I. Fiber Theory, Formation, and Characterization

1. Fiber Theory and Formation

INTRODUCTION

The word "textile" was originally used to define a woven fabric and the processes involved in weaving. Over the years the term has taken on broad connotations, including the following: (1) staple filaments and fibers for use in yarns or preparation of woven, knitted, tufted or non-woven fabrics, (2) yarns made from natural or man-made fibers, (3) fabrics and other products made from fibers or from yarns, and (4) apparel or other articles fabricated from the above which retain the flexibility and drape of the original fabrics. This broad definition will generally cover all of the products produced by the textile industry intended for intermediate structures or final products.

Textile fabrics are planar structures produced by interlacing or entangling yarns or fibers in some manner. In turn, textile yarns are continuous strands made up of textile fibers, the basic physical structures or elements which makes up textile products. Each individual fiber is made up of millions of individual long molecular chains of discrete chemical structure. The arrangement and orientation of these molecules within the individual fiber, as well as the gross cross section and shape of the fiber (morphology), will affect fiber properties, but by far the molecular structure of the long molecular chains which make up the fiber will determine its basic physical and chemical nature. Usually, the polymeric molecular chains found in fibers have a definite chemical sequence which repeats itself along the length of the molecule. The total number of units which repeat themselves in a chain (n) varies from a few units to several hundred and is referred to as the degree of polymerization (DP) for molecules within that fiber.
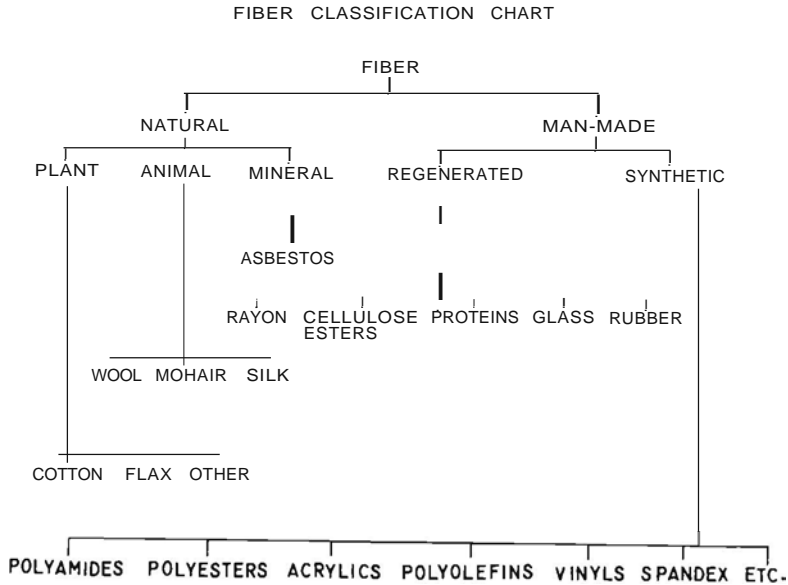
FIBER   CLASSIFICATION   CHART

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                                    FIBER
              ┌───────────────────────┴───────────────────────┐
           NATURAL                                         MAN-MADE
      ┌───────┼───────┐                          ┌─────────────┴─────────────┐
    PLANT  ANIMAL  MINERAL                   REGENERATED               SYNTHETIC
                       │                          │
                   ASBESTOS                       │
                                                  │
                 RAYON  CELLULOSE  PROTEINS  GLASS  RUBBER
                         ESTERS
           WOOL  MOHAIR  SILK

    COTTON  FLAX  OTHER
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POLYAMIDES   POLYESTERS   ACRYLICS   POLYOLEFINS   VINYLS   SPANDEX   ETC.

Figure 1-1.   Classification of natural and man-made fibers.

FIBER   CLASSIFICATION

Textile fibers are normally broken down into two main classes, natural and man-made fibers.   All fibers which come from natural sources (animals, plants, etc.) and do not require fiber formation or reformation are classed as natural fibers.   Natural fibers include the protein fibers such as wool and silk, the cellulose fibers such as cotton and linen, and the mineral fiber asbestos.   Man-made fibers are fibers in which either the basic chemical units have been formed by chemical synthesis followed by fiber formation or the polymers from natural sources have been dissolved and regenerated after passage through a spinneret to form fibers.   Those fibers made by chemical synthesis are often called synthetic fibers, while fibers regenerated from natural polymer sources are called regenerated fibers or natural polymer fibers.   In other words, all synthetic fibers and regener-

ated fibers are man-made fibers, since man is involved in the actual fiber formation process. In contrast, fibers from natural sources are provided by nature in ready-made form.

The synthetic man-made fibers include the polyamides (nylon), polyesters, acrylics, polyolefins, vinyls, and elastomeric fibers, while the regenerated fibers include rayon, the cellulose acetates, the regenerated proteins, glass and rubber fibers. Figure 1-1 shows a classification chart for the major fibers.

Another method of classifying fibers would be according to chemical structure without regard of the origin of the fiber and its starting materials. In this manner all fibers of similar chemical structure would be classed together. The natural man-made fiber classification given in Figure 1-1 does this to a certain extent. In this way, all fibers having the basic cellulosic unit in their structures would be grouped together rather than separated into natural and man-made fibers. This book essentially presents the fibers in groups of similar basic chemical structure, with two exceptions. In one case the elastomeric fibers have been grouped together due to their exceptional physical property, high extensibility and recovery. In the other case, new fibers which do not properly "fit" into anyone category have been placed in a separate chapter. An outline for the arrangement for fibers by chemical class as presented in this sourcebook follows:

Cellulosic Fibers
    Cotton
    Flax
    Other natural cellulosic
      fibers
    Rayon

Cellulosic Ester Fibers
    Acetate
    Tri aceta te

Protein (Natural Polyamide)
  Fibers
    Wool
    Silk
    Other natural and regen-
      erated protein fibers

Polyamide (Nylon) Fibers
    Nylon 6 and 6,6
    Arami d
    Other nylon fibers

Polyester Fibers
    Polyethylene terephthalate
    Poly-l,4-cyclohexylenedi-
      methylene terephthalate
    Other polyester fibers

Acrylic and Modacrylic Fibers
    Acrylic
    Modacryl ic
    Other acryl i cs

Polyolefin Fibers
    Polyethylene
    Polypropyl ene

Vi nyl Fi bers
    Vinyon
    Vinal
    Vinyon-vinal matrix
    Saran
    Polytetrafluoroethylene

Elastomeric Fibers
    Rubber
    Spandex
    Other elastomeric fibers

Mineral and Metallic Fibers
    Gl ass
    Inorganic
    Asbestos
    Metallic

Miscellaneous Fibers
    Novaloid
    Carbon
    Poly(m-phenylenediben-
      zimidazole)
    Polyimide

FIBER PROPERTIES

There are several primary properties necessary for a polymeric material to make an adequate fiber: (1) fiber length to width ratio, (2) fiber uniformity, (3) fiber strength and flexibility, (4) fiber extensibility and elasticity, and (5) fiber cohesiveness.

Certain other fiber properties increase its value and desirability in its intended end-use but are not necessary properties essential to make a fiber. Such secondary properties include moisture absorption characteristics, fiber resiliency, abrasion resistance, density, luster, chemical resistance, thermal characteristics, and flammability. A more detailed description of both primary and secondary properties follows.

Primary Properties

Fiber Length to Width Ratio: Fibrous materials must have sufficient length so that they can be made into twisted yarns. In addition, the width of the fiber (the diameter of the cross section) must be much less than the overall length of the fiber, and usually the fiber diameter should be 1/100 of the length of the fiber. The fiber may be "infinitely" long, as found with continuous filament fibers, or as short as 0.5 inches (1.3 em), as found in staple fibers. Most natural fibers are staple fibers, whereas man-made fibers come in either staple or filament form depending on processing prior to yarn formation.

