabrics are manufactured by preparing the equivalent of a warp beam containing several hundred ends. Each end passes through its own needle and is formed into loops which intersect with adjacent loops. Thus, a flat looped fabric is knitted using only "warp" yarns without the necessity of "filling" yarns being interwoven.

The two major types of warp knits are tricot and Raschel. Based on the number of yarns and guide bars used, tricot knits are identified as single [Figure 4.1(d)], two (Figure 4.50), three and four (or more) bar tricots. Raschel knitting is suitable for making highly patterned, lacy, crocheted or specialty knits (Figure 4.51). In general, Raschel machines are used for the production of knit structures for industrial applications. For increased structural support in the filling direction, additional filling yarns can be inserted as shown in Figure 4.52.

Figure 4.53 shows a schematic of a warp knitting machine. The knitting elements required for a warp knitting machine include:

- needles arranged in one or more solid bar to function as a unit (called a needle bar)
- yarn guides, one for each warp yarn, arranged in solid bars, one for each different warp, to function as a unit (called guide bars)
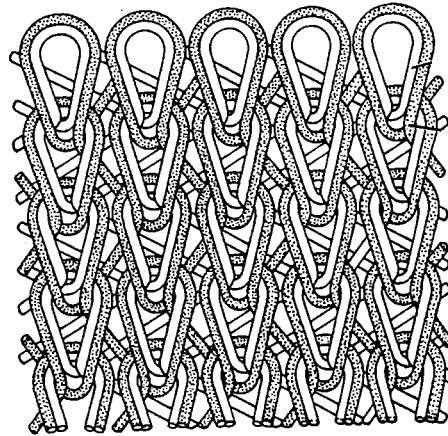

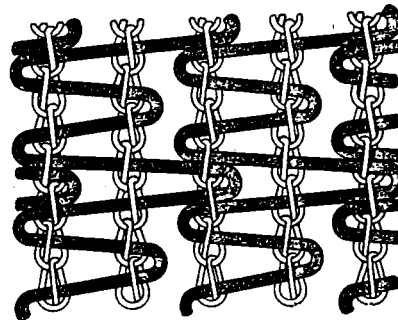**FIGURE 4.50** A two-bar tricot (courtesy of Noyes Publications).

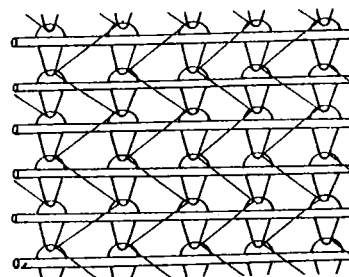**FIGURE 4.51** Simple Raschel crochet knit (courtesy of Noyes Publications).

FIGURE 4.52 Weft inserted warp knit structure (courtesy of Karl Mayer).

Dyeing, Printing and Finishing

W. PERKINS

Greige fabric as it comes from the manufacturing machine may or may not be ready for its end-use function. If fabrics are to be dyed, coated, impregnated, preshrunk or otherwise finished, it is usually necessary to remove the warp size and other impurities which may interfere with dyeing or prevent proper adhesion of a coating or finish.

1. PREPARING FABRICS FOR DYEING AND FINISHING

Most textile materials and fabrics require pretreatments before they can be dyed and finished. The required preparatory treatments depend on the type of fiber in the material and particular dyeing and finishing treatments that are to be done. Generally, fibers containing the most types and the greatest amount of impurities require the greatest amount of preparation for dyeing and finishing.

Most preparatory processes for dyeing and finishing involve heating the fabric or treating it with chemicals. Therefore, the potential is present for thermal and chemical damage to the fibrous polymer comprising the fabric. Fabrics can also be damaged mechanically in most preparatory processes. High temperature thermal treatments are often beneficial to fabrics containing thermoplastic fibers while these treatments are not beneficial or desirable on fabrics containing only non-thermoplastic fibers.

The following discussion of preparation for dyeing and finishing is general and reference is made to many types of fibers and textile materials.

Typical processes for preparation of materials for dyeing and finishing are as follows:

- heat setting
- singeing
- desizing
- scouring
- bleaching
- mercerizing

The sequence shown is common but many variations may be used. Virtually all materials go through some of these processes prior to dyeing and some materials in fabric form are subjected to all of them.

1.1 Heat Setting

The dimensional stability, dyeability, and other properties of thermoplastic fibers are affected by repeated heating and cooling, or the heat history, of the material. The main purposes of heat setting are as follows:

- to stabilize the material to shrinkage, distortion, and creasing
- to crease, pleat, or emboss fabrics
- to improve the dyeability of fabrics

Heat relieves stresses in the amorphous regions of thermoplastic fibers. When the fiber is heated above its glass transition temperature, the molecules in the amorphous regions can move, and the material can be formed into a new shape. When the temperature is decreased, the material stays in its new shape. Thus, creases that have developed in the fabric can be pulled out, and the width of the fabric can be changed somewhat in the heat setting process. Creases can be per-

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manently set in the fabric by heat setting if desired. Heat setting is used to permanently set twist and crimp in yarns.

Problems or defects that may be caused by heat setting or improper control of the heat setting process include the following:

- permanent set wrinkles
- strength loss
- improper hand or feel in the fabric
- permanent set stains
- non-uniform dyeing
- improper fabric width or weight

1.2 Singeing

In singeing, the fibers that protrude from the fabric are burned away to give the fabric a smoother surface. Singeing is usually done by passing the fabric through a burning gas flame at high speed followed by quenching in water or the desizing bath to extinguish the smoldering fibers. Alternatively, the fabric may be passed close to a very hot plate to ignite the protruding fibers. Singeing is sometimes done after scouring since heating of the fabric in the singer can increase the difficulty of removing size and soil from the fabric.

Extreme care must be taken when singeing fabrics containing thermoplastic fibers. Thermoplastic fibers such as polyester melt when singed, and the fiber ends form beads on the fabric surface.

Yarns, sewing threads, felts, and carpet backing can also be singed. Yarn singeing is usually called gassing.

1.3 Desizing

Desizing is the process of removing the size material from the warp yarns in woven fabrics. Most of the size must be removed before the fabric can be dyed satisfactorily. Residual size prevents the yarns and fibers from wetting quickly and can affect dye absorption in either batch or continuous dyeing. Most synthetic sizes are water soluble by design so that they can be easily washed from the fabric. Typical synthetic sizes are polyvinyl alcohol, acrylic copolymers, and carboxymethyl cellulose. Starch is also com-

mon in size formulations. Starch is not very soluble in water and must be chemically degraded in order to remove it from the fabric. Starch used in sizing is often modified to improve its properties and removability in desizing. Lubricants added to size formulations to enhance the fabric manufacturing process may be more difficult to remove than the size itself. Virtually all size formulations contain lubricants derived from natural fats and waxes. Virtually complete removal of these lubricants is required before the fabric can be dyed. The desizing step removes mostly size and not much lubricant. Most of the lubricant is removed in the scouring process.

Fabrics containing only water soluble sizes can be desized using hot water perhaps containing wetting agents and a mild alkali. Fabrics that contain starch are usually desized with enzymes. Enzymes are complex organic substances that catalyze chemical reactions in biological processes. They are formed in the living cells of plants and animals. A particular enzyme catalyzes a very specific reaction. An enzyme is usually named by the kind of substance degraded in the reaction it catalyzes. Thus, enzymes that hydrolyze and reduce the molecular weight of starch are called amylases because they hydrolyze the amylose and amylopectin molecules in starch. The hydrolysis of starch catalyzed by amylase enzymes produces starch fragments that are soluble enough to be washed from the fabric. Mineral acids and oxidizing agents can also be used to degrade starch so that it can be removed in desizing.

1.4 Scouring

Scouring of textile materials refers to removal of impurities by wet treatments so that the impurities do not interfere with dyeing and finish applications. The amounts and types of impurities present depend on the type of fiber in the material. Materials containing only synthetic fibers usually contain only the lubricants that have been added to aid in manufacturing of the material and soil deposited on the material in manufacturing processes and handling. Up to 2/3 of raw wool is impurities such as suint (dried perspiration), dirt, and fat or grease. Most of these impurities must be removed; so preparation of wool is quite different from and more

up in a separate container. After dyeing, each individual warp is back wound onto a warper beam (section beam) and becomes a supply package for the slasher.

3. PRINTING

Printing produces localized coloration of textile materials. Each color applied in a printing process must be applied in a separate step or position in the printing machine. Printing methods may be classified as direct, discharge, or resist.

(1) Direct printing—Dye in a thickened formulation is applied to selected areas of the fabric producing a colored pattern.

(2) Discharge printing—A discharging agent destroys dye on selected areas on a fabric which was previously dyed a solid shade. A white pattern remains where the dye was discharged. Alternatively, a discharge formulation containing dyes that are resistant to discharging produces a second color where the discharge is applied to the previously dyed fabric.

(3) Resist printing—Dye is applied to a fabric but not fixed. A resist formulation is printed on selected areas of the fabric. The resist agent prevents fixation of the dye in subsequent processing. The unfixed dye is washed away leaving a white pattern. If the resist agent is applied before the dye, the method is called a preprint process. If the dye is applied first followed by the resist formulation, the method is called an overprint process.

Printing methods may also be classified according to the process used to produce the pattern. Screen printing and roller (gravure) printing are the two most common printing methods used in textiles. Ink jet printing, heat transfer printing, and methods based on reliefs are also practiced in textiles.

Screen printing uses the principle of stencils. It is a resist method in the sense that the screen is made to resist penetration by the print formulation in areas where printing is not desired. Dye or pigment in a thickened formulation is forced by a blade or roller called a squeegee through a permeable screen onto a fabric underneath the screen. Screen printing may be done with either flat or cylindrical screens.

The printing mechanism in roller printing (gravure printing) is intaglio. A print roller is engraved with a pattern. Color deposited in the engravings is transferred to the fabric in the printing process.

4. FINISHING

Finishing is a general term which usually refers to treatments on textile fabrics after dyeing or printing but before the fabrics are cut and sewn into final products. However, many of the finishing principles covered in the following sections apply to treatment of yarns and garments as well.

Finishes have a wide variety of functions all of which are intended to make the fabric more suitable for its intended use. Functions of finishes include the following:

- Accentuate or inhibit some natural characteristic of the fabric. Examples are softening, stiffening (firming), delustering, brightening, and changing surface characteristics.
- Impart new characteristics or properties to the fabric. Durable press finishes, flame retardant finishes, and many other chemical treatments are examples of finishes which impart new characteristics.
- Increase life and durability of the fabric.
- Set the fabric so it maintains its shape and structure.
- Set dyes.

Finishes may be categorized as mechanical or chemical. Often, mechanical finishing is thought of as modification of dry fabric by a machine and chemical finishing as treatment of fabric with aqueous solutions of chemicals. However, this distinction sometimes fails because water and chemical formulations are often used in treatments that are best classified as mechanical finishes. Furthermore, most chemical finishes involve the use of machines which subject the fabric being finished to various degrees of mechanical action. Perhaps finishes can best be classified as mechanical or chemical depending

AFTER 8 YEARS

IN %

THICKNESS

BREAKING LOAD — WARP / WEFT

BREAKING ELONGATION — WARP / WEFT

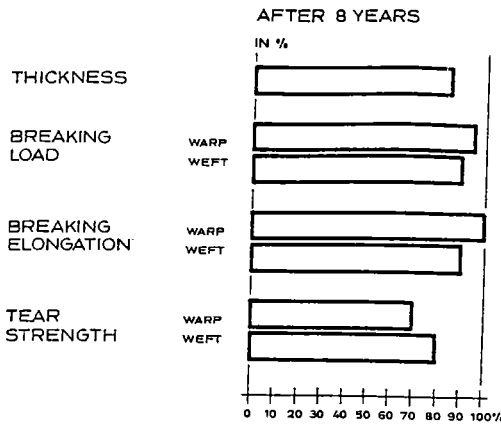TEAR STRENGTH — WARP / WEFT

0 10 20 30 40 50 60 70 80 90 100%

FIGURE 6.3 Residual properties of PVC coated polyester fabric after eight years of use in air structure (The Textile Institute [5]).

years of loading, revealed that the strength loss was around 10%. In another study on PVC coated polyester fabrics after eight years in an air structure, similar results were found which are shown in Figure 6.3. The rather low tear strength is the result of the brittleness developed in the fabric during its use.

Blumberg compared Teflon® coated fiberglass fabric with PVC coated polyester fabric. His results are shown in Figure 6.4.

Coated fabrics made of synthetic fibers have replaced conventional canvas cloth, which is generally made of cotton, almost in every application. The reason for this is the improved
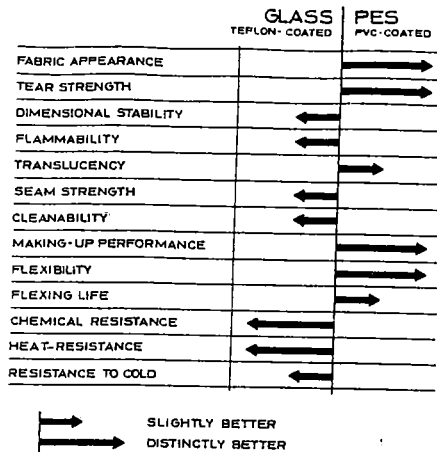
properties of synthetic coated fabrics. Figure 6.5 shows the stress-strain curves of canvas cloth and coated nylon and polyester fabrics.

3. APPLICATIONS OF COATED FABRICS IN BUILDING STRUCTURES

Membrane structures can be divided into four categories: tent, clear-span, air and tensile structures. Although each structure type has specific characteristics, there are some structures that may fall under more than one category. Some manufacturers categorize membrane structures by temporary or permanent usage. The common denominator in all of the membrane structures is textile fabric. The most widely used textile materials for architecture and construction are polyester coated with polyvinyl chloride (PVC), woven fiberglass coated with polytetrafluoroethylene (PTFE) and silicone-coated fiberglass. Figure 6.6 shows application examples of textiles in architecture and construction.

3.1 Tents

Tents and shelters were probably the first constructions in which textiles were used as building materials. Tents have been traditionally used for various purposes by nomadic people, traders, military, explorers, and campers. More recently,

	GLASS TEFLON-COATED	PES PVC-COATED
FABRIC APPEARANCE		→
TEAR STRENGTH		→
DIMENSIONAL STABILITY	←	
FLAMMABILITY	←	
TRANSLUCENCY		→
SEAM STRENGTH	←	
CLEANABILITY	←	
MAKING-UP PERFORMANCE		→
FLEXIBILITY		→
FLEXING LIFE		→
CHEMICAL RESISTANCE	←	
HEAT-RESISTANCE	←	
RESISTANCE TO COLD	←	

→ SLIGHTLY BETTER
➡ DISTINCTLY BETTER

FIGURE 6.4 Comparison of Teflon® coated glass fabric and PVC coated polyester fabric (The Textile Institute [5]).

FIGURE 6.5 Tensile behavior of linen canvas cloth and synthetic coated fabrics. 1: linen canvas, 2: PVC coated nylon, 3: PVC coated polyester fabric. Prime (') indicates filling direction testing (Elsevier Science [2]).

Modular shelters Exhibition stands Sun shade

Polyvalent hall Covered tennis courts Storage hall

Polyvalent hall Covered terrace Military equipment hangars

Removable inflatable roof Storage hangars Radar cover

Tribune cover Covered pedestrian lane Service station

Sport centre Bicycles shelters Escalator exit

Façade blinds Architectural blinds Office blinds

Solar protection for glass roof conservatory blinds glass dome cover

FIGURE 6.6 Application examples of industrial fabrics in architecture and construction (courtesy of Ferrari).

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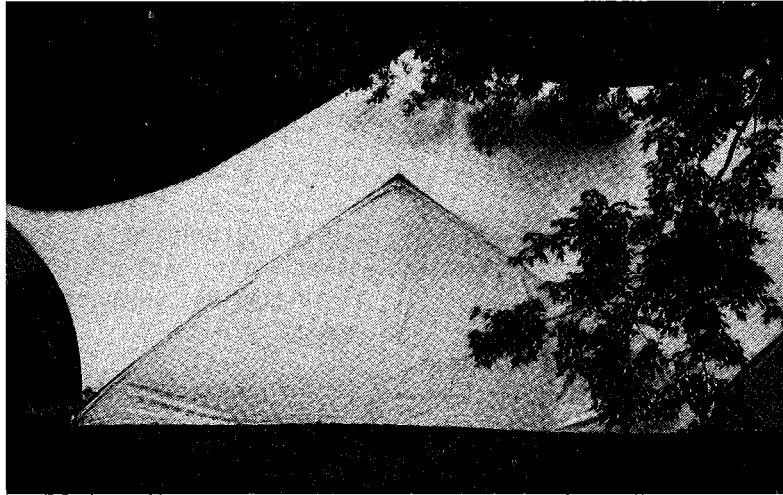
FIGURE 6.7 Pole tent (courtesy of Armbruster Manufacturing Co.).

new tent constructions were developed for building construction, business, exhibitions, entertainment, leisure and recreation.

In pole tents, the fabric is draped or hung rather than tensioned (Figure 6.7). Tension tents include various tensile structure characteristics and therefore fall between tents and tensile structures (Figure 6.8). Tensile tents have tensioned fabric that provides clear span and they do not require guys. Pole tents and tensile tents are mass produced.

The most widely used fabrics for tent walls are polyesters and vinyls. Table 6.3 shows typical properties of heavy duty coated tent fabrics.
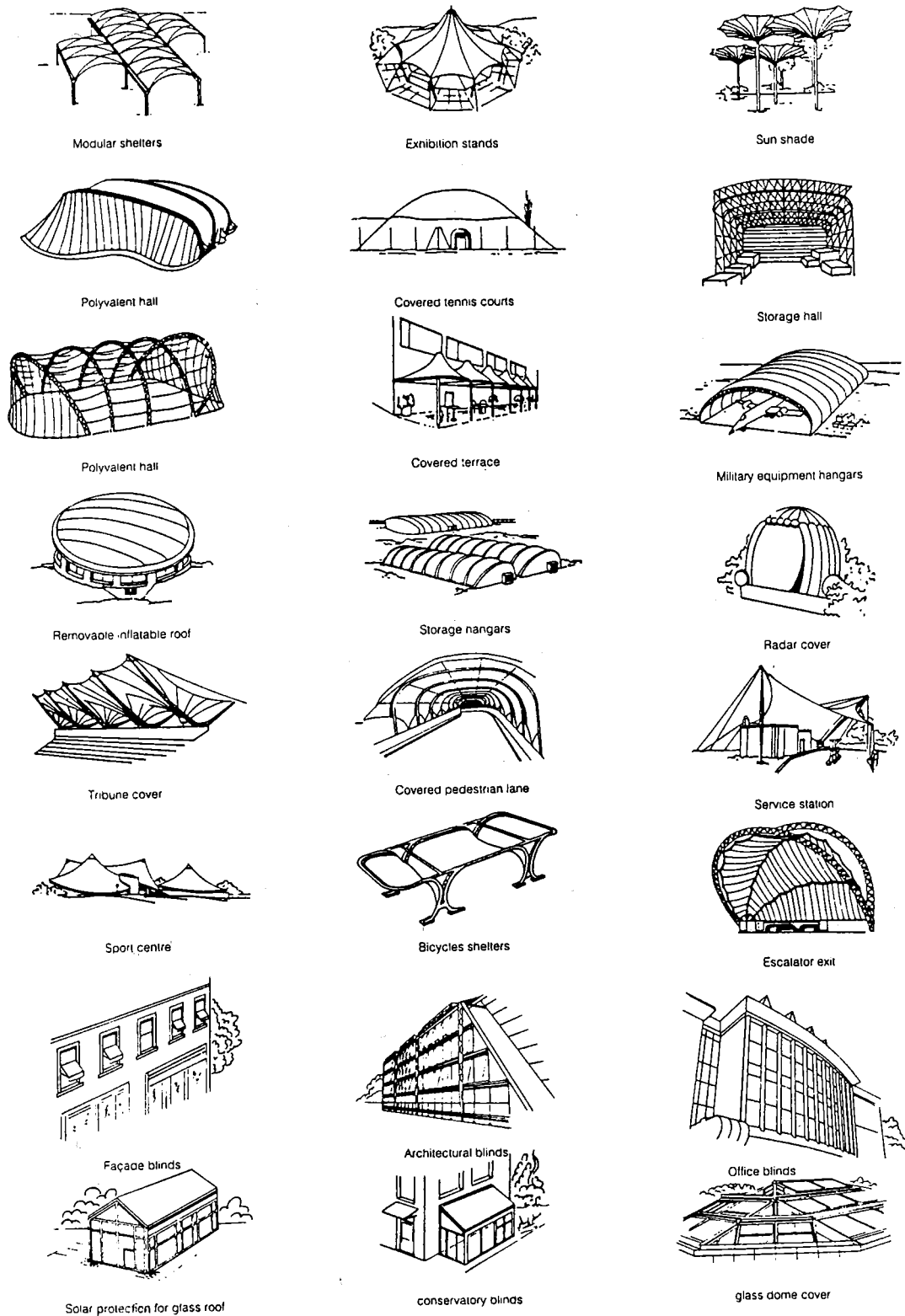
3.2 Clear-Span Structures

Clear-span structures provide clear space beneath the fabric, free of poles and other supporting elements. They are also known as clear-span tents. In a clear-span, the fabric is pulled taut through channels in the frame's ribs, i.e., no poles or masts are used. Well built clear-spans are very stable and have been used in many commercial and industrial applications. They are more permanent than tents and less permanent than air or tensile structures. Clear-spans can accommodate doors, flooring, insulation, elec-

FIGURE 6.8 Tension tent (courtesy of Armbruster Manufacturing Co.).

TABLE 6.3 Typical Properties of a Heavy Duty Tent Fabric (Herculite Products, Inc.).

Weight	16 oz/sq yd
Tear strength	150 lb (warp) × 160 lb (filling)
Tensile strength	300 lb (warp) × 290 lb (filling)
Low temperature resistance	−40°F
Hydrostatic burst	450 psi
Flame retardance	0.6 sec, 3.7 inch

tricity and HVAC easier than tents. PVC coated polyester is the most widely used fabric for clear-span structures.

3.3 Tension Structures

In tension structures, metal pylons, tensioning cables, wooden or metal frameworks are used to support the fabric. A relatively minimal support system, which must be rigid, is required for these structures because the fabric carries most of the load. Tension structures are curvilinear and therefore a fabric system must have or develop curvature to resist applied loads (Figure 6.9). The fabric is highly tensioned and therefore must have good strength.

Although tension structures can be designed in various shapes, the basic building block shapes are generally hyperbolic paraboloid and the hyperboloid. The fabric is double curved, with the curvatures opposing each other from a single intersecting point. The crossed arch appears parabolic in cross section and as an "X" when viewed from above. The two main ways to attach fabric to anchorages are sleeves and clamps. Figure 6.10 shows the installation stages of a tension structure as a stadium roof. Figures 6.11–6.14 show several tension structures.

3.4 Air Structures

Air-supported structures can be built in two ways:

(1) Air pressure inside the envelope provides tensioning and maintains required configuration and stability (Figure 6.15). The main components of an air-supported system are the envelope (fabric), inflation system (fans), anchorage system (cables and foundation) and doors and access equipment. PVC coated polyester is the most widely used fabric. The collapse of some large-scale stadium domes in the early 1980s affected the acceptance of air supported structures. However, well-built air structures are quite stable and strong. Pressurized air-supported structures are modular buildings. They can be designed to form nearly any shape provided that surfaces are curved. Simple domes and "bubbles" are the most common (Figure 6.16).

(2) Air-inflated ribs (air beams) are used to support the structure (Figure 6.17). Air beams are pressurized air-inflated support tubes.
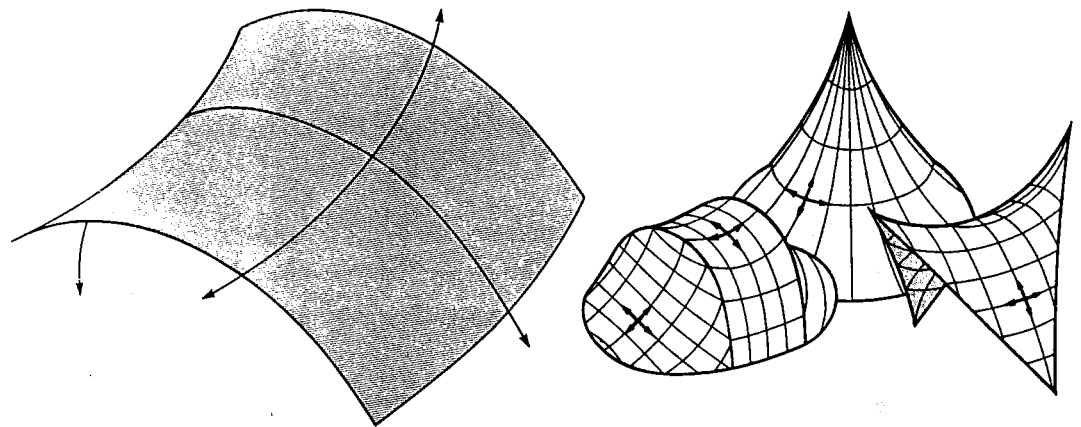
FIGURE 6.9 Schematic of tension structures (The Textile Institute [1]).
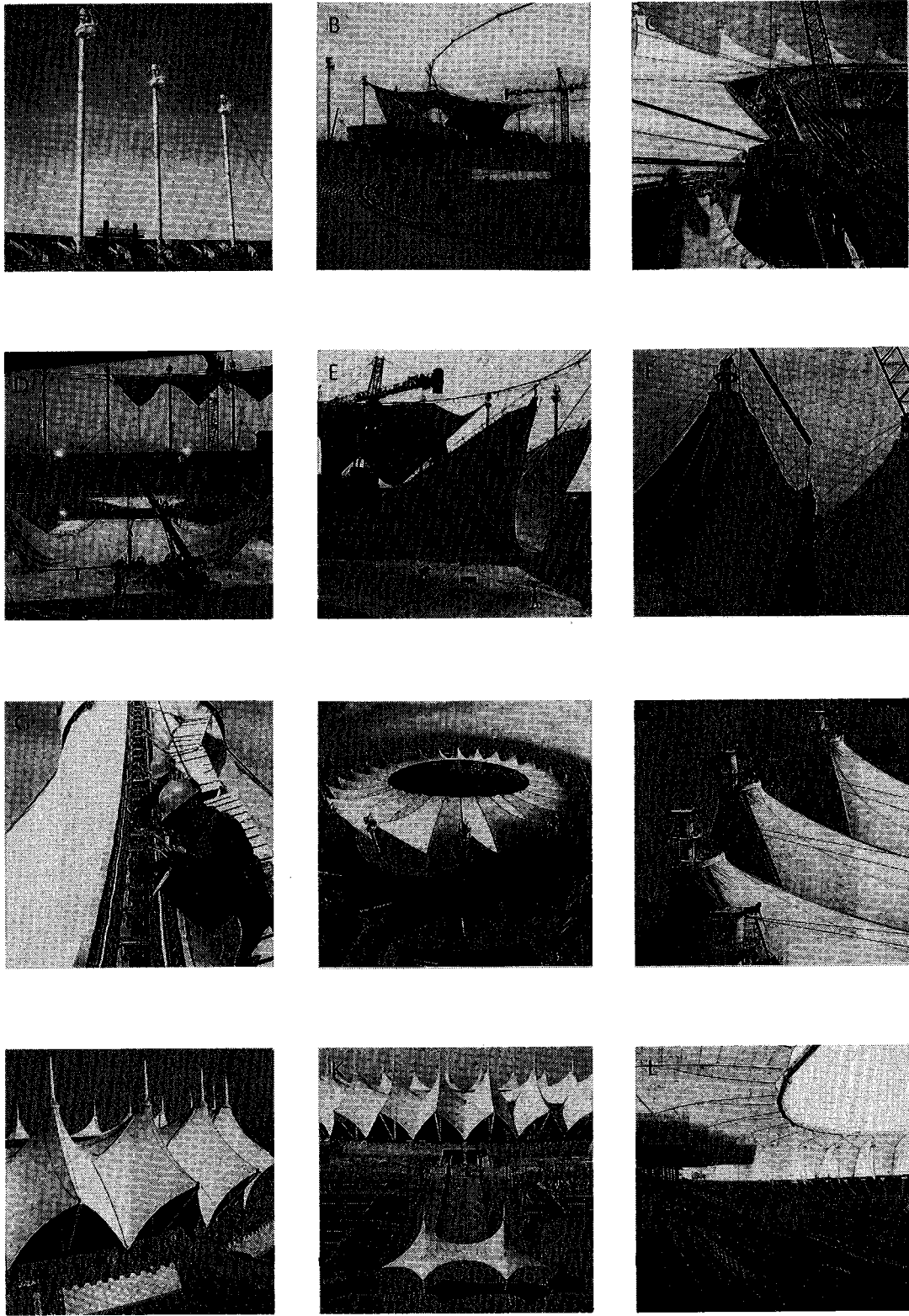
FIGURE 6.10 Installation stages of a tension structure stadium roof (courtesy of Birdair, Inc.).

