23 July 1971, Volume 173, Number 3994 **SCIENCE**

Polyester Fiber: From Its Invention to Its Present Position

The structure and properties of this versatile synthetic fiber have led to remarkable growth in many end uses.

Alfred E. Brown and Kenneth A. Reinhart

During the past several decades, science and technology have contributed greatly to the development, commercialization, and continuing growth of a host of polymeric products, which are used as fibers, plastics, or films. Among these products, polyester fibers have attracted particular attention because their consumption in the United States in 1970 exceeded for the first time that of nylon fibers. In addition, 1970 was the second successive year in which the consumption of man-made fibers exceeded that of the natural fibers cotton and wool.

There are many reasons for the rapid growth and broad use of polyester: for example, the achievements of polymer chemists and physicists in manipulating chemical structure and morphology to achieve a wide range of properties required for various uses, the significant breakthroughs in organic synthesis and process chemistry which led to low-cost raw materials, and the very favorable economics of large-scale manufacturing. This article presents an overview of developments in polyester fibers since they were invented 30 years ago, with emphasis on polyester chemistry, molecular structure, properties, and end uses.

Man-made fibers comprise two categories: synthetic and regenerated fibers. Polyester fibers, like nylon, acrylic, and polypropylene fibers, belong to the synthetic category of man-made fibers because they are made by converting small molecules, or monomers, to very large molecules, or polymers, by chemical reaction and then shaping these synthetic polymers into fibrous form. Rayon, acetate, and triacetate are the regenerated fibers, which are prepared by chemically treating the natural polymer cellulose, and regenerating it into fibrous form. It is the synthetic fibers, first made on a commercial scale in the early 1940's, that have been responsible for the enormous growth in the consumption of man-made fibers.

During the 1960's, the use of polyester increased steadily, and at times spectacularly, in such major areas as durable press garments, carpets, and textured knit fabrics. In 1970 it was used on a very large scale as a reinforcing fiber in automobile tires. Total production of polyester in 1970 was about 1.7 billion pounds, compared to about 1.5 billion pounds of nylon (1 pound equals 0.45 kilogram) (*1*). Predictions of opportunities for future growth are very favorable, since polyester is not only economical, but the most versatile of the many synthetic fibers now available.

All fibers are based on polymers, molecules that have a high molecular weight and are formed by combining small molecules into long chain molecules. The stringing together of several thousand monomer units to form a polymer chain is accomplished by polymerization. In this process, chemists use individual monomers, or mixtures of two or more, and control their spatial arrangement to produce polymers that are converted to fibers with the desired qualities of strength, durability, elasticity, dyeability, and chemical resistance. Herman Mark (*2*), a pioneer in the field of polymers described three principles that determine the properties of polymers and their usefulness as strong, durable materials in either fibrous, plastic, film, or rubbery forms:

1) The capability of the chains to arrange themselves in a crystalline or ordered structure;

2) The degree of stiffness, flexible or inflexible, of the chain; and

3) Whether or not the chains are chemically cross-linked.

By using combinations of these three principles, it is possible to achieve various properties with polymers, as shown schematically in Fig. 1. Each corner of the triangle represents one of the basic principles, and the sides and center of the triangle indicate various combinations. The chart outlines examples based on the polymer characteristics.

It was during the early 1930's that Wallace Carothers and his co-workers at Du Pont discovered the scientific principles that laid the foundation for all development of synthetic fibers and that resulted in the invention of nylon 66 in 1935 (*3*). His studies established the following principles for a useful synthetic fiber:

1) The molecular weight of the polymer should be high, not less than 12,000.

2) The polymer should be capable of being crystallized, or oriented, or both (these properties are generally possessed by linear polymers, provided there are no side groups to destroy linear symmetry and the close packing of chains).

3) Three-dimensional polymers are unsuitable.

The authors are, respectively, president and group leader at the Celanese Research Company, Summit, New Jersey 07901.

Invention of Polyester

The useful fiber-forming properties of polyester were first recognized in 1941, by J. R. Whinfield and J. T. Dickson (*4*). The crucial idea came to the inventors from a study of the work of Carothers, who had turned his attention to polyamides after having examined the aliphatic polyesters and found them to have too low a melting point and poor thermal and hydrolytic stabilities (*5*). Whinfield employed "intelligent thought, reading of the literature, and imagination" in proposing that molecular symmetry has a profound effect on the fiber-forming properties of polyester polymers (*3*, p. 161). He established the soundness of his concepts by concentrating on the symmetrical, aromatic polyesters. He found that the polymer derived from terephthalic acid (TPA) and ethylene glycol, poly(ethylene terephthalate) (Fig. 2), was fiber-forming and crystallizable. Poly(ethylene terephthalate), hereafter referred to as polyester or PET, also had a high melting point and was resistant to hydrolysis. In 1941, Whinfield and Dickson submitted a patent application in which they described the polycondensation of ethylene glycol and terephthalic acid to obtain a stiff, straight chain polymer that could be aligned and crystallized by forming fibers from the molten polymer. This led to the dominant patent on PET (*6*).