Fiber Uniformity: Fibers suitable for processing into yarns and fabrics must be fairly uniform in shape and size. Without sufficient uniformity of dimensions and properties in a given set of fibers to be twisted into yarn. the actual formation of the yarn may be impossible or the resulting yarn may be weak, rough, and irregular in size and shape and unsuitable for textile usage. Natural fibers must be sorted and graded to assure fiber uniformity, whereas synthetic fibers may be "tailored" by cutting into appropriate uniform lengths to give a proper degree of fiber uniformity.

Fiber Strength and Flexibility: A fiber or yarn made from the fiber must possess sufficient strength to be processed into a textile fabric or other textile article. Following fabrication into a textile article. the resulting textile must have sufficient strength to provide adequate durability during end-use. Many experts consider a single fiber strength of 5 grams per denier to be necessary for a fiber suitable in most textile applications, although certain fibers with strengths as low as 1.0 gram per denier have been found suitable for some applications.

The strength of a single fiber is called the tenacity, defined as the force per unit linear density necessary to break a known unit of that fiber. The breaking tenacity of a fiber may be expressed in grams per denier (g/d) or grams per tex (g/tex). Both denier and tex are units of linear density (mass per unit of fiber length) and are defined as the number of grams of fiber measuring 9000 meters and 1000 meters, respectively. As a result, the denier of a fiber or yarn will always be 9 times the tex of the same fiber. Since tenacities of fibers or yarns are obtained by dividing the force by denier or tex, the tenacity of a fiber in grams per denier will be 1/9 that of the fiber tenacity in grams per tex.

As a result of the adaption of the International System of Units. referred to as SI. the appropriate length unit for breaking tenacity becomes kilometer (km) of breaking length or Newtons per tex (N/tex) and will be equivalent in value to g/tex.

The strength of a fiber. yarn, or fabric can be expressed in terms of force per unit area, and when expressed in this way the term is tensile strength. The most common unit used in the past for tensile strength has been pounds force per square inch or grams force per square centimeter. In 51 units, the pounds force per square inch x 6.895 will become kilopascals (kPa) and grams force per square centimeter x 9.807 will become megapascals (MPa) .

A fiber must be sufficiently flexible to go through repeated bending without significant strength deterioration or breakage of the fiber. Without adequate flexibility, it would be impossible to convert fibers into yarns and fabrics, since flexing and bending of the individual fibers is a necessary part of this conversion. In addition, individual fibers in a textile will be subjected to considerable bending and flexing during end-use.

Fiber Extensibility and Elasticity: An individual fiber must be able to undergo slight extensions in length (less than 5%) without breakage of the fiber. At the same time the fiber must be able to almost completely recover following slight fiber deformation. In other words, the extension deformation of the fiber must be nearly elastic. These properties are important because the individual fibers in textiles are often subjected to sudden stresses, and the textile must be able to give and recover without significant overall deformation of the textile.

Fiber Cohesiveness: Fibers must be capable of adhering to one another when spun into a yarn. The cohesiveness of the fiber may be due to the shape and contour of the individual fibers or the nature of the surface of the fibers. In addition, long-filament fibers by virtue of their length can be twisted together to give stability without true cohesion between fibers. Often the term "spinning quality" is used to state the overall attractiveness of fibers for one another.

Secondary Properties

Moisture Absorption and Desorption: Most fibers tend to absorb moisture (water vapor) when in contact with the atmosphere. The amount of water absorbed by the textile fiber will depend on the chemical and physical structure and properties of the fiber, as well as the temperature and humidity of the surroundings. The percentage absorption of water vapor by a fiber is often expressed as its moisture regain. The regain is determined by weighing a dry fiber, then placing it in a room set to standard temperature and humidity ($21°$ ± $1°$ C and 65% relative humidity [RH] are commonly used). From these measurements, the percentage moisture regain of the fiber is determined:

$$\text{Percentage regain} = \frac{\text{Conditioned weight - Dry weight}}{\text{Dry weight}} \times 100\%$$

Percentage moisture content of a fiber is the percentage of the total weight of the fiber which is due to the moisture present, and is obtained from the following formula:

Percentage moisture content $\underline{\text{Conditioned weight}} \text{ - } \underline{\text{Dry weight}}$ x 100%
Conditioned weight

The percentage moisture content will always be the smaller of the two values.

Fibers vary greatly in their regain, with hydrophobic (water-repelling) fibers having regains near zero and hydrophilic (water-seeking) fibers 1ike cotton, rayon, and wool having regains as high as 15% at 21°C and 65% RH. The ability of fibers to absorb high regains of water affects the basic properties of the fiber in end-use. Absorbent fibers are able to absorb large amounts of water before they feel wet, an important factor where absorption of perspiration is necessary. Fibers with high regains will be easier to process, finish, and dye in aqueous solutions, but will dry more slowly. The low regain found for many man-made fibers makes them quick drying, a distinct advantage in certain appl ications. Fibers with high regains are often desirable because they provide a "breathable" fabric which can conduct moisture from the body to the outside atmosphere readily, due to their favorable moisture absorption-desorption properties. The tensile properties of fibers as well as their dimensional properties are known to be affected by moisture.

<u>Fiber Resiliency and Abrasion Resistance</u>: The ability of a fiber to absorb shock and recover from deformation and to be generally resistant to abrasion forces is important to its end-use and wear characteristics. In consumer use, fibers in fabrics are often placed under stress through compression, bending, and twisting (torsion) forces under a variety of temperature and humidity conditions. If the fibers within the fabric possess good elastic recovery properties from such deformative actions, the fiber has good resiliency and better overall appearance in end-use. For example, cotton and wool show poor wrinkle recovery under hot moist conditions, whereas polyester exhibits good recovery from deformation as a result of its high resiliency. Resistance of a fiber to damage when mobile forces or stresses come in contact with fiber structures is referred to as abrasion resistance. If a fiber is able to effectively absorb and dissipate these forces without damage, the fiber will show good abrasion resistance. The toughness and hardness of the fiber is related to its chemical and physical structure and morphology of the fiber and will influence the abrasion of the fiber. A rigid, brittle fiber such as glass, which is unable to dissi-

pate the forces of abrasive action, results in fiber damage and breakage, whereas a tough but more plastic fiber such as polyester shows better resistance to abrasion forces.   Finishes can affect fiber properties including resiliency and abrasion resistance.

Luster: Luster refers to the degree of light that is reflected from the surface of *a* fiber or the degree of gloss or sheen that the fiber possesses.   The inherent chemical and physical structure and shape of the fiber *can* affect the relative luster of the fiber.   With natural fibers the luster of the fiber is dependent on the morphological form that nature gives the fiber, although the relative luster can be changed by chemical and/or physical treatment of the fiber as found in processes such *as* mercerization of cotton.   Man-made fibers can vary in luster from bright to dull depending on the amount of delusterant added to the fiber.   Oelusterants such *as* titanium dioxide tend to scatter and absorb light, thereby making the fiber appear duller.   The desirability of luster for *a* given fiber application will vary and is often dependent on the intended end-use of the fiber in *a* fabric or garment form and on current fashion trends.

Resistance to Chemicals in the Environment: A textile fiber to be useful must have reasonable resistance to chemicals it comes in contact with in its environment during use and maintenance.   It should have resistance to oxidation by oxygen and other gases in the air, particularly in the presence of light, and be resistant to attack by microorganisms and other biological agents.   Many fibers undergo light-induced reactions, and fibers from natural sources are susceptible to biological attack, but such deficiencies can be minimized by treatment with appropriate finishes.   Textile fibers come in contact with a large range of chemical agents on laundering and dry cleaning and must be resistant from attack under such conditions.