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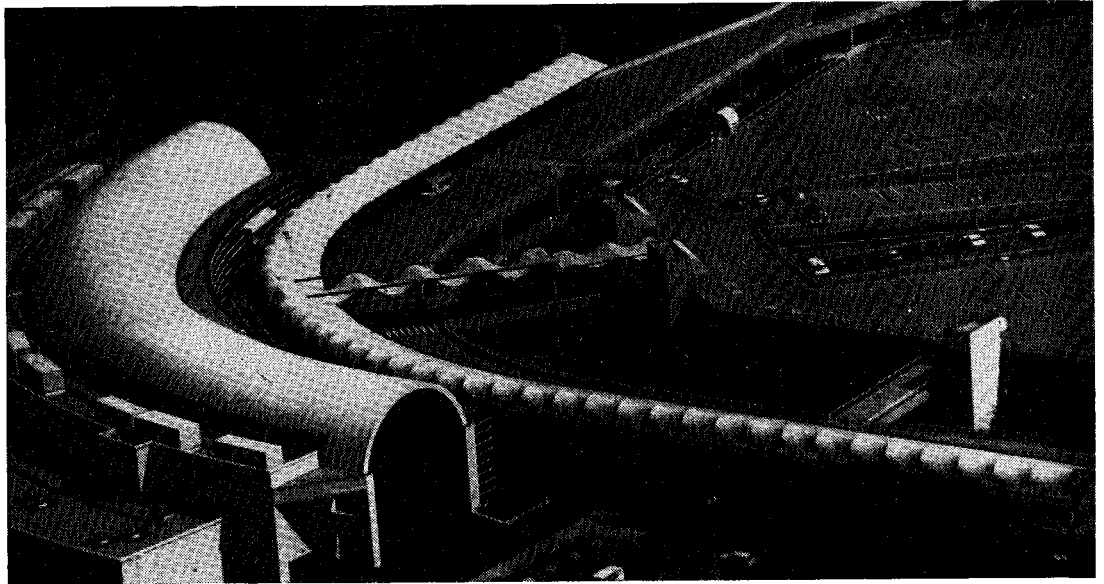
FIGURE 6.11 Coated fabric is used to cover high traffic access areas at Jacksonville International Airport, Jacksonville, Florida (courtesy of Birdair, Inc.).
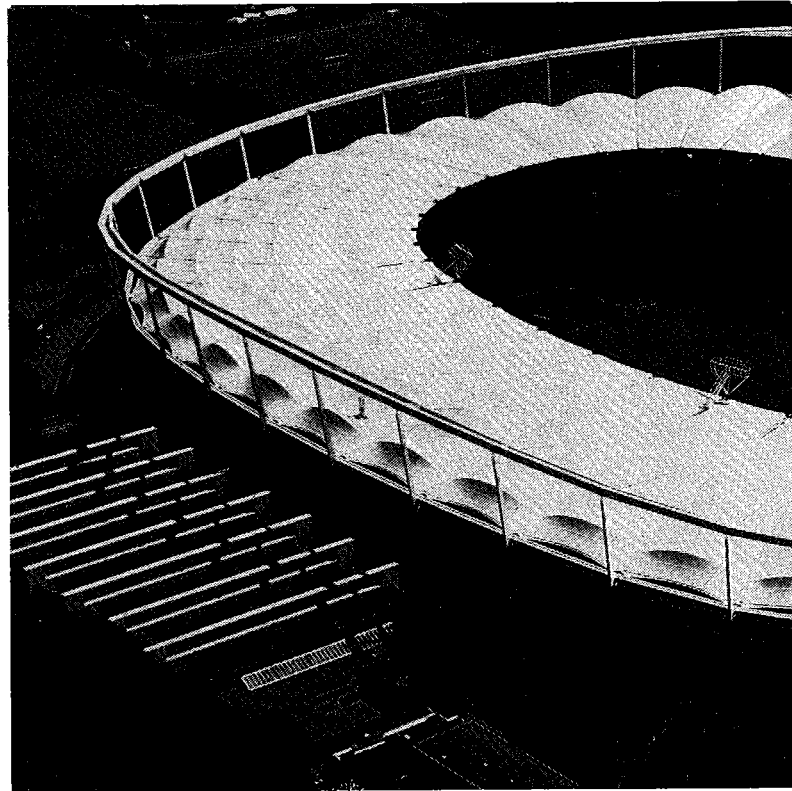
FIGURE 6.12 Polyester coated fabric was used to replace a worn-out stadium roof in 1993 in Stuttgart, Germany. The membrane structure consists of 35,000 m^2 membrane and 100,000 individual parts which is the largest of its kind in Europe (courtesy of Hoechst Celanese).

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FIGURE 6.13 San Diego Convention Center, San Diego, California (courtesy of Birdair, Inc.).
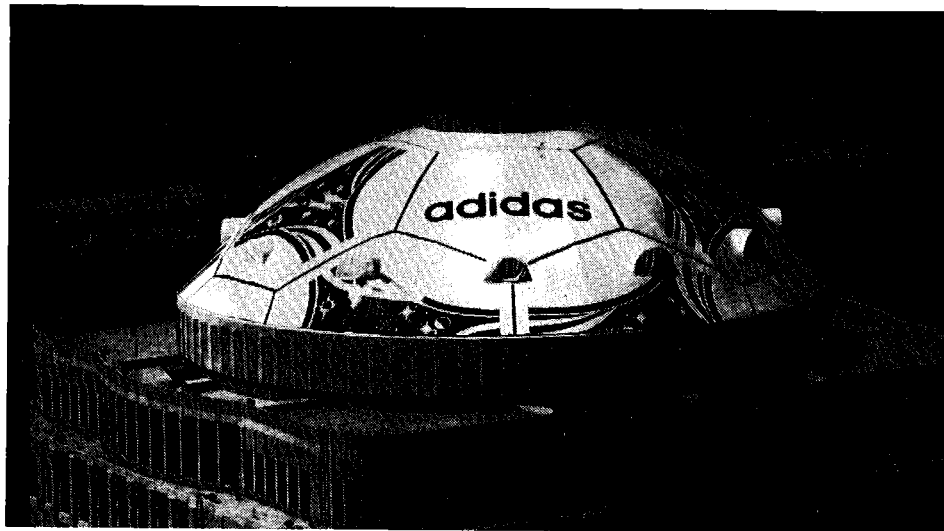
FIGURE 6.14 The roof of Orlando City Hall (Florida) was designed as a soccer ball to commemorate the 1994 World Cup Soccer finals (courtesy of IFAI).
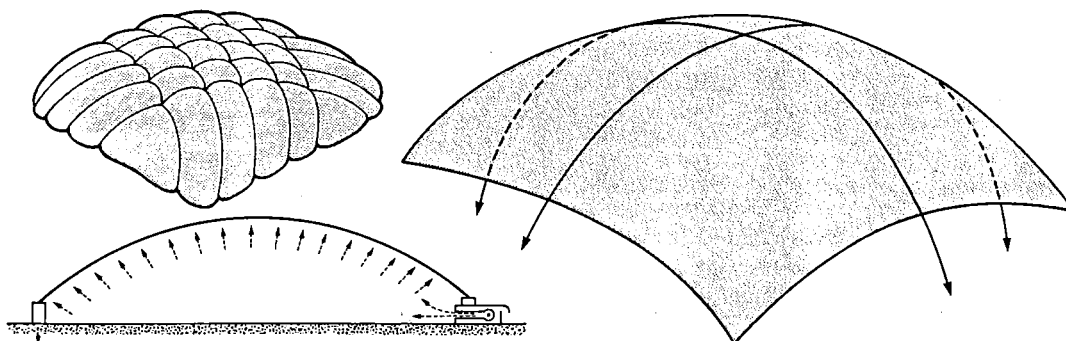
FIGURE 6.15 Schematic of a pressurized air-supported structure (The Textile Institute [1]).

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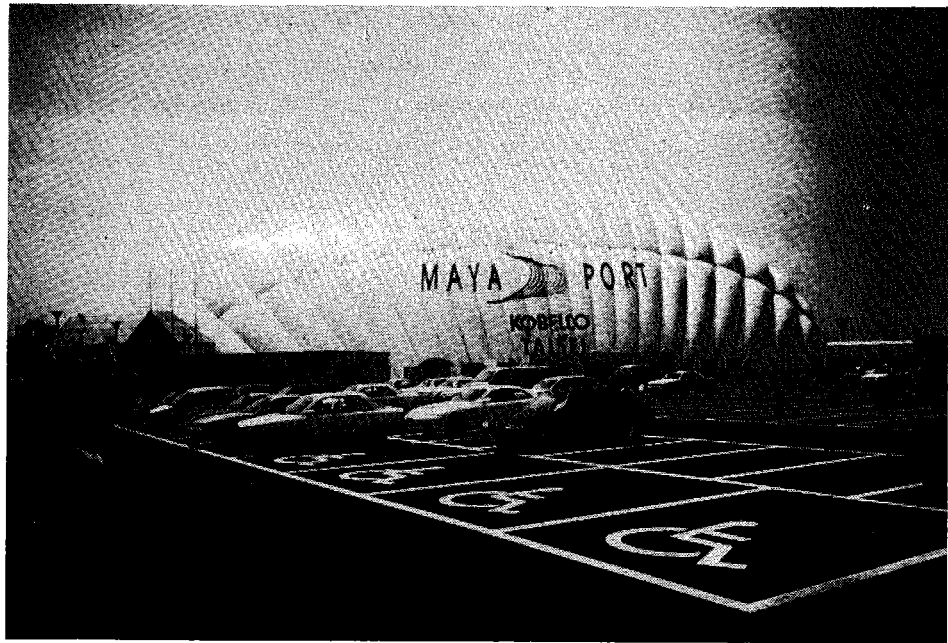
FIGURE 6.16 Pressurized air structure (courtesy of IFAI).
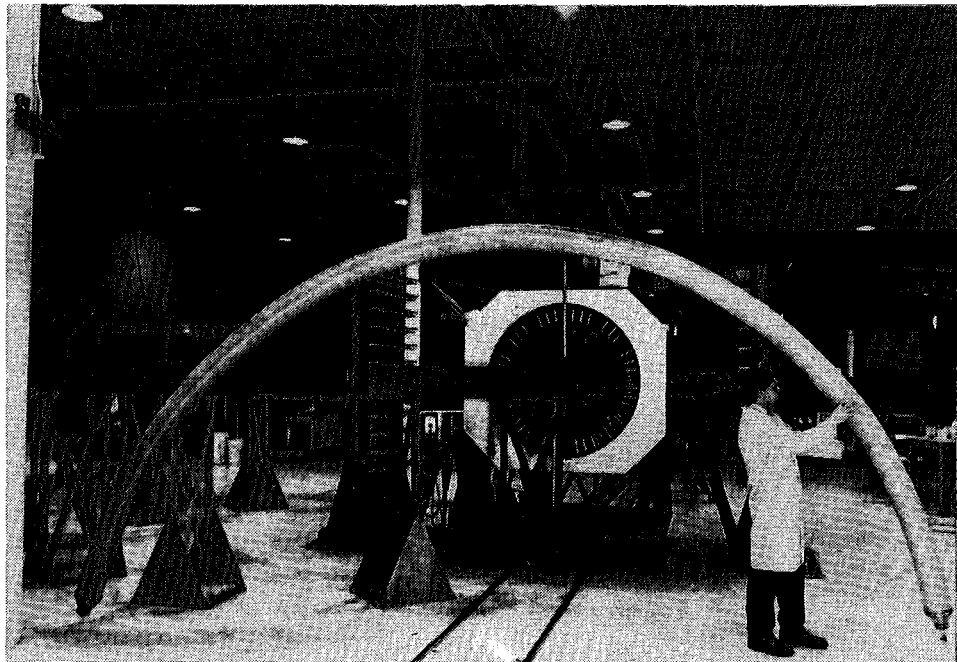
FIGURE 6.17 Inflatable air beam for an air-supported structure (courtesy of Albany International).

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The interior of the structure itself is not pressurized. Wide diameter supports (up to 42 inch) use low air pressure (4 to 10 psi) and narrow-diameter supports (4 to 18 inch) use high air pressure (30 to 100 psi) [6]. They are currently used for lightweight, easy-to-transport military structures although civil applications may have good potential in the near future. Polyester and nylon are the materials of choice. For high pressures aramid fibers may be needed. The width/height ratio may be a limitation for a single air structure but this limitation can be overcome by conjoining several modules together.

There are approximately 150 big fabric structures in the world which were built within the last twenty years, including Georgia Dome in Atlanta (cable supported, Figure 1.2), Silver Dome in Detroit (where Teflon® coated glass fabric was used), Bullock's department store in San Mateo, California, Hoosier Dome in Indianapolis (air structure) and the Carrier Dome in Syracuse. The Carrier Dome is air supported and made of glass fiber coated with a fluoropolymer dispersion (Figure 6.18). For the large-span areas such as stadium roofs and airport terminals, tension designs are preferred. For example, over 500,000 m² of PTFE coated glass fabric was used in the construction of the Haj Terminal building for Jeddah International Airport in Saudi Arabia which was completed in 1982. It is the world's largest tensile structure [7]. The newest tension fabric structure is the terminal at the new Denver International Airport which has a coated fabric roof that consists of two layers of Teflon® coated woven fiberglass (Figure 1.10). The fabric is designed to allow enough light transmission for plants. The roof is suspended by steel masts and cables, covering an area of 20,000 m² [8].

Lighter polyester fabrics (6 to 8 ounces per square yard) are used as acoustic and insulated liners. Waterproof, flame retardant tarpaulins are used in cold weather construction. The fabric keeps heat in, so construction can continue all winter, even at 40 degrees below zero (Figure 6.19). Heavier polyester materials such as 20 to 26 ounce fabrics, are suitable for long-term ex-terior use. Fiberglass based fabrics have been the material of choice for stadium domes (both air and cable supported) and other permanent structures especially in the United States.

3.5 Designing with Coated Fabrics

The major functional requirements for permanent architectural fabrics are listed in Table 6.4.

Mainly three types of stresses act on an architectural fabric:

(1) Stresses due to applied load to tension the fabric

(2) Weight of suspended fabric

(3) Stresses induced by natural forces due to wind, rain and snow

The calculation of the loads depends on the region where the structure will be installed. Snow loads push the fabric down while wind loads tend to pull the structure upward. Wind can affect a fabric structure in two ways: laterally across the top, or, if the structure is open-sided, up from below. Heavier loads necessitate stronger anchoring which may require additional or larger cables, stronger connecting hardware, and larger foundations or reinforced perimeter walls into which to ground the anchors. Properly

TABLE 6.4 Functional Requirements for Permanent Architectural Fabrics (Chemfab).

Tensile strength	500 lb/inch for air-supported structures
	650 lb/inch for pretensioned structures
Durability	Retain functional integrity for at least twenty years
Fire safety	Find acceptance within existing building codes
Energy efficiency	Provide adequate daylighting without artificial illumination
	Provide acceptable thermal gain/loss characteristics
Cost	Provide life cycle cost competitive to conventional construction
Aesthetics	Constitute an exciting structural alternative to traditional structural options

gravities of some geotextile materials are: polypropylene = 0.90, polyester = 1.38, nylon = 1.14, polyethylene = 0.92 (Table 17.2).

The geometry of geotextiles is essentially characterized by the fact that the thickness is much smaller than the two other dimensions, the length and the width. In other words geotextiles are bidimensional products. Thickness of a geotextile is measured at a specified pressure of 2.0 kPa [5]. Thickness is important for in-plane water flow.

The mass per unit area (oz/yd^2 or g/m^2) characterizes the quantity of material in the direction perpendicular to the plane of a geotextile [6]. In general, fabric cost and some mechanical properties are related to mass per unit area.

Most geotextiles are very flexible in nature with very low bending resistance or stiffness as a result of the mechanical property of the fibers used. In stiffness or flex test [7], the geotextile gravitationally bends under its own weight. Flexibility of geotextiles enables them to be produced and shipped into rolls and installed easily. Functionally, reinforcement may be important in reinforcement applications.

3.2 Mechanical Properties

Important mechanical properties of geotextiles are compressibility, tensile strength, seam strength, tear, burst, impact and puncture strength.

Compressibility of woven and thermally bonded nonwoven geotextiles is low. Needlepunched geotextiles have high compressibility. Compression of a geotextile reduces its transmissivity (in-plane flow) and permittivity (cross-plane flow) since it changes the pore structure of the fabric.

Tensile properties are important properties of geotextiles. Adequate tensile strength is necessary for all types of geotextile functions and installation. In general, maximum tensile stress, elongation at break, toughness and modulus values are reported from tensile tests. Toughness is the work done per unit volume before fabric failure which is the area under the stress-strain curve. Figure 9.6 shows typical load-elongation curves of woven and nonwoven geotextiles. Various specimen sizes for tensile testing of geotextiles are indicated in ASTM D 4595 (wide

width strip method) and ASTM D 4632 (grab method). Mostly 4″ and 8″ wide samples are used for tensile testing (20″ wide samples may also be used). Figure 9.7 shows the wide-width tensile test of a nonwoven geotextile sample. A wide specimen is especially needed for nonwovens because of their necking during testing.

In confined tensile tests, the specimen is surrounded by soil to simulate the in situ conditions. Figure 9.8 shows a plot of confined and unconfined load-elongation curves for a woven and needlepunched nonwoven geotextile. Confinement significantly increased the load values for the nonwoven geotextile.

Geotextile fabric ends are seamed together for property continuity either in a shop or in the field. Various types of seams are used for different fabrics. Seaming is usually done by sewing the ends together. Other methods of seaming include epoxy, resin, and mechanical seaming. Several sewn seam types are shown in Figure 9.9.

Although 100% seam efficiency is desired, it is hardly possible. 90% seam efficiency is considered to be good. Seam efficiency (SE) is defined as

$$SE\,(\%) = (T_s/T_g) \times 100 \qquad (9.1)$$

where T_s is the tensile strength of the seam area and T_g is the tensile strength of the geotextile without a seam. Seam efficiency decreases with increasing fabric strength. In testing of sewn
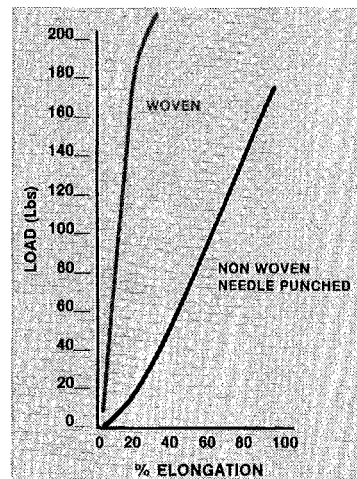
FIGURE 9.6 Typical tensile load-elongation diagrams of woven and nonwoven geotextiles [8].
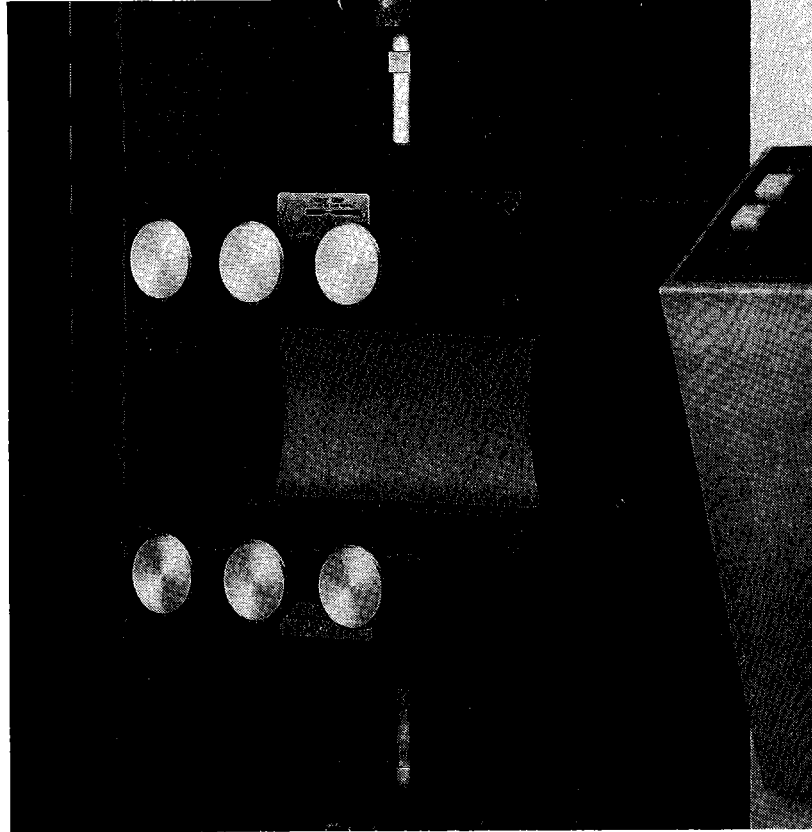
FIGURE 9.7 Wide-width tensile test of a geotextile [9].
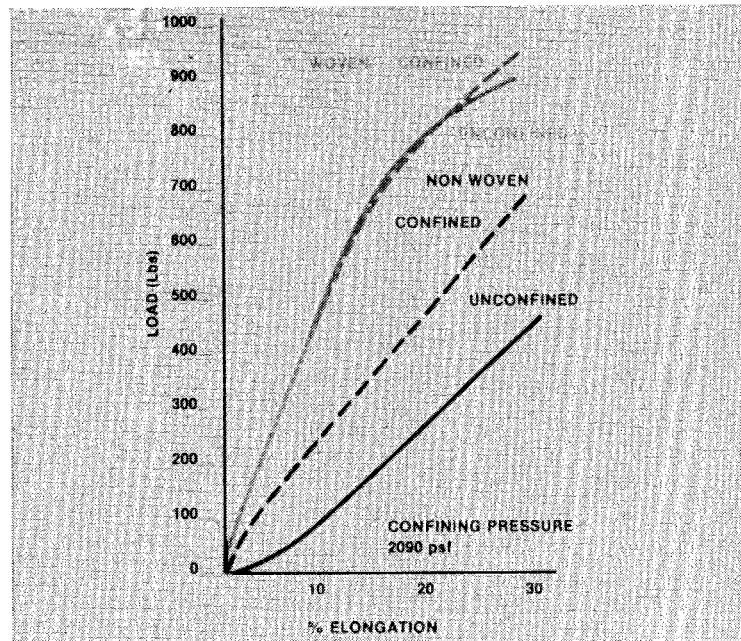
FIGURE 9.8 Load-elongation curves of confined and unconfined geotextiles [8].

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'prayer' seam
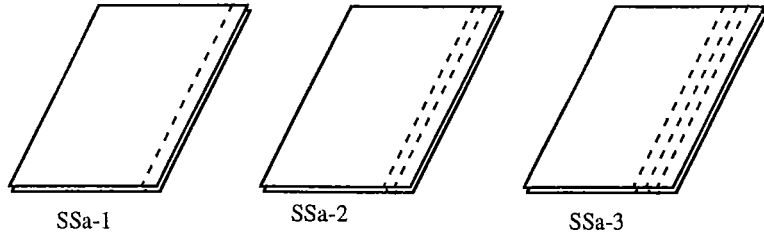
SSa-1   SSa-2   SSa-3

'J' seam
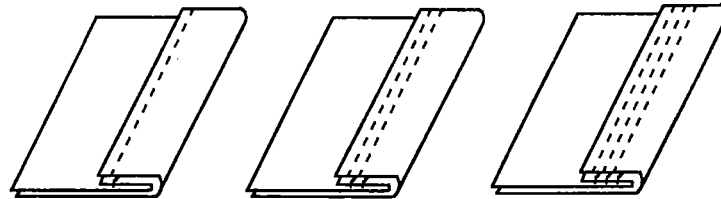
SSn-1   SSn-2   SSn-3

double 'J' seam
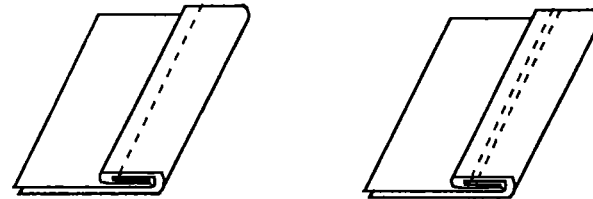
Ssp-1   SSp-2

'butterfly' seam
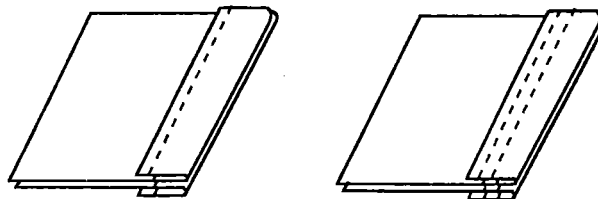
SSd-1   SSd-2

FIGURE 9.9 Sewn seam types for geotextiles [10].

geotextile seam strength (ASTM D 4884), an eight inch wide seam is gripped in its entire width with clamps of a tensile testing machine. A longitudinal (perpendicular) force is applied at a specified rate of extension until the seam or the fabric ruptures.

Properties related to the ability of a geotextile to withstand damage are typically the resistance to tear and puncture. ASTM D 4533 is used for trapezoidal tear test of geotextiles. The puncture test is done according to ASTM D 4833. Figure 9.10 shows schematics of some of the mechanical tests for geotextiles.

3.3 Properties Influencing Soil-Geotextile Interaction

Two kinds of interactions are possible between soil and geotextile: mechanical and physical. The mechanical interaction is characterized by the shear strength developed between soil and geotextile. Soil to geotextile friction is very critical in reinforcement. A high contact shear strength is required when geotextile is used to reinforce soil and a low contact shear strength is required when soil and geotextile are designed to move against each other. The shear strength is governed by the angle of internal friction developed between soil and geotextile. Two different tests are done to test the friction behavior of geotextiles: direct shear and pullout tests (Figure 9.11).

In direct shear (ASTM D 5321), the geotextile is fixed to the bottom half of the shear box which moves against the other half that contains soil under normal stress. Shear forces versus normal forces are plotted from which shear strength parameters can be obtained. The pullout test is carried out with the geotextile embedded in the soil. This test is usually performed with a normal stress or surcharge, which represents normal stress in the field, applied above the topsoil layer. The horizontal force applied to pull the geotextile out of the soil is recorded as shown in Figure 9.12. Pullout resistance is calculated by dividing the maximum load attained by the test specimen width. Plot of pullout resistance versus deformation at different points along the geotextile can be obtained for different applied normal stresses. From this information, response curve interac-
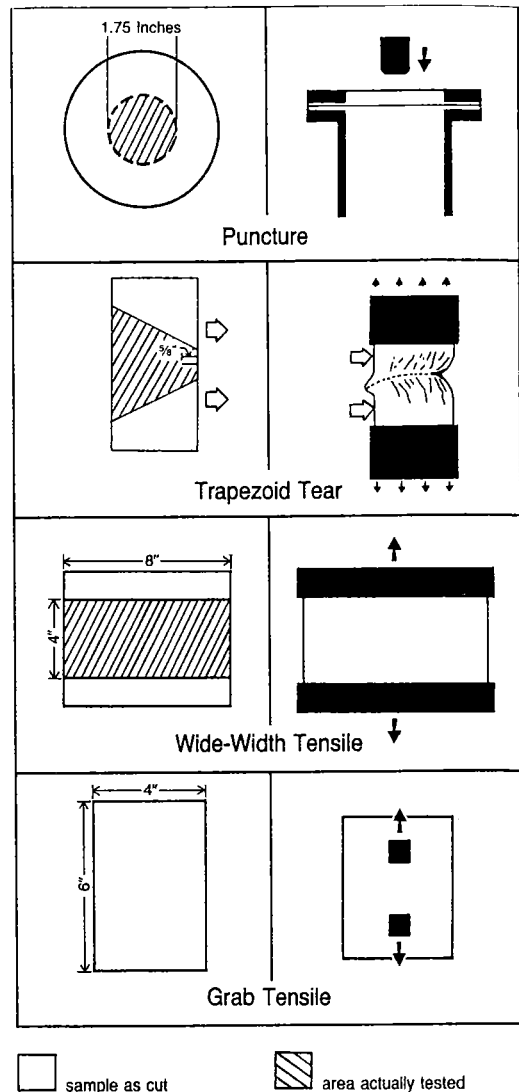
FIGURE 9.10 Schematics of some mechanical tests for geotextiles [1].

tion coefficients can be generated. ASTM is currently developing a standardized pullout test method.

Swan [11] studied the effect of geotextile geometry on the shear strength parameters of a geotextile. He showed that the fabric geometry greatly influences the shear strength parameters of a geotextile for a given soil type. His study also showed that the geotextiles having similar strength, construction and yarn geometry can have different shear strength in a particular soil due to difference in geotextile geometry.

- military hospital supplies, gauze, bandages, slings
- towels
- aircraft fuel cells
- sandbags
- equipment packs
- gas mask bags
- duffle bags
- cargo and flare parachutes
- mail bags
- bomb curtains for Air Force and Navy
- draperies, carpets
- sheets, blankets
- cots
- sewing threads for protective apparel
- load-carrying equipment
- electrical insulation
- ammunition pouches, gun covers

2. PROTECTIVE CLOTHING AND INDIVIDUAL EQUIPMENT

In the past, the main objective of military protective clothing was to protect the soldier from environmental effects such as rain, snow, cold, heat and wind as well as to give him freedom to maneuver. With the development of chemical, biological, thermonuclear and more effective fragmentation weapons, small arms surveillance and sensor systems, the requirements for military protective clothing have increased dramatically. Textiles used in military clothing have to satisfy strict, quantifiable requirements.