Development Problems

Terephthalic acid was not a common chemical substance in 1941, and a commercially feasible synthesis had to be developed. Such efforts are ordinarily the province of the chemical industry, not textile firms. Thus, Calico Printers' Association Ltd. entered into an agreement with Imperial Chemical Industries (ICI) to develop PET in the United Kingdom and throughout the world, with the exception of the United States. American rights to PET were sold to Du Pont. The large increase in funding from ICI accelerated the development. A commercial process for TPA was developed by oxidation of *para*-xylene, which was available from coal tar and petroleum oils. Ethylene glycol was already in commercial production. Means were found to prepare the materials in a state of high purity, in order to prevent degradation during the course of polymerization, and means of controlling the average molecular weight of the polymers were identified.

Although technical people today are well aware of the relationships among costs of research, development, and commercialization activities in taking an invention from the laboratory to the marketplace, it is interesting to read Whinfield's own account of the PET developments (*7*):

> While it is difficult to estimate the actual cost of the discovery itself, it may be noted that this was made in a small textile laboratory which certainly required less than the equivalent of $50,000 a year to maintain. To take this discovery from the laboratory through the phase of pilot plants and the appraisal of their products involved expenditure amounting to more than 100 times this sum, while the capital investment for commercial production represented a multiplication of the estimated discovery cost by a factor of at least 600. This is a very high rate of progression, and illustrates clearly the fact that while ideas and the acquisition of new knowledge may be cheap enough, the conversion of these ideas and this knowledge to practical use is a rather costly undertaking.

The funding for PET development in Britain up to the end of 1950 was in excess of 6 million dollars. An additional 30 million dollars were spent to construct plants that were to produce 11 million pounds of yarn and fiber annually by the end of 1954. In the United States, Du Pont pursued development work independently, introduced experimental quantities of PET in 1950, and established the first full-scale production in early 1953. Production has expanded at an ever-increasing rate, and many new domestic and foreign producers have emerged. World production was estimated in excess of 3 billion pounds in 1970.

Manufacture

PET is the dominant linear homopolymer polyester structure. Others have been investigated extensively (*8*), but the only one to achieve commercial significance is Eastman Kodak Company's poly(1,4-cyclohexanedimethylene terephthalate), in which ethylene glycol is replaced by 1,4-cyclohexanedimethanol. This polymer has a higher melting point than PET does.

The raw materials used in the preparation of PET are TPA prepared from alkyl benzenes, and ethylene glycol or ethylene oxide. Increased production of polyester has been accompanied by increased capacity for the raw materials and lower bulk cost. Ethylene glycol and TPA are available in large supply at 6½ to 7½ cents per pound and 14 to 15 cents per pound, respectively. As a result of these prices and the low cost of manufacture, polyester fiber is economically very competitive with other fibers in the uses to which PET is suited.

Purity of raw materials is essential to producing a polymer with a high molecular weight and no color-forming bodies. Normally, TPA was purified by converting it to dimethyl terephthalate

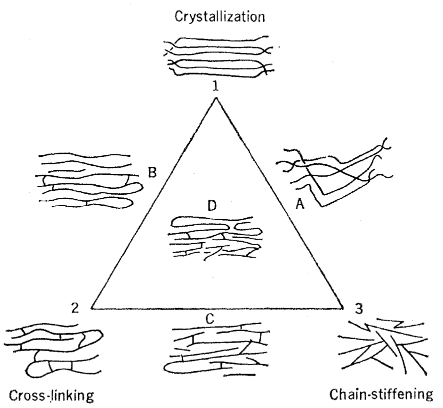

Fig. 1. Principles of polymer structure.

Location	Polymer characteristics	Examples	Uses
1	Flexible and crystallizable chains	Polyethylene	Plastics and films
2	Cross-linked, amorphous networks of flexible chains	Phenolformaldehyde	Thermoset plastics
3	Rigid chains	Polyimides	High temperature plastics
A	Crystalline domains in a viscous network	Polyester	Fibers, plastics, and films
		Cellulose acetate	Fibers, plastics, and films
B	Moderate cross-linking with some crystallinity	Polychloroprene Polyisoprene	Oil-resistant rubber Resilient rubber
C	Rigid chains, partly cross-linked	Heat-resistant materials	Jet and rocket engines
D	Crystalline domains with rigid chains between them and cross-linking between chains	Materials of high strength and temperature resistance	Buildings and vehicles

(DMT) and purifying the ester. Processes for the purification of TPA itself have recently been developed. The purified materials are reacted with glycol to make the monomer bis(β-hydroxyethyl) terephthalate (BHET), which is formed by the reaction of DMT with glycol (with an appropriate catalyst such as manganese acetate), or from the direct esterification of TPA with glycol. The BHET is polycondensed by removing excess glycol, with an appropriate catalyst such as antimony trioxide. Molecular weight, or the degree of polymerization, is determined from melt viscosity. Methods for purifying the BHET monomer prior to polycondensation have been described (*9*). This allows use of crude TPA for the synthesis.