Oensity: The density of a fiber is related to its inherent chemical structure and the packing of the molecular chains within that structure. The density of a fiber will have a noticeable effect on its aesthetic appeal and its usefulness in given appl ications.   For example, glass and silk fabrics of the same denier would have noticeable differences in weight due to their broad differences in density.   Fishnets of polypropylene fibers are of great util ity because their density is less than that of water.   Oensities are usually expressed in units of grams per cubic centimeter, but in 51 units will be expressed as kilograms per cubic meter, which gives a value 1000 times larger.

Thermal and Flammability Characteristics: Fibers used in textiles must be resistant to wet and dry heat, must not ignite readily when coming in contact with a flame, and ideally should self-extinguish when the flame is removed. Heat stability is particularly important to a fiber during dyeing and finishing of the textile and during cleaning and general maintenance by the consumer. Textile fibers for the most part are made up of organic polymeric materials containing carbon and burn on ignition from a flame or other propagating source. The chemical structure of a fiber establishes its overall flammability characteristics, and appropriate textile finishes can reduce the degree of flammability. A number of Federal, state, and local statutes eliminate the most dangerous flammable fabrics from the marketplace.

Primary Fiber Properties from an Engineering Perspective

The textile and polymer engineer must consider a number of criteria essential for formation, fabrication, and assembly of fibers into textile substrates. Often the criteria used will be similar to those set forth above concerning end-use properties. Ideally a textile fiber should have the following properties:

1. A melting and/or decomposition point above 220°C.
2. A tensile strength of 5 g/denier or greater.
3. Elongation at break above 10% with reversible elongation up to 5% strain.
4. A moisture absorptivity of 2%-5% moisture uptake.
5. Combined moisture regain and air entrapment capability.
6. High abrasion resistance.
7. Resistance to attack, swelling, or solution in solvents, acids, and bases.
8. Self-extinguishing when removed from a flame.

FIBER FORMATION AND MORPHOLOGY

Fiber morphology refers to the form and structure of a fiber, including the molecular arrangement of individual molecules and groups of molecules within the fiber. Most fibers are organic materials derived from carbon combined with other atoms such as oxygen, nitrogen, and halogens. The basic building blocks that organic materials form as covalently-bonded organic compounds are called monomers. Covalent bonds involve the sharing of electrons between adjacent atoms within the monomer, and the structure

trons between adjacent atoms within the monomer, and the structure of the monomer is determined by the type, location, and nature of bonding of atoms within the monomer and by the nature of covalent bonding between atoms. Monomers react or condense to form long-chain molecules called polymers made up of a given number (n) of monomer units which are the basic building unit of fibers.   On formation into fibers and orientation by natural or mechanical means the polymeric molecules possess ordered crystalline and nonordered amorphous areas, depending on the nature of the polymer and the relative packing of molecules within the fiber.   For a monomer A the sequence of events to fiber formation and orientation would appear as shown in Figure 1-2.
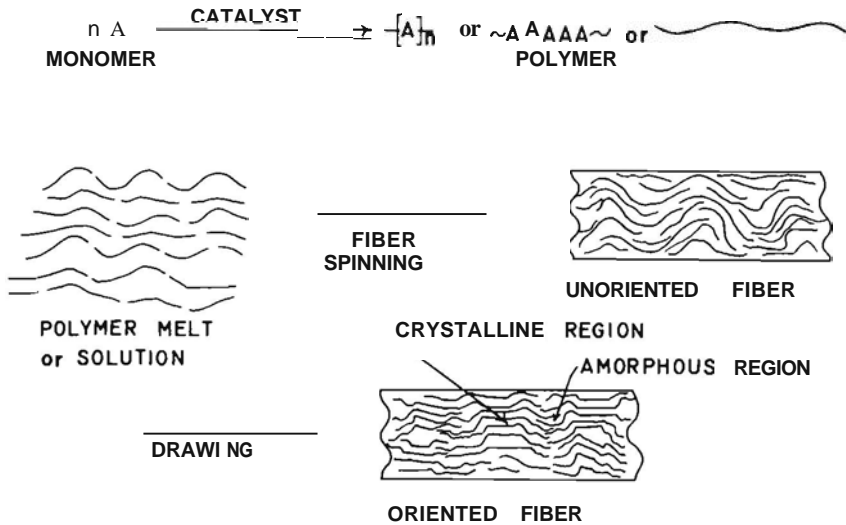
Figure 1-2. Polymerization sequence and fiber formation.

Polymers with repeating units of the same monomer (An) would be referred to as homopolymers.   If a second unit B is introduced into the

basic structure, structures which are copolymers are formed with structures as outlined in Figure 1-3.
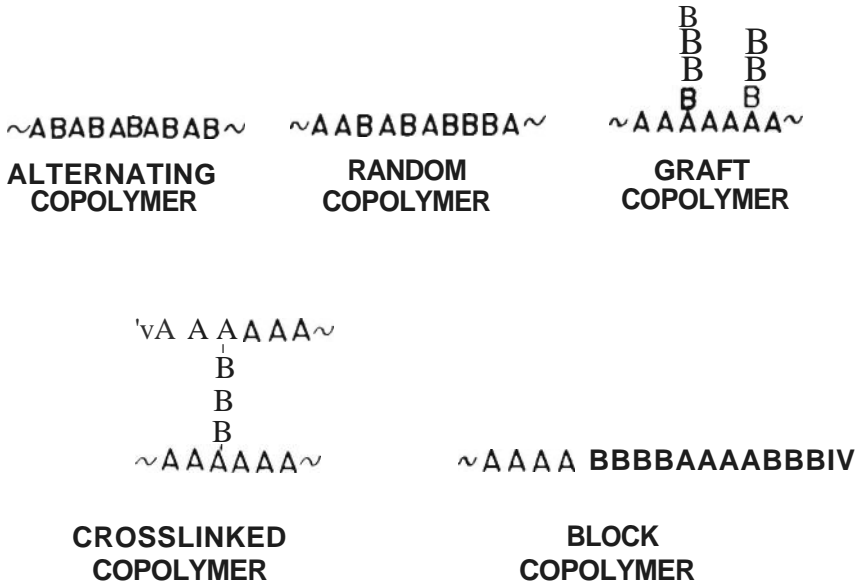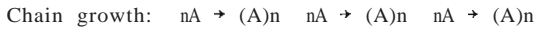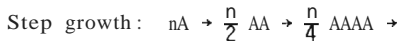
~ABABABABAB~

ALTERNATING COPOLYMER

~AABABABBBA~

RANDOM COPOLYMER

B
B
B   B
B   B
B   B
~AAAAAAA~

GRAFT COPOLYMER

'vA A A A A A~
B
B
B
~AAAAAA~

CROSSLINKED COPOLYMER

~AAAA BBBBAAAABBBIV

BLOCK COPOLYMER

Figure 1-3.   Copolymer structures.

Polymer Formation

Synthetic polymers used to form fibers are often classified on the basis of their mechanism of polymerization--step growth (condensation) or chain growth (addition) polymerization.   Step growth polymerization involves multifunctional monomers which undergo successive condensation with a second monomer or with itself to form a dimer, which in turn condenses with another dimer to form a tetramer, etc., usually with loss of a small molecule such as water.   Chain growth involves the instantaneous growth of a long molecular chain from unsaturated monomer units, followed by initiation of a second chain, etc.   The two methods are outl ined below schematically:

Step growth: $nA \rightarrow \frac{n}{2} AA \rightarrow \frac{n}{4} AAAA \rightarrow$

Chain growth: $nA \rightarrow (A)n$ $nA \rightarrow (A)n$ $nA \rightarrow (A)n$

The average number of monomer repeating units in a polymer chain (n) is often referred to also as the degree of polymerization, DP. The DP must exceed an average 20 units in most cases to give a polymer of sufficient molecular size to have desirable fiber-forming properties. The overall breadth of distribution of molecular chain lengths in the polymer will affect the ultimate properties of the fibers, with wide polymer size distributions leading to an overall reduction of fiber properties. Although the polymers from natural fibers and regenerated natural fibers do not undergo polymerization by the mechanisms found for synthetic fibers, most natural polymers have characteristic repeating units and high degrees of polymerization and are related to step growth polymers. Basic polymeric structures for the major fibers are given in Figure 1-4.
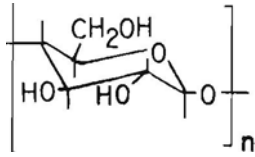
Fiber Spinning

Although natural fibers come in a morphological form determined by nature, regenerated and synthetic man-made fibers can be "tailor-made" depending on the shape and dimensions of the orifice (spinning jet) that the polymer is forced through to form the fiber. There are several methods used to spin a fiber from its polymer, including melt, dry, wet, emulsion, and suspension spinning.