In modern military establishments the individual soldier is treated as a "system" (Figure 11.3). The clothing of a soldier consists of uniforms, hosiery, knitwear, underwear, shirtings, etc. The purpose of military protective clothing is to help maximize the survivability, sustainability and combat effectiveness of the individual soldier system against extreme weather conditions, ballistics, and nuclear, biological, chemical (NBC) warfare [4,5].

The major requirements for an advanced integrated combat clothing system can be grouped into four categories [1]:

- physical requirements: durability to prolonged exposure to inclement weather

FIGURE 11.3 A soldier and his equipment is considered a "system" (courtesy of the U.S. Army).

and heavy wear, good tensile and tear strength and abrasion resistance
- environmental requirements: water repellency, windproofness, snow-shedding and insectproofness
- physiological requirements: low weight, easy to wear, minimum heat stress, air, moisture and vapor permeability and comfort
- battlefield requirements: ballistic protection, flame resistance, resistance to chemical and biological agents, resistance to long range thermal effects of nuclear weapons, good camouflage properties and low noise generation

In addition to these requirements, uniforms for special duties may require other properties such as resistance to propellant fuels, strong

TABLE 11.1 Recent Advances in Military Clothing [5].

Technology	Materials	Items
High performance fibers/fabrics	Kevlar® Spectra®	Lightweight combat helmet
Fine denier fibers	Nylon (staple and filament)	Hot weather battle-dress uniform arctic overwhite
Microdenier fibers	Synthetic down (Primaloft®)	Cold weather clothing and sleeping bags
Stitchless seaming	Synthetic fabrics	Chemical protective clothing Rainwear Sleeping bags Cold weather clothing

acids, and liquefied gases (oxygen, nitrogen, ammonia).

Some of these requirements may be in conflict. For example increasing environmental protection may create physiological concerns such as heat stress and fatigue. The requirements on the military uniform dictated by battlefield conditions may impair the operational efficiency of the soldier. Physical properties must give the clothing durability for extended periods of use. Low weight and bulk are usually preferred for operational efficiency but in the case of ballistic vests, the level of protection would probably be reduced. Tightly woven fabrics may provide improved water resistance, but reduce air permeability.

Recent advances in military clothing include high performance fibers/fabrics, flame resistant materials, microdenier fibers, bioengineered fibers, blended yarns and stitchless seaming. These new technologies have led to the materials and end products that are shown in Table 11.1. Table 11.2 shows integrated protection provided by recently improved battle-dress uniform fabrics.

2.1 Ballistic Protection

Principles of Ballistic Protection

Ballistic protection of a soldier involves protection of the body and eyes against projectiles with various shape, size, and impact velocity. The principle of ballistic protection by cloth armor is to dissipate the energy of the fragment/shrapnel through stretching and breaking the yarns in the many layers of high performance woven fabrics in the ballistic vest (Figure 11.4). Each fabric layer reduces the energy of the projectile. In each layer, impact energy from the struck fibers is absorbed and dispersed to other fibers in the weave of the fabric. Their transfer occurs at crossover points where the fibers are interwoven. In general, a plain balanced, woven fabric is preferred for ballistic protection to maximize the number of crossover points. Since the woven fibers work together to dissipate the impact energy, a relatively large area of the fabric becomes involved in preventing the bullet's penetration [7].

Two conflicting requirements have to be met

TABLE 11.2 Integrated Protection Offered by the New, Improved Battle-Dress Uniform Fabrics [5].

Fabric Characteristics	Nylon, Cotton	Nomex®, Kevlar®, P-140	Cotton, Kevlar®, Nylon, P-140
Flame resistance	N	Y	Y
Liquid chemical agent resistance	Y	N	Y
Electrostatic resistance	N	Y	Y
Day/night camouflage	Y	Y	Y
Durability	Y	Y	Y+
Weight (oz/yd²)	7.0	5.5	6.5
Cost ($/linear yd)	4.00	20.00	11.00 (estimate)

Y: yes, N: no.

14.1

Sports and Recreation Textiles

S. ADANUR

1. INTRODUCTION

Textile materials are used in virtually every sport from exercising to camping to football. High performance textile fibers and fabrics are used in uniforms, equipment and sport facilities.

Textile manufacturers today are giving themselves an edge in the increasingly competitive sports and recreation market by developing their own signature products. Creating new fabrics is usually a lengthy and expensive process. Companies put their fibers and fabrics through rigorous tests to measure strength, abrasion resistance and breathability among other things. Several companies even have environmental labs where they can alter temperature and humidity conditions while athletes work out wearing the prototype garments.

Use of textile structural composites in sporting goods is increasing. Their applications include composite roller blades, bike frames, golf clubs, tennis rackets, ski and surf equipment, etc. Sports such as golf, baseball and tennis rely heavily on composites for their essential equipment. These sports would be drastically different if composite materials were not used. Due to their high strength and durability, composites have won favor in the sporting industry. Figure 14.1 shows some of the sporting goods made of composites.

2. SPORTS UNIFORMS

Today's fast-moving and innovative technology has forced manufacturers to go to extreme measures in order to keep up with market demands and competition when it comes to activewear for athletes and exercisers. With activewear now a booming $3.1 billion a year industry, manufacturers are subjecting fabrics to strenuous tests and "workouts" to ensure that people can enjoy sports and other recreational activities without having to worry about getting wet or chilled.

Sport garments that are used next to the skin are usually made of plain or satin woven fabrics. Warp knits made from continuous filament fibers and weft knits made of spun yarns are widely used in shirts for active sports like football (Figure 14.2). Nylon, cotton, polyester/cotton and polyester/viscose are common fibers in sport shirts. Nylon and polyester warp knit fabrics offer light weight, stretchability and drapeability. Warp knit shirts made from mixtures of acetate, nylon and polyester can be piece-dyed [1].

For very active sports, synthetic fibers are preferred because they do not retain moisture and therefore do not get heavy upon sweating like cotton does. Synthetic sports uniforms also have better dimensional stability. Synthetic fibers offer the three major requirements in today's high technology sports uniforms:

- warmth, wind resistance, moisture wicking and lightness
- comfort and feel of natural fibers
- style and a variety of colors

With the advanced technology, however, natural fibers like cotton and wool are making a comeback in high performance, outdoor activities. For example, cotton now can be made windproof, breathable and water resistant.

Spandex is a superfine polyurethane fiber that can stretch up to five times its original length and

FIGURE 14.1 Examples of sporting goods made of composites (courtesy of Nippon Oil Company).
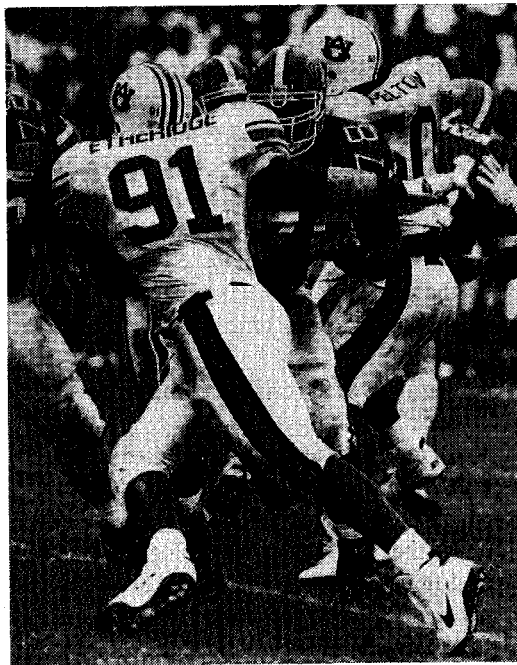
FIGURE 14.2 Knit fabrics provide strength and stretch for active sports (courtesy of Auburn University Photographic Services).

recover immediately. Lycra® Spandex, an elastane fiber, is widely used in swimwear, skiwear and gymnastic uniforms. It offers close-fitting, stretching and non-restrictive properties. A blend of Spandex and other fibers such as cotton, silk, rayon, wool, nylon, Supplex®, Tactel®, polypropylene, merino wool, angora and even cashmere are used in a variety of activewear.

For heavier fabrics, such as track suits and jogging suits, nylon, polyester, acrylics, and their blends with acetate, cotton and wool are used. These fabrics may be brushed inside for warmth and are cut loosely for comfort.

Dedicated exercisers who were no longer willing to abandon fresh-air workouts in the off-season, needed clothes that would protect them from the elements but would let the heat of the sport escape. Cotton, wool and goose down tend to become saturated with sweat—hardly ideal conditions considering damp fabrics chill the body twenty-five times faster than dry ones. So wool gave way to polypropylene, which is a petroleum-based fiber that absorbs virtually no moisture. Polyester replaced goose down. Nylons that feel like cotton were unveiled in the early 1980s. Fabric manufacturers have engineered sophisticated synthetic fibers that use a combination of mechanisms to wick away wetness by using an inner hydrophobic (water-hating) layer that pushes perspiration away from the skin to an outer hydrophilic (water-loving) layer where the moisture easily evaporates.

In 1976, W. L. Gore & Associates developed an innovative fibrous material important to sports and exercise lovers—Gore-Tex®. It is a film-like membrane, or laminate, with the consistency of Saran Wrap and billions of micropores per square inch that made regular fabric both waterproof and breathable. Each micropore is smaller than a drop of water; therefore, the rain cannot penetrate. However, the micropore is bigger than a molecule of water vapor, so perspiration can penetrate the garment and evaporate outside. Gore-Tex is bonded to the inside surface of the fabric by adhesive dots, rather than continuously. Its pores will not clog up from body oils.

In 1983 a subsidiary of Thoratec Laboratories Corp. in Berkeley, California developed a fabric called Bion® II which differs from Gore-Tex® in

dex, an elas-
wear, skiwear
close-fitting,
roperties. A
uch as cotton,
ex®, Tactel®,
ora and even
ctivewear.

ack suits and
acrylics, and
and wool are
ed inside for
nfort.

o longer will-
ts in the off-
protect them
he heat of the
se down tend
-hardly ideal
rics chill the
dry ones. So
, which is a
s virtually no
oose down.
nveiled in the
ers have en-
ers that use a
ck away wet-
obic (water-
on away from
water-loving)
aporates.

tes developed
important to
-Tex®. It is a
with the con-
billions of
made regular
thable. Each
water; there-
However, the
ule of water
e the garment
bonded to the
hesive dots,
will not clog

Laboratories
loped a fabric
Gore-Tex® in

that it is a continuous film through which perspiration diffuses to evaporate on the outside surface. Bion II can also be laminated directly to the cloth and is thin, thus making it able to produce fabrics with good feel and drapeability.

Flame and abrasion resistant textiles such as Nomex® are used to protect race car drivers in case of an accident. Hoods, undergarments, socks, suits, shoes and gloves made of high performance textiles are used for protection (Figure 14.3).

Fabrics made of 100% acrylic fibers are used in hunting. Fabrics are usually treated with rain and stain repeller. Fabric colors and patterns can vary according to the terrain. Depending on the purpose, high-visibility or low-visibility (camouflage) fabrics are used (Figures 14.4 and 14.5).

The use of textile fabrics in the upper part of training and jogging shoes is increasing at the expense of leather. The fabrics in footwear are generally made of three layers: woven nylon outside, foam in the middle and warp knit fabric inside. Textile fabrics offer many advantages over leather including consistent and more regular quality, lightweight when wet and washability for easy care. Unlike leather, fabrics dry-up soft after wetting. Fabrics can be made in various colors which is important from a fashion point of view. By using mesh fabrics, ventilation can be increased. Nonwovens, such as melt-bonded nylon, are also used as inner fabrics in footwear [1].

2.1 Winter Activewear

New fibers are being created to replace the old, traditional synthetic fibers for outdoor sports. For example, the classic cotton windbreaker has now been replaced by an all-weather garment made of high filament nylon treated with a waterproof/breathable microporous membrane. Desscente, a Japanese sportswear firm, is manufacturing top-of-the-line skiwear of Solar A, a cloth which contains particles known as zirconium carbide that absorb solar energy and convert it into thermal power. Ski fabrics have been designed which change their porosity depending on the temperature. In another garment development, ski fabrics can change their

FIGURE 14.3 Race car driver suits are made of flame resistant textiles (courtesy of DuPont).

color as a result of the intensity of sunlight. The fibers used for winter activewear are listed in Table 13.26, Chapter 13.0, Safety and Protective Textiles.

Gentec Corporation developed a laminate that incorporates an impermeable water barrier to prevent any wetness from penetrating from the exterior. Figure 14.6 shows the schematic of this principle. It provides protection against rain, snow, sleet and wind. The perspiration is transferred to the exterior, keeping the wearer dry and comfortable. Good abrasion resistance, flex-
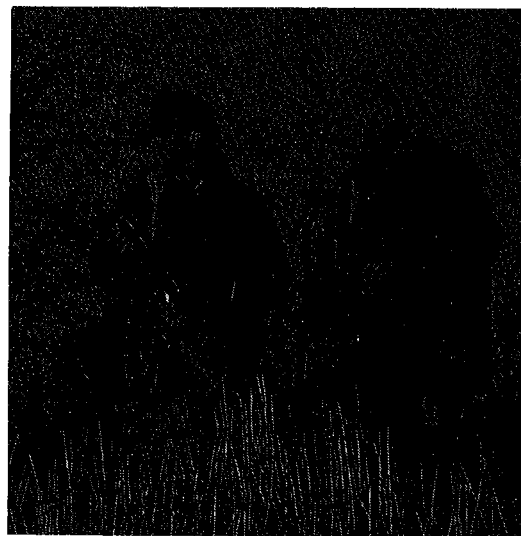
FIGURE 14.4 High visibility apparel for hunting (courtesy of Highland Industries).

FIGURE 14.6 Schematic of the principle of a water-proof, breathable laminate fabric (courtesy of Gentec Corporation).

ibility and strength combined with the light weight and breathability provides good wet weather protection.

3. CAMPING AND HIKING

Various tent structures and materials have been developed for camping purposes. General tent structures are covered in Chapter 6.0, Architecture and Construction Textiles.

Recently, tent fabrics have been developed with insecticide built in the fabric. For example, Expel®, developed by Graniteville Co., is treated with the effective insecticide permethrin, in formulation with other active ingredients. It was reported that Expel® bug repellant fabric keeps its repellency for two years [2].

Sleeping bags are made of synthetic microdenier fibers such as Primaloft® from Albany International [3], which is a 0.5 denier polyester fiber (Chapter 13.0). A fiber is considered microfiber if it is less than one denier. Microfibers can be as small as 0.001 denier. They are effective in heat insulation and are widely used in leisurewear and sportswear (Figure 14.7). Microfibers have also been used in tents for very cold weather. Polyester and polyamide are widely used. Another major application area for microdenier fibers is fashionwear. Table 14.1 shows typical properties of sleeping bags.

FIGURE 14.5 Low visibility uniform for hunting (courtesy of Milliken & Company).

Low moisture regain is also needed for outdoor applications. Polypropylene, polyamide, polyester and acrylic fibers are widely used in artificial playing structures. To have colorfastness on the top surface, colorants are added into molten polymer before extrusion of the fibers. These colorants are inert and unaffected by light and various weather conditions. Although green is predominant, artificial fiber surface can be made in any color. Artificial surfaces are suitable for painting to mark the field lines. Artificial fiber surfaces also allow relatively easy replacement of worn out or damaged parts. The damaged section is cut out and a new piece is seamed or bonded in.

When designing an artificial sports surface, the characteristics of that particular sport should be considered very carefully. For example, the artificial surface should cause the bouncing of a ball similar to the natural surface, otherwise the character of that particular sport would be altered. Surface must be uniform for even bouncing, and comfortable for the players. Especially important, the artificial fibers should not cause damage to player's skin upon contact during sliding.

Polymeric all-weather surfaces are used on track fields. These surfaces are around 10 mm thick and are made of solid PVC, polyurethane and other polymers with a non-slip surface. They are bonded to a concrete or asphalt substrate as shown in Figure 14.15.

Field Covers

Textile field covers are used to protect the playing surface from rain, snow, blistering sunshine and freezing winds (Figure 14.16). Professional football and baseball teams are required by league rules to have one [7].

Fabric weight is critical for field covers. The cover must be light enough to move around but heavy enough to withstand severe weather conditions. Baseball covers can weigh as much as 2,500 lbs. Polyvinyl chloride is widely used as a coating and laminate. PVC provides waterproofness, mildew resistance and protects the fabric from the sun's unltraviolet rays. Plasticizers in the resin protects the fabric from cracking at $-40°F$. Both laminated and coated fabrics are used as field covers. Polyester and nylon are the most common materials as supporting fabrics in field covers. Polyester offers good dimensional stability at different temperatures and good UV resistance. Nylon is considered to be more suitable for field covers than the polyester but it is prone to shrinkage.

12. HOT-AIR BALLOONING

Rip-stop woven nylon fabrics in the range of $30-60$ g/m^2 weight are used for hot-air ballooning. Rip-stop design is suitable to prevent the

tough-resilient tufted nylon fibers
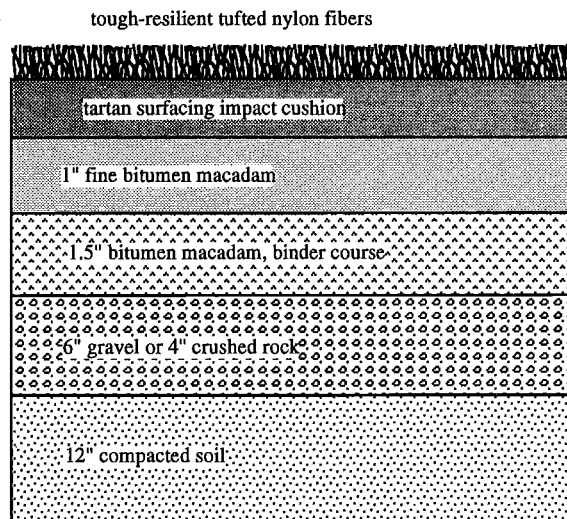
FIGURE 14.15 Typical cross section of a tartan turf [6].
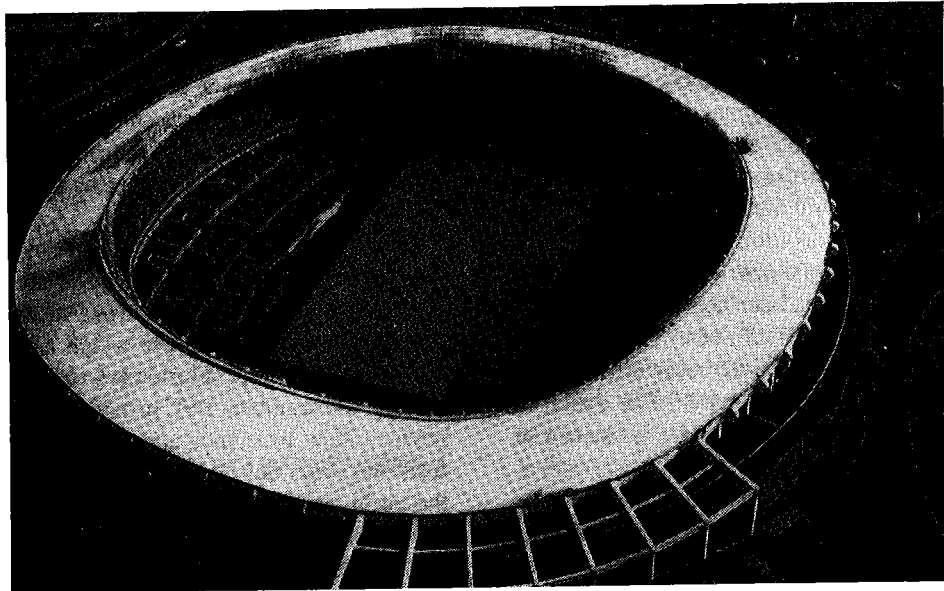
FIGURE 14.16 Field cover used to protect the playing surface in a stadium (courtesy of Cooley, Inc.).
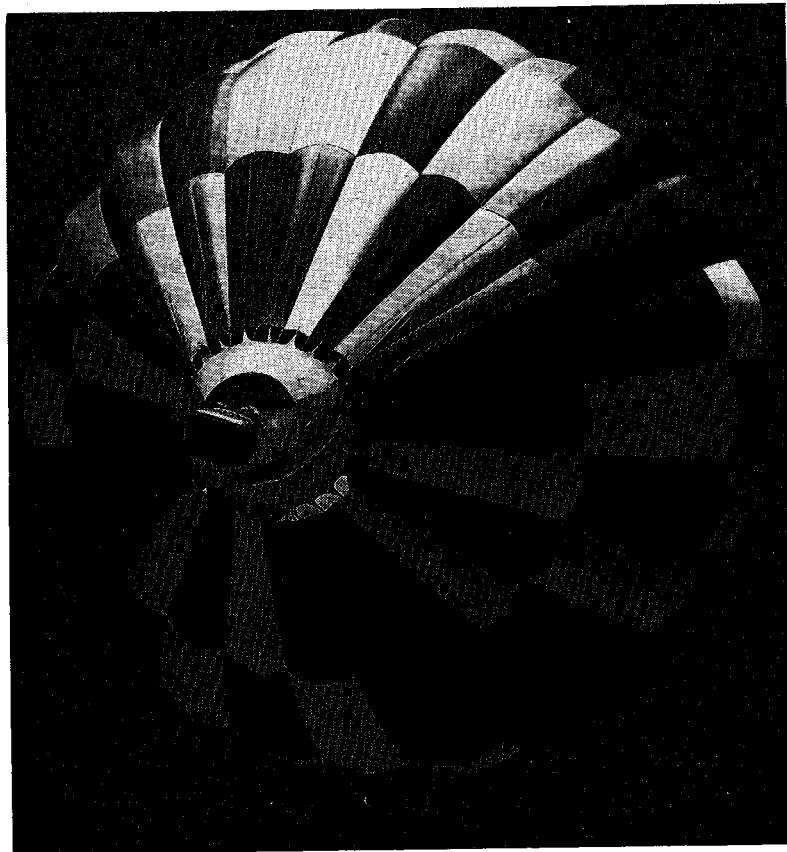
FIGURE 14.17 Hot-air balloon (courtesy of Queen Light Electronic Ind., Ltd.).
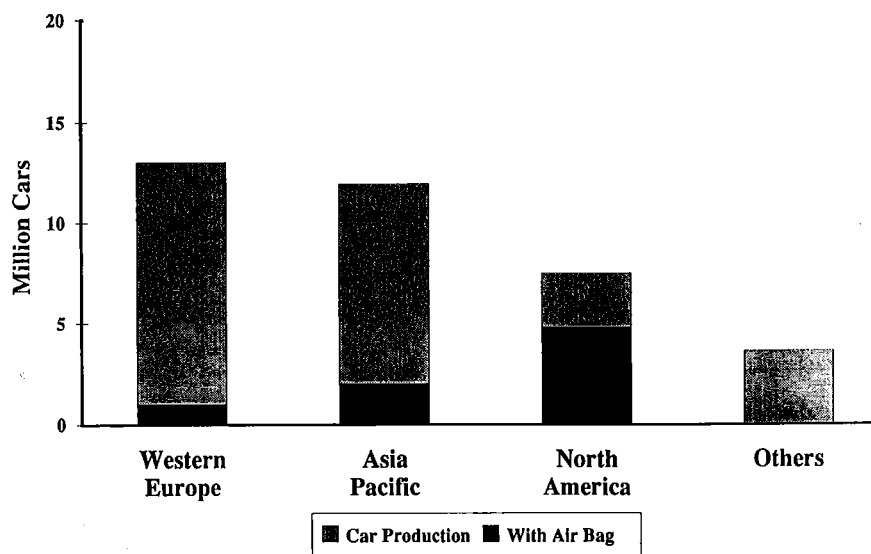
FIGURE 15.8 The 1992 world car production with airbags (*Automotive News* [8]).

to seat belts alone, airbags have reduced death by 28%, serious injury by 29% and hospitalization by 24%.

The first airbags were introduced in the early 1970s by General Motors but were not readily accepted by the consumer. The market for airbags was assured in the United States when the Department of Transportation (DOT) implemented the Federal Motor Vehicle Safety Standard (FMVSS) 208 in 1984 [7]. Because of this law, the United States leads the commercialization of the airbag as shown in Figure 15.8.

3.1 Materials and Properties of Airbags

The main requirements in airbag fiber materials are high strength, heat stability, good aging characteristics, energy absorption, coating adhesion and functionality at extreme hot and cold conditions. At present, coating is used only for driving side airbags. Tear strength, toughness and fog resistance of bag materials are important. Packageability and strength are critical for bag performance. Softness for reduced skin abrasion is desired.

The most widely used yarns in the airbag market are 315, 420, 630 and 840 denier Nylon 6,6 yarn. Nylon 6 is also used in a small percentage of U.S. made airbags. DuPont, Allied-

Signal, Akzo and Toray are the major fiber suppliers of airbags. Table 15.4 shows physical properties of Nylon 6,6 airbag fibers. PET, which has good dimensional stability even at humid environmental conditions and good compaction, is beginning to be used in certain applications as airbag material.

Driver and passenger side bags differ slightly in their properties as shown in Table 15.5. Passenger side fabrics have different properties and are uncoated because the gas that inflates the airbag is dispersed over a larger area. Fabrics must be free of knots, splices, spots and broken ends.

3.2 Manufacturing

Airbags are made of woven fabrics. In the United States, airbag fabrics are manufactured

TABLE 15.4 Typical Properties of Nylon 6,6 Airbag Yarns (courtesy of AlliedSignal).

Denier	420	840
Filaments	68	140
Tenacity (g/d)	7.9	8.4
Elongation (%)	21	21
Free shrinkage (% at 177°C)	6.1	6.5
Melting temperature (°C)	256	256

*TABLE 15.5 Typical Characteristics of Driver
and Passenger Side Fabrics Used
in Airbags (courtesy of AlliedSignal).*

Driver Side	Passenger Side
25 × 25 plain weave 840 denier Nylon 6,6 Scoured, heat set, coated	25 × 25 rip stop 840 denier Nylon 6,6 Scoured, heat set
46 × 46 plain weave 420 denier Nylon 6,6 Scoured, heat set, coated	41 × 41 plain weave 630 denier Nylon 6,6 Scoured, heat set
	49 × 49 plain weave 420 denier Nylon 6,6 Scoured, heat set

by Milliken, JPS Automotive, Takata/Highland Industries, Clark-Schwebel, and Stern & Stern. Reeves International of Italy is a major manufacturer in the world. Figure 15.9 shows a typical dense woven fabric for airbags.

After weaving, the driver side airbag fabric is coated with black neoprene rubber or silicon rubber. Major requirements for coating are good adhesion, antiblocking, long term flexibility, resistance to cyclic temperature change (from −40°F to 250°F), ozone resistance, long term

stability, low air permeability and low cost. Table 15.6 shows typical fabric properties of an 840 denier nylon airbag fabric. Coating companies in the United States include Reeves, Takata/Highland, Milliken, Alpha and Bradford.

Cutting and sewing of airbag fabrics demand careful attention. Dimensional tolerances are very small. Sewing thread fiber type, weight, construction and coating need to be selected properly. Nylon 6,6, Polyester and Kevlar® aramid fibers are used for sewing threads. Sewing patterns and stitch types are critical to the performance of the airbags.

An airbag module consists of airbag, inflator, mounting hardware and molded cover. Crash sensors and diagnostics are used as part of the system. Major module manufacturers are located in the United States (American Bag Co. division of Milliken, Reeves, AlliedSignal Safety Restraints, Takata/Highland Industries, Morton International, TRW Inc., GM-Inland Fisher Guide, Breed), Europe (Electrolux Autoliv, TWR Repa) and Japan (Takata Industries). The module manufacturing companies are responsible for designing, testing, constructing, certifying and supplying the car man-
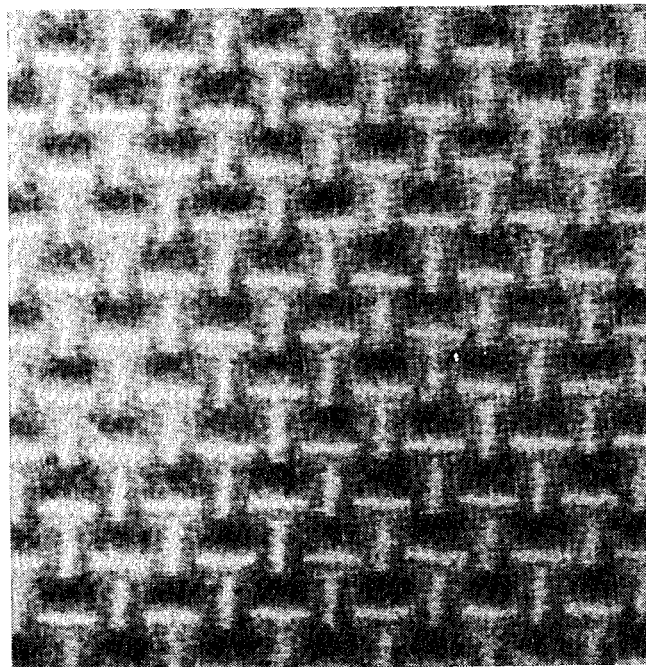
FIGURE 15.9 A dense woven airbag fabric (courtesy of Sulzer Ruti).