Batch polymerization is the main source of the world production of PET polymer. However, large-scale operations are finding advantages in continuous polymerization and direct spinning systems. The elimination of solid polymer, subsequent blending, and remelting lead to cost savings in large-capacity operations. Continuous polymerization and direct spinning also minimize the competitive reactions that lead to the thermal degradation encountered in batch processing, thereby making it easier to achieve high-strength industrial yarns of a high molecular weight for tire cord. A typical system of continuous polymerization consists of a melter, ester exchange column, glycol flash vessel, low polymerizer, high polymerizer, and a molten polymer manifold system that feeds several banks of spinning heads.

Polyester is converted to the fibrous form by melt spinning, the process in which a fiber is formed by the extrusion of a melted polymer through a spinneret into a cooling zone. The spinneret is a metallic cap, with microscopic holes in a flat surface. Molten polymer is forced through the spinneret and emerges as thin filaments. The production of fiber by melt spinning is preferred over the other two principal commercial methods, dry and wet spinning. In dry spinning, the polymer, which is dissolved in a solvent, is passed through a spinneret and formed into a fiber by the evaporation of the solvent. In wet spinning, the polymer solution is extruded through a spinneret into a coagulating bath.

Melt spinning allows great versatility in control of fiber diameter, structure, and cross-sectional shape. The molten polymer (at about 290°C) is forced through a sand-bed filter to a stainless steel spinneret. The throughput of polymer is controlled by a metering pump that generates the pressure required for forcing the molten polymer through the filter-spinneret assembly (*10*). Since hydrolytic degradation of PET is very high under molten conditions, it is essential to the maintaining of PET's molecular weight and desirable properties that extremely dry conditions obtain when it is transferred to the spinneret.

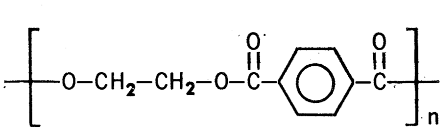

Fig. 2. PET structural formula.

$$\left[-O-CH_2-CH_2-O-\overset{O}{\overset{\|}{C}}-C_6H_4-\overset{O}{\overset{\|}{C}}-\right]_n$$

The extruded filaments solidify in air below the spinneret. Variables in polymer molecular weight, melt viscosity, polymer throughput, spinneret geometry, tension on the molten filaments, quench rate, and drawdown (amount of stretching between the spinneret and the take-up reel) affect the structural morphology of the extruded filaments. Normally, filaments are amorphous at this stage, but show orientation (a degree of alignment of the macromolecular units) along the fiber axis because of the viscoelastic response of the polymer.

Drawing, relaxing, and stabilization produce the oriented crystalline structure that gives the fiber its characteristic properties of strength, modulus, recovery, toughness, dimensional stability, and so on. Drawing is the stretching of fibers of low molecular orientation to several times their original length; relaxing is the releasing of strains and stresses in the drawn fibers; and stabilization is the treatment of the fibers with heat to enable them to resist further changes in dimensions.

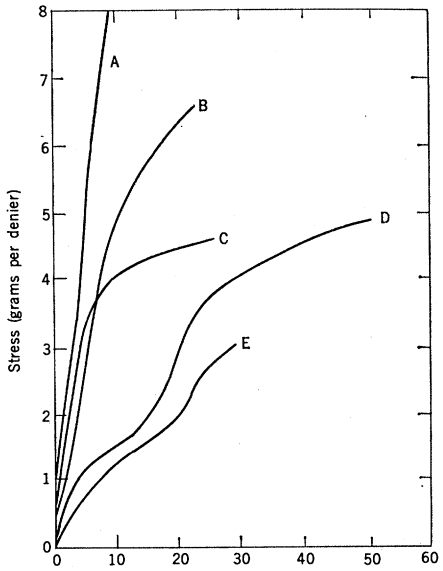

Fig. 3. Stress-strain behavior of polyester fibers: (A) high tensile strength PET filament; (B) high tensile strength PET staple; (C) regular tensile strength PET filament; (D) regular tensile strength PET staple; (E) poly(1,4-cyclohexanedimethylene terephthalate).

In the drawing process, PET, as spun yarn, is heated above its glass transition temperature (~ 80°C). During stretching, the molecular chains in the amorphous filament respond by a viscous process, involving the relative movement of chains, and by an elastic process, involving their uncoiling. At high stress, the resulting orientation induces crystallization, reinforces the structure, and impedes viscous flow. Normally, an ordered crystalline structure is produced, the degree or order depending markedly on the temperature, rate of stretching, and draw ratio.