Melt spinning is the least complex of the methods. The polymer from which the fiber is made is melted and then forced through a spinneret and into air to cause solidification and fiber formation.

Dry and wet spinning processes involve dissolving the fiber-forming polymer in an appropriate solvent, followed by passing a concentrated solution (20%-50% polymer) through the spinneret and into dry air to evaporate the solvent in the case of dry spinning or into a coagulating bath to cause precipitation or regeneration of the polymer in fiber form in the case of wet spinning. There is a net contraction of the spinning solution on loss of solvent. If a skin of polymer is formed on the fiber followed by diffusion of the remainder of the solvent from the core of the forming fiber, the cross section of the fiber as it contracts may collapse to form an irregular popcornlike cross section.

   Emul sion spinning is used only for those fiber-forming polymers that are insoluble.   Polymer is mixed with a surface-active agent (detergent) and possibly a solvent and then mixed at high speeds with water to form an emulsion of the polymer.   The polymer is passed through the spinneret and into a coagulating bath to form the fiber.
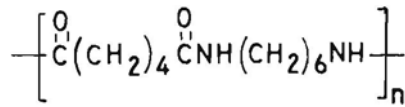
CELLULOSE
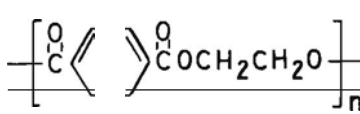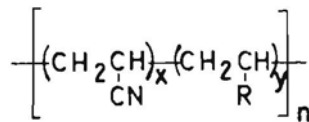**COTTON)RAYON)ETC.**
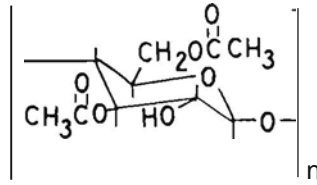
CELLULOSE   ACETATE
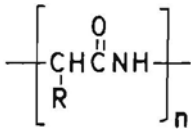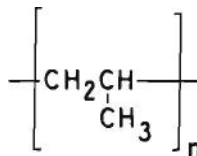
PROTEIN
WOOL/SILK,ETC.

NYLON   6)6

POLYESTER

ACRYLIC

POLYPROPYLENE

Figure 1-4.   Basic polymeric structures for major fibers.

In suspension spinning, the polymer is swollen and suspended in a swelling solvent. The swollen suspended polymer is forced through the spinneret into dry hot air to drive off solvent or into a wet non-solvent bath to cause the fiber to form through coagulation.

The spinning process can be divided into three steps:

(1)   flow of spinning fluid within and through the spinneret under high stress and sheer.

(2)   exit of fluid from the spinneret with relief of stress and an increase in volume (ballooning of flow).

(3)   elongation of the fluid jet as it is subjected to tensile force as it cools and solidifies with orientation of molecular structure within the fiber.

Common cross sections of man-made fibers include round, trilobal, pentalobal, dog-bone, and crescent shapes. When two polymers are used in fiber formation as in bicomponent or biconstituent fibers, the two components can be arranged in a matrix, side-by-side, or sheath-core configuration. Round cross sections are also found where skin formation has caused fiber contraction and puckering (as with rayons) has occurred or where the spinneret shape has provided a hollow fiber. Complex fiber cross-sectional shapes with special properties are also used. See Figure 1-5.

Fiber Drawing and Morphology

On drawing and orientation the man-made fibers become smaller in diameter and more crystalline, and imperfections in the fiber morphology are improved somewhat. Side-by-side bicomponent or biconstituent fibers on drawing become wavy and bulky.

In natural fibers the orientation of the molecules within the fiber is determined by the biological source during the growth and maturity process of the fiber.

The form and structure of polymer molecules with relation to each other within the fiber will depend on the relative alignment of the molecules in relationship to one another. Those areas where the polymer chains are closely aligned and packed close together are crystalline areas within the fiber, whereas those areas where there is essentially no molecular

alignment are referred to as amorphous areas. Dyes and finishes can pene-
trate the amorphous portion of the fiber, but not the ordered crystall ine
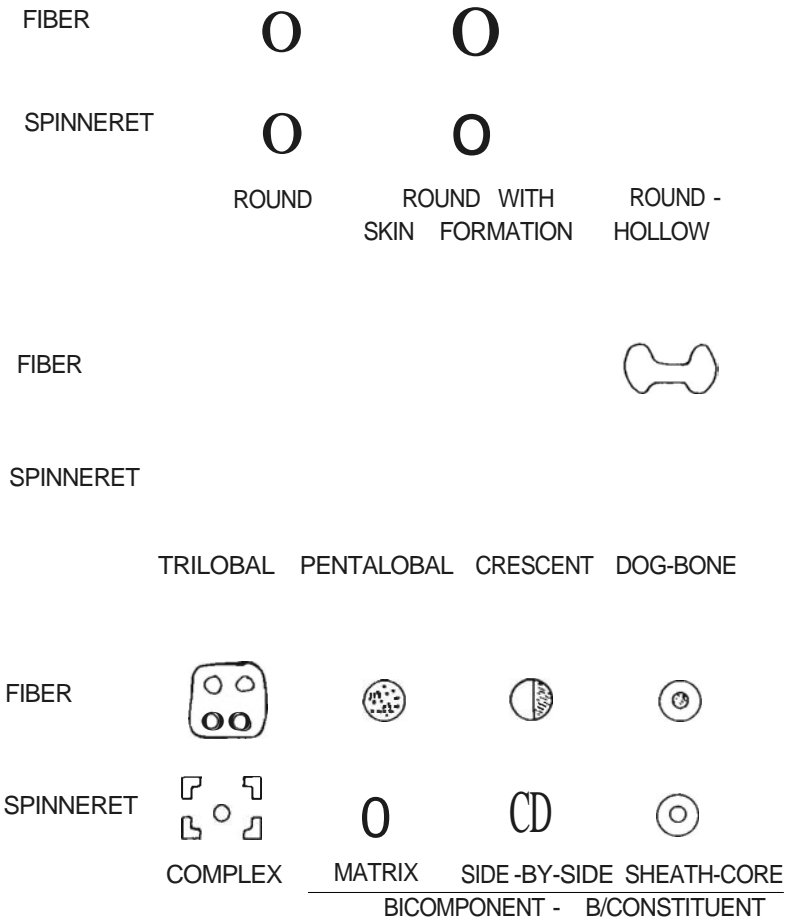portion.

CROSS-SECTION

Figure 1-5.   Fiber cross sections.