000040

Fiber Properties and Technology

S. ADANUR

The major properties of textile fibers that have important industrial textile usage are included in this chapter. There are many synthetic fibers of the same generic class, manufactured by different companies. For those fibers which are reasonably well known or widely used, properties are listed generically and by trade names. Fibers with lesser known trade names are grouped under their proper generic class, with ranges of values being given wherever possible. The continual introduction of new man-made fibers makes it a genuinely impossible task to present a tabulation which will remain up-to-date for any reasonable length of time. Fiber names, types, and properties are constantly changing. Therefore, caution should be exercised in using the numerical data presented in the following tables. This chapter also discusses the significance of fiber properties as they influence the performance characteristics of yarns and fabrics.

Appendix 4 lists the characteristics, industrial uses and manufacturers of generic man-made fibers and trade names. Figure 17.1 shows longitudinal and cross-sectional photographs of selected industrial fibers.

1. REFRACTIVE INDEX

The refractive index (n) of a substance is defined as the ratio of the velocity of light in a vacuum to the velocity of light through the substance. Because of the molecular orientation within fibers, the speed of light along the fiber axis is usually different from that transverse to the fiber axis. The greater the amount of orientation and degree of crystallinity, the greater will be the difference between the refractive in-

dices which are parallel with, and transverse to, the fiber axis. The difference is called the "birefringence." For all fibers except Saran® the parallel index n_ϵ is greater than the transverse index n_ω, and so the birefringence is always positive. Refractive indices are useful for identifying fibers and, in research, indicating the nature of molecular order in experimental fibers. While refractive index may influence fiber luster, the effect of fiber crimp and the state of aggregation of fibers in yarns and yarns in fabrics are of far greater significance in obtaining or preventing fabric luster. Except as it is a measure of molecular order, which in turn may influence the tensile and elastic properties of fibers, refractive index is of no special significance in the industrial textile picture. Table 17.1 lists refractive indices and birefringences of natural and man-made fibers.

2. DENSITY (SPECIFIC GRAVITY) OF FIBERS

Table 17.2 lists densities of fibers. Density is defined as the ratio of a substance's unit volume weight to that of water at 4°C.

3. FIBER FINENESS AND DIAMETERS

Table 17.3 lists fiber diameters (μm) based on filament deniers for selected fibers.

4. FIBER STRENGTH AND TENACITY

While it might be desirable to catalog the absolute breaking strengths of individual fibers,

555

Name	Photomicrographs
Asterisk denotes trademark	Cross section, 500X Longitudinal, 250X

Name

Asterisk denotes
trademark

Polyester

Photomicrographs

Cross section, 500X
Longitudinal, 250X

*A.C.E.
*Compet
Allied

* Dacron
Du Pont

*Fortrel
Wellman

4DG
Eastman

*Tairilin
Nan Ya Plastics Corp.,
America

*Trevira
Hoechst Celanese
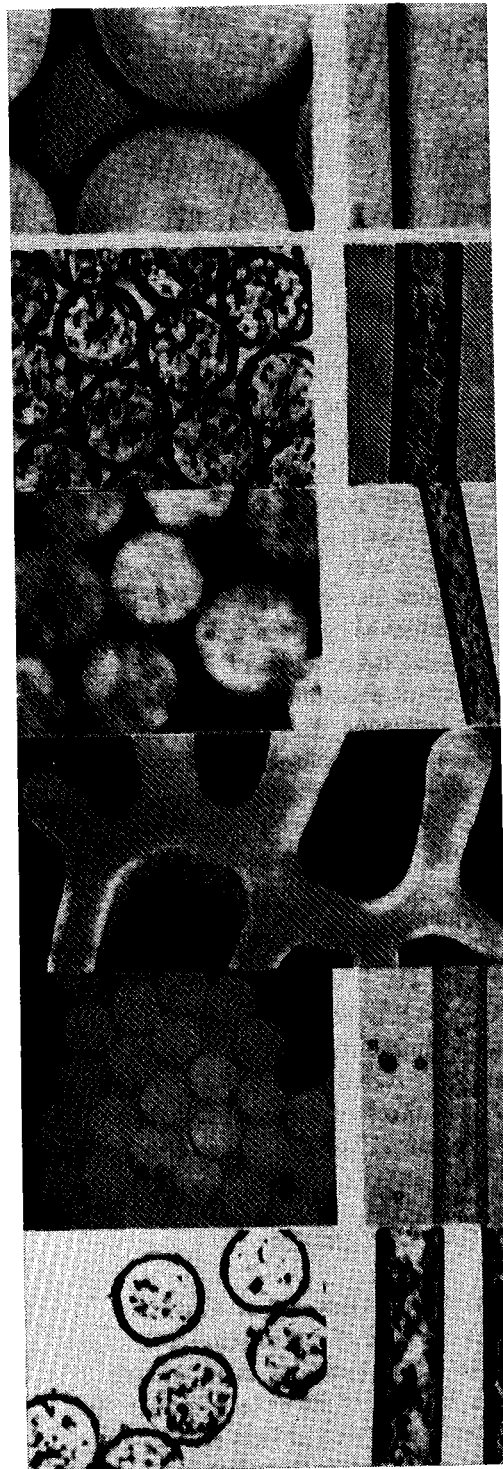
FIGURE 17.1 Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

556

000042

Name	Photomicrographs
Asterisk denotes trademark	Cross section, 500X Longitudinal, 250X

Carbon

    *Thornel
    Amoco
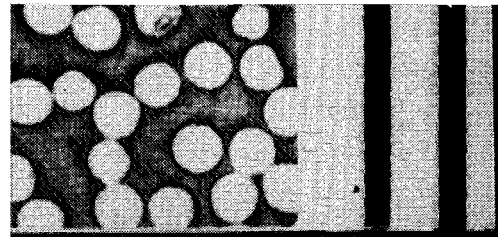
Nylon

    Nylon 6

    Nylon 6,6
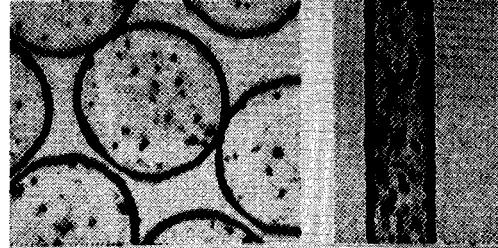
Lyocell

    * Tencel
    Courtaulds

Rayon

    *Fibro
    Courtaulds

    Cuprammonium

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

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Name	Photomicrographs
Asterisk denotes trademark	Cross section, 500X Longitudinal, 250X

Rayon
North American
Rayon Corp.

*Saran
Pittsfield Weaving

Acetate

Acetate

Sulfar

*Ryton
Amoco
(Licensed by Phillips)

Acrylic

* Acrilan
Monsanto

*Creslan
*MicroSupreme
Cytec
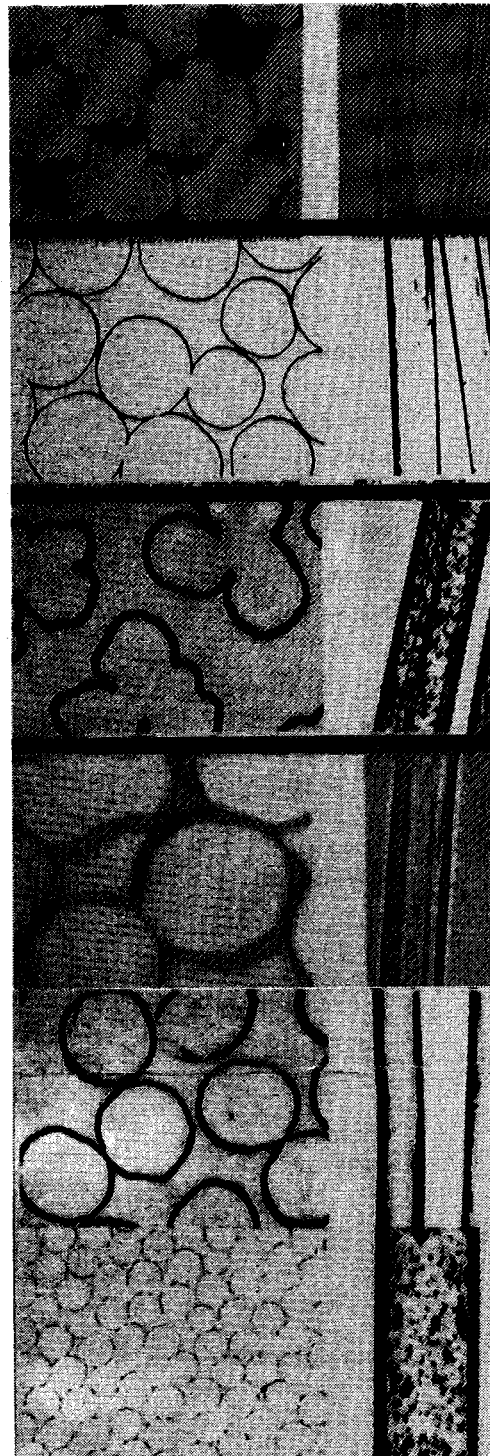
FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

558

000044

Name	Photomicrographs

Name

Asterisk denotes·
trademark

Modacrylic

* SEF
Monsanto

Olefin

Polyethylene
Hercules

* Herculon
Hercules

*Marvess
*Alpha
Amoco

*Essera,
*Marquesa Lana,
*Patlon III
Amoco

*Spectra 900
*Spectra 1000
Allied

Photomicrographs
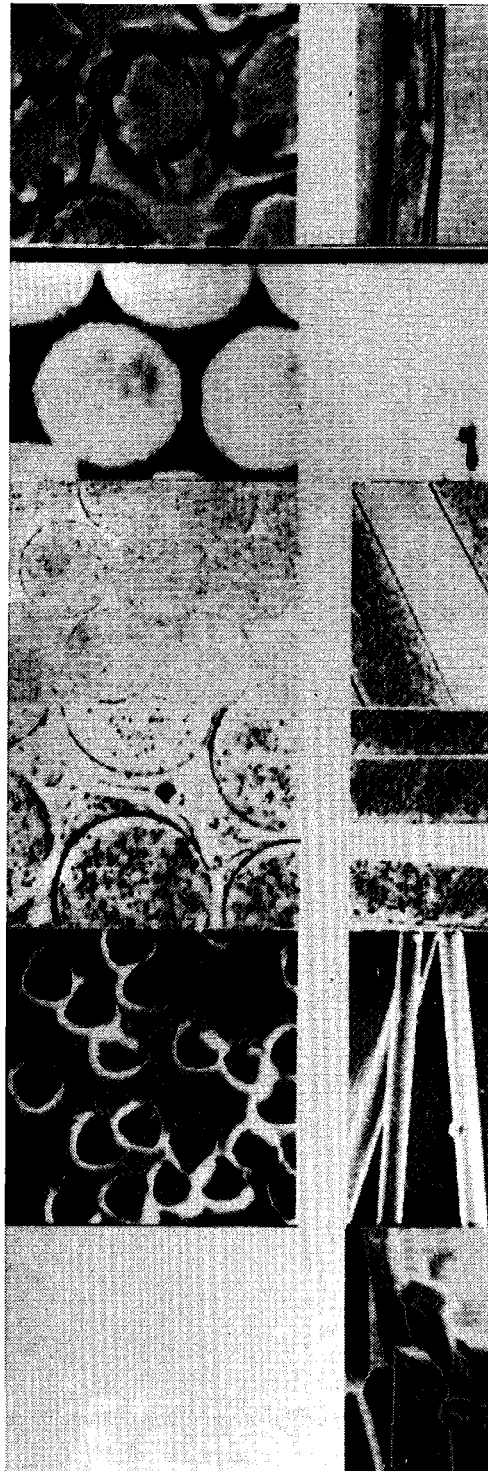
Cross section, 500X
Longitudinal, 250X

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

559

Name	Photomicrographs

Name
Asterisk denotes·
trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X

***Fibrilon**
Synthetic Industries

Spandex

***Glospan/
Cleerspan, S-85**
Globe

*** Lycra**
Du Pont

Glass

Glass

Aramid

*** Kevlar**
Du Pont

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

560

| **Name** | **Photomicrographs** |
| Asterisk denotes trademark | Cross section, 500X
Longitudinal, 250X |

* Nomex
Du Pont

Fluorocarbon

* Gore-Tex
W. L. Gore

* Teflon
Du Pont

Polybenzimidazole

PBI
Hoechst Celanese

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

TABLE 17.1 Refractive Indices and Birefringences of Fibers ([1], Fiber Manufacturers' Data).

Fiber	Refractive Index		Birefringence $(n_\epsilon - n_\omega)$
	Parallel (n_ϵ)	Transverse (n_ω)	
Acetate	1.479	1.477	0.002
Acrylic	1.525	1.520	0.004
Aramid			
Nomex®	1.790	1.662	0.128
Kevlar®	2.322	1.637	0.685
Asbestos	1.5–1.57	1.49	0.01–0.08
Cotton, raw	1.580	1.533	0.047
Cotton, mercerized	1.57	1.52	0.05
Fluorocarbon	1.37	–	–
Glass	1.547	1.547	0.000
Modacrylic	1.536	1.531	0.005
Novoloid	1.650	1.648	0.002
Nylon			
Nylon 6	1.568	1.515	0.053
Nylon 6,6	1.582	1.519	0.063
Nytril	1.484	1.476	0.008
Olefin			
Polyethylene	1.556	1.512	0.044
Polypropylene	1.530	1.496	0.034
Polycarbonate	1.626	1.566	0.060
Polyester			
Dacron®	1.710	1.535	0.175
Kodel®	1.632	1.534	0.098
Cuprammonium rayon	1.548	1.527	0.021
Viscose rayon	1.547	1.521	0.026
Saran	1.603	1.611	−0.008
Silk	1.591	1.538	0.053
Spandex	1.5	–	–
Triacetate	1.472	1.471	0.001
Vinal	1.543	1.513	0.030
Vinyon (PVC)	1.541	1.536	0.005
Wool	1.556	1.547	0.009

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TABLE 17.2 Density of Fibers [1,2].

Fiber	Density (mg/mm³)
Polyester	
ACE®	1.38
Compet®	1.38
Dacron®	1.34–1.39
Fortrel®	1.38
Tairilin®	1.38
Trevira®	1.38
Thornel® carbon	
High strength	1.77
High modulus	1.77
Ultra-high modulus	1.96
Nylon 6	1.14
Nylon 6,6	1.13–1.14
Tencel® lyocell	1.56
Viscose rayon	1.52
Cuprammonium rayon	1.53
Saran	1.62–1.75
Acetate	1.32
Ryton® sulfar	1.37
Acrylic	1.17
Modacrylic	1.35
Nytril	1.20
Polyethylene, low density	0.92
Polyethylene, high density	0.95
Polypropylene	0.90
Spectra® olefin	0.97
Lycra® spandex	1.2
E-glass, single filament	2.54–2.69
S-glass, single filament	2.48–2.49
Glass, multifilament	2.5
Aramid	
Kevlar®	1.44
Nomex®	1.38
Fluorocarbon	
Gore-Tex®	0.8–2.2
Teflon®	2.1
Polybenzimidazole	1.43
Asbestos	2.1–2.8
Flax	1.54
Cotton	1.54
Novoloid	1.28
Polycarbonate	1.21
Silk	1.35
Vinyon (PVC)	1.40
Wool	1.31

cross-sectional shapes and areas of fibers can vary widely. When subjected to a tensile force, the total strength of a fiber is dependent upon both its intrinsic ability to remain intact and upon its dimensions. The absolute value of a

fiber's strength may be meaningless until it is related to its cross-sectional area or its linear density, i.e., weight per unit length. As is the custom with all engineering materials, fiber breaking strengths can be listed on a pounds per square inch (psi) basis. More commonly, however, the textile trade uses the term "tenacity" to describe strength on a grams per denier (gpd) basis. This is because it is easier to determine a fiber's or yarn's weight per length than its weight per cross-sectional area, because yarn weight is an important textile physical and economic factor. Since denier is based upon weight per unit length, it is obvious that tenacity is influenced by the specific gravity of the fiber, while strength per unit area is not. The relationship between these properties is:

tensile strength (lb per sq. in. or psi)

$$= 12{,}800 \times \text{tenacity (grams per denier or gpd)}$$

$$\times \text{ specific gravity} \qquad (17.1)$$

In Table 17.4 tensile strengths are listed in psi and grams per denier for various fibers. The relationship between tex and denier is:

$$\text{tex} = \frac{\text{denier}}{9} \qquad (17.2)$$

Textile fibers are relatively light, therefore they can be highly efficient on a strength-to-weight ratio basis. High tenacity nylon, for example, with a specific gravity of 1.14 may have a tenacity of 9 grams per denier (81 grams per tex) as compared with a high strength steel (500,000 psi) or about 3.5 gpd. On a cross-sectional area basis, high tenacity nylon has a strength exceeding 100,000 psi.

While textile fibers may have high tenacities, often the corresponding strength of the textile fabric is disproportionately lowered, due to the inefficient translation of fiber strength into yarn strength and yarn strength into fabric strength. This is particularly true with staple fibers. Because of non-uniform fiber lengths, interfiber slippage, random fiber orientation within the yarn, and the helical path of fibers due to yarn

TABLE 17.3 Fiber Diameters of Various Textile Fibers [3].

Denier	Viscose Rayon	Acetate and Vinyon	Nylon	Polyester	Olefin
1	9.6	10.3	11.1	10.1	12.5
2	13.6	14.5	15.7	14.3	17.7
3	16.7	17.8	19.3	17.5	21.7
4	19.3	20.6	22.3	20.2	25.0
5	21.6	23.0	24.9	22.6	28.0
6	23.6	25.2	27.3	24.8	30.7
7	25.5	27.3	29.5	26.8	33.1
8	27.3	29.1	31.5	28.6	35.4
9	28.9	30.9	33.4	30.4	37.5
10	30.5	32.6	35.2	32.0	39.6
12	33.4	35.7	38.6	35.1	43.3
14	36.1	38.5	41.7	37.9	46.8
16	38.6	41.2	44.5	40.5	50.1
18	40.9	43.7	47.3	42.9	53.1
20	43.1	46.1	49.9	45.3	56.0

twist, only a part of the theoretically available strength, based upon the number of fibers in the yarn cross section, will actually result in the yarn.

Cotton has a tenacity of about 3.0 to 4.9 gpd (27 to 44 gpt). Because it exists only as staple, its fiber strength is not completely convertible into equivalent yarn strength, the efficiency of the conversion being on the order of magnitude of 50%. Thus, cotton yarns usually have tenacities not in excess of about 3 gpd (27 gpt). The competitive advantages of multi-filament high tenacity rayon, nylon, or other synthetic yarns become obvious.

It should be apparent that strength per se is not the only criterion by which the performance of textiles should be judged. Textile yarns and fabrics are normally used because they have flexibility and moderate strength, coupled with the ability to deform or strain under load, thereby absorbing energy, and the ability to recover or retract when the load is removed. Many other chemical and physical properties will influence the ultimate selection of the fiber and the yarn and fabric into which it is converted.

5. FIBER BREAKING ELONGATION

Table 17.5 lists breaking elongations or strains which fibers can undergo up to the point of fail-

ure. As a general rule it can be stated that an inverse relationship exists between fiber strength and elongation. For natural cellulosic fibers, linen and ramie are stronger but have lower elongations than cotton; the animal fibers are much weaker but have greater elongations than the cellulosics. Glass fibers are very strong but very brittle, i.e., they have low elongations. In the manufacture of man-made fibers, for a particular generic type, a range of inverse strength-elongation values is normally obtainable. Thus nylon can be made with a tenacity of 9 gpd (81 gpt), an elongation of 12% or 5 gpd (45 gpt) and an elongation of 30%.

6. FIBER LOAD-ELONGATION DIAGRAMS

Figure 17.2 shows fiber tenacity (gpd) versus percent elongation diagrams. Often such diagrams are popularly but somewhat erroneously called "stress-strain" curves. Actually the tenacity scale should be converted to a pounds per square inch (psi) scale in order to produce a true stress versus strain diagram. A variety of fibers with a wide range of tenacity-elongation diagrams is available. The selection of a fiber for a particular purpose, of course, is dependent upon many property requirements. The shape of a fiber's load-elongation diagram, initially and after the fiber has been cyclically loaded and

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TABLE 17.4 Tensile Properties of Fibers [2].

Fiber	Breaking Tenacity (gpd)		Tensile Strength (psi)
	Standard	Wet	
Polyester			
A.C.E® and Compet®			
Filament—HT	8.3–9.0	9.0	135,000–160,000
Dacron®			
Staple and tow	2.4–7.0	2.4–7.0	39,000–106,000
POF	2.0–2.5	2.0–2.5	33,000–42,000
Filament—RT	2.8–5.6	2.8–5.6	50,000–99,000
Filament—HT	6.8–9.5	6.8–9.5	106,000–168,000
Fortrel®			
Staple series 400—RT	4.8–6.0	4.8–6.0	85,000
Staple series 300—HT	6.0–6.8	6.0–6.8	102,000
PO filament	2.0–2.5	2.0–2.5	80,000–88,000
Tairilin®			
POY	2.0–3.0	2.0–3.0	33,000–42,000
Staple	4.5–7.0	4.5–7.0	80,000–102,000
Trevira®			
Staple	3.5–6.0	3.5–6.0	41,000–105,000
POF	2.0–2.5	2.0–2.5	33,000–42,000
Filament—HT	7.2–8.2	7.2–8.2	118,000–140,000
Thornel® carbon			
High strength	24.1	24.1	550,000
High modulus	21.3	21.3	500,000
Ultra-high modulus	10.8	10.8	270,000
Nylon			
Nylon 6			
Staple	3.5–7.2		62,000–98,000
Monofil. and filament—RT	4.0–7.2	3.7–6.2	73,000–100,000
BCF—RT	2.0–4.0	1.7–3.6	
Filament—HT	6.5–9.0	5.8–8.2	102,000–125,000
Nylon 6,6			
Staple and tow	2.9–7.2	2.5–6.1	
Monofil. and filament—RT	2.3–6.0	2.0–5.5	40,000–106,000
Filament—HT	5.9–9.8	5.1–8.0	86,000–134,000
Tencel® lyocell—HT	4.8–5.0	3.8–4.2	
Rayon			
Fibro®			
RT—Multi-lobed	2.3	1.1	
IT—0.9 den or 0.25 in and up	3.0	1.5	
Cuprammonium, filament	1.95–2.0	0.95–1.1	
Rayon			
Filament—RT	1.9–2.3	1.0–1.4	
Filament—HT	4.9–5.3	2.8–3.2	
Saran®, monofilament	1.2–2.2	1.2–2.2	15,000–27,000
Acetate, filament and staple	1.2–1.4	0.8–1.0	20,000–24,000
Ryton® sulfar, staple	3.0–3.5	3.0–3.5	35,000–40,000
Acrylic			
Acrilan®, staple and tow	2.2–2.3	1.8–2.4	30,000–40,000
Creslan®, staple and tow	2.0–3.0	1.6–2.7	30,000–45,000
MicroSupreme, staple	2.0–3.0	1.6–2.7	30,000–45,000
SEF® modacrylic, staple	1.7–2.6	1.5–2.4	29,000–45,000

(continued)

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TABLE 17.4 (continued).

Fiber	Breaking Tenacity (gpd)		Tensile Strength (psi)
	Standard	Wet	
Olefin			
Polyethylene			
Monofilament, low density	1.0-3.0	1.0-3.0	11,000-35,000
Monofilament, high density	3.5-7.0	3.5-7.0	30,000-85,000
Herculon®			
Staple	3.5-4.5	3.5-4.5	41,000-52,000
Buff filament	3.0-4.0	3.0-4.0	35,000-47,000
Marvess® and Alpha®			
Staple and tow	2.0-5.0	2.0-5.0	60,000-100,000
Multifilament	2.5-5.5	2.5-5.5	20,000-50,000
Essera®, Marquesa Lana®, Pation® III			
BCF	2.5-3.5	2.5-3.5	30,000-40,000
Staple	2.5-4.0	2.5-4.0	30,000-45,000
Spectra® 900	30	30	375,000,000
Spectra® 1000	35	35	425,000,000
Fibrilon®			
Staple	2.5-5.5	2.5-5.5	12,000-60,000
Fibrillated	3.5-5.0	2.5-5.0	40,000-60,000
Multifilament—RT	2.5-5.5	2.5-5.5	20,000-50,000
Spandex			
Glospan®/Cleerspan, S-85, multifilament	0.7		11,000
Lycra®			
Type 126, 127	1.0		11,000-14,000
Type 128	0.8		
Glass			
Single filament—E-glass	15.3	15.3	450,000-550,000
Single filament—S-glass	19.9	19.9	650,000-700,000
Multifilament	9.6	6.7	313,000
Aramid			
Kevlar®			
Kevlar 29/Kevlar 49	23	21.7	425,000
Kevlar 149	18		340,000
Kevlar 68	24.0		425,000
Kevlar HT (129)	26.5		490,000
Nomex®, staple and filament	4.0-5.3	3.0-4.1	90,000
Fluorocarbon			
Gore-Tex®	3.0-4.0	3.0-4.0	85,000-115,000
Teflon®			
TFE multifil., staple, tow, flock	0.9-2.0	0.9-2.0	40,000-50,000
FEP, PFA monofilament	0.5-0.7	0.5-0.7	14,000-20,000
PBI, staple	2.6-3.0	2.1-2.5	50,000
Asbestos	2.5-3.1		80,000-300,000
Cotton	3.0-4.9	3.3-5.39	59,500-97,000
Silk	2.4-5.1	1.75-4.01	38,500-88,000
Wool	1.0-1.7	0.85-1.44	16,500-28,000
Steel	3.5	3.5	512,500

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

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TABLE 17.5 Breaking Elongation, Elastic Recovery, Stiffness and Toughness of Fibers [2].