Structure

Drawn polyester fibers are composed of crystalline and noncrystalline regions. The unit cell has been deduced for both poly(ethylene terephthalate) (*11*) and poly(1,4-cyclohexanedimethylene terephthalate) (*12*) by means of x-ray diffraction studies. For PET, the unit cell is triclinic and contains one repeating unit. The molecules are nearly planar in configuration, and their side-by-side arrangement is such that corresponding structural units lie on planes that are perpendicular to the fiber axis; thus aromatic rings, carbonyl groups, and so on face one another in exact register in the crystal.

The physical properties of the fiber, such as tensile strength and shrinkage, are related to the degree of crystallinity and the molecular orientation in polyester fibers. The degree of crystallinity can be measured by x-ray diffraction (*13*). Measurements of overall molecular orientation (both crystalline and noncrystalline) are obtained by optical methods. Combinations of x-ray diffraction techniques and optical methods have been used to determine the orientation in each phase (*14*).

Highly oriented (high draw ratio) yarns show the highest tensile strength and initial modulus or stiffness. An increase in molecular weight increases both tensile strength and extensibility, whereas changes in draw ratio affect

Table 1. Physical properties of polyester fibers (mechanical properties at 21°C, 65 percent relative humidity, using 60 percent per minute strain rate).

Property	Poly(ethylene terephthalate)				Poly(cyclohexanedimethylene terephthalate) staple and tow
	Filament yarns		Staple and tow		
	Regular tensile strength	High tensile strength	Regular tensile strength	High tensile strength	
Breaking strength (g/denier)*	2.8–5.6	6.0–9.5	2.2–6.0	5.8–6.0	2.5–3.0
Breaking elongation (%)	19–34	10–34	25–65	25–40	24–34
Initial modulus (g/denier)*	75–100	115–120	25–40	45–55	24–35
Elastic recovery (%)	88–93 (at 5% elongation)	90 (at 5% elongation)	75–85 (at 5% elongation)		85–95 (at 2% elongation)
Moisture regain† (%)	0.4	0.4	0.4	0.4	0.34
Specific gravity	1.38	1.38	1.38	1.38	1.22
Melting temperature (°C)	265	265	265	265	290

* Grams per denier—grams of force per denier. Denier is linear density, the mass for 9000 meters of fiber. † The amount of moisture in the fiber at 21°C, 65 percent relative humidity.

one at the expense of the other. Fiber modulus increases with increasing molecular weight and increasing draw ratio. The high fiber modulus achievable in PET is usually attributed to the stiffness in the chain of the polymer molecule and alignment of the polymer chains into a highly oriented (in the fiber direction) structure (*15*).

Like other synthetic fibers, PET is available commercially in three forms:

► Filament yarn—a yarn composed of one or more filaments that run the whole length of the yarn.

► Tow—a large number of continuous fibers collected into a loose strand that is substantially without twist.

► Staple—fiber prepared by cutting tow to short lengths for conversion into yarn by the conventional methods used for most natural and synthetic fibers.

Continuous-filament textile yarns are usually made on a draw twister. The draw, or stretch, is achieved by passing the yarn over a heated surface between rolls of different speeds. The drawn yarn is wound up on a cylindrical tube; the package size is usually 2 to 6 pounds of yarn. In spin-draw processes, which have been developed more recently (*16*), the extruded filaments pass directly over a series of heated stretch rolls and are wound up at high speeds. Tire cord is normally made by such a spin-draw process.

In the manufacture of staple, very large tows of undrawn yarn are made by combining several smaller tows (up to 250,000 filaments). They are then drawn between pairs of rolls operating at different speeds, with the tow heated above the glass transition temperature. The tow is crimped, dried, and heat stabilized, and is either packaged as tow or cut to the desired staple length.

Physical Properties

The different stress-strain curves of staple and filament polyester fibers are illustrated in Fig. 3. The unique "tailorability" of the polyester fibers to encompass a wide range of properties makes it possible to produce many mechanical property variants for a large variety of textile and industrial end uses. The mechanical properties of the variants shown in Fig. 3 can be related to some areas of end use as follows:

1) Tire cord and high-strength, high-modulus industrial yarns.

2) High-modulus staple fiber for blending with cotton, to give optimum processability to durable press fabrics.

3) Textile filament yarn for woven and knit fabrics.

4) Regular polyester staple for 100 percent polyester fabrics, carpet yarns, and blending with cotton or wool. Polyester tow for fiberfill.

5) Regular poly(1,4-cyclohexanedimethylene terephthalate) staple for carpet yarns.

The toughness of a fiber is measured by the total area under the stress-strain curve. Toughness is the amount of work or energy required to break the fiber, as well as a measure of the work or energy that can be absorbed by the fiber as it is loaded to any given stress or level of elongation. All of the polyester variants described in Fig. 3 require a great deal of work before they can be broken and are capable of absorbing considerable energy under normal conditions in the specific applications for which they are manufactured. The physical properties of the various polyester fibers shown in Fig. 3 are summarized in Table 1.