A number of theories exist concerning the arrangement of crystalline
and amorphous areas within a fiber. Individual crystal line areas in a

fiber are often referred to as microfibrils. Microfibrils can associate
into larger crystalline groups, which are called fibrils or micelles.
Microfibrils are 30-100 Å (1O-le meters) in length, whereas fibrils and
micelles are usually 200-600 Å in length. This compares to the individual
molecular chains, which vary from 300 to 1500 Å in length and which are
usually part of both crystalline and amorphous areas of the polymer and
therefore give continuity and association of the various crystalline and
amorphous areas within the fiber. A number of theories have been developed
to explain the interconnection of crystalline and amorphous areas in the
fiber and include such concepts as fringed micelles or fringed fibrils,
molecular chain foldings, and extended chain concepts. The amorphous areas
within a fiber will be relatively loosely packed and associated with each
other, and spaces or voids **will** appear due to discontinuities within the
structure. Figure 1-6 outlines the various aspects of internal fiber mor-
phology with regard to polymer chains.

FIBRIL **ICROFIBRIL** **INTRACHAIN FOLDING**
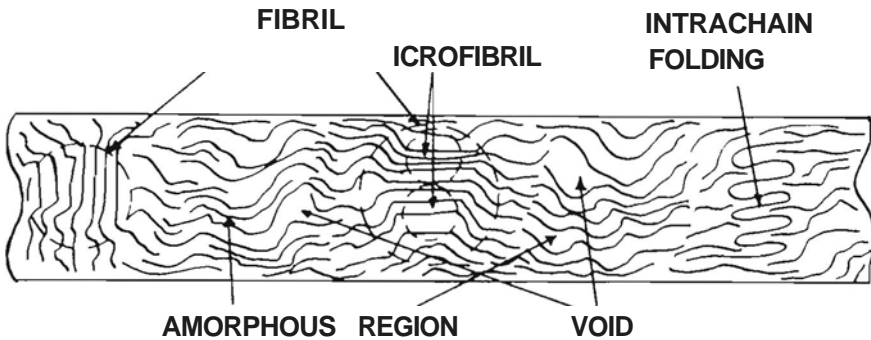
AMORPHOUS REGION **VOID**

Figure 1-6.   Aspects of internal fiber morphology.

The forces that keep crystalline areas together within a fiber include chemical bonds (covalent, ionic) as well as secondary bonds (hydrogen bonds, van der Waals forces, dipole-dipole interactions). Covalent bonds result from sharing of electrons between atoms, such as found in carbon-carbon, carbon-oxygen, and carbon-nitrogen bonding, within organic compounds. Covalent bonds joining adjacent polymer chains are referred to as crosslinks. Ionic bonding occurs when molecules donate or accept electrons from each other, as when a metal salt reacts with acid side chains on a polymer within a fiber. Chemical bonds are much stronger than secondary bonds formed between polymer chains, but the total associative force between polymer chains can be large, since a very large number of such bonds may occur between adjacent polymer chains. Hydrogen bonds are the strongest of the secondary bonds and occur between electropositive hydrogen atoms and electronegative atoms such as oxygen, nitrogen, and halogens on opposing polymer chains. Nylon, protein, and cellulosic fibers are capable of extensive hydrogen bonding. Van der Waals interactions between polymer chains occur when clouds of electrons from each chain come in close proximity, thereby promoting a small attractive force between chains. The more extended the cloud of electrons, the stronger the van der Waals interaction will be. Covalent bonded materials will show some uneven distribution of electron density over the molecule due to the differing electronegativity of the atoms and electron distribution over the molecule to form dipoles. Dipoles on adjacent polymer chains of opposite charge and close proximity are attracted to each other and promote secondary bonding.

When a synthetic fiber is stretched or drawn, the molecules in most cases will orient themselves in crystalline areas parallel to the fiber axis, although crystalline areas in some chain-folded polymers such as polypropylene can be aligned vertical to the fiber axis. The degree of crystallinity will be affected by the total forces available for chain interaction, the distance between parallel chains, and the similarity and uniformity of adjacent chains. The structure and arrangement of individual polymer chains also affects the morphology of the fiber. Also, <u>cis-trans</u> configurations or optical isomers of polymers can have very different physical and chemical properties.

<u>Bulking</u>, <u>Texturizing</u>, and <u>Staple</u> <u>Formation</u>

Thermoplastic man-made fibers can be permanently heat-set after drawing and orientation. The fiber will possess structural integrity and will not shrink up to that setting temperature. Also, thermoplastic fibers or yarns from these fibers can be texturized to give three dimensional loft

and bulkiness (1) through fiber deformation and setting at or near their softening temperature, (2) through air entanglement, or (3) through differential setting within fibers or yarns (Table I).   Schematic representations of these methods are given in Figure 1-7.
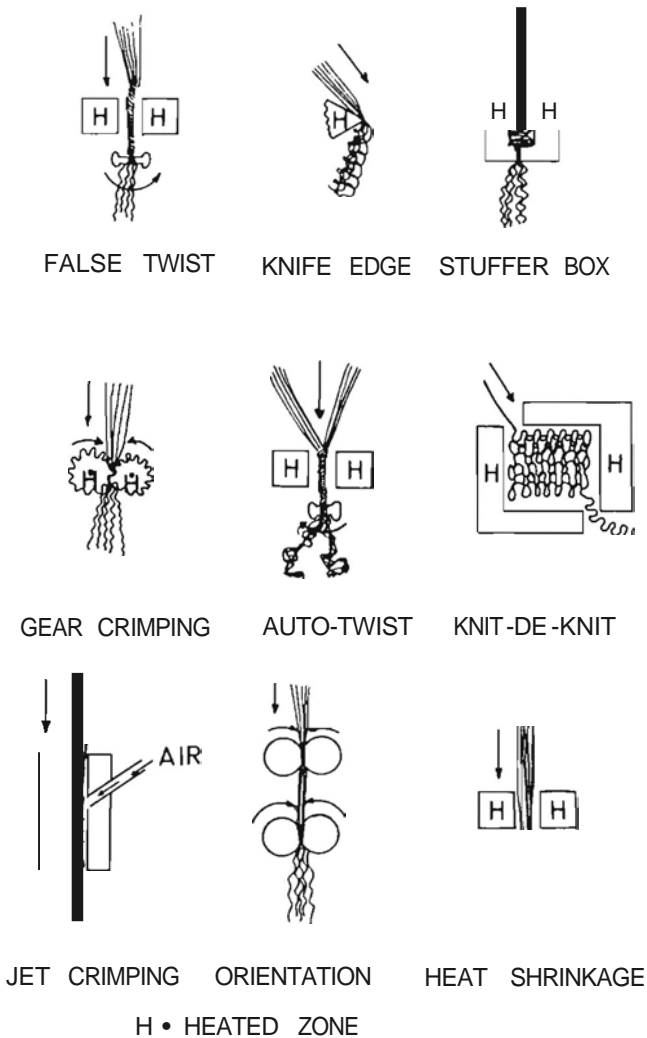
FALSE TWIST   KNIFE EDGE STUFFER BOX

GEAR CRIMPING   AUTO-TWIST   KNIT-DE-KNIT

JET CRIMPING   ORIENTATION   HEAT SHRINKAGE

H • HEATED ZONE

Figure 1-7.   Texturizing methods.

TABLE I. TEXTURIZING METHODS

Heat-setting Techniques	Air Entanglement	Differential Setting
False twist Knife edge Stuffer box Gear crimping Autotwist Knit-de-knit	Air jet	Bicomponent-biconstituent fiber orientation Heat shrinkage of thermoplastic fibers in a blend

Heat-Setting Techniques: The false twist heat-setting technique is extremely rapid, inexpensive, and most widely used. The filament fiber tow is brought in contact with a high-speed spindle running vertical to the moving tow. This action results in a high twist in the tow up to the spindle. The twisted tow is heated near its softening point before passing the spindle and then cooled and untwisted to give a wavy bulky yarn. In knife edge texturizing, filament tows or yarns are passed over a heated knife edge under tension. The fibers near the knife edge are changed in overall orientation in relation to the unheated yarns or portion of the filaments away from the knife edge, thereby causing bulking of the yarn. In stuffer box texturizing, the filament tow is fed into a heated box, causing the tow to double up against itself. On removal, the cooled tow retains the zigzag configuration caused by the process. In gear crimping, the tow is passed between heated intermeshing gears. On cooling the fibers retain the shape induced by the heated gears. In autotwisting, two tows or yarns are twisted together and then heat set. On untwisting the yarns have equal but opposite twists, which causes a spiral bulking of the yarn. In the knit-de-knit process a yarn is fill knitted, heat set, cooled, and de-knitted to give a bulked yarn retaining the shape and curvature of the knit.