Fiber	Breaking Elongation (%)		Elastic Recovery (%)	Average Stiffness (gpd)	Average Toughness (gpd)
	Standard	Wet			
Polyester					
A.C.E.® and Compet®					
Filament—HT	13–22	13–15	77 at 5%; 75 at 10%	55–56	0.7–0.9
Dacron®					
Staple and tow	12–55	12–55	82 at 3%	12–17	0.2–1.1
POF	120–150	120–150			1.3–1.8
Filament—RT	24–42	24–42	76 at 3%	10–30	0.4–1.1
Filament—HT	12–25	12–25	88 at 3%	30	0.5–0.7
Fortrel®					
Staple series 400—RT	44–55	44–55			1.3–1.8
Staple series 300—HT	24	24			
PO filament	120–150	120–150			
Tairilin®					
POY	120–170	120–170			1.3–1.8
Staple	28–6	28–55	88 at 3%	10–30	0.3–1.5
Trevira®					
Staple	18–60	18–60	67–86 at 2% 57–74% at 5%	7–31	0.28–1.50
POF	130–145	130–145			1.3–1.8
Filament—HT	10–20	10–20	99 at 1%	54–77	0.35–0.55
Thornel® carbon					
High strength	1.6	1.6	100	1,500	
High modulus	1.0	1.0	100	2,300	
Ultra-high modulus	0.38	0.38	100	3,000	
Nylon					
Nylon 6					
Staple	30–90	42–100	100 at 2%	17–20	0.64–0.78
Monofil. and filament—RT	17–45	20–47	98–100 at 1–10%	18–23	0.67–0.90
BCF—RT	30–50	30–60			
Filament—HT	16–20	19–33	99–100 at 2–8%	29–48	0.75–0.84
Nylon 6,6					
Staple and tow	16–75	18–78	82 at 3%	10–45	0.58–1.37
Monofil & filament—RT	25–65	30–70	88 at 3%	5–24	0.8–1.25
Filament—HT	15–28	18–32	89 at 3%	21–58	0.8–1.28
Tencel® lyocell—HT	14–16	16–18		30	0.34
Rayon					
Fibro®					
RT—Multi-lobed	18–22				
IT—0.9 den or 0.25 in and up	18–22				
Cuprammonium, filament	8–14	24–28			
Rayon					
Filament—RT	20–25	24–29			
Filament—HT	11–14	13–16			
Saran®, monofilament	15–25	15–25	95 at 5–10%	5–10	0.165–0.265
Acetate, filament and staple	25–45	35–50	48–65 at 4%	3.5–5.5	0.17–0.30
Ryton® sulfar, staple	35–45		100 at 2%; 86 at 10%	10–20	
Acrylic					
Acrilan®, staple and tow	40–55	40–60	99 at 2%; 89 at 5%	5–7	0.4–0.5
Creslan®, staple and tow	35–45	41–50		6–8	0.62
MicroSupreme, staple	30–40	30–40		6–8	0.62
SEF® modacrylic, staple	45–60	45–65	100 at 1%; 95 at 10%	3.8	0.5

(continued)

TABLE 17.5 (continued).

| Fiber	Breaking Elongation (%)		Elastic Recovery (%)	Average Stiffness (gpd)	Average Toughness (gpd)
	Standard	Wet			
Olefin					
Polyethylene					
Monofilament, low density	20–80	20–80	Up to 95 at 5% 88 at 10%	2–12	0.3
Monofilament, high density	10–45	10–45	Up to 100 at 1–10%	20–50	
Herculon®					
Staple	70–100	70–100	96 at 5%; 90 at 10%	20–30	1–3
Buff filament	80–100	80–100	96a at 5%; 90 at 10%	20–30	1–3
Marvess® and Alpha®					
Staple and tow	60–100	80–98	90–93 at 5%; 83 at 10%	3–10	1.5–4
Multifilament	20–50	85–99	92–96 at 5%; 87 at 10%	12–25	0.75–3.00
Essera®, Marquesa Lana®, Pation® III					
BCF	40–60	40–60	90 at 5%; 65–90 at 10%	5–10	0,9–1.05
Staple	30–450	30–450			
Spectra® 900	3.6	3.6		1,400	
Spectra® 1000	2.7	2.7		2,000	
Fibrilon®					
Staple	30–150	30–150	93 at 5%; 85 at 10%		
Fibrillated	14–18	14–18	85 at 5%; 75 at 10%		
Multifilament—RT	30–100	30–100	95 at 5%; 85 at 10%	12–25	0.75–3.00
Spandex					
Glospan®/Cleerspan, S-85, multifilament	600–700		99% at 50% (S-7) 98% at 200% (S-5)	0.17 (S-7) 0.05 (S-5)	
Lycra®					
Type 126, 127	400–625		97 at 50%	0.13–0.20	2.00
Type 128	800		99 at 200%		
Glass					
Single filament—E-glass	4.8	4.8	100	320	0.37
Single filament—S-glass	5.3–5.7	5.3–5.7	100	380	0.53
Multifilament	3.1	2.2	100	310	0.15
Aramid					
Kevlar®					
Kevlar, Kevlar 29/Kevlar 49	4.0/2.5	4.0/2.5	100 at 1%, 2%, 3%	500/900	
Kevlar 149	1.5		100 at 1%	1,110	
Kevlar 68	3.0		100 at 1%, 2%	780	
Kevlar HT (129)	3.3		100 at 1%, 2%	755	
Nomex®, staple and filament	22–32	20–30		70–120	
Fluorocarbon					
Gore-Tex®	5–20	5–20			
Teflon®					
TFE multifil., staple, tow, flock	19–140	19–140		1.0–13.0	0.15
FEP, PFA monofilament	40–62	40–62		7.0	0.10–0.12
PBI, staple	25–30	26–32		9–12	0.40
Cotton	3–7		74 at 2%; 45 at 5%	60–70	0.15
Silk	10–25		92 at 2%; 51 at 10%	60–116	0.4–0.8
Wool	25–35	25–50	99 at 25%; 63 at 20%	4.5	0.35

HT: high tenacity.
POF: partially oriented filament.
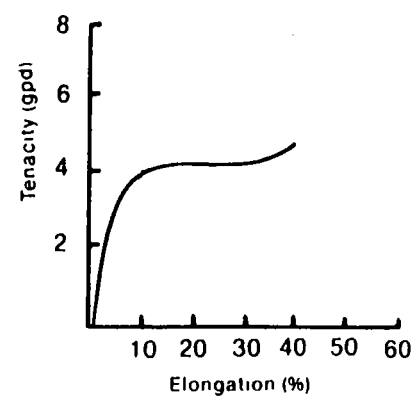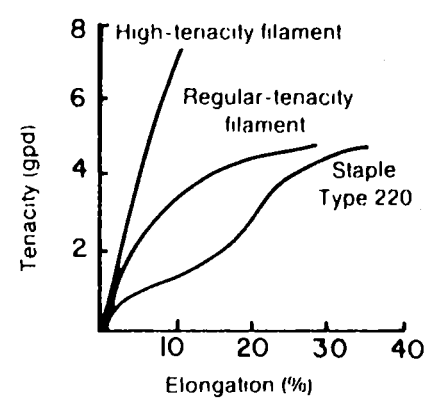POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

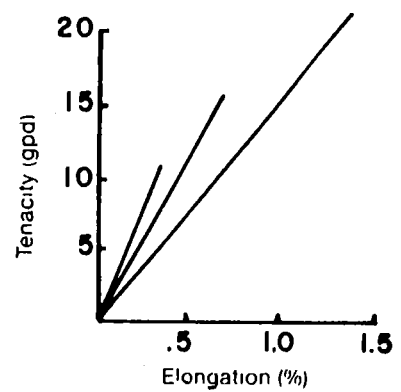Tenacity (gpd) vs Elongation (%)
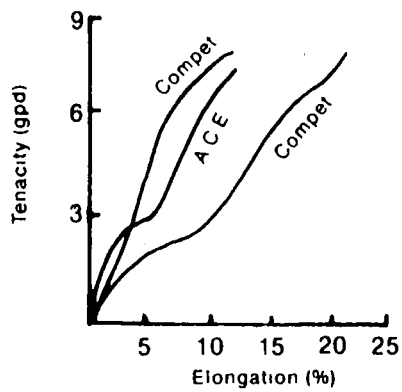
A.C.E.*, Compet*
Polyester

Polyester

Trevira*
Polyester

Thornel*
Carbon
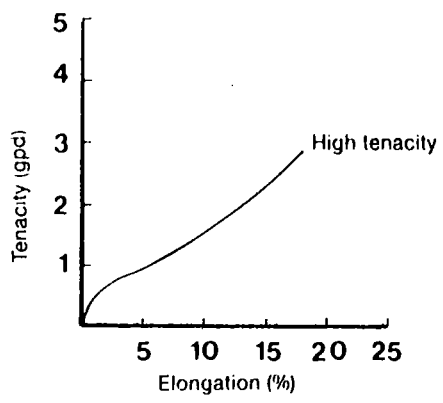
Fibro*
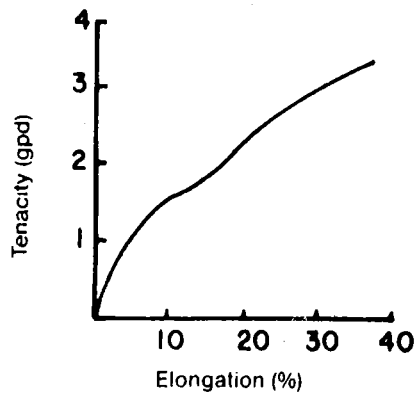Rayon
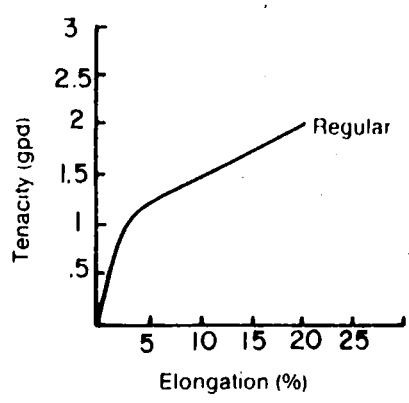
Cuprammonium

FIGURE 17.2 Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

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Ryton*
Sulfar
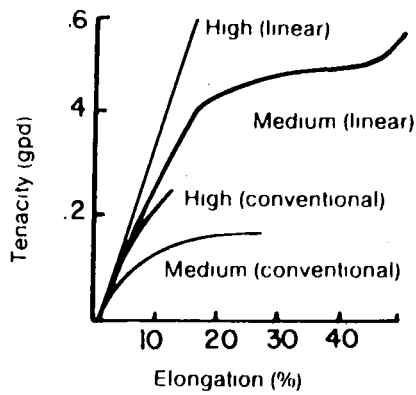
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Acrylic

Polyethylene
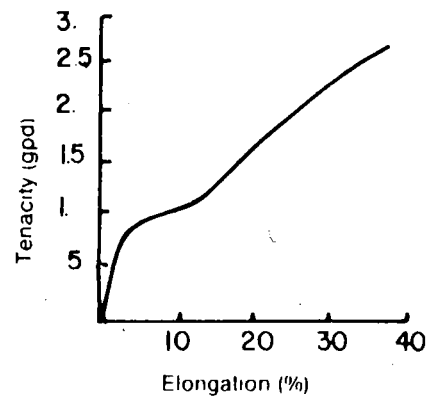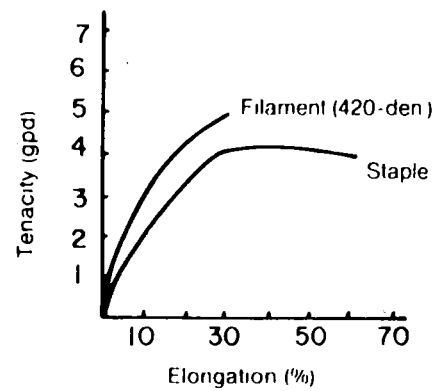
Herculon*
Olefin

Fibrilon*
Olefin
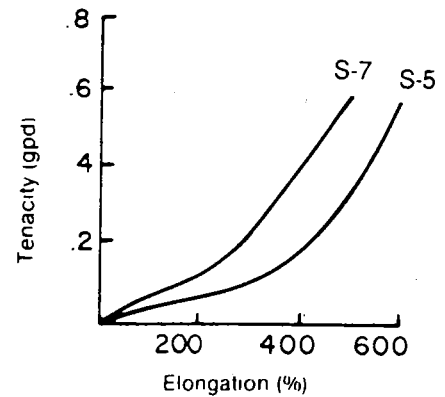
Glospan*
Spandex

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

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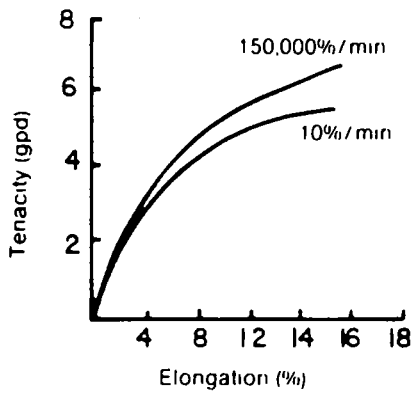
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Aramid
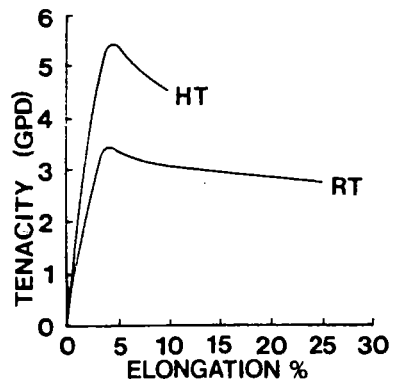
Gore-Tex*
Fluorocarbon
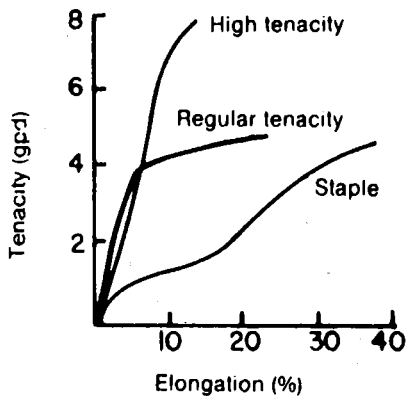
Dacron*
Polyester
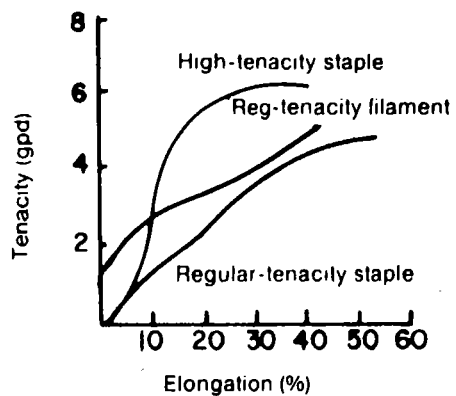
Fortrel*
Polyester
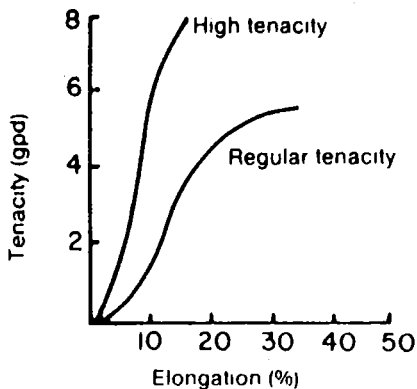
Nylon 6
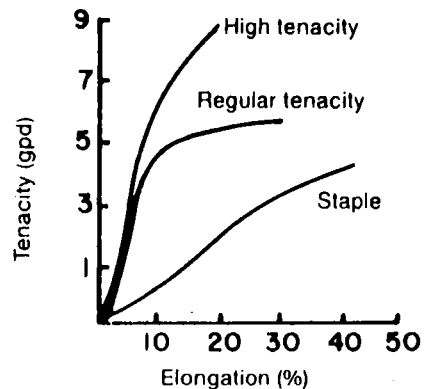
Nylon 6,6

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

571

Saran

Flat

Round

Percent extensibility

Rayon

High tenacity

Regular tenacity

Elongation (%)

Tenacity (gpd)

Creslan*
Acrylic

Tenacity (gpd)

Elongation (%)

Acrylic

Tenacity (gpd)

Elongation(%)

Marvess*
Olefin

Tenacity (gpd)

Elongation (%)

Marquesa Lana*, etc.
Olefin

Marquesa Lana
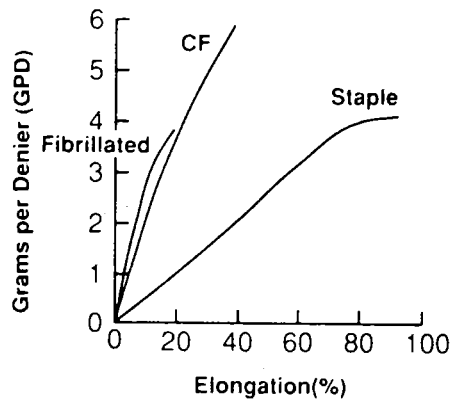Amoco XXV

Patlon III

Tenacity (gpd)

Elongation (%)

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

572

Tencel*
Lyocell

Acetate

SEF*
Modacrylic
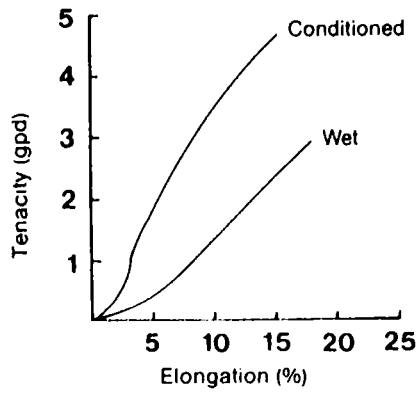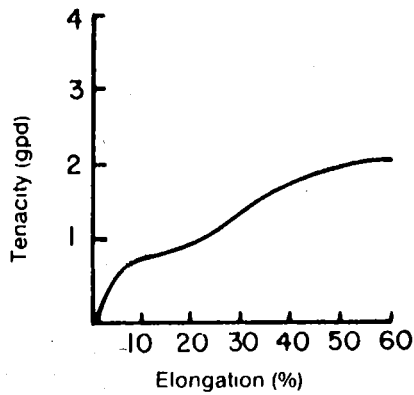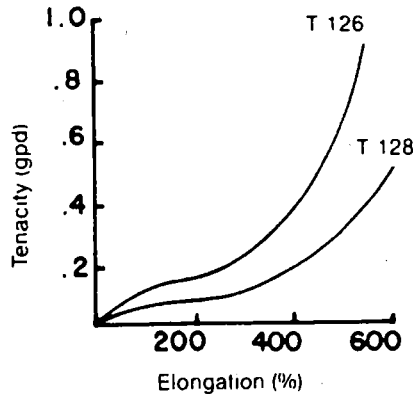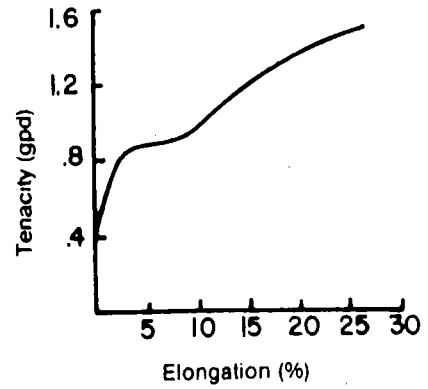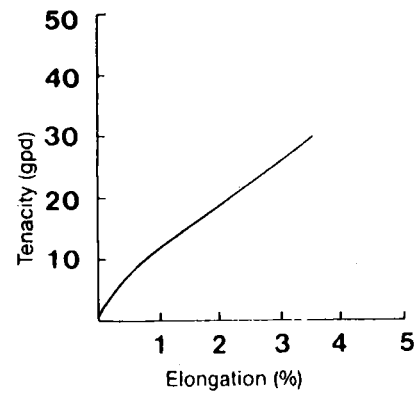
Spectra 900*
Olefin

Lycra*
Spandex
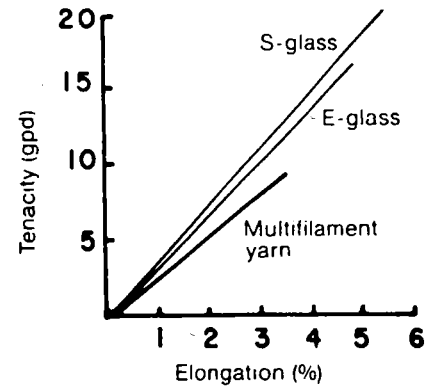
Glass

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

573

000059
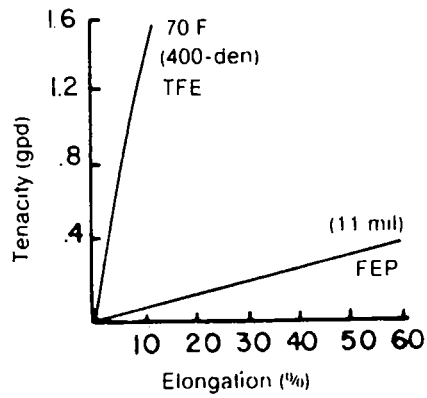
Teflon*
Fluorocarbon
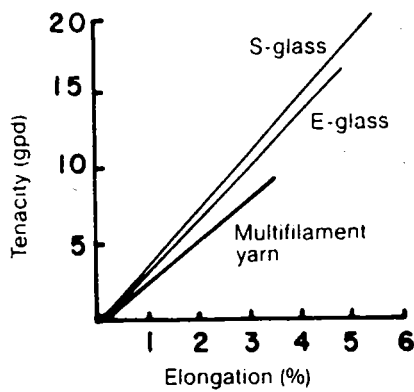
Glass
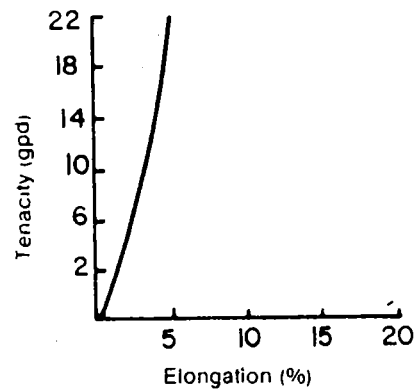
Kevlar*
Aramid
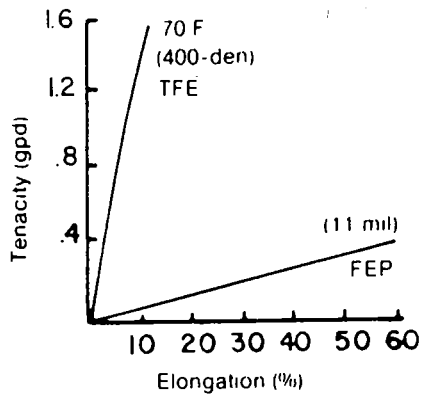
Teflon*
Fluorocarbon
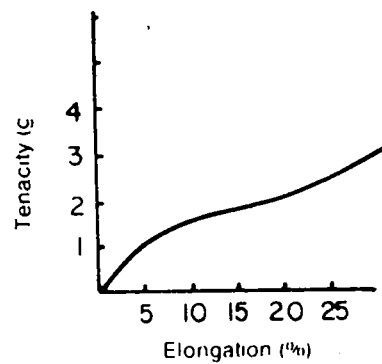
PBI
Polybenzimidazole

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

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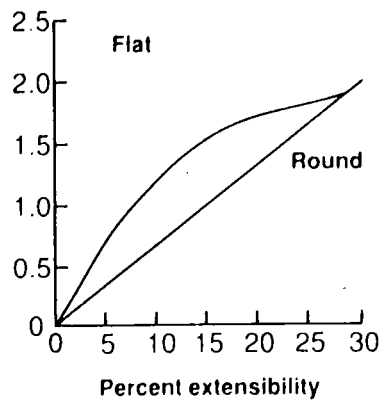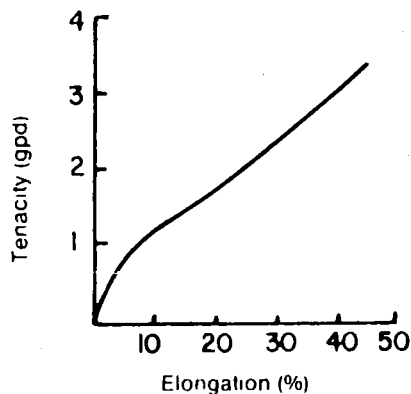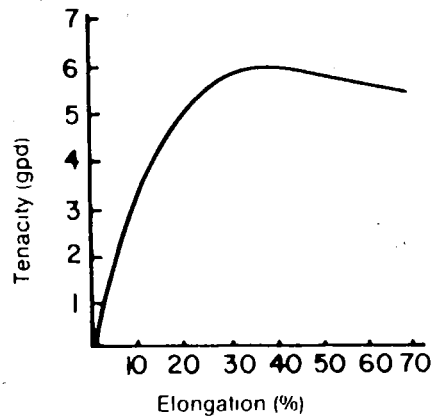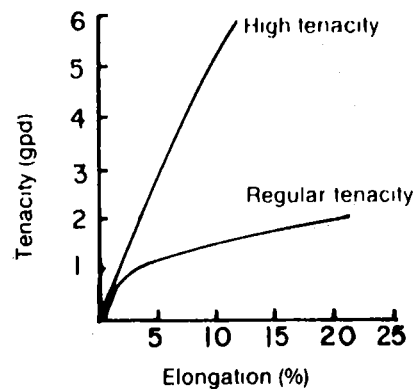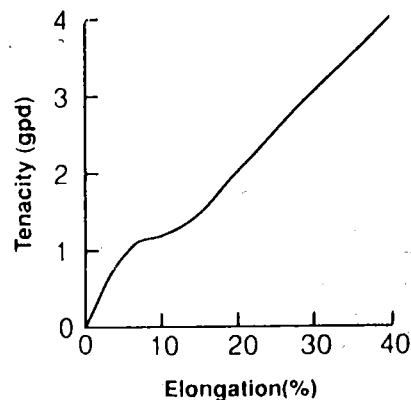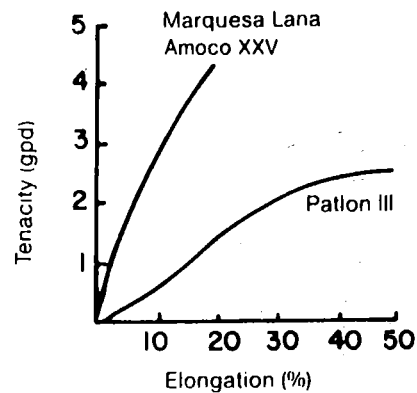unloaded at loads below rupture, is important in terms of the fiber's influence on such fabric properties as breaking and tear strength, energy absorption, dimensional stability, and abrasion resistance.

7. VISCOELASTICITY

Examination of fiber load-elongation diagrams shows that they are normally "non-Hookean," i.e., they do not obey Hooke's law which states that the strain (elongation) is linearly proportional to the applied stress (load). Figure 17.3 for a typical polyester, for example, shows an original region OA which is approximately linear. Point A is called the "proportional limit." Beyond this point, region AB develops where additional incremental loads produce proportionately larger increases in elongation, due to the propensity of the fiber to "creep," or slowly elongate under load. A slope change occurs at point B, followed by a stiffening region BC where additional loads beyond B cause smaller changes in elongation. Finally there is a second flow region CD.

Textile fibers and other high polymers such as rubbers, elastomers, films, and plastics which exhibit such varying "stress-strain" properties are stated to be "viscoelastic." The molecular and structural nature of these materials is such

that during selected periods of progressive loading, they may function in a perfectly "elastic" or "spring-like" manner. During other periods of loading a "viscous flow" or creep type of deformation occurs. These two mechanisms most often act in varying contributory amounts at the same time and thus produce a viscoelastic type of stress-strain response.

The above description pertains to the application of a tensional force in one time loading to rupture. If a specimen is strained (elongated) to a value below rupture and the strain producing force is then removed, a strain recovery will usually take place. Repeated load applications and removals produce strains and recoveries which are dependent upon the material's viscoelastic properties. The phenomenon becomes complex, giving rise to hysteresis [Figure 17.10(b)]. The elongation recovery or "repeated stress" characteristics of fibers is discussed later in the chapter. They are of great significance because they influence such properties as fabric dimensional stability, wrinkle resistance, abrasion resistance, and energy absorption.

8. ELASTIC MODULUS

The ratio of stress to strain is called the "modulus" of a material. High modulus materials are stiff; they show small elongation under
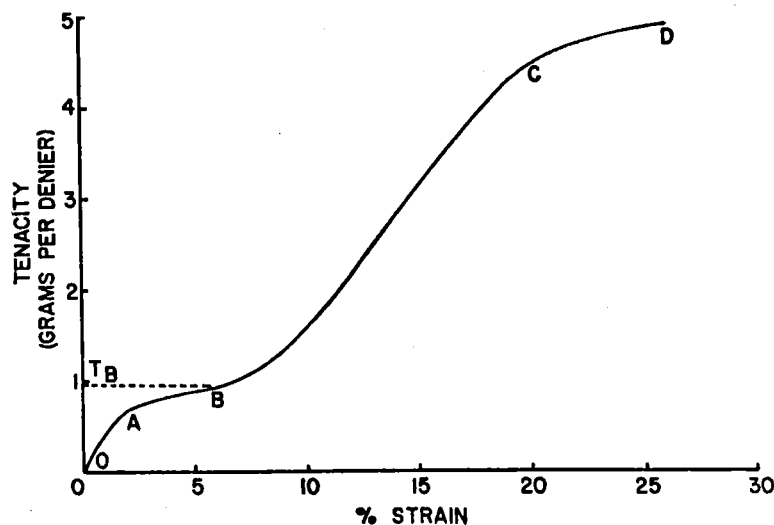
FIGURE 17.3 Analysis of a typical polyester tenacity-elongation diagram.

load. Low modulus materials are extensible; they show high elongation under load. "Young's modulus" is defined by ASTM as the ratio of change in stress to change in strain within the elastic limit of the material. The ratio is calculated from the stress, expressed in force per unit cross-sectional area, and the strain, expressed as a fraction of the original length. Young's modulus is of great value to the engineers utilizing wood, structural steel, and concrete since these materials are used below their elastic limits, and small deformations under load can be calculated with a reasonable degree of precision. The textile engineer and technologist also make use of this ratio, but because load-elongation diagrams of textiles are not usually linear over their entire use range, the "tensile modulus" of a fiber is not a constant and should be used only under conditions where

it is properly defined. ASTM also lists the following moduli definitions for textile materials:

- initial modulus: the slope of the initial straight-line portion of the stress-strain curve
- chord modulus: the ratio of the change in stress to the change in strain between two specified points in the stress-strain curve

8.1 Determination of Initial Modulus

In the case of a fiber exhibiting a region that obeys Hooke's law (i.e., has a linear region), a continuation of the linear region of the curve is constructed as shown in Figure 17.4. The intersection point B is the zero-strain point from which strain is measured. The initial modulus is
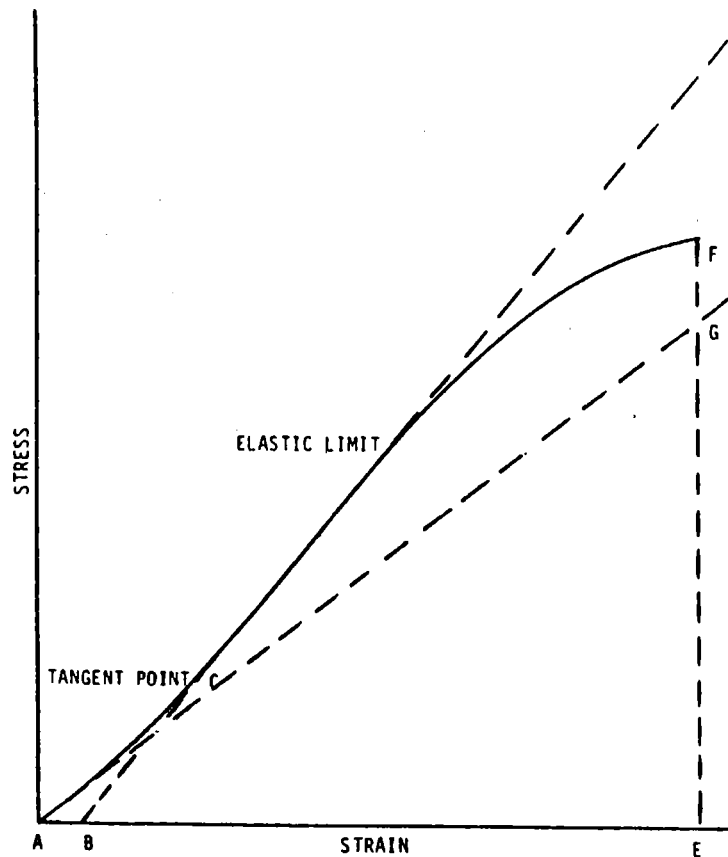
FIGURE 17.4 Construction of initial modulus for materials with Hookean region [4].
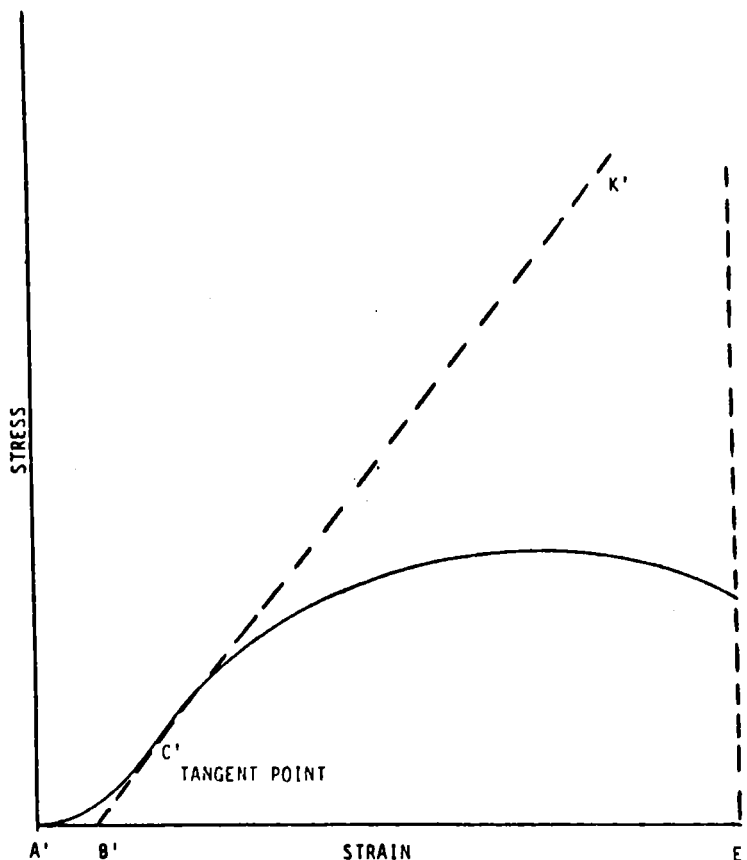
FIGURE 17.5 Construction of initial modulus for materials with no Hookean region [4].

determined by dividing the stress at any point along the line BD by the strain at the same point (measured from point B). Point C, the point where line BD first touches the stress-strain curve is the tangent point.