Polyester fibers, like other organic fibers, show nonlinear and time-dependent elastic behavior. Under load, creep will occur, and there will be delayed recovery on removal of the load. The elasticity of PET fiber at low levels of strain increases with increased structural orientation, which is the degree of alignment of the molecules in the fiber direction.

Table 2. Consumption of polyester fibers in the United States. [Source: Textile Economics Bureau, Incorporated]

End use	Estimated consumption of polyester fibers (millions of pounds)		
	1968	1969	1974
Staple			
Men's and boys' wear	425	510	850
Women's and children's wear	130	160	345
Home furnishings			
Bedding (sheets, pillowcases, spreads)	110	135	275
Fiberfill	40	45	85
Fabrics	30	35	80
Rugs and carpets	75	110	195
Miscellaneous	20	25	70
Total	830	1020	1900
Filament			
Men's and boys' wear	15	30	55
Women's and children's wear	65	125	225
Home furnishings	15	20	65
Tire cord	100	135	290
Miscellaneous	15	10	45
Total	210	320	680

Uses of PET

The volume of polyester fibers in a large number of end uses is expanding at a rapid rate. Many modifications or variants of PET have been developed for a wide variety of applications in men's, women's, and children's apparel, carpeting and home furnishings, tire cord, and other industrial markets.

A marked increase in the growth rate of PET occurred in the early 1960's, with the introduction and wide consumer acceptance of the concept of "easy-care" fabrics (also referred to as durable press, permanent press, and no-iron). These terms are all used to indicate that fabrics containing PET can be set or stabilized so that the resulting configuration is maintained during wear or use, with little or no ironing after laundering. Thus, trouser creases or skirt pleats are there for the life of the garment. For these uses, PET staple fiber is blended with cotton in a 50 : 50 or 65 : 35 ratio of PET to cotton. Blends with rayon are also common. The cotton or rayon is always treated with resin so that it too is set. During the past decade, the concept has spread to encompass women's dress goods, blouses, and sportswear; men's dress shirts, sportswear, and slacks; children's clothing; and durable press sheets, pillowcases, and bedspreads, as well as drapery fabrics and tablecloths. Polyester staple fiber is also blended with wool to produce fabrics for lightweight suits, enabling them to retain creases and resist wrinkles.

The recent development of textured PET yarn for knit fabrics is a major achievement. Such knit garments are wrinkle resistant and are used in women's and men's garments. This has become the major end use of polyester textile filaments. Textured yarns are continuous filament yarns, in which the filaments have been crimped or have been looped at random to give the yarn greater volume or bulk. Polyester filament yarn is easily textured and gives good dimensional stability to knits that are set with heat.

Polyester is used both in washable scatter rugs as well as in conventional carpets, particularly shag rugs. This end use consumed 110 million pounds in 1969. Polyester is used for other home furnishings such as drapery and upholstery fabrics.

Rayon and nylon cords were used to reinforce rubber tires prior to 1965, the year that PET was commercially introduced in this use. High performance caused the rapid expansion in sales of PET tire yarns to the 200 million pounds per year level in 1970 (*17*). Tire cord made of PET is equal in strength to nylon, but whereas nylon tires "flatspot," PET tires do not. When driving on tires with flatspots, which develop after the tire has been standing in the cold overnight, the consumer feels thumps for the brief period before the rotating tire warms up and all tire and cord segments are fully round again (*18*). Dimensional stability of tire cords is an extremely important property. The factors of shrinkage at elevated temperature, growth under load, and sensitivity to moisture combine to determine (i) how the fabric reacts to dipping for adhesion, calendering, tire building, and curing; (ii) uniformity of tire dimensions and tire balance; and (iii) performance of the tire with respect to growth, flatspotting, and ride characteristics. The all-around stability of PET is better than that of either rayon or nylon (*19*). Adhesion of the PET cords to rubber was a problem initially, but it was solved by developing new adhesive systems. Other areas for high tensile strength PET yarns are V-belts, sewing threads, and industrial fabrics.

Table 3. Estimated U.S. capacity for polyester fiber in 1970.

Producer	Brand name	Pounds (millions)
Allied Chemical		10 filament
American Enka	Encron	40 staple and filament
Beaunit	Vycron	80 staple and filament
Dow Badische	Anavor	30 staple and filament
Du Pont	Dacron	500 staple, 100 filament
Eastman Chemical	Kodel	250 staple
Fiber Industries*	Fortrel	350 staple, 175 filament
FMC (American Viscose)	Avlin	25 staple, 15 filament
Goodyear Tire and Rubber		6 filament
Hystron Fibers	Trevira	60 staple, 12 filament
IRC Fibers (American Cyanamid)		25 filament
Monsanto	Blue C	60 staple
Phillips Fibers	Quintess	25 staple and filament
Total		1,760

* Owned jointly by Celanese Corporation and Imperial Chemical Industries Ltd.