Air Entanglement: In air entanglement texturizing, a fiber tow is loosely fed into and through a restricted space and a high-speed air jet is impinged on the fibers at a *45°* angle. The loose fibers within the tow are looped to give a texturized effect.

Differential Setting: Heat shrinkage techniques cause a bulking of fiber tows containing different fibers through heating one component of the blend sufficiently to cause heat shrinkage of the fiber and compaction, contraction, and bulking.   Side-by-side bicomponent and biconstituent fibers recover different degrees on each side from fiber stretching and causing a waving, crimping, or bulking of the fiber.

Staple Formation

Continuous filaments can be cut into staple by wet or dry cutting techniques.   In wet cutting, the wet spun fiber is cut to uniform lengths right after spinning, while dry cutting involves partial cutting, debonding, and shuffling of the dry tow to form a sliver.

Before the filament or staple is used in yarn spinning, spin finishes are added to give lubricity and antistatic characteristics to the fibers and to provide a greater degree of fiber cohesiveness.   Such finishes are usually mixtures including such materials as fatty acid esters, mineral oils, synthetic esters, silicones, cationic amines, phosphate esters, emulsifiers, and/or nonionic surfactants.   Spin finishes are formulated to be oxidation resistant, to be easily removed by scouring, to give a controlled viscosity, to be stable to corrosion, to resist odor and color formation, and to be non-volatile and readily emulsifiable.

STRUCTURE-PROPERTY RELATIONSHIPS

The basic chemical and morphological structure of polymers in a fiber determine the fundamental properties of a fabric made from that fiber. Although physical and chemical treatments and changes in yarn and fabric formation parameters can alter the fabric properties to some degree, the basic properties of the fabric result from physical and chemical properties inherent to the structure of the polymer making up the fiber.   From these basic properties, the end-use characteristics of the fiber are determined. To that end, in the following chapters we will describe the various textile fibers in terms of their basic structural properties, followed by physical and chemical properties, and finally the end-use characteristics inherent to constructions made from the fiber.

Initially the name and general information for a given fiber is set forth followed by an outline of the structural properties, including information about chemical structure of the polymer, degree of polymerization, and arrangement of molecular chains within the fiber.   Physical properties

include mechanical (tensile) and environmental properties of the fiber, whereas the effect of common chemicals and chemically induced processes on the fiber is listed under chemical properties. The end-use properties are then listed and include properties coming inherently from the structural, physical, and chemical properties of the fiber as well as end-use properties that involve evaluation of performance, subjective aspects, and aesthetics of the fabrics. Where possible, the interrelationships of these properties are presented.

2. Fiber Identification and Characterization

FIBER IDENTIFICATION

Several methods are used to identify fibers and to differentiate them from one another. The most common methods include microscopic examination, solubility tests, heating and burning characteristics, density or specific gravity, and staining techniques.

Microscopic Identification

Examination of longitudinal and cross-sectional views of a fiber at 100 to 500 magnifications gives detailed information with regard to the surface morphology of the fiber. Positive identification of many natural fibers is possible using the microscope, but positive identification of man-made fibers is more difficult due to their similarity in appearance and due to the fact that spinning techniques and spinneret shape can radically alter the gross morphological structure of the fiber.

Sol ubil ity

The chemical structure of polymers in a fiber determines the fiber's basic solubility characteristics, and the effect of solvents on fibers can aid in the general fiber classification. Various classification schemes involving solubility have been developed to separate and identify fibers.

Heating and Burning Characteristics

The reaction of fibers to heat from an open flame is a useful guide in identification of fibers. When thermoplastic fibers are brought close to a flame, they will melt, fuse, and shrink, whereas nonthermoplastic fibers will brown, char, or be unaffected by the flame. On contact with an open flame, fibers of organic polymers will ignite and burn. The nature of the burning reaction is characteristic of the chemical structure of the fiber. On removal from the flame, fibers will either self-extinguish or continue to burn. The odor of gases coming from the decomposing fibers and the nature of any residual ash are characteristic of the fibrous polymer being burned.

Density or Specific Gravity

Fiber density may be used as an aid in fiber identification. Fiber density may be determined by using a series of solvent mixtures of varying density or specific gravity. If the specific gravity of the fiber is greater than that of the liquid, the fiber specimen will sink in the liquid. Conversely, if the specific gravity of the fiber is less than that of the liquid, the fiber specimen will float. Thereby an approximate determination of fiber density may be made.

Staining

Fibers have differing dyeing characteristics and affinities dependent on the chemical and morphological structure of the fiber. Prepared dye mixtures containing dyes of differing affinities for various fiber types have been used extensively as identification stains for undyed fabrics. Since some fiber types may dye to similar shades with these dye mixtures, two or more stains usually must be used to confirm the fiber content. Staining is effective only for previously undyed fibers or for fibers where the dye is stripped from the fiber prior to staining.

STRUCTURAL, PHYSICAL, AND CHEMICAL CHARACTERIZATION

A number of methods are available for characterization of the structural, physical, and chemical properties of fibers. The major methods available are outlined in this chapter, including a brief description of each method and the nature of characterization that the method provides.

Optical and Electron Microscopy

Optical microscopy (OM) has been used for many years as a reliable method to determine the gross morphology of a fiber in longitudinal as well as cross-sectional views. Mounting the fiber on a slide wetted with a liquid of appropriate refractive properties has been used to minimize light scattering effects. The presence of gross morphological characteristics such as fiber shape and size and the nature of the surface can be readily detected. Magnifications as high as x1500 are possible, although less depth of field exists at higher magnifications. Scanning electron microscopy (SEM) can be used to view the morphology of fibers with good depth of field and resolution at magnifications up to xlO,OOO. In scanning electron microscopy, the fiber must first be coated with a thin film of a conducting metal such as silver or gold. The mounted specimen then is scanned with an electron beam, and particles emitted from the fiber surface are detected and analyzed to form an image of the fiber. Transmission electron microscopy (TEM) is more specialized and more difficult to perform than SEM. It measures the net density of electrons passing through the thin cross sections of metal-coated fibers and provides a method to look at the micromorphology of a fiber.

Elemental and End-Group Analysis

The qualitative and quantitative analysis of the chemical elements and groups in a fiber may aid in identification and characterization of a fiber. Care must be taken in analysis of such data, since the presence of dyes or finishes on the fibers may affect the nature and content of elements and end-groups found in a given fiber. Gravimetric and instrumental chemical methods are available for analysis of specific elements or groups of elements in fibers. Specific chemical analyses of functional groups and end-groups in organic polymers that make up fibers may be carried out. For example, analyses of amino acids in protein fibers, amino groups in polyamides and proteins, and acid groups in polyamides and polyesters aid in structure determination, molecular characterization, and identification of fibers.

Infrared Spectroscopy

Infrared spectroscopy is a valuable tool in determination of functional groups within a fiber. Functional groups in a polymer absorb infrared energy at wavelengths characteristic of the particular group and lead to changes in the vibrational modes within the functional group. As a result

of the infrared absorption characteristics of the fiber, specific functional groups can be identified. Infrared spectroscopy of fibers can be carried out on the finely divided fiber segments pressed in a salt pellet or through the use of reflectance techniques. Functional groups in dyes and finishes also can be detected by this technique.