In the case of a fiber that does not exhibit any linear region (Figure 17.5), a tangent K'B' is constructed to the maximum slope. Point B' is the zero point from which strain is measured. Point C', the point where line K'B' first touches the stress-strain curve, is the tangent point. The initial modulus is determined by dividing the stress at any point along line B'K' by the strain at the same point (measured from point B').

8.2 Determination of Chord Modulus

In a typical stress-strain curve, a straight line is constructed through the zero-stress axis, such as zero strain point A" and a second point, such as 10% strain, point M" (Figure 17.6). The chord modulus is determined by dividing the stress at any point along line A"M" (or its extension) by the strain at the same point.

Figure 17.6 also represents a straight line constructed through any two specified points, point Q" and point R", other than zero and 10% strain. In this case, the line extends through the zero stress axis at point B". This intersection is the zero strain point from which strain is measured. The chord modulus can be determined by dividing the stress at any point along line Q"R" (or its extension) by the strain at the same point (measured from point B").

The modulus is also called the "stiffness" of the material since the higher the modulus the greater the resistance to deformation.

FIGURE 17.6 Construction of chord modulus [4].

Since engineering stress is given in pounds per square inch, modulus units for engineering materials normally are reported as psi per unit strain, or simply psi. Again, because convenient textile nomenclature uses the denier system, Young's moduli of fibers are reported as grams per denier per unit strain, i.e., the hypothetical tenacity required to strain the filament 100%, presuming strain extended at a rate equal to that of the initial slope of the stress-strain curve. The modulus (stiffness) is usually reported simply as "grams per denier." Moduli of major textile fibers are given in Table 17.5. Extensible fibers such as wool, acetate and acrylic have low textile moduli. Nylon and polyester can be drawn to varying degrees so that their moduli may have varying ranges (on the average, polyester slightly higher than nylon). Glass at 300 has a high modulus. However, carbon,

Spectra® olefin, and Kevlar® aramid fibers have moduli far above the range of other textile fibers. This is why these high modulus fibers, yarns, or fabrics are used in plastic laminates where minimum distortion under load is required. However, because of their high modulus and inability to deform under load (i.e., brittleness), excessively high stress concentrations may be induced in these fibers, and they may fail. In other low modulus fibers, the high strains resulting from the application of the non-uniform loads reduce the stress concentration, and the fiber can remain intact. This, among other reasons, is why high modulus fibers have not found wide use in textile fabrics where repeated flexing and abrasion, both being examples of non-uniform loading, are required. In uses where deformations are necessary, particularly under impact conditions, low modulus ma-

terials are advantageous, for the material will then extend rather than permit the buildup of an excessive force.

9. TOUGHNESS OR ENERGY ABSORPTION

The load-elongation diagram is a measure of work done or energy absorbed by the filament. This property is also called "toughness." Units normally are grams per denier (or tex). Table 17.5 lists energy absorption capacities of the various fibers.

Figure 17.7 shows that equal areas (i.e., energies) under a load-elongation diagram can be obtained via many different paths. For example, the area bounded by OBC is equal to OB'C'; but for Case I it is obtained via high strength and low elongation, while for Case II the strength is lower but the elongation is higher.

Except in those cases where energy must be absorbed with a minimum amount of deformation or elongation in the specimen, in order that the material maintain its dimensional stability, a combination of load bearing and elongation capacities is usually desirable. For example, glass is strong but its elongation is too low to be a good energy absorber. Wool is weak but is quite extensible, and so can absorb significant amounts of energy. However, because its load supporting capability is low and because the wool yarn, cord or fabric would become highly distorted, normally it is not used for industrial purposes. Cotton, high tenacity rayon, and especially polyester and nylon are tough, and hence have been widely used in ropes, conveyor

FIGURE 17.7 Energy absorption diagram.

belts, bagging, webbings, tents, awnings, and a wide array of industrial uses where a combination of lightness, strength, and toughness is required. Such end items usually are used many times, and therefore a further requirement is that they can repeatedly deform and absorb energy under load, and retract when the load is removed.

10. ELONGATION-RECOVERY PROPERTIES

If a vertically suspended textile fiber is dead-loaded with a weight equal, for example, to about half of its breaking load, the fiber will immediately elongate a fixed amount (Figure 17.8, part A). This elongation from 0 to 1 is called the "instantaneous elastic deflection" (IED). If the weight is then left hanging on the fiber for many minutes or hours, the fiber will continue to elongate or "creep" at a slow rate from 1 to 2 (part B). If the weight is then removed, the fiber will immediately and instantaneously recover or spring back by an amount approximately equal to the original IED. The recovery (from 2 to 3, part C) is called the "instantaneous elastic recovery" (IER). If the weight is then kept off, the fiber will tend to "creep back" and return to its original length. The amount which it recovers (3 to 4, part D) is called "primary creep" or "creep recovery." The amount by which it fails to return to its original length (4 to 0), is called "secondary creep" or "permanent set." Diagrammatically, the elongation versus time curve is depicted in Figure 17.9.

The instantaneous elastic deflection obeys Hooke's law, which states that the strain (elongation) is linearly proportional to the applied stress. Thus, if progressively increasing weights are hung on the fiber, the resulting IED's will be proportional to the applied loads and a linear load-IED diagram results. The creep portion of the elongation is the viscous effect referred to earlier. While, in practice, textiles may be dead loaded under a constant force, more often they are subjected to a heterogeneous combination of repeated below-rupture stresses and strains. When a specimen is progressively loaded to a

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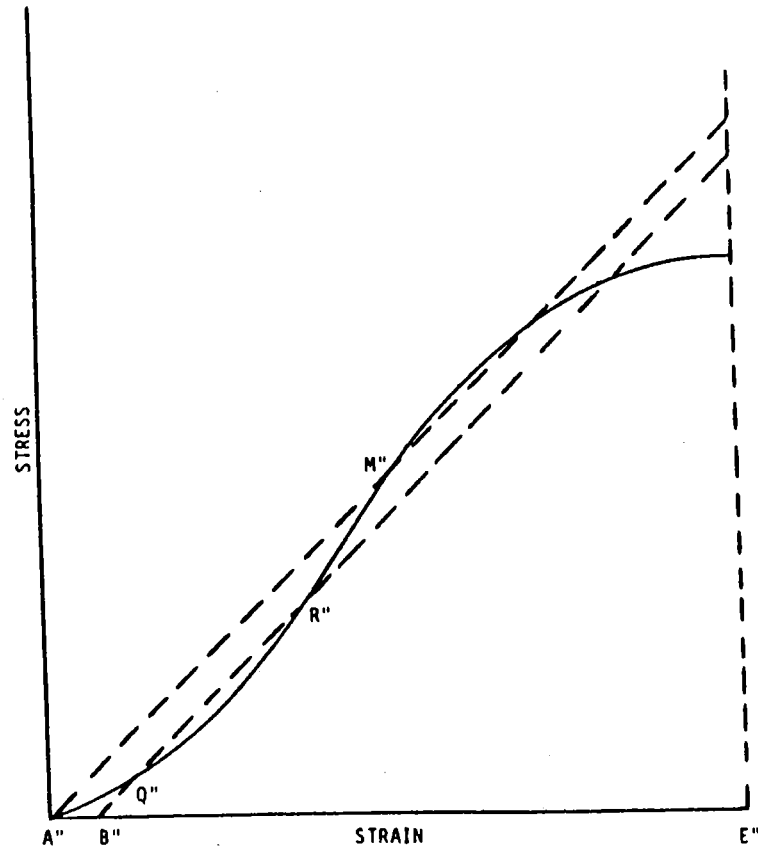required. In
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FIGURE 17.6 Construction of chord modulus [4].

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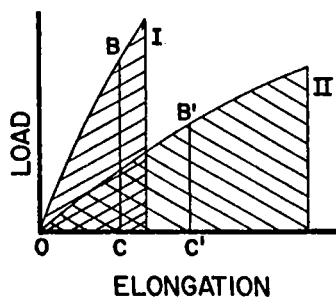

FIGURE 17.7 Energy absorption diagram.

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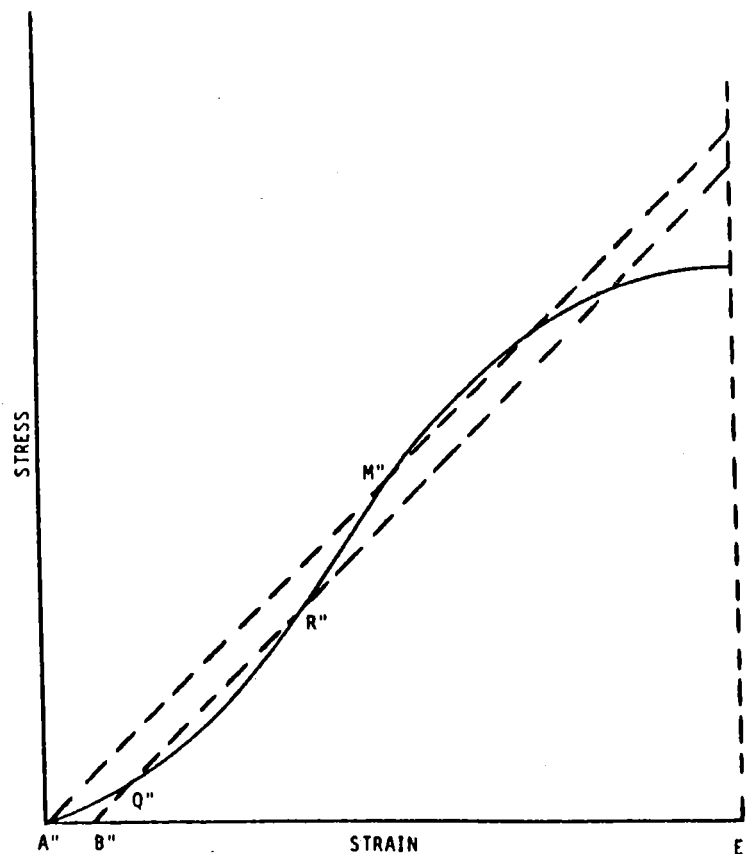
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FIGURE 17.8 Elongation properties of a fiber under constant load.
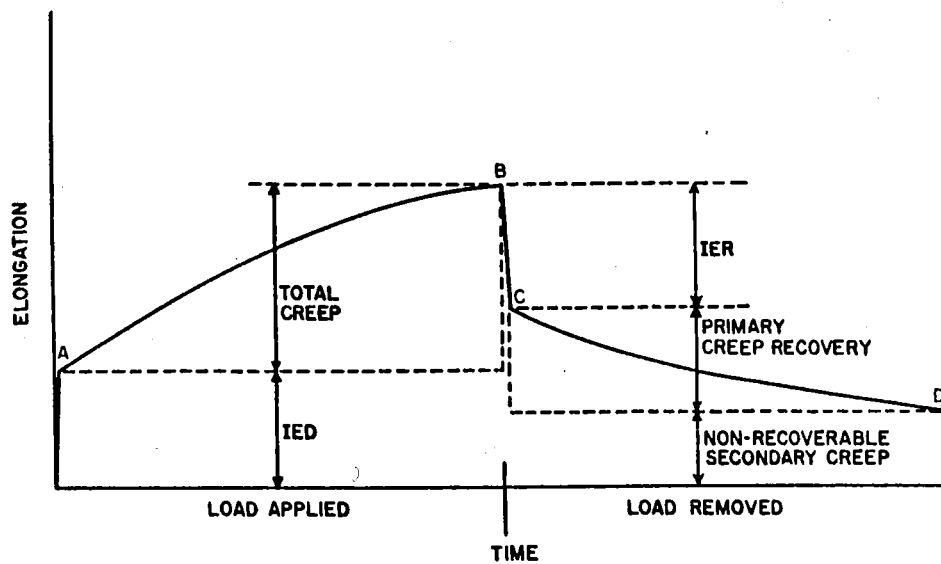
FIGURE 17.9 Elongation as a function of time under constant load and load removal.
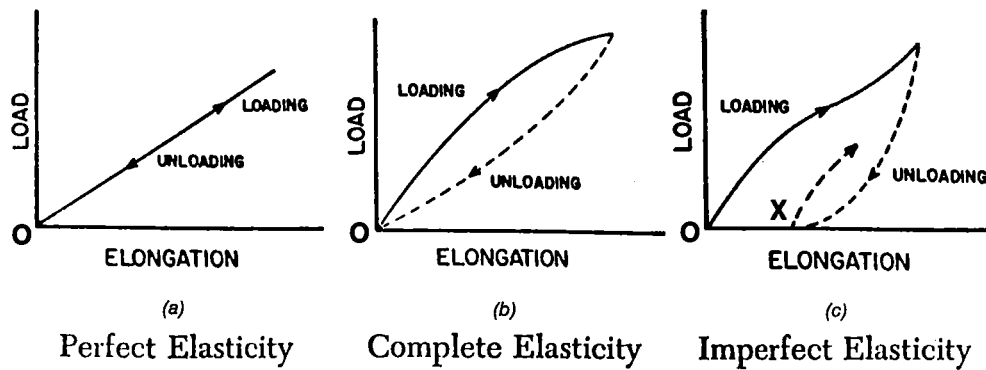
FIGURE 17.10 Three types of elasticity.

level below its rupture point, and then the load is progressively removed, one of the three types of load-elongation-recovery diagrams shown in Figure 17.10 will result.

Figure 17.10(a) depicts a truly Hookean material where the strain (elongation) is proportional to the applied stress (load) over the entire curve. Only instantaneous elastic deflection and recovery exist, thus producing a straight line for both loading and unloading, the two lines being superimposed at all points. Such a condition represents "perfect elasticity."

Figure 17.10(b) represents a condition where the strain is not proportional to the load, thus creep causes additional elongation. However, all the creep is primary, and upon load removal, complete recovery takes place, but via a path different from the loading curve, thus producing a "hysteresis" area. The primary creep recovery, while complete, is delayed and requires a longer recovery than the original loading time to be completed. Such a condition represents "complete elasticity." Figure 17.10(c) also represents a condition where the strain is not proportional to the load, thus creep causes additional elongation. Here, however, secondary as well as primary creep exists. Upon load removal recovery is incomplete, and a "permanent set" represented by O-X results. Such a condition represents "imperfect (and incomplete) elasticity."

Significance of Elongation-Recovery Properties

The abilities to deform upon load application and recover upon load removal are two of the most important properties which textile fabrics must have. Several pertinent examples are cited.

(1) Ability to absorb energy repeatedly—In order to be repeatedly useful, pump diaphragms, aircraft arrestation cables, conveyor belts, tire cords, fire hoses, crane slings, and the like must be capable of retracting absorbing energy. This is accomplished by the materials' elongation under load. If a fabric is to be used more than once, it must be capable of retracting to its original dimension after use in order that it again will have the ability to absorb an equal amount of energy on second or subsequent uses. If most of the elongation is non-recoverable secondary creep, the energy absorption capacity on a subsequent use will be significantly reduced to the point where failure may result.

(2) Ability to maintain dimensional stability— A tarpaulin, truck cover, auto seat cover, or tent may be subjected to deforming forces resulting from handling, or wind and weather. Its ability to deform or "roll with the punch" on load application, and return to its original dimension on load removal is necessary if the fabric is to be capable of absorbing stresses and strains repeatedly without becoming distorted and out-of-shape. In the case of conveyor belts, while high modulus-low elongation fabrics are usually demanded to keep "stretch" to a minimum, nevertheless the ability of the material to "give" slightly under load and recover upon load removal is a prerequisite.

(3) Wrinkle resistance—When fabrics are creased, yarns and fibers are bent in a manner such that some portions are in compression, and others are in tension. Creases which develop will be removable as a function of the ability of the fibers to recover from the imposed strains.

(4) Abrasion resistance—As will be discussed later in the chapter, a fabric's abrasion resistance is governed in part by the capacity of its fibers to absorb energy repeatedly at stresses below rupture. The fibers must be able to deform under the force produced by the abrasive action and to recover when the force is removed. Then, upon a subsequent abrasion stroke, the fibers again can deform and absorb energy without failure.

Table 17.5 shows the percent recovery of fibers which have been strained by varying amounts. After being strained 2%, staple Nylon 6, upon load removal, will recover to its original unstrained dimension. The Nylon 6 is thus said to recover 100% from the 2% strain. After 3% strain, regular tenacity Nylon 6,6 recovers 88%. This recovery capability, coupled with its high energy absorption permits it to repeatedly absorb large quantities of energy, thus accounting for nylon's excellent abrasion resistance.

11. RATE OF RECOVERY PROPERTIES

The more quickly and completely a fiber recovers from an imposed strain, the more nearly perfectly elastic it is. The ratio of the instantaneous elastic deflection to the total deflection may be used as a criterion of elasticity. The integrated closeness from a theoretical graph of perfect elasticity versus elongation is also used as a criterion under the term "elasticity index."

12. BENDING, COMPRESSION, SHEAR, AND TORSION STRAINS

In addition to tensile forces and strains, there are four other types of deformations to which engineering materials including textiles, may be subjected. These are simple compression, shear, torsion, and bending (Figure 17.11).

One of the outstanding attributes which a textile fiber must have is flexibility. In fact, this requirement probably should be included as an integral part of the definition of a textile fiber. The ability of the fiber repeatedly to bend and recover without failure is vital for most fabric uses. The stiffness of a textile fiber or any structural beam, is directly proportional to its elastic modulus, and to the fourth power of its diameter. The modulus is governed by the intrinsic nature of the fiber substance, i.e., the arrangement of atoms in the molecule, the amount of crystallinity, and the molecular orientation.

Organic fibers, in general, have stiffness moduli in the range of 10 to 200 grams per denier (Table 17.5). Rubbery or elastomeric materials have moduli of about 0.1 to 0.5 gpd. Glass, metals, and ceramics are in the range of 250 to 350. Conventional organic fibers have sufficient flexibility for most textile uses when their diameters are in the 10 to 70 micron range. In order for glass, ceramic, and metallic fibers to enjoy equal flexibility, they must be of even smaller diameter because of their higher moduli. Furthermore, the stiffness increases in direct proportion to the fourth power of the diameter, and so it becomes obvious that high modulus fibers must be drawn to very fine diameters if they are to be sufficiently flexible to perform as textiles. Furthermore, the specific gravities of glass, ceramics, and metals are considerably higher than the organic polymers. Therefore, inorganic fiber diameters must be small, not only to attain flexibility, but also to reduce fiber weight.

In simple compression, forces act in opposition to the direction they assume for tension. In the case of textiles, unless the fiber, yarn, or fabric is very short; true and complete compression does not exist, for the fiber will buckle and bending will result. This produces tension on the outside portion of the fiber and compression on the inside. Similarly, torsion and shear forces are negligible in flexible textile fibers, since the initial development of such forces produces strains in the material of such a magnitude that the forces immediately become tensional.

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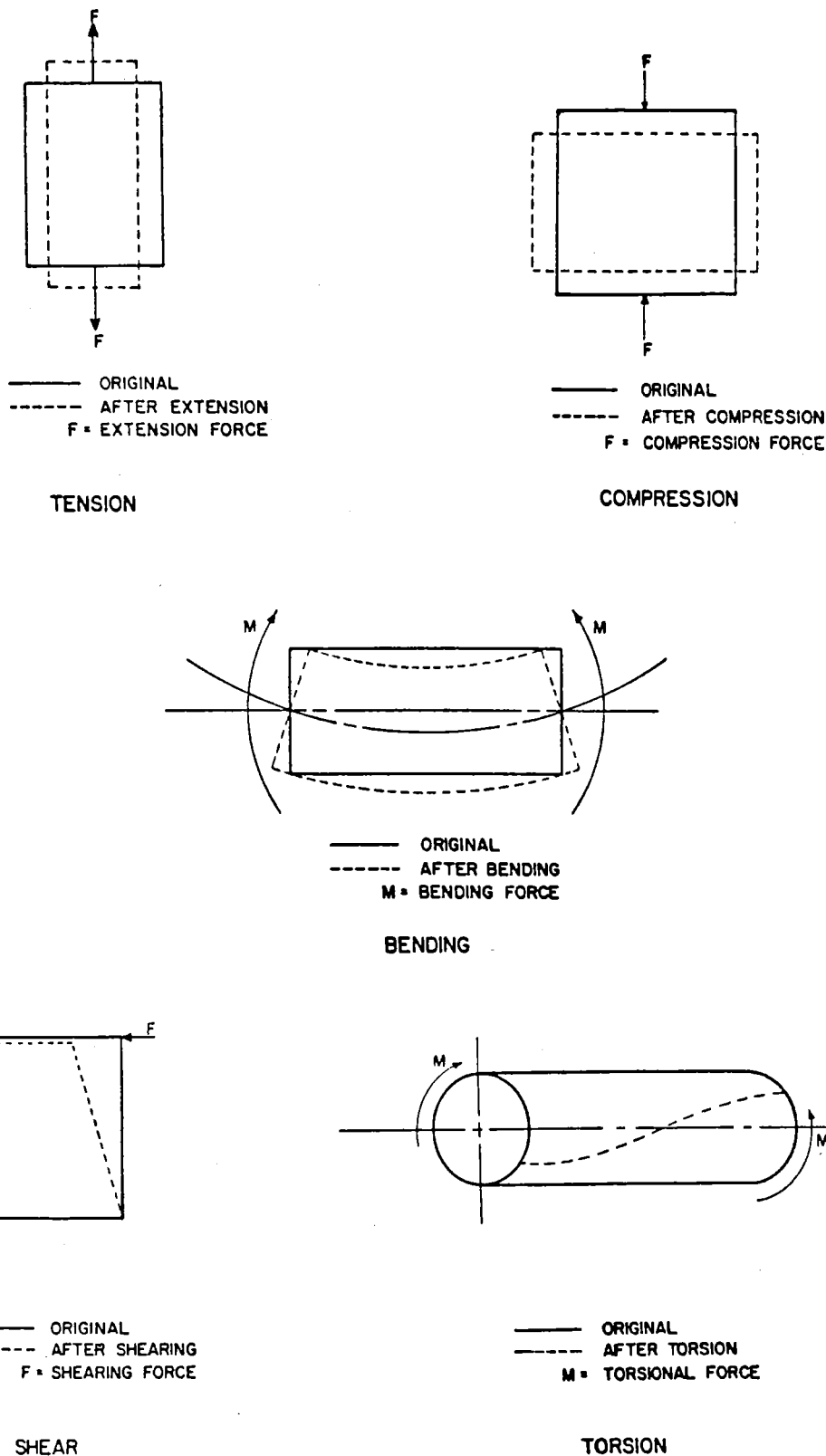
FIGURE 17.11 Types of forces and resulting strains.

13. LOOP STRENGTH

Table 17.6 lists fiber loop and knot strengths. The loop strength test consists of looping one length of a fiber through another loop as shown in Figure 17.12, and elongating the loops until rupture occurs. As the rupture elongation increases, the loop strength efficiency also increases. The reason being that in low elongation brittle fibers, high stresses are quickly built up and tensile failure occurs. High elongation fibers can extend rather than fail, and a more efficient break ultimately results. When a fiber is bent around itself, a tension strain develops on the outside and a compression strain on the inside.
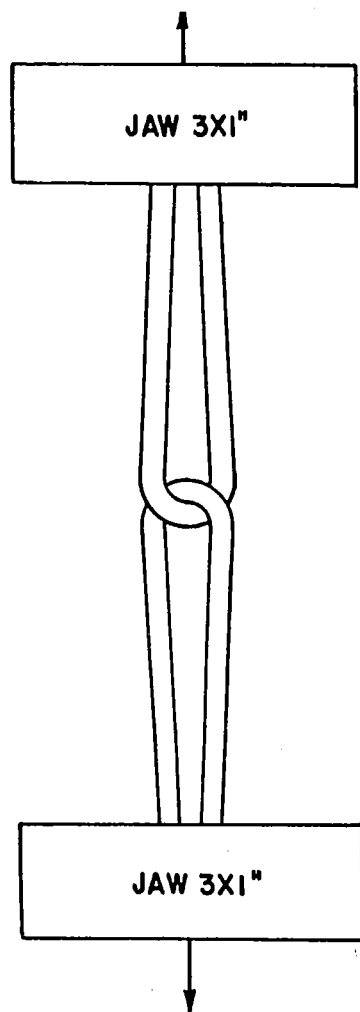
The greater the rupture elongation, the greater is the ability of the fiber to bend without failing.

High modulus fibers have low loop strength efficiences and weak, extensible fibers have higher efficiencies. Remember, however, that a less efficient, but originally stronger, fiber may have a higher absolute loop strength than a more efficient weaker fiber. Cotton has a remarkably high loop strength accompanying its nominal elongation. Aramids, nylon and polyester being tough, strong fibers, exhibit high absolute loop strength.

14. KNOT STRENGTH

Knot strengths of several fibers are listed in Table 17.6. The knot test consists of making a simple overhand loop (Figure 17.13) and then subjecting the specimen to a tensile pull. The general efficiencies (i.e., the ratio of knot to tensile strength) of knot strengths are about the same as for loop strengths, and for the same reasons.

Loop and knot strengths of yarns and cords are functions of the intrinsic fiber properties and the geometry of the yarn or cord structure. The actual formation of a knot can cause selected fibers, depending upon their position within the yarn, cord, or rope, to be bent into a configuration so that the resulting strain exceeds the fiber's rupture elongation, and therefore some fiber breakage occurs. Other fibers in the knot are not so strained, and so complete failure of all fibers is avoided. The higher its rupture elongation the greater is the opportunity for the fiber to be strained without failure. After a knot is formed in a yarn and it is then subjected to a loading force, the necking down or compacting of the knot into a smaller, denser structure can also produce excessive strains in certain fibers, depending upon their position. All of the fibers within the knot are not subjected to the same amount of strain. This maldistribution of stresses and strains among the fibers causes some to fail prematurely. The load they were carrying then is transferred to the remaining intact fibers. However, this added load may then exceed the capacity of the adjacent fibers and they, too, fail. Thus, the failure proceeds from fiber to fiber and the entire cord or rope fails.

FIGURE 17.12 Loop strength test.

TABLE 17.6 Fiber Loop and Knot Strengths [2].