Fiberfill made of PET is widely used in mattresses, sleeping bags, pillows, and so on. Fiberfill is crimped staple or tow that is used as filling material. It replaces, or is blended with, feathers and down, and is formed into sheets for use as a lightweight filling material in insulation. Filling materials of PET are resilient, stable, and can be laundered without losing these properties. A breakdown of polyester staple and filament in various end uses is given in Table 2.

Resistance to Degradation

Polyester fibers resist environmental conditions well. The resistance of PET to sunlight is exceeded only by the acrylics. To improve PET's performance, light stabilizers and antioxidants are added prior to melting and extruding.

The most important chemical reaction in polyester is hydrolysis, which produces breaks in the chains and reduces the physical strength by reducing molecular weight. The attack by water itself is rapid if the temperature is sufficiently high. At 100°C in water, 20 percent of the strength of polyester is lost after 1 week, whereas at 70°C for several weeks there is no measurable loss of strength (*20*). Basic substances attack the fibers in two different ways: strong alkalies, such as caustic soda, etch the surface of the fibers and reduce their strength; ammonia and other organic bases penetrate the structure initially through the noncrystalline regions, causing degradation and loss of strength.

Polyester fibers have excellent resistance to dry-cleaning solvents and conventional bleaches. The resistance is conditioned by the degree of crystallinity and molecular orientation present in the fiber.

Dyeing and Finishing

Because PET does not have reactive dyesites, it is normally dyed with disperse dyes, which act primarily through diffusion and are bound in the fiber through secondary bonds. The structural orientation of the PET fibers greatly influences the rate at which they can be dyed. The greater the orientation, the slower the dyeing rate. The rate can be accelerated by adding to the dye bath chemicals that cause the PET fibers to swell and allow more rapid penetration of the dyes.

A continuous dyeing process called Thermosol is widely used to apply disperse dyes to PET fabrics. The fabrics are padded with the dyes, dried, and then heated (205° to 240°C for 30 to 60 seconds) to diffuse and fix the dyes in the PET fibers. The fabrics most commonly dyed by this procedure are the 50:50 and 65:33 blends of PET and cellulosics. Several manufacturers have introduced polyester fibers that are modified to have anionic dyesites. These fibers can be dyed with disperse and cationic dyes; when used in blends with regular polyester, unique multicolor effects can be obtained. Thermally stable, melt-soluble dyes have also been made to color the polymer prior to spinning (*21*).

Chemical finishing of polyester-cellulosic blends is a very important part of durable press. It is not a finish for PET, but a system whereby the cotton in the PET blends is given a resin cross-linking treatment to improve its recovery power and wrinkle resistance. The best known durable press system (*22*) involves the following five steps: (i) the dyed PET and cotton blend is impregnated with an aminoplast resin derivative, (ii) the fabric is dried, (iii) the garments are cut and sewn, (iv) creases are pressed into the garments, and (v) the garments are placed in an oven and the resins cured. This is referred to as a delayed or postcured system. Curing resins before cutting and sewing the fabric, as is the case with durable press sheets, is referred to as precuring. The concept of using a blend with a higher percentage of PET to produce no-resin durable press has been recently introduced. Durable press is achieved in this polyester variant (80 percent polyester to 20 percent cellulosics) by hot head pressing at 170° to 195°C (*23*).

Many of the unique properties of polyester are achieved by treating the drawn fiber or fabric structure with heat. The relaxation of stress, caused by heating the filament above the glass transition temperature, can be used to set a given length or shape, which is then stable at lower temperatures. Further crystallization during this heat treatment also reinforces the structure and raises the transition temperature (*24*).

Heat setting is used to develop maximum performance in polyester fibers, either alone or in blends with natural fibers. It makes fabrics resistant to shrinkage during tumble drying, pressing, or ironing. It also makes fabrics resistant to wrinkles during wear and helps to produce the easy-care properties for which polyester fabrics are noted.

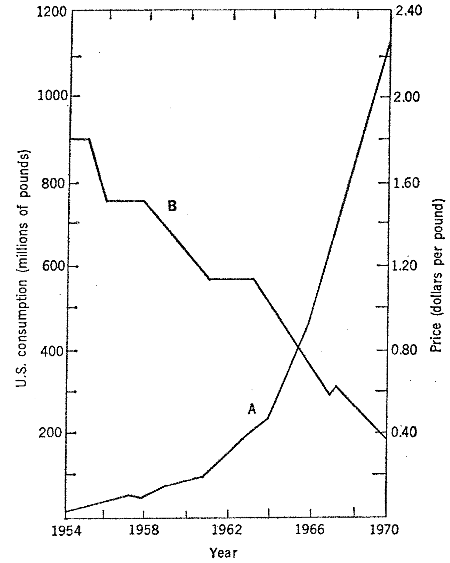

Fig. 4. Increase in total PET staple consumption with corresponding change in price of 1.5 denier per filament staple; (A) total consumption; (B) price. [Source: (*10*, p. 36) and estimates by Textile Economics Bureau, Incorporated.]