Ultraviolet-Visible Spectroscopy

The ultraviolet-visible spectra of fibers, dyes, and finishes can provide clues concerning the structure of these materials, as well as show the nature of electronic transitions that occur within the material as light is absorbed at various wavelengths by unsaturated groups giving an electronically excited molecule. The absorbed energy is either harmlessly dissipated as heat, fluorescence, or phosphorescence or causes chemical reactions to occur that modify the chemical structure of the fiber. Ultraviolet-visible spectra can be measured for a material either in solution or by reflectance. Reflectance spectra are particularly useful in color measurement and assessment of color differences in dyed and bleached fibers.

Nuclear Magnetic Resonance Spectroscopy

Nuclear magnetic resonance (NMR) spectroscopy measures the relative magnitude and direction (moment) of spin orientation of the nucleus of the individual atoms within a polymer from a fiber in solution in a high-intensity magnetic field. The degree of shift of spins within the magnetic field and the signal splitting characteristics of individual atoms such as hydrogen or carbon within the molecule are dependent on the location and nature of the groups surrounding each atom. In this way, the "average" structure of long polymeric chains can be determined. Line width from NMR spectra also can provide information concerning the relationship of crystalline and amorphous areas within the polymer.

X-Ray Diffraction

X-rays diffracted from or reflected off of crystalline or semicrystalline polymeric materials will give patterns related to the crystalline and amorphous areas within a fiber. The size and shape of individual crystalline and amorphous sites within the fiber will be reflected in the geometry and sharpness of the x-ray diffraction pattern and will provide an insight into the internal structure of polymeric chains within a fiber.

Thermal Analysis

Physical and chemical changes in fibers may be investigated by measuring changes in selected properties as small samples of fiber are heated at a steady rate over a given temperature range in an inert atmosphere such as nitrogen. The four thermal characterization methods are (1) differential thermal analysis (OTA), (2) differential scanning calorimetry (OSC), (3) thermal gravimetric analysis (TGA), and (4) thermal mechanical analysis (TMA) .

In OTA, small changes in temperature (ΔT) in the fiber sample compared to a reference are detected and recorded as the sample is heated. The changes in temperature (ΔT) are directly related to physical and chemical events occurring within the fiber as it is heated. These events include changes in crystallinity and crystal structure, loss of water, solvents, or volatile materials, melting, and decomposition of the fiber. OSC is similar to OTA but measures changes in heat content (ΔH) rather than temperature (ΔT) as the fiber is heated, and it provides quantitative data on the thermodynamic processes involved. In an inert gas such as nitrogen, most processes are endothermic (heat absorbing). If OTA or OSC is carried out in air with oxygen, data may be obtained related to the combustion characteristics of the fiber, and fiber decomposition becomes exothermic (heat generating). TGA measures changes in mass (ΔM) of a sample as the temperature is raised at a uniform rate. TGA provides information concerning loss of volatile materials, the rate and mode of decomposition of the fiber, and the effect of finishes on fiber decomposition. TMA measures changes in a specific mechanical property as the temperature of the fiber is raised at a uniform rate. A number of specialized mechanical devices have been developed to measure mechanical changes in fibers, including hardness and flow under stress.

Molecular Weight Determination

Molecular weight determination methods provide information concerning the average size and distribution of individual polymer molecules making up a fiber. Molecular weights enable one to calculate the length of the average repeating unit within the polymer chain, better known as the degree of polymerization (OP). The distribution of polymer chain lengths within the fiber provides information concerning selected polymer properties.

The major molecular weight determination methods include number average molecular weights $(\bar{M}_n)$, determined by end-group analysis,

osmometry, cryoscopy, and ebullioscopy; weight average molecular weights $(\bar{M}_w)$, determined by light scattering and ultracentrifugation; and viscosity molecular weights $(\bar{M}_v)$, determined by the flow rate of polymer solutions. Since each method measures the average molecular weight of the polymer differently, the molecular weight values obtained will differ depending on the overall number and distribution of polymer chains of varying lengths present in the fiber. The differences in value between $\bar{M}_n$ and $\bar{M}_w$ provide measures of the breadth of distribution of polymers within the fiber. By definition the distribution of molecular weights for a given polymer will always be $\bar{M}_w > \bar{M}_v > \bar{M}_n$.

Mechanical and Tensile Property Measurements

Mechanical and tensile measurements for fibers include tenacity or tensile strength, elongation at break, recovery from limited elongation, stiffness (relative force required to bend the fiber), and recovery from bending. The tensile properties of individual fibers or yarns are usually measured on a tensile testing machine such as an Instron, which subjects fibers or yarns of a given length to a constant rate of force or loading. The force necessary to break the fiber or yarn, or tenacity, is commonly given in grams per denier (g/d) or grams per tex (g/tex), or as kilometer breaking length in the SI system. The elongation to break of a fiber is a measure of the ultimate degree of extension that a fiber can withstand before breaking. The degree of recovery of a fiber from a given elongation is a measure of the resiliency of the fiber to small deformation forces. The stiffness or bendability of a fiber is related to the overall chemical structure of the macromolecules making up the fiber, the forces between adjacent polymer chains, and the degree of crystallinity of the fiber. Mechanical and tensile property measurements can provide valuable insights into the structure of a fiber and its projected performance in end-use.

Specific Gravity

The specific gravity of a fiber is a measure of its density in relation to the density of the same volume of water, and provides a method to relate the mass per unit volume of a given fiber to that of other fibers. Specific gravity relates to some degree to the nature of molecular packing, crystallinity, and molecular alignment in the fiber. Specific gravity of a fiber will give an idea of the relative weight of fabrics of identical fabric structure but of differing fiber content. End-use properties such as hand, drapability, and appearance are affected by fiber density.

Environmental Properties

Environmental properties include those physical properties which relate to the environment in which a fiber is found. Moisture regain, solvent solubility, heat conductivity, the physical effect of heat, and the electrical properties depend on the environmental conditions surrounding the fiber. The uptake of moisture by a dry fiber at equilibrium will depend on the temperature and relative humidity of the environment, Solvent solubilities of 'fibers will depend on the solubility parameters of the solvent in relation to fiber structure and crystallinity. Heat conductivity, the physical effect of heating such as melting, softening, and other thermal transitions, and electrical properties of a fiber depend on the inherent structure of the fiber and the manner in which heat or electrical energy is acted upon by the macromolecules within the fiber. Environmental properties are measured by subjecting the fiber to the appropriate environmental conditions and measuring the property desired under such conditions.

Chemical Properties

The chemical properties of fibers include the effects of chemical agents including acids, bases, oxidizing agents, reducing agents, and biological agents such as molds and mildews on the fiber and light- and heat-induced chemical changes within the fiber. Acids and bases cause hydrolytic attack of molecular chains within a fiber, whereas oxidizing and reducing agents will cause chemical attack of functional groups through oxidation (removal of electrons) or reduction (addition of electrons). Such chemical attack can change the fiber's structure and possibly cleave the molecular chains within the fiber. Biological agents such as moths on wool or mildew on cellulosics use the fiber as a nutrient for biological growth and subsequently cause damage to the fiber structure.

Sunlight contains ultraviolet, visible, and infrared light energy. This energy can be absorbed at discrete wavelength ranges by fibers depending on the molecular structure of the fiber. Ultraviolet and visible light absorbed by a fiber will cause excitation of electrons within the structure, raising them to higher energy states. Shorter ultraviolet wavelengths are the most highly energetic and give the most highly excited states. Visible light usually has little effect on the fiber, although its absorption and reflectance of unabsorbed light will determine the color and reflectance characteristics of the fiber. Infrared energy absorbed will increase the vibration of molecules within the fiber and causes heating of the fiber. The excited species within the fiber can return to their

original (ground) state through dissipation of the energy as molecular vibrations or heat without significantly affecting the fiber. Ultraviolet and some visible light absorbed by the fiber, however, can lead to molecular scission within the fiber and cause adverse free radical reactions, which will lead to fiber deterioration.