Fiber	Loop Strength (gpd)	Knot Strength (gpd)
Polyester		
A.C.E® and Compet®, filament—HT	6.0–7.0	5.0–6.0
Dacron®		
Staple and tow	2.1–6.4	2.1–6.4
Filament—RT	2.5–5.2	
Filament—HT	5.6–5.8	
Fortrel®		
Staple series 400—RT	4.4–5.6	
Staple series 300—HT	5.6–6.0	
Tairilin®, staple	2.0–5.6	
Trevira®		
Staple	1.2–5.6	2.0–5.6
Filament—HT	4.4–6.7	4.0–6.3
Nylon		
Nylon 6		
Monofil. and filament—RT	3.8–5.6	3.8–5.5
BCF—RT	2.0–3.0	2.0–3.0
Filament—HT	5.1–10.1	4.8–6.7
Nylon 6,6		
Staple and tow	3.7–5.9	3.7–5.9
Monofil. and filament—RT	2.0–5.1	2.0–5.1
Filament—HT	5.0–7.6	5.0–7.6
Tencel® lyocell—HT	2.2–2.6	2.1–2.3
Cuprammonium rayon, filament	2.15–2.25	
Saran®, monofilament	0.7–1.1	1.0–1.7
Acetate, filament and staple	1.0–1.2	1.0–1.2
Acrylic		
Acrilan®		1.9–2.6
Creslan®, staple and tow	1.9–2.3	
MicroSupreme, staple	2.5–3.0	
SEF® modacrylic, staple		1.6–2.5
Olefin		
Polyethylene		
Monofilament, low density		1.0–2.5
Monofilament, high density	2.5–4.0	2.5–4.5
Herculon®		
Staple	3.0–4.0	
Bulk filament	2.5–3.5	
Glass, multifilament	4.0	0.9
Aramid		
Kevlar®		
Kevlar 29/Kevlar 49	10.5	7.6
Nomex®, staple and filament	4.0–5.0	
Fluorocarbon		
Gore-Tex®	2.5–3.3	2.5–3.3
Teflon® TFE multifil., staple, tow, flock	0.8–1.4	0.8–1.4
Cotton, mercerized	2.5	

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

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FIGURE 17.13 Simple knot test.

The same mechanisms described above for fibers in a yarn, or strands in a rope, exist with respect to individual filaments. Here the cells or fibrils of a natural fiber, or the molecular chains or crystals in natural or man-made fibers, may be considered to be similar, with respect to the fiber, as are fibers with respect to yarns. Individual fibrils are strained non-uniformly and failure ultimately results. The lower the elongation capacity of the units making up the fiber, the less the opportunity for elongation balance adjustment, and the lower the knot and loop strength efficiency.

15. FRICTION

In textile processing, fibers or yarns move relative to each other, or over metal or ceramic parts and frictional forces are generated. Carding, drafting, combing, spinning, winding, weaving, and finishing are all influenced by friction. Spun yarn strength and elongation, fabric smoothness and "hand," abrasion resistance, tendency to generate static dimensional stability, and seam slippage are also dependent upon this important property.

When one body slides over the surface of another, a resistance to the relative motion is developed which is called "frictional force," or more simply, "friction." Static or starting friction is the force which opposes the tendency of a body at rest to start to slide over another. Kinetic friction is the force which opposes the motion of two surfaces sliding by each other. When the frictional force F is divided by the normal force N which develops between the two sliding surfaces, the resulting quotient is called the friction coefficient (Figure 17.14):

$$\mu = \frac{F}{N} \qquad (17.3)$$

where

μ = coefficient of friction
F = frictional force
N = normal force

The friction which develops in textile processing or use can be fiber-to-fiber or fiber-to-other material surfaces. Therefore, in listing friction coefficients it is necessary to specify the two materials involved. The direction of rubbing of fibers or yarns, whether longitudinally or transversely, will influence friction coefficients. Even the directions of longitudinal motion along a fiber can and do produce significant and useful differences in frictional effects. For example, the ability of wool to felt is partly attributable to a greater resistance to sliding motion in the tip-to-root direction of the fiber, rather than from root-to-tip. The difference is called the differential friction effect (DFE). The

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FIGURE 17.14 Frictional forces between two sliding surfaces.

scale structure of wool and other fur fibers is considered to act as a ratchet which allows motion in one direction, but resists it in the other, thus producing DFE (Figure 17.15).

16. ABRASION AND WEAR RESISTANCE

It is necessary to define these two terms at the outset. Textile technologists generally agree that

the "abrasion" is confined to the pure action of rubbing, as exemplified by most of the standard abrasion machines (Chapter 20.0, Textile Testing) which function on the basis of a repetitive rubbing or abrasive action. The term *wear* is employed in a much broader sense and encompasses all of the interacting factors which may cause fabrics to fail; for example, rubbing, flexing, snagging, impacting, stretching, twisting, and exposure to chemicals, wind, sunlight, weather, wetting, drying, heating, and the like.

Much time and effort have been expended; the technical literature is replete with articles, and the industry is constantly faced with the problems of predicting the abrasion and wear resistance of new fibers and fabrics. The problems are complex. They include the selection of laboratory abrasion test methods and specifications, determination of the intrinsic abrasion resistance of new candidate fibers, the influence of yarn and fabric geometry, and the degree to which laboratory abrasion and other physical

FIGURE 17.15 Surface of various fibers: 1. wool, 2. cashmere, 3. mohair, 4. camel, 5. mink, 6. cotton, 7. rayon (courtesy of Albany International).

tests correlate with service performance. It is beyond the scope of this book to discuss in great detail and review the work of the many people who have engaged in research in this important area of textile technology. However, the following sections discuss the concepts which various investigators have proposed with respect to the intrinsic abrasion resistance of textile fibers and other materials. The influence of yarn and fabric structure on abrasion resistance and a description of laboratory abrasion testers is given in Chapter 19.0, Fabric Properties and Technology.

The criteria selected to judge abrasion or wear resistance must be based upon the fabric's function. For example, for a tarpaulin, maintenance of breaking and tear strength is required. Changes in fabric thickness, weight, water permeability, electrical resistivity, surface luster, color, air permeability, the initial appearance of broken threads, or formation of a hole, are other criteria that are used or have been considered. Probably the three most widely used laboratory criteria are:

(1) Direct visual comparison of fabric appearance against a known standard, after both the test sample and the standard have been abraded for a selected number of cycles

(2) Determination of the number of abrasion cycles required to form a hole or for the fabric to fail

(3) Determination of the strength loss caused by a selected number of abrasion cycles or, more properly, a graph of abrasion cycles versus strength loss

Abrasion Mechanisms

Backer [5] proposed three mechanisms which may develop during the abrasion of a textile fiber:

(1) Smooth frictional wear such as occurs when two smooth metal surfaces are rubbed together—This kind of abrasion would be typified by sliding a fabric over a polished wooden table.

(2) Surface cutting or grinding of the fiber by a

sharp abradant of small particle size relative to the fiber diameter—This action would be typified by rubbing the fabric with a fine piece of emery cloth, and is representative of the way many laboratory abrasion testers abrade fabrics.

(3) Fiber rupture or slippage caused by rubbing the fiber with an abradant where the particle size is large compared with the fiber diameter—The fiber is then caught and plucked like a violin string. The fiber may be broken, or partially or completely pulled away from its neighbors in the yarn and fabric, thus producing a disrupted appearance.

In addition to fiber degradation or attrition, these mechanisms particularly the third, can significantly alter the positions of the yarns in the fabric, cause the fabric to distort, and otherwise change the fabric structure. Backer also pointed out that transverse rubbing action across a fiber can produce tension within the fiber.

Hamburger [6] examined the influence of the tensional repeated stress properties of fibers on abrasion resistance. He states that abrasion is a repeated stress application caused by the cyclical application and removal of stresses of a low order of magnitude. For the fiber to be abrasion resistant, it must be capable of repeatedly absorbing the energy imparted to it by the abrasive action. Therefore, it must have the ability to elongate under load application, and recover to its original dimension upon load removal. This ability to deform and recover completely is governed by the relationship between instantaneous elastic deflection, primary creep, and secondary creep. Since secondary creep is removed during the first (or second or few) loading (abrasion) cycles, the energy represented by secondary creep contributes little to abrasion resistance. Hamburger proposes that intrinsic abrasion resistance is correlative with the energy absorption of "mechanically conditioned" fibers free of secondary creep. He lists five fiber properties requisite for high abrasion resistance:

- low elastic modulus
- large immediate elastic deflection

- high ratio of primary to secondary creep
- high magnitude of primary creep
- high rate of primary creep

Hamburger determined an "energy coefficient" which is a measure of the fiber's residual energy absorption after secondary creep has been removed, and a "durability coefficient" which is a laboratory measure of the rate of loss of fiber strength with abrasion cycles. A linear correlation between these two factors appears to exist, and demonstrates that apparently abrasion resistance is dependent upon the repeated capacity of the fiber to absorb energy.

Susich [7] observed that staple yarns were always more severely abraded than corresponding multifilament yarns. He stated that although high elastic energy of fibers is the main factor necessary to prevent inherent abrasion damage, yarn extensibility, surface, and friction must also be taken into account.

In a general assessment of fiber abrasion resistance, it appears reasonable to state that types 6,6 and 6 nylon are most outstanding in their abrasion resistance. Polyester fiber is often considered as second only to nylon. Cotton has good abrasion resistance, and probably follows behind nylon and polyester. Since cotton is stronger when wet than dry, this is an added advantage which most other fibers do not have. Its wet strength and toughness give cotton excellent wet as well as dry abrasion resistance, and explains why cotton fabrics are still used in industrial applications. Wool, because of its high elongation and recovery properties, has remarkably good abrasion resistance. The acrylic fibers, viscose, acetate and regenerated protein fibers probably follow about in that order. Polyvinyl alcohol, polypropylene, and polyethylene all appear to be in the range approaching nylon for abrasion resistance.

17. MOISTURE ABSORPTION PROPERTIES

All of the natural fibers, as well as the regenerated cellulosic and protein fibers, are
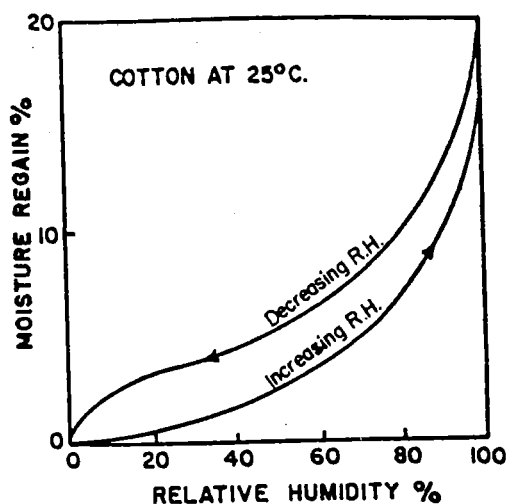
FIGURE 17.16 Relative humidity versus percent moisture regain of cotton fiber.

hygroscopic; that is, they have the ability to absorb water in the form of vapor or liquid. Hygroscopic material will absorb moisture from, or release moisture to, the surrounding air until an equilibrium moisture content is attained. Figure 17.16 shows a plot for cotton of percent moisture regain, defined below, as a function of progressively increasing relative humidity. If a dry fiber is brought to equilibrium in an increasingly humid atmosphere the water content at any relative humidity will be less than that which would result from bringing the fiber to equilibrium from a wet condition. Thus, Figure 17.16 shows moisture absorption and desorption curves which superimpose only at the 0 and 100% rh values, an area of hysteresis resulting when fabrics are conditioned from the dry versus the wet side. The moisture content of a textile material will influence its weight, its general dimensions, and many of its physical properties.

The amount of moisture is usually determined by weighing a specimen on a balance of proper sensitivity, bone drying in an oven at about 220°F and reweighing the bone dry specimen (Chapter 20.0, Textile Testing).

Percent moisture content is defined as the weight of water calculated as a percentage of the original weight of sample:

% moisture content

$$= \frac{\text{original weight} - \text{bone dry weight}}{\text{original weight}} \times 100$$

(17.4)

Percent moisture regain is defined as the weight of water calculated as a percentage of the bone dry weight:

% moisture regain

$$= \frac{\text{original weight} - \text{bone dry weight}}{\text{bone dry weight}} \times 100$$

(17.5)

17.1 Standard Moisture Regain of Fibers

Because many textile materials vary in physical dimensions, weight and properties as a function of their moisture content, it is necessary to describe precisely the water content of the air with which the textile is in equilibrium if a property is to have any meaning. In the United States, standard atmospheric conditions are 65% relative humidity and 70°F (21°C). Table 17.7 lists moisture regains of the various fibers when brought to equilibrium under these conditions of humidity and temperature. All other physical properties of fibers, yarns, or fabrics given in this book are the values obtained at standard conditions unless otherwise designated.

17.2 Commercial Moisture Regains for Fibers

Depending upon conditions of harvesting or manufacturing, hygroscope fibers can vary widely in moisture regain with a concomitant variation in true fiber weight. Therefore, for economic reasons the purchase or sale of cotton, wool, rayon, etc. must be based upon a standard amount of moisture. The normal practice is for a laboratory, often an independent organization agreeable to both buyer and seller, to measure the average moisture regain of the entire fiber lot. The actual weight of the lot is then

corrected to a standard regain agreed upon by the trading parties. Table 17.8 lists accepted commercial regains established by the separate industries for their fibers. Because of the fiber price per pound, and the size of the lots, the regain must be determined accurately. Proper selection of the test sample so that it is in fact truly representative of the lot is of equal importance.

The "as received" weight of a lot may be corrected to the accepted commercial regain weight by the following formula

$$W_c = W_l \frac{100 + R_c}{100 + R_l} \qquad (17.6)$$

where

W_c = lot weight calculated to accepted commercial regain
W_l = lot weight "as received"
R_c = percent accepted commercial regain
R_l = percent regain of "as received" lot

The bone dry weight of a lot may be corrected to the accepted commercial regain weight as follows:

$$W_c = W_b \frac{100 + R_c}{100} \qquad (17.7)$$

where W_b is bone dry weight of lot.

18. FIBER SWELLING PROPERTIES

Table 17.9 lists the swelling properties of fibers when immersed in water. Upon wetting, most hygroscope textile fibers exhibit a slight increase in length and a considerable increase in diameter and cross-sectional area. The influence of all of these interacting effects on fabric air and liquid permeability and on shrinkage are discussed in Chapter 19.0, Fabric Properties and Technology on "Cover Factor," "Fabric Density and Packing Factor," "Air Permeability," and "Water Repellency." Since hygroscopic fibers themselves do not shorten upon wetting, fabric shrinkage must be caused by other mechanisms.

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TABLE 17.7 Moisture Regain of Fibers [2].

Fiber	Moisture Regain (%)	
	70°F, 65% rh	70°F, 95% rh
Polyester		
A.C.E® and Compet®		
Filament—HT	0.4	
Dacron®		
Staple and tow	0.4	
POF		
Filament—RT	0.4	
Filament—HT	0.4	
Tairilin®, staple	0.4	0.6
Trevira®		
Staple	0.4	0.6
POF	0.4	0.6
Filament—HT	0.4	0.6
Nylon		
Nylon 6		
Staple	2.8–5.0	3.5–8.5
Monofil. and filament—RT	2.5–5.0	3.5–8.5
Filament—HT	2.8–5.0	3.5–8.5
Nylon 6,6		
Staple and tow	4.0–4.5	6.1–8.0
Monofil. and filament—RT	4.0–4.5	6.1–8.0
Filament—HT	4.0–4.5	6.1–8.0
Tencel® lyocell—HT	11.5	
Rayon		
Fibro®		
RT—Multi-lobed	11	27
IT—0.9 den or 0.25 in and up	11	27
Cuprammonium, filament	11	
Rayon		
Filament—RT	11	
Filament—HT	11	
Saran®, monofilament	0	N/A
Acetate, filament and staple	6.3–6.5	14
Ryton® sulfar, staple	0.6	
Acrylic		
Acrilan®, staple and tow	1.5	3.5
Creslan®, staple and tow	1.0–1.5	2.0–2.5
MicroSupreme, staple	1.0–1.5	2.0–2.5
SEF® modacrylic, staple	2.5	

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TABLE 17.7 (continued).

Fiber	Moisture Regain (%)	
	70°F, 65% rh	70°F, 95% rh
Olefin		
Polyethylene		
Monofilament, low density	Negligible	Negligible
Monofilament, high density	Negligible	Negligible
Herculon®		
Staple	0.01	
Bulk filament	0.01	
Marvess® and Alpha®		
Staple and tow	−0.1	
Multifilament	−0.1	
Essera®, Marquesa Lana®, Pation® III		
BCF	0.01–0.1	
Staple	0.01–0.1	
Spectra® 900	Negligible	Negligible
Spectra® 1000	Negligible	Negligible
Fibrilon®		
Staple	0.01	0.01
Spandex		
Glospan®/Cleerspan, S-85, multifilament	Less than 1	
Lycra®		
Type 126, 127	1.3	
Glass		
Single filament−E-glass	None	Up to 0.3
Single filament−S-glass	None	Up to 0.3
Multifilament	None	Up to 0.3
Aramid		
Kevlar®		
Kevlar 29/Kevlar 49	4.3	6.5/6.0
Kevlar 149	1.2	2.3
Kevlar 68	4.3	
Kevlar HT (129)	4.3	
Nomex®, staple and filament	4.5	7.5
Fluorocarbon		
Gore-Tex®	0	0
Teflon®		
TFE multifil., staple, tow, flock	0	0
FEP, PFA monofilament	0	0
PBI, staple	15	20
Asbestos	1.0	3.0
Cotton	8.5	15
Silk	11	25
Wool	16	29

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

TABLE 17.8 Commercial Moisture Regain Values of Fibers [8].

Fiber	Moisture Regain (%)
Acetate (secondary)	6.5
Acrylic	1.5
Aramid, for	
Plastic reinforcement	3.5
Filtration fabrics and safety apparel	4.5
Reinforcement of rubber goods	7.0
Azlon	10.0
Cotton	
Natural cotton yarn	7.0
Dyed cotton yarn	8.0
Mercerized cotton yarn	8.5
Flax (raw)	12.0
Fluorocarbon	0.0
Glass	0.0
Hemp	12.0
Jute	13.75
Linen	8.75
Metallic	0.0
Modacrylic	
Class I	0.4
Class II	2.0
Class III	3.0
Nylon (polyamide)	4.5
Olefin	0.0
Polyester	0.4
Ramie	
Raw	7.6
Scoured	7.8
Rayon (regenerated cellulose)	11.0
Rubber	0.0
Saran	0.0
Silk	11.0
Spandex	1.3
Triacetate (primary)	3.5
Vinal	4.5
Vinyon	0.0
Wools (all forms)	13.6

19. WET FIBER STRENGTHS

Table 17.4 lists wet and dry fiber tenacities. Natural cellulosic fibers such as cotton, are 10 to 15% stronger when wet than when "dry" under standard conditions. This is of obvious advantage in end uses where fabrics are apt to become wet.

The natural cellulosics are the only fibers presently known whose wet strengths exceed dry strengths. The natural animal fibers, including silk and wool, have wet strengths which are 75 to 90% of dry strengths. Regenerated cellulose fibers such as viscose and cuprammonium rayons have wet strengths in the order of 45 to 60% of dry. The wet strengths of high modulus rayons range from 60 to 75% of dry. The modified cellulosics, such as acetate, also have wet strengths which are 60 to 80% of dry. Because many of the hydrophilic (water absorbing) hydroxyl groups in these fibers have been replaced by more hydrophobic (water resisting) acetate groups, the tendency for such fibers to absorb water is less, and so they are somewhat less sensitive to strength losses when wet.

As a general rule it can be stated that, for man-made fibers, the lower their moisture regains and liquid water absorption capacity, the less sensitive they are to wet strength losses. Thus nylon 6,6, with a moisture regain of 4.5% (Table 17.7), has a wet strength of about 85–90% of dry, while Dacron® polyester, with a regain of 0.4% has a wet strength just about equal to its dry strength. While the general rule is valid, care should be exercised in its employment, for the nature of the polymer also influences the strength loss upon wetting.

Wet Yarn Strengths

Because cotton has higher strength when wet than dry, it follows that yarns made from cotton will also be stronger at higher moisture regains as well as when wet. This is in fact the case, the increase for wet yarns being on the order of 25 percent. In addition to the intrinsic wet fiber strength increase, wet cotton fibers swell radially, thus causing a denser packing of fiber against fiber. The total frictional force increase reduces fiber slippage and so a stronger yarn results. For natural animal, regenerated cellulosic and synthetic fibers, generally the ratio of wet-to-dry yarn strengths is about the same as their respective wet-to-dry fiber strengths.

20. WET FIBER BREAKING ELONGATIONS

Table 17.5 lists wet rupture elongations. As a general rule, for both the natural and re-

TABLE 17.9 Fiber Swelling Properties.

Fiber	Length Increase (%)	Diameter Increase (%)	Cross-Sectional Area Increase (%)
Glass	—	—	0
Nylon 6,6 high tenacity	1.2	1.9–2.6	1.6–3.2
Polyethylene, low density	—	—	0
Dacron polyester, regular	0.1	0.3	0.6
Lycra spandex	Approx. 1.0		Approx. 1.0
Viscose rayon, regular	3–5	25–52	50–113
Viscose rayon, high tenacity	—	—	50
Cuprammonium rayon	4	32–53	56–62
Acrilan acrylic	—	—	Approx. 5
Orlon acrylic	0.2	2.4	4.8
Acetate	0.14	9–14	—
Cotton, raw	1.2	14–30	40–42
Cotton, mercerized	0.1	17	24–46
Flax	—	—	47
Jute	0.37	20	40
Ramie	—	—	37 (bleached)
Silk	1.7	16–20	19
Wool	1.2	16	25

generated hydrophilic fibers, the water absorbed may be considered as a plasticizer. The fiber's modulus is reduced and the total elongation-to-rupture increases. The increase for the natural cellulosic fibers, e.g., cotton, is small.

The regenerated cellulosic fibers normally have appreciably greater wet elongations than dry. Usually the greater their wet strength loss, the greater will be their rupture-elongation gain. For example, the high modulus rayons have higher wet strength than do the regular rayons, their wet elongations are concomitantly lower, and therefore they have better wet dimensional stability. The synthetic fibers are more hydrophobic and are therefore less sensitive to water. Thus there is little difference in the wet and dry strength-elongation properties of the acrylics, the polyesters, the polyolefins, and the like. Nylon, being somewhat hydrophilic, is proportionately sensitive to water.

21. EFFECT OF RELATIVE HUMIDITY ON TENACITY-ELONGATION DIAGRAMS

For all fibers except cotton, tenacities and moduli are lower and elongations are higher as relative humidity increases. Obviously the

greater elongation resulting from the plasticity of wet fibers can either by recoverable or non-recoverable. For natural fibers the wet recovery properties often equal or surpass the dry properties, having high instantaneous elastic recovery, high primary creep recovery, and low permanent set. The regenerated hygroscopic fibers usually have poorer recovery properties. The hydrophobic synthetic fibers, being insensitive to water, show little or no change.

22. THERMAL PROPERTIES OF FIBERS

The influence of heat on the properties of fibers is of paramount importance with respect to textile processing as well as use. All of the natural fibers and the regenerated cellulosic and protein fibers are non-thermoplastic. They do not soften with heat, but instead char and decompose. Most synthetic fibers and the modified cellulosics such as acetate, are thermoplastic and have specific melting points.

Thermoplasticity in a fiber can be advantageous or disadvantageous, depending upon processing or requirements. Because of their cross-linked molecular structure, cotton and wool are essentially temperature insensitive and so do not soften in the 200–300°F range, nor

stiffen at temperatures below freezing. Thus they can be ironed with relative safety, and do not significantly shrink, stretch, or lose strength at elevated temperatures. For processing or end uses where plasticity is necessary, water and/or steam are used rather than heat as the plasticizing means.

The thermoplastic fibers are temperature sensitive. As temperature increases, strength normally is lowered, rupture elongation may increase, and the tensional modulus thus is reduced. Unless the fiber is permanently damaged by heat, the effect often is reversible. As the fiber cools it may reassume its original properties. However, the heat exposure may produce a permanent thermal shrinkage with an accompanying increase in rupture elongation and a decrease in both strength and tenacity. This shrinkage is removable only by restretching the fiber at an elevated temperature. Thermoplasticity is an attribute when it is desired to heatset the fibers within the yarn and fabric, i.e., to make them conform permanently to the position and form into which they are placed, or where the fabric itself must then be molded or reshaped. Thermoplasticity is a disadvantage when a fabric becomes excessively limp or tacky or shrinks or distorts at high temperatures, or becomes stiff and brittle at low temperatures.

Heat may influence the properties and functions of textiles in many ways. Important criteria to consider are (1) softening, melting, or decomposition temperatures; (2) tendency of the fiber and fabric to shrink when heat-relaxed, or stretch when heated and tensioned; (3) ability of the fabric to be heat set; (4) ability of the fabric to function properly at elevated temperatures in one time or in repeated use; and (5) ability of the fabric to function properly at room temperature (or some other lower temperature) after exposure at high temperature for a given period of time.

Table 17.10 shows the effect of heat on fiber properties of various fibers. Normally for a textile fiber to be industrially useful it should not become tacky or soften below about 300°F. Upper temperature limits depend upon, end-use requirements, and upon the ability of the finishing plant to provide a temperature which can

heat set the fabric in order to stabilize it and to remove wrinkles and distortions.

Table 13.2 (Chapter 13.0) lists the commercially available high temperature fibers and Table 13.3 gives their properties.

23. EFFECT OF HEAT ON THE TENSILE PROPERTIES OF FIBERS

Two subjects must clearly be separated for the influence of heat upon fiber properties:

(1) Tensile properties of fibers tested at elevated temperatures
(2) Tensile properties of fibers tested at room temperature after exposure to elevated temperatures for selected time periods

The former indicates the capability of the fiber to perform at the required elevated temperature. The latter is often used as a criterion of heat degradation resistance.

Fabric degradation by heat normally is a function of temperature, time, relative humidity, and air circulation. Since many heat degradation processes involve oxidation, the greater the air circulation the greater will be the amount of oxygen which comes in intimate contact with the fiber, and the more rapid will be the degradation. Of course, for those fibers which are insensitive to oxygen, this factor is of no consequence.

For those industrial textile uses where the item will be subjected to a tension at an elevated temperature, it is important that the fiber does not become soft and extensible at that temperature. Glass is generally used for heat insulation and heat resisting applications. While it does not begin to lose strength until 600°F, its abrasion resistance is poor, and it cannot be used where prolonged flexing or rubbing is required. Protective silicone finishes improve the abrasion resistance of glass fabrics, making them useful in certain applications, for example, high temperature resisting gas filtration fume bags. Nylon is strong and tough, but it degrades rather quickly at elevated temperatures in the presence of air, and this limits its high temperature use. For example, when exposed at 350°F for 6 hours, 210 denier type 6,6 nylon yarn loses

TABLE 17.10 Effect of Heat on Fiber Properties [2].

Fiber	Effect of Heat
Polyester	
A.C.E®	Softens at 464°F. Melts at 500°F.
Compet®	Melts at 488°F.
Dacron®	Sticks at 440 to 445°F. Melts at 482°F.
Fortrel®	Melts at 478 to 490°F.
Tairilin®	Sticks at 440–450°F. Melts at 485–495°F.
Trevira®	Softens at 445 to 465°F. Melts at 495°F.
Thornel® carbon	Does not melt. Oxidizes very slowly in air at temperatures above 600°F.
Nylon	
Nylon 6	Melts at 419 to 430°F. Slight discoloration at 300°F when held for 5 hr. Decomposes at 600 to 730°F.
Nylon 6,6	Sticks at 445°F. Melts at 480 to 500°F. Yellows slightly at 300°F when held for 5 hr.
Tencel® lyocell	Does not melt. Loses strength at about 300°F and begins to decompose at about 350°F under extended periods of exposure.
Rayon	
Fibro®	Does not melt. Loses strength at 300°F and decomposes at 350 to 464 under extended periods of exposure.
Cuprammonium	Does not soften, stick or melt. Decomposes at 350°F under extended exposure.
Rayon	Does not melt. Loses strength at 300°F and begins to decompose at about 325°F.
Saran	
Saran®	Melts at 240–280°F; will not support combustion; self extinguishing.
Acetate	Sticks at 350 to 375°F. Softens at 400 to 445°F. Melts at 500°F.
Sulfar	
Ryton®	Outstanding resistance to heat (melts at 285°C). Excellent resistance to aerial oxidation, most chemicals. Retains 70% + original strength to 400°F for 5,000 hr.
Acrylic	
Acrilan®	Does not melt.
Creslan®	Sticks at 420 to 450°F. Safe ironing at 300°F.
MicroSupreme	Does not melt.
SEF® modacrylic	Does not melt. Boiling water shrinkage equals 1%. Excellent resistance to shrinkage in dry heat. At 390°F, 5% shrinkage.
Olefin	
Polyethylene	Low density softens at 225 to 230°F, melts at 230 to 250°F. High density softens at 240–260°F, melts at 225 to 280°F. Low density shrinks 5–8% at 165°F, 50–60% at 212°F. High density shrinks 3–5% at 165°F, 8–12% at 212°F.
Herculon®	Softens at 285 to 330°F. Melts at 320 to 350°F. Decomposes at 550°F. Zero to 5% shrinkage at 212°F; 5 to 12% at 265°F.
Marvess® and Alpha®	Fiber softens at 300–320°F. Melts at 320–340°F. Decomposes at 550°F.
Essera®, Marquesa Lana®, and Pation® III	Softens at 285–340°F. Melts at 325–340°F. 0–5% shrinkage at 212°F. 5–12% shrinkage at 265°F.
Spectra®	Melts about 300°F.
Fibrilon®	Fiber softens at 290–310°F, melts at 320°F, and decomposes at 550°F.

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TABLE 17.10 (continued).