The success and rapid growth of polyester fibers tend to overshadow the areas in which limitations in the properties of the fibers inhibited market penetration and growth (*25*). Polyester fibers faced several major problems. The hydrophobic nature of PET makes it difficult to dye. The strength of PET fibers leads to pilling, the formation of fuzzy balls on the fabric surface by the rubbing of loose ends too long and strong to break away. Because of its hydrophobicity, polyester shows some affinity for oily soil, at times making it difficult to wash the soil out. Polyester fibers also tend to develop static under conditions of low humidity. During recent years, these and other problems were the subject of intensive research and development efforts by the manufacturers of polyester. As a result, they have developed PET variants, already commercially available, that are more easily dyed, show less pilling, are cleaner after laundering, and are antistatic.

The world production capacity of PET was increased to 4.7 billion pounds in 1970, of which the U.S. capacity was appproximately 1.8 billion pounds (*26*) (Table 3). Major factors in the growth of polyester staple and filament are (i) the expansion of end uses such as durable press, textured filament, and tire cord; (ii) the entry of new producers into the market; and (iii) competitive prices due to the increased volumes. The price-volume relationships for staple are shown in Fig. 4, where the total consumption from 1954 to 1970 is indicated, with corresponding changes in price of 1.5 denier per filament staple.

It has been estimated that the consumption of polyester fiber in the United States will almost double from 1969 to 1974, reaching 2.6 billion pounds in 1974; it is expected to reach 4 billion pounds by 1979 (*27*). The projected increases show the major gains in staple for durable press applications, and in filament for both textured knits and tire cord (Table 2). Half of all automobile tires being produced in the United States are reinforced with polyester cord, and 85 percent of new automobile, original-equipment tires in the United States contain polyester cord.

Summary

The use of polyester fibers has grown more rapidly than that of any other man-made fiber. Many factors have contributed to this growth. Polyester's unique physical properties of strength, high modulus, elasticity, and durability are the basis for its success. The tailorability of the fiber makes it possible to generate a whole family of property variants for a wide variety of end uses. The ready availability and low cost of the raw materials, the continuing advances in polymerization technology, and the versatility of the melt spinning process have also been major factors in establishing polyester as the leading man-made fiber.

New end uses have had a major impact on the growth of polyester. Most notable was the introduction of durable press fabrics for clothing and home furnishings. The consumer preference for easy-care fabrics and garments makes the durable press area one of continuing growth. Two relatively new areas where growth is expected to continue at a rapid rate are tire cord and textured knits for women's and men's outerwear.

References and Notes

1. *Dly. News Rec.* **159**, 1 (24 November 1970); *Chem. Spotlight* **25**, 2 (8 January 1971).
2. H. F. Mark, *Sci. Am.* **217**, 148 (September 1967).
3. R. Hill, *J. Soc. Dyers Colour* **68**, 160 (1952).
4. J. R. Whinfield and J. T. Dickson were working in the laboratories of Calico Printers' Association Ltd. in England.
5. J. Jewkes, D. Sawers, R. Stillerman, *The Sources of Invention* (Norton, New York, ed. 2, 1970) pp. 310–312.
6. J. R. Whinfield and J. T. Dickson, *British Patent No. 578,079* (29 August 1946).

7. J. R. Whinfield, *Text Res. J.* **23**, 289 (1953).
8. I. Goodman and J. A. Rhys, *Polyesters* (Elsevier, New York, 1956), vol. 1.
9. *Chem. Eng. News* **48**, 42 (23 November 1970).
10. G. Farrow and E. S. Hill, in *Encyclopedia of Polymer Science and Technology*, H. F. Mark, N. G. Gaylord, N. M. Bikales, Eds. (Interscience, New York, 1969), vol. 11, p. 11.
11. R. Daubeny, C. W. Bunn, C. J. Brown, *Proc. Roy. Soc. London Ser. A* **226**, 531 (1954).
12. C. A. Boye, *J. Polym. Sci.* **55**, 275 (1961).
13. W. O. Statton, *J. Appl. Polym. Sci.* **7**, 803 (1963).
14. G. Farrow and J. Bagley, *Text. Res. J.* **32**, 587 (1962).
15. I. M. Ward, *J. Macromol. Sci.—(Part B) Physics* **1**, 667 (1967).
16. J. G. Gillet, R. Lipscomb, R. B. Macleod, *British Patent No. 874,652* (10 August 1961).
17. Estimate based on 1969 consumption of 172 million pounds [*Text. Organon* **41**, 199 (1970)].
18. W. E. Claxton, M. J. Forster, J. J. Robertson, G. R. Thurman, *Text. Res. J.* **36**, 903 (1966).
19. E. J. Kovac and T. M. Kersker, *ibid.* **34**, 69 (1964).
20. *Chemical Properties of "Terylene": The Effect of Water and Steam* (Technical Bulletin B3, ed. 1, Imperial Chemical Industries Fibres Ltd., Harrogate, England, 1962).
21. *Reports on the Progress of Applied Chemistry* (Society of Chemical Industry, Gordon, London, 1969), vol. 54, p. 540.
22. Koret Company, *United States Patent No. 2,974,432* (1961).
23. *Fabrication of Durable Press Garments From Fabrics of 80% Fortrel Polyester/20% Cellulosic Staple* (Technical Bulletin TBP–30, Celanese Fibers Marketing Co., Charlotte, N.C., 1970).
24. A. B. Thompson and D. W. Woods, *Trans. Faraday Soc.* **52**, 1383 (1956).
25. E. V. Burnthall and J. Lomartire, *Text. Chem. Color* **2**, 218 (1970).
26. *Mod. Text. Mag.* **51**, 31 (March 1970).
27. J. V. Sherman, *Barrons* **50**, 11 (21 September 1970).