Heating a fiber to progressively higher temperatures in air will lead to physical as well as chemical changes within the fiber. At sufficiently high temperatures, molecular scission, oxidation, and other complex chemical reactions associated with decomposition of the fiber will occur causing possible discoloration and a severe drop in physical and end-use properties for the fiber.

END-USE PROPERTY CHARACTERIZATION

End-use property characterization methods often involve use of laboratory techniques which are adapted to simulate actual conditions of average wear on the textile or that can predict performance in end-use. Often quantitative numerical values cannot be listed in comparing the end-use properties of a given textile fiber; nevertheless, relative rankings are possible and can give useful information about the suitability of a fabric from a given fiber type for a specific application. It must be emphasized that one must be most careful in interpreting results from test methods and extrapolating the findings to actual wear and use conditions. The ultimate properties of fibers in end-use do reflect the underlying morphological, physical, and chemical characteristics inherent to the fiber. All major end-use properties and characteristics considered in this handbook are outlined below. End-use methods are usually voluntary or mandatory standards developed by test or trade organizations or by government agencies. Organizations involved in standards development for textile end-use include the following:

American Association of Textile Chemists and Colorists (AATCC)
American National Standards Institute (ANSI)
American Society for Testing and Materials (ASTM)
Consumer Product Safety Commission (CPSC)
Federal Trade Commission (FTC)
Society of Dyers and Colorists (SDC)
International Standards Organization (ISO)

<u>Characteristics</u> <u>Related</u> to <u>Identity,</u> <u>Aesthetics,</u> and <u>Comfort</u>

Fibers are known by common, generic, and trade names. The Textile Fiber Products Identification Act, administered by the Federal Trade Commission, established generic names for all major classes of fibers based on the structure of the fiber. Common natural fibers often are al so designated by their variety, type, or country of origin, whereas man-made fibers manufactured by various firms are designated by trade name. Nevertheless, the labeled textile must include the generic name of the fiber(s) and the percentage content of each fiber within the textile substrate. Often trade names are selected which will convey to the consumer a particular "feeling," property, or use for that fiber. Nylon is an example of a trade name (selected by duPont for their polyamide fiber) which came into such common usage that it eventually was designated as the generic name of this fiber class by the Federal Trade Commission (FTC). As new fibers of novel structure are developed and commercialized, new generic names are designated by the FTC.

A number of fiber end-use properties in textile constructions relate to the aesthetic, tactile, and comfort characteristics of the fiber. Such properties include appearance, luster, hand (feel or touch), drapability, absorbency, overall comfort, crease retention, pilling, and wrinkle resistance. All of these factors are affected to varying extents by the particular properties desired from the textile structure and its intended use. Many of these properties are related to inherent properties of the fibers, which are translated into textile structures prepared for end-use.

The overall appearance and luster of a textile can be related to the shape and light absorbing and scattering characteristics of the individual fiber within the structure. The "hand" or "handle" or a textile structure is a complex synthesis of tactical responses by an individual, and is characteristic of the particular fiber or fiber blend and overall structure of the textile substrate. The drapability of textiles is related to the fiber stiffness and bendabil ity within the complex structural matrix making up the textile. The moisture absorbency and comfort of a fiber is related to its chemistry and morphology and to the way it absorbs, interacts with, and conducts moisture. In addition, comfort is related to the yarn and fabric structure into which the individual yarns have been made. Crease retention and wrinkle resistance of a fiber in a textile construction are directly related to the inherent chemical and morphological characteristics of the fiber as they depend on deformation and recovery under dry and moist conditions. The pill ing characteristics of a fiber in a textile construction

are related to the ease with which individual fibers may be partially pulled from the textile structure and to the tenacity of the individual fibers. Fibers in loose, open textile structure are readily pulled from the textile. If the fiber is strong, the fiber tangles with other loose fibers and mixes with lint and fiber fragments to form a pill. Weaker fibers such as cotton, however, usually break off before pill formation occurs.

Characteristics Related to Durability and Wear

The useful life of a fabric depends on a number of factors, including the strength, stretch, recovery, toughness, and abrasion resistance of the fiber and the tearing and bursting resistance of the fabrics made from that fiber. The composite of these factors coupled with the conditions and type of end-use or wear will determine the durability characteristics of a textile structure made from the fiber.

Fibers must be of minimum strength in order to construct textile structures with reasonable wear characteristics. The wear and durability of a fabric will tend to increase with increasing fiber strength. Textile structures made from fibers able to withstand stretching and deformation with good recovery from deformation will have improved durability particularly when subjected to bursting or tearing stresses. The relative toughness of the fiber also will affect the fabric durability, with tougher fibers giving the best performance. Tough but resilient fibers will also be resistant to abrasion or wear by rubbing the fiber surface. Abrasion of a textile structure usually occurs at edges (edge abrasion), on flat surfaces (flat abrasion), or through flexing of the textile structure resulting in interfiber abrasion (flex abrasion).

Physical and Chemical Characteristics and Response of Fiber to Its Environmental Surroundings

The physical and chemical characteristics of a fiber affect a number of important end-use properties: (1) heat (physical and chemical) effect on fibers, including the safe ironing temperature and flammability, (2) wetting of and soil removal from the fiber, including laundering, drycleaning, and fiber dyeability and fastness, and (3) chemical resistance, including resistance to attack by household chemicals and atmospheric gases, particularly in the presence of sunlight.

Fibers respond to heat in different ways. Thermoplastic fibers such as polyesters soften and eventually melt on heating without extensive decomposition, thereby permitting setting of the softened fiber through stretching and/or bending and subsequent cooling. Other fibers, such as the cellulosics and protein fibers, decompose before melting and therefore cannot be set using physical means. The safe ironing temperature of a fabric is determined by the softening and/or decomposition temperature of the fiber and must be significantly below this temperature. At sufficiently high temperatures, fibers are chemically attacked by oxygen in the atmosphere which accelerates fiber decomposition. If the temperature and heat input is sufficiently high or **if** a flame is involved, the fiber will ignite and burn and thereby decompose at a more rapid rate. On removal from the heat source, some fibers will self-extinguish, whereas others will sustain flaming combustion and continue to burn. The burning characteristics of a fiber depends on its inherent chemical structure and the nature of any finishes or additives present on the fiber.

When soil is removed from a fabric as in laundering or dry-cleaning, the individual fibers must be resistant to attack or damage caused by additives such as detergents, the solvent medium used, and mechanical agitation. Fabrics constructed of fibers that swell in water or dry-cleaning solvents can undergo profound dimensional changes on wetting. Also, fibers with surface scales such as wool undergo felting in the presence of moisture and mechanical action.

The dyeability of a fiber is dependent on the chemical and morphological characteristics of the fiber, the ability of the fiber to be effectively wetted and penetrated by the dyeing medium, and the diffusion characteristics of the dye in the fiber. Since most dyeing processes are done in water medium, hydrophilic fibers generally dye more readily than the more hydrophobic fibers. The fastness of the dye on the fiber will be dependent on the nature and order of physical and/or chemical forces holding the dye on the fiber and the effect of environmental factors such as sunlight, household chemicals, and mechanical action (crocking) on the dye-fiber combination.

The chemical resistance of a fiber can have a profound effect on end-use. The fibers that are sensitive to chemical attack by household chemicals such as bleach are limited in their end-uses. The resistance of fibers to attack by atmospheric gases including oxygen, ozone, and oxides of nitrogen, particularly in the presence of sunlight and moisture, can also be important considerations in certain end-uses.