Fiber	Effect of Heat
Spandex	
Glospan®/Cleerspan, S-85	Good dimensional stability. Sticks at 420°F.
Lycra®	Good dimensional stability. Can be heat set. Sticks at 347–392°F. Melts at 446°F.
Glass	None burn. At 650°F, E holds 75% tensile strength; S 80%; multifilament 50%. E softens at 1,350 to 1,611°F; melts at 2,050 to 2,160°F. S softens at 1,560 to 1,778°F; melts at 2,720°F.
Aramid	
Kevlar®	Difficult to ignite. Does not propagate flame. Does not melt. Decomposes at about 900°F.
Nomex®	Does not melt. Decomposes at 700°F.
Fluorocarbon	
Gore-Tex®	Extremely heat resistant. Can be safely used from −350°F to +550°F. Melts at 620°F.
Teflon®	
TFE	Extremely heat resistant. Safely used at −350°F to +550°F. Melts at 620°F.
FEP,PFA	Extremely heat resistant. Continuous use temperature: FEP, 400°F, PFA 500°F.
PBI	Will not ignite. Does not melt. Decomposes in air at 860°F. Retains fiber integrity and suppleness upon flame exposure. High char yield.
Asbestos	Weight loss 0.5 to 1% after exposure at 1,400°F for 2 hours. Stable up to 1,490°F.
Cotton	Yellows at 250°F, decomposes at 300°F.
Silk	Decomposes at 300°F. Rapid disintegration above 340°F.
Wool	Decomposes at 275°F, chars at 570°F.

54% of its original strength. Dacron® polyester has better heat aging resistance, losing only 8% when exposed under the same conditions.

24. FIBER FLAMMABILITY

Several terms related to the burning behavior of textiles are defined by the ASTM as follows [9]:

- combustible textiles: "a textile that will ignite and burn or that will give off vapors that will ignite and burn when subjected to external sources of ignition"
- flame resistance: "the property of a material whereby flaming combustion is prevented, terminated, or inhibited following application of a flaming or nonflaming source of ignition, with or without subsequent removal of the ignition source"
- flammability: "those characteristics of a material that pertain to its relative ease of ignition and relative ability to sustain combustion"

- flammable textile: "any combustible textile that burns with a flame"
- heat resistance: "the extent to which a material retains useful properties as measured during exposure of the material to a specified temperature and environment for a specified time"
- inherent flame-resistance: "flame resistance that derives from an essential characteristic of the fiber from which the textile is made"
- non-combustible textile: "a textile that will neither ignite nor give off vapors that will ignite when subjected to external sources of ignition"
- non-flammable textile: "any combustible textile that burns without a flame"

Cotton and other cellulosics, as well as cellulose acetate, will ignite readily and are not self-extinguishing. Once they are ignited, they will continue to burn, even when the igniting flame is removed. Silk, wool, and all the other animal fibers will burn, but are self-extinguishing. Synthetic organic fibers have varying degrees of flammability depending upon their composi-

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tions. Nylon 6,6 is stated to be moderately difficult to ignite and self-extinguishing. Glass does not burn. Carbon does not melt but oxidizes very slowly in air at temperatures above 600°F. Kevlar® aramid is difficult to ignite, does not propagate flame and does not melt. It decomposes at about 900°F. Nomex® aramid does not melt and decomposes at 700°F. Gore-Tex® and Teflon® are extremely heat resistant. They can be safely used from −350°F to +550°F. PBI will not ignite nor melt but decomposes in air at 860°F. It retains fiber integrity and suppleness upon flame exposure.

Because burning is an oxidation process, for those fibers which will burn, the type of yarns and fabrics into which they are manufactured will directly influence the burning rate. Dense, heavy fabrics will not burn as readily as will lofty, open, thin, or brushed pile fabrics. For these latter types, the oxygen in the air can surround each fiber and accelerate the burning rate. Here, if the fibers are combustible and finely dispersed, a rapid flash burning can develop. In addition to the intrinsic flammability of the fiber, and the textile into which it is manufactured, precaution must be taken to insure that a fabric finish or coating applied to impart a certain property do not produce a dangerously flammable fabric.

24.1 Flammable Fabrics Act

In 1953, the U.S. Congress passed the Flammable Fabrics Act to ban easily ignitable fabrics and wearing apparel from the market. The Act stated that "no article of wearing apparel or fabric subject to the Act and Regulations shall be marketed or handled if such article or fabric, when tested according to the procedures prescribed . . . is so highly flammable as to be dangerous when worn by 'individuals.' " These were mainly brushed or high pile cellulosic fabrics used occasionally in such garments as sweaters and children's costumes.

In 1967, the Act was amended to cover interior furnishings as well as fabrics and all wearing apparel which present an unreasonable risk from fire. In 1972, an Act of Congress established a new Consumer Product Safety Agency. In 1973, responsibility for both issuing and enforcing flammability regulations was transferred from the Commerce Department to the Agency.

The flammability standard described in the Act states, "Any fabric or article of wearing apparel shall be deemed so highly flammable within the mean . . . of this Act as to be dangerous when worn by individuals if such fabric or any uncovered or exposed part of such article of wearing apparel exhibits rapid and intense burning when tested under the conditions and in the manner prescribed in . . . 'Flammability of Clothing Textiles, Commercial Standard 191-53.' " This standard specified the methods for testing fabric flammability and classifies fabrics as follows.

Class 1. Normal Flammability

These textiles are generally accepted by the trade as having no unusual burning character.

* textiles that do not have a raised fiber surface, but have a time of flame spread in the test of 3.5 seconds or more
* textiles having a raised fiber surface that have a time of flame spread in the test of more than 7 seconds or that burn with a surface flash (time of flame spread less than 7 seconds) provided the intensity of the flame is insufficient to ignite or fuse the base fabric

Class 2. Intermediate Flammability

These textiles are recognized by the trade as having flammability characteristics between normal and intense burning. Textiles having a raised fiber surface that have a time of flame spread in the test of 4 to 7 seconds, inclusive, and the base fabric is ignited or fused.

Class 3. Rapid and Intense Burning

These textiles are considered dangerously flammable and are recognized by the trade as being unsuitable for clothing because of their rapid and intense burning.

- textiles that do not have a raised fiber surface, but that have a time of flame spread in the test of less than 3.5 seconds
- textiles having a raised fiber surface that have a time of flame spread in the test of less than 4 seconds, and the base fabric is ignited or fused

The chemical textile industries have expended large amounts of money and effort in developing flame resisting finishes for apparel, decorative and industrial fabrics. By law, curtains, draperies and other textiles in public buildings must be flameproof. Fire and flame resistance test methods are explained in Chapter 20.0, Textile Testing. Flame retardant finishes are included in Chapter 5.0, Section 5.1.

25. RESISTANCE OF FIBERS TO MILDEW, AGING, SUNLIGHT AND ABRASION

Table 17.11 lists mildew, aging, sunlight and abrasion properties of various fibers. Wool and cotton tend to turn yellow with age. Where necessary, bleaching the cotton with hypochlorite

TABLE 17.11 Resistance of Fibers to Mildew, Aging, Sunlight and Abrasion [2].

Fiber	Resistance to Mildew, Aging, Sunlight and Abrasion
Polyester	
A.C.E®	Excellent resistance to mildew; good to abrasion, aging and sunlight with some deterioration after prolonged exposure to sunlight.
Compet®	Excellent
Dacron®	Not weakened by mildew. Excellent resistance to aging and abrasion. Prolonged exposure to sunlight causes some strength loss.
Fortrel®	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some strength loss.
Tairilin®	Excellent resistance to mildew, aging, abrasion. Excellent resistance to sunlight, but prolonged exposure causes some strength loss.
Trevira®	Not attacked by mildew. Excellent resistance to aging and abrasion. Excellent resistance to sunlight, but prolonged exposure causes some strength loss.
Thornel® carbon	Excellent resistance to mildew, aging, and sunlight. Poor abrasion resistance.
Nylon	
Nylon 6	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some degradation.
Nylon 6,6	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some deterioration.
Tencel® lyocell	Attacked by mildew. Good resistance to aging, sunlight and abrasion.
Rayon	
Fibro®	Attacked by mildew. Resistance to aging, sunlight and abrasion is good. Long exposure to sun yellows some intermediate rayons; aging deteriorates them.
Cuprammonium	Attacked by mildew. Stable to aging. Not affected by sunlight. Good resistance to abrasion.
Rayon	Attacked by mildew. Good resistance to sunlight, abrasion and aging.
Saran	
Saran®	Not attacked by mildew. Good resistance to aging, sunlight and abrasion.
Acetate	Impervious to aging. Good resistance to mildew discoloration and sunlight (some lose strength from long exposure). Fair abrasion resistance.
Sulfar	
Ryton®	Excellent resistance to mildew, aging and sunlight. Fair abrasion resistance.
Acrylic	
Acrilan®	Excellent resistance to mildew, aging and sunlight. Good resistance to abrasion.
Creslan® and MicroSupreme	Excellent.
SEF® modacrylic	Excellent resistance to mildew, aging and sunlight. Good resistance to abrasion.

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TABLE 17.11 (continued).

Fiber	Resistance to Mildew, Aging, Sunlight and Abrasion
Olefin	
Polyethylene	Not attacked by mildew. Good resistance to aging, sunlight and abrasion.
Herculon®	Not attacked by mildew. Good resistance to aging, indirect sunlight and abrasion. Can be stabilized to give good resistance to direct sunlight.
Marvess® and Alpha®	Not attacked by mildew. Good resistance to aging and abrasion. Stabilizers provide good resistance to sunlight fading.
Spectra®	Excellent resistance to mildew, aging and abrasion. Some loss of strength with long exposure to sunlight.
Fibrilon®	Not attacked by mildew. Good resistance to aging and abrasion. Stabilizers provide good resistance to sunlight fading.
Spandex	
Glospan®/Cleerspan, S-85	Excellent resistance to aging and abrasion. Sunlight exposure causes mild discoloration but no loss of physical properties.
Lycra®	
Type 126,127	Mildew, aging: no effect. Strength loss from prolonged sunlight. Good abrasion resistance.
Type 128	Excellent abrasion and aging resistance.
Glass	Not attacked by mildew, although binder may be affected by it. Excellent resistance to aging and sunlight.
Aramid	
Kevlar®	Excellent resistance to mildew and aging. Prolonged exposure to sunlight causes deterioration, but fibers self-screening. Good abrasion resistance.
Nomex®	Excellent resistance to mildew and aging. Prolonged exposure to sunlight causes some strength loss. Good abrasion resistance.
Fluorocarbon	
Gore-Tex®	Excellent resistance to mildew, aging, sunlight and abrasion.
Teflon®	Not weakened by mildew. Excellent resistance to aging and sunlight. Good abrasion resistance.
PBI	Good resistance to mildew and aging. Prolonged exposure to sunlight will cause darkening and some loss of tensile strength. Good abrasion resistance.

or peroxide, and the wool with sulfur dioxide or peroxide will remove the yellow color. Exclusive of any microbial or mildew degradation, weathering and sunlight cause a slow but progressive loss in strength and serviceability for cotton and rayon. Acetate is probably more resistant than rayon. Wool generally has good resistance to sunlight, weathering, and aging. This appears quite logical when one considers the natural environment of sheep.

25.1 Mildew and Rot Damage

The terms mildew, rot, and decay are variously used to indicate growth upon or damage to textiles by microorganisms such as fungi and bacteria. The major types of fungi affecting textiles are the molds such as penicillium and aspergillus, and the soil molds such as actinomycetes. Bacteria which cause textile damage are most frequently of the bacillus or rod type. The terms *decay* and *mildew* are usually associated with damage by fungi, and *rot* with bacterial damage.

Since microorganisms require water and warmth to flourish and spread, all of the natural and regenerated hydrophilic vegetable and animal fibers are susceptible to microbial damage. Cotton, linen, viscose and cuprammonium rayons, and other cellulose based fibers, are subject to breakdown where, via a process called glycolysis, the cellulose is converted by the enzyme cellulase to cellobiose. This is then converted to glucose which serves as the food for the microorganism. Mildew is often manifested in cotton and other cellulosics by a musty odor, the formation of discolored and black areas, fabric tendering, and ultimately complete decay. Some mildews produce brightly colored spots, and often fluoresce strongly in ultraviolet

light. Therefore, an inexpensive ultraviolet or "black light" lamp is a useful tool for mildew identification.

Wool, other animal fibers, and regenerated proteins are usually not quite so sensitive but they, too, can be decomposed by specific bacteria, actinomycetes, and molds which attack keratin through the production of proteolytic enzymes by these organisms. The intact cuticle and epicuticle of the wool fiber are relatively inert to such enzymes, hence such attack is more rapid on wool which previously has been mechanically or chemically damaged.

Mildew most often develops when textiles are folded and stored for lengthy periods in a warm moist atmosphere. A relative humidity of about 82% for cotton and 85% for wool is required for mildew and mold growth. Bacterial requirements are higher. Wool must ordinarily be exposed to a relative humidity of approximately 95%, or must have a moisture content on the order of 20% to support active bacteria growth. Temperatures of 75 to 100°F are optimal for most microorganisms. Local condensation can start mildew growth, occasionally at a relative humidity which is lower than expected. Once started, mildew can absorb water hygroscopically from the air or from local condensation and continue its growth. This is why packaged or folded fabrics, without adequate ventilation, will sometimes mildew in relatively "dry" rooms.

Synthetic fibers have chemical structures not found in nature. Therefore, microorganisms do not attack them. Most synthetic fibers have little or no tendency to absorb water, a necessary component required by all microorganisms if they are to survive. Clearly, this is another reason why synthetic fibers are mildew resistant. Even a slight modification in the chemical structure of a natural or regenerated fiber may be sufficient to preclude microbial attack. The nylons, polyesters, acrylics, and all other completely synthetic fibers are completely impervious to mildew growth and attendant damage. A word of caution is necessary. Often synthetic yarns may be sized, or fabrics finished, with natural gums, starches, waxes or the like that are susceptible to mildew growth. This may make it appear that the fibers themselves are be-

ing attacked. Tests usually show that while the fiber may be stained, it suffers no actual deterioration and strength loss; only the finish is attacked.

25.2 Insect and Rodent Damage

Basically the same comments made above for mildew and rot damage hold for insect damage. The natural fibers are susceptible to damage by carpet beetles, cockroaches, ants, silverfish, and moth larvae. The synthetic fibers usually are not attacked. Many insects will eat natural fibers. They may cut through synthetic or other fibers which are not attractive as food in order to liberate themselves or reach an attractive food source, or they may eat an unattractive fiber which is coated or contaminated with an attractive material. Thus, while synthetic fibers normally are not subject to insect damage, they can be damaged under specific environmental conditions. Rodents, in cases of extreme hunger, may attempt to eat cellulose or keratin base fibers. They probably will not eat synthetic fibers, but might damage them by gnawing.

26. CHEMICAL RESISTANCE OF FIBERS

Table 17.12 lists the effect of acids, alkali solvents, and special chemicals on various fibers. Because of the many fibers and many chemicals, it is impractical to list all of the effects. The "state of aggregation" (i.e., position and orientation) of fibers in yarn, and yarn in fabric, the chemical concentration, temperature, and length of exposure time also influence reaction rates and extents of degradation.

Cotton and rayon have fairly good resistance to weak acids, for example, but are severely damaged by even dilute solutions of strong acids such as sulfuric and hydrochloric. These cellulosic fibers have good resistance to strong alkalis. Mercerizing strength caustic (20% sodium hydroxide) will swell the fibers and can ultimately degrade them.

Wool shows high resistance to weak and strong acids, but is disintegrated and dissolved by alkalis. Bleaching must be accomplished on

TABLE 17.12 Chemical Resistance of Fibers [2].

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Polyester		
A.C.E®	Good resistance to organic acids. Good resistance to inorganic acids at room temperature; moderate resistance at 212°F. Disintegrates in concentrated hot alkalis.	Excellent resistance to bleaches and other oxidizing agents.
Compet®	Excellent resistance to acids.	
Dacron®	Good resistance to most mineral acids. Dissolves with partial decomposition in concentrated solution of sulfuric acids. Good resistance to weak alkalis. Moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents. Generally insoluble except in some phenolic compounds.
Fortrel®	Good resistance to most mineral acids. Dissolves with partial decomposition by concentrated solutions of sulfuric acid. Good resistance to weak alkalis and moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents. Generally insoluble except in some phenolic compounds.
Tairilin®	Good resistance to most mineral acids; fair resistance to concentrated sulfuric acid. Good resistance to weak alkalis; moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents.
Trevira®	Excellent resistance to mineral and organic acids at room temperature. Good resistance to weak alkalis at room temperature. Good resistance to weak alkalis at room temperature. Moderate resistance to strong alkalis, depending on concentration, temperature and time.	Excellent resistance to bleaches and oxidizing agents.
Thornel® carbon	Excellent resistance to acids and alkalis, even at high concentrations and temperatures. Strong oxidizers will degrade fiber.	Inert to all known solvents. Poor resistance to hypochlorite.
Nylon		
Nylon 6	Strong oxidizing agents and mineral acids cause degradation. Others cause loss in tenacity and elongation. Resists weak acids. Soluble in formic and sulfuric acids. Hydrolyzed by strong acids at elevated temperatures. Substantially inert in alkalis.	Can be bleached in most bleaching solutions. Generally insoluble in organic solvents. Soluble in some phenolic compounds.
Nylon 6,6	Unaffected by most mineral acids, except hot mineral acids. Dissolves with partial decomposition in concentrated solutions of hydrochloric, sulfuric and nitric acids. Soluble in formic acid. Substantially inert in alkalis.	Can be bleached in most bleaching solutions. Generally insoluble in most organic solvents. Soluble in some phenolic compounds.

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TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Tencel® lyocell	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fiber. Strong alkaline solutions cause swelling and reduce strength. Can be mercerized.	Attacked by strong oxidizing agents. Not damaged by bleaches. Generally insoluble in common organic solvents.
Rayon Fibro®	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fiber. Strong alkaline solutions cause swelling and reduce strength.	Attacked by strong oxidizing agents. Not damaged by hypochlorite or peroxide. Generally insoluble except in cuprammonium and a few complex compounds.
Cuprammonium	Hot acids or high concentrations tend to disintegrate fiber. Strong caustic solutions tend to swell fiber and reduce strength.	Not affected by solvents. Insoluble in common organic solvents. Damaged by normal concentrations of hypochlorite or peroxide bleaches.
Rayon	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fibers. Strong alkaline solutions cause swelling and reduce fiber strength.	Attacked by strong oxidizing agents. Not damaged by bleaches. Generally insoluble in common organic solvents.
Saran Saran®	Generally good resistance to acids and most alkalis. Sodium hydroxide and ammonium derivatives, in conjunction with heat, cause discoloration.	Generally good resistance to bleaches and solvents. Esters and ethers may be detrimental in varying degrees.
Acetate	Deteriorates in concentrated solutions of strong acids. Unaffected by weak acids. Strong alkalis saponify into regenerated cellulose.	Attacked by strong oxidizing agents. Not damaged by mild hypochlorite or peroxide bleaching conditions. Soluble in phenol, acetone, concentrated and glacial acetic acid.
Sulfar Ryton®	Outstanding resistance to acids and alkalis except hot concentrated sulfuric acids and concentrated nitric acid.	Excellent resistance to all solvents at high temperatures.
Acrylic Acrilan®	Good to excellent resistance to mineral acids. Fair to good resistance to weak alkalis; moderate resistance to strong, cold solutions.	Good resistance to bleaches and common solvents.
Creslan® and MicroSupreme	Generally good resistance to mineral acids and weak alkalis. Moderate resistance to strong alkalis at room temperature.	Unaffected by dry cleaning solvents. Can be bleached with sodium chlorite.
SEF® modacrylic	Resistant to most acids. Good resistance to weak alkalis; moderate resistance to strong, cold alkalis.	Good resistance to bleaches, dry cleaning fluids and most common solvents.

(continued)

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TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Olefin Polyethylene	Low density: excellent resistance to acids and alkalis, with the exception of oxidizing agents. High density: excellent resistance to acids and alkalis, with the exception of oxidizing agents.	Low density: resists well below 150°F. Swells in chlorinated hydrocarbons at room temperature. Soluble at 160 to 175°F. High density performs generally the same but not as pronounced.
Herculon®	Excellent resistance to most acids and alkalis with the exception of elevated temperature exposure to chlorosulfonic acid, concentrated nitric acid and certain oxidizing agents.	Resistant to bleaches and most solvents. Some swells in chlorinated hydrocarbons at room temperature and dissolves at 160°F and higher. Others swell only at elevated temperatures.
Marvess® and Alpha®	Excellent resistance to concentrated acids and alkalis.	Resistant to bleaches and most solvents. Chlorinated hydrocarbons cause swelling at room temperature and dissolve fibers at 160°F and higher.
Essera®, Marquesa Lana®, Patlon® III	Excellent resistance to most acids and alkalis with the exception of elevated temperature exposure to some acids.	Resistant to bleaches and most solvents. Some hydrocarbons will cause swelling at room temperature. Some solvents will dissolve above 200°F.
Spectra®	Excellent resistance to most acids and alkalis, with the exception of elevated temperature exposure to some acids.	Resistant to most solvents, good resistance to bleaches. Some hydrocarbons cause swelling, especially at elevated temperatures.
Fibrilon®	Excellent resistance to concentrated acids and alkalis.	Resistant to bleaches and most solvents. Chlorinated hydrocarbons cause swelling at room temperature and dissolve fiber at 160°F and higher.
Spandex Glospan®/ Cleerspan, S-85	Resistant to mild acids and alkalis. Is degraded by strong acids and alkalis at high temperatures.	Good resistance to deterioration by bleaches. Discolored slightly by hypochlorite bleach. Resistant to solvents and oils except glycols.
Lycra® Type 126,127	Good resistance to most acids. Slightly yellowed by dilute hydrochloric, sulfuric acids. Good resistance to most alkalis.	Hypochlorite bleaches discolor. Can use perborate. Good resistance to most solvents, oils.
Type 128	Resistant to mild acids and alkalis. Degraded by strong acids and alkalis at high temperatures.	Good resistance to discoloring. Strength loss by hypochlorite bleaches.

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TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Glass	Resists most acids and alkalis.	Unaffected.
Aramid		
Kevlar®	Good resistance to dilute acids and bases. Degraded by strong mineral acids and, to lesser extent, by strong mineral bases. Best chemical resistance from Kevlar 149.	Should not be bleached. Excellent solvent resistance.
Nomex®	Unaffected by most acids, except some strength loss after long exposure to hydrochloric, nitric and sulfuric. Generally good resistance to alkalis.	Unaffected by most bleaches and solvents except for slight strength loss from exposure to sodium chlorite.
Fluorocarbon		
Gore-Tex®	Essentially inert to acids and alkalis.	Essentially inert to bleaches and solvents except for alkali metals at high temperature and/or pressure.
Teflon®	Essentially inert to acids and alkalis.	Most chemical-resistant fiber known. The only known solvents are alkali metals and certain perfluorinated organic liquids at temperatures about 570°F.
PBI	Excellent resistance to most acids and alkalis. Some strength loss with strong alkali at elevated temperatures. Excellent organic solvent resistance.	Unaffected by most bleaches and solvents.

the neutral or acid side. Certain reducing agents are employed to modify the wool by rupturing sulfur-sulfur bonds. The wool is then more "plastic" and can be set into a desired shape. Reoxidation then reforms the bonds and the fiber then maintains its new configuration.

All of the natural fibers are unaffected by the common hydrocarbon and aromatic solvents.

The polyesters have good resistance to most mineral acids and to weak alkalis, but are disintegrated by strong hot alkali. They have good resistance to oxidizing agents and to most organic solvents except phenols. Generally speaking, the polyesters are considered to have better chemical resistance than the polyamides. The acrylics and modacrylics generally have excellent chemical resistance. They have excellent acid resistance, fair alkali resistance and are impervious to many solvents. The modacrylics are softened or dissolved by certain ketones. Saran has excellent acid and alkali resistance although it is sensitive to ammonia. It is unaffected by most common solvents, but is degraded by certain esters and ethers. Polyethylene and polypropylene have excellent acid and alkali resistance, but are sensitive to alkaline oxidizing

agents. Their general chemical and solvent resistance is high. They are normally soluble in hot chlorinated hydrocarbons.

27. ELECTROSTATIC PROPERTIES OF FIBERS

Both in processing and in use, the generation of static electricity on textile materials is at least a nuisance, and can be expensive or dangerous. During conversion of fiber to yarn and yarn to fabric, the large fiber surface areas are conducive to generating and holding electrostatic charges. These charges develop as the result of fiber to fiber, fiber to machinery, or even fiber to air friction. Most textile fibers are good or excellent electrical insulators; hence, electric charges cannot be conducted away. So the intensity of charge increases until fibers or yarns, all with the same charge, repel each other with accompanying "wildness" of fibers which then will not process properly. If the charge on the fibers is opposite to that on card clothing, drafting rolls, or other machinery parts, the fibers will stick to those parts of the machine oppo-

sitely charged, and processing may be slowed down or stopped. Static generation by conveyor belts and the like operating in areas where there are solvent fumes may be dangerous because a discharge spark may cause explosion and fire.

Truly distilled water is a relatively poor electrical conductor, but natural waters which contain even small quantities of soluble mineral salts are excellent conductors. Those fibers which have high moisture regains usually do not present quite as many static problems as do those which are impervious to water. If the relative humidity is sufficiently high, almost all textile fibers can be processed without electrostatic difficulty. As the humidity decreases, processing problems increase, usually geometrically with the synthetic hydrophobic fibers being the first to cause trouble. The polyesters, acrylics, olefins, and the polyamides having the lowest moisture regain are most likely to develop static charges. Rayon, silk, wool, and cotton can absorb water and hence can dissipate charges more easily. However, at low relative humidity all fibers may show processing difficulty. The textile industry, therefore, makes wide use of humidification during carding, combing, spinning, and weaving. Combing or spinning oils, warp sizes, and other processing chemicals usually contain anti-stats to eliminate the static problem. Static also may be eliminated by running the material over alpha particle radioactive sources which ionize the surrounding air.

Chemical anti-stats usually contain polar groups within their molecule. These act as conductors to prevent charge buildup or to conduct away any charges which do develop. Anti-stats also may be nothing more than humectants or water absorbing materials. The ionized water present on the textile will dissipate the static electricity. While generally an inverse relation exists between moisture regain and charge buildup, the intrinsic nature of the fiber polymer substance may also have a great bearing on static forming characteristics.

28. ELECTRICAL RESISTIVITY

Proper evaluation of the electrostatic properties of a fiber or fabric requires that all of the mechanisms for charge generation and dissipation be considered.

To pass a steady flow of electric charge, or current through any material requires a voltage. Ohm's law states that the ratio of applied voltage to current flow is called the electrical resistance. The lower the resistance, the more easily the current will flow. Flow can take place through either the volume of the material or along its surface, and the resulting resistances are called "volume resistance" and "surface resistance," respectively. Materials with high resistance will build up and hold electrostatic charges because the current cannot flow easily and allow the charge to leak off. Thus, a direct relationship normally exists between a fabric's surface or volume resistance and its tendency to build up a bothersome electrostatic charge.

Since water (other than distilled) is a good conductor, surface and volume resistances for all fibers are essentially inversely functional with moisture regain. Large changes in resistance result from small changes in regain. Many hydrophobic fibers may have high volume resistances because they are impervious to water. Their surface resistances may be proportionately lower, however, because they have thin or even molecular layers of water adhering to their surfaces. Methods for measuring resistivities are given in Chapter 20.0, Textile Testing.

Fiber	Manufacturer	Major Characteristics	Industrial and Home Furnishing Uses
POLYESTER			
Strialine	BASF Corporation		
Tolaram	Tolaram Fibers, Inc.		
Trevira	Hoechst Celanese Corporation		
Trevira Finesse	Hoechst Celanese Corporation		
Untra Touch	BASF Corporation		
PBI			
PBI logo	Hoechst Celanese Corporation	Highly flame resistant; outstanding comfort factor combined with thermal and chemical stability properties; will not burn or melt; low shrinkage when exposed to flame	Suitable for high performance protective apparel such as firemens' turnout coats, astronaut space suits and applications
RAYON			
Beau-Grip	North American Rayon		
Fibro	Courtaulds Fibers Inc.	Highly absorbent; soft and comfortable; easy to dye; versatile; good drapeability	Medical/surgical products, tire, cord, industrial products, bedspreads, blankets, carpets, curtains, draperies, sheets, tablecloths, upholstery
SPANDEX			
Glospan/ Clearspan, S-85	Globe		
Lycra	E. I. du Pont de Nemours & Company, Inc.	Can be stretched 500 percent without breaking; can be stretched repeatedly and recover original length; lightweight; stronger, more durable than rubber; resistant to body oils	Surgical hose, ski pants, athletic apparel
SULFAR			
Ryton	Amoco Fibers	High performance fibers with excellent resistance to harsh chemicals and high temperatures; excellent strength retention in adverse environments; flame retardant; non-conductive	Filter fabric for coal-fired boiler bag houses, paper machine clothing, electrical insulation, electrolysis membranes, filter fabrics for liquid and gas filtration, high performance composites, gaskets and packings
VINYON			
Vinyon	Hoechst Celanese Corporation	Softens at low temperature; high resistance to chemical; non-toxic	Used in industrial applications as a bonding agent for nonwoven fabrics and products such as tea bags and automotive headliners