Enzymatic Modification of Transfer RNA

Modified nucleosides form at the polynucleotide level, but their function is not established.

Dieter Söll

Transfer RNA *(1)* defines a class of macromolecules that are of key importance in cellular processes. Each cell contains about 60 different tRNA species which can be separated by a variety of techniques. Each tRNA species can be esterified with its specific amino acid by the cognate aminoacyl-tRNA synthetase (aminoacylation reaction). The main and best understood role of tRNA is in ribosome-mediated protein synthesis where aminoacyl-tRNA ensures the correct codon-directed insertion of its amino acid into the growing peptide chain *(2)*. To date only a few other roles of tRNA are known: it participates in the synthesis of bacterial cell walls and in the transfer of amino acids onto proteins and phospholipids *(3)*. The involvement of tRNA in virus infection, cell differentiation, hormone action, and regulatory mechanisms has been suggested. However, there is no conclusive evidence for direct tRNA participation in any of these processes *(2)*.

Transfer RNA is unique among cellular RNA species because it contains a large number of modified nucleotides. The chain length of the known tRNA molecules varies between 75 and 87 nucleotides, and their content of modified bases can reach 20 percent *(4)*. All the known primary sequences can be arranged in a cloverleaf model of secondary structure. An example is given in Fig. 1. The three-dimensional structure of tRNA is not yet known. With the exception of the anticodon and the C-C-A-acceptor end (carrying the amino acid), no nucleotide sequences or structural features can yet be assigned to the other functions of the tRNA molecule or designated as recognition sites for enzymes interacting with tRNA *(5)*. The number of structural varieties of modified nucleosides found in tRNA is surprisingly large *(6)*. About 50 modified nucleosides have been isolated from tRNA of various organisms. The structure of 37 of these nucleosides has been determined. Some examples are given in Fig. 2. Most of these nucleosides are characterized by a relatively simple modification of one of the four major nucleosides. The methylated nucleosides can be divided into two classes in which the methylation of the parent nucleoside took place either on the heterocyclic moiety (for example, ribothymidine, Fig. 2) or on the ribose group (for example, 2′-*O*-methylguanosine, Fig. 2). In the thionucleosides a sulfur has replaced an oxygen (for example, 4-thiouridine, Fig. 2). Hydrogenation of the 5-6 double bond of the pyrimidine ring leads to the formation of reduced pyrimidine nucleosides (for example, dihydrouridine, Fig. 2). The most interesting simple modified nucleoside is pseudouridine (Fig. 2), which possesses a carbon-glycosidic linkage instead of the common nitrogen-glycosidic one. Recently, nucleosides with more complex modifications have become known. These hypermodified nucleosides contain a larger side chain or an additional ring structure bearing functional groups such as a carboxyl, hydroxyl, or ester group or an allylic double bond. Threonylcarbamoyladenosine (Fig. 2), the fluorescent nucleoside Y (Fig. 2), 6-(3-methylbut-2-en-1-ylamino) purine riboside commonly called N^6-(Δ^2-isopentenyl)adenosine (Fig. 2), and its 2-methylthio derivative, are the most well known.

With the progress in the techniques of tRNA purification and sequence analysis, the position of the modified nucleosides in the primary sequences of the tRNA molecules has become known. Generally, there is a clustering of modified nucleosides in the loop regions (Fig. 1). Ribothymidine in tRNA is always located 23 nucleotides from the acceptor end in the sequence G-T-ψ-C. The hypermodified nucleosides are located adjacent to the 3′ end of the anticodon. An interesting pattern of their distribution in the various acceptor RNA species has emerged. The occurrence of isopentenyladenosine or some close derivatives of it in *Escherichia coli*, *Lactobacillus*, yeast, or rat liver tRNA are restricted to tRNA species which have an adenosine residue in the third position of the anticodon and correspondingly recognize codons starting with U *(7–9)* (first horizontal

---

The author is associate professor in the department of molecular biophysics and biochemistry at Yale University, New Haven, Connecticut.