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### Brief History of Fibers from Synthetic Polymers

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## Brief History of Fibers from Synthetic Polymers

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### ABSTRACT

The history of fully synthetic fibers covers only ~50 years and yet today production of synthetic fibers is in billions of kilograms per year. The development of these fibers depended upon advances and discoveries in polymer synthesis, new spinning methods and, in some cases, new polymer solvents. The first such fibers were prepared by Carothers and co-workers (in particular Julian Hill) of the Du Pont Co. in the early 1930s in studies on condensation polymers. They first did key experiments with polyesters but then turned to the higher melting aliphatic polyamides for development. Nylon 66 was promotionally produced in 1938. Since then many synthetic polymers have been examined for fiber formation. Polyacrylonitrile fibers became commercial in 1950 after a search for spinning solvents by Houtz. In 1953 poly(ethylene terephthalate) fibers were manufactured following research by Whinfield and Dickson. Discoveries by Ziegler, Natta, and others in the 1950s led to isotactic polypropylene and fibers therefrom. The nylons, polyesters, polyacrylics, and polyolefins comprise the present major classes of synthetic fibers. In addition there has been developed at lower volumes a variety of fibers of considerable and growing importance. Many represent innovations of polymer- and fiber-making technology and in uses. Examples are Spandex elastic fibers, heat- and flame-resistant fibers from polyfluorocarbons, polybenzimidazole and aramids, and high-strength, high-modulus fibers from graphite and aramids.

The terms "man-made fibers" and "synthetic fibers" are usually interpreted to mean all fibers which are not natural. This then would include those made by forming or re-forming cellulose, proteins, and their derivatives. The intent here is to discuss primarily the fibers from wholly synthetic polymers. A few key dates on the origin of fibers from regenerated cellulose and cellulose derivatives are given. There is included for comparative purposes some discussion on glass and graphite even though they may be regarded as falling in different chemical and structural categories.

## CELLULOSE AND CELLULOSE DERIVATIVE FIBERS

Fibers prepared from cellulose and its derivatives have been well known since Count Hilaire de Chardonnet in France spun fibers from cellulose nitrate and regenerated the cellulose structure by hydrolysis in the early 1880s. The process was patented in 1885 and Chardonnet silk was in commercial production by 1891. Related experiments had been carried out earlier by Swan in England but were not pursued to commercialization.

About 1890 the first fibers from cuprammonium hydroxide solutions of cellulose were prepared by Fremery and Urban in Germany. Spinning from cuprammonium solutions came to useful production in 1900. Cross and Bevan in England discovered cellulose xanthate solutions of cellulose in 1892, and the viscose fiber process was developed by 1903.

In the United States the American Viscose Co. began commercial fiber production from viscose at Marcus Hook, Pennsylvania, in 1910. The Dupont Fibersilk Co. began operation of its first viscose plant at Buffalo, New York, in 1921. The name "rayon," as a replacement for "artificial silk," came into use in 1924.

Cellulose acetate was made by Schutzenberger as early as 1869. Cross and Bevan in 1894 made cellulose triacetate which was soluble in chloroform. In 1903 Miles showed that partial hydrolysis gave an ester which was acetone soluble, but it was not until the work of Henry and Camille Dreyfus in England that a fiber process was developed. Their cellulose acetate fiber was marketed under the name Celanese in England in 1921. In 1924 an allied company, now the Celanese Corp., was making and selling the fiber in the United States. The Du Pont Co. acquired process know-how and rights from French manufacturers and began United States production of cellulose acetate fiber at Waynesboro, Virginia, in 1929.

By 1938 rayon consumption in the United States was at 300 million pounds and surpassed wool consumption for the first time, but was only about 10% of total cotton consumption.

## WHOLLY SYNTHETIC FIBERS

The history of fibers from wholly synthetic polymers covers less than 50 years and yet today involves production of over 25 billion annual pounds with worldwide distribution of manufacture and use.

Some dates for the beginnings of new fibers and their manufacture are given in Table 1. The generic class names as used in the United States are employed, and because of this grouping the order is not strictly chronological.

No attempt will be made to elaborate on all the events in a particular fiber's history nor credit all the manufacturers who have entered the marketplace. These details are available by combining the data in a number of major reviews.

There is sometimes difficulty in choosing exact dates for the beginnings of manufacture because of the stepwise nature of the development and introduction of a product. Fibers are made experimentally. They are tested internally and market-tested externally. The initial production may bear a temporary or code name. Pilot-plant product may be sold and there are limited area sales. Announcements of plans for a plant are made and public showings of a product are held. During these transitions, the product properties may be improved and even the composition may be changed. The whole subject is probably not of great importance, but it does lead to confusion in trying to correlate the dates selected by various writers.

## POLYAMIDES

The first wholly synthetic fiber was based on a polyester from trimethylene glycol and 1,16-hexadecane dicarboxylic acid and was described in a publication by Carothers and Hill in 1932 [32]. The process of strengthening by cold-drawing was described. Fibers were made by dry-spinning from chloroform and by melt spinning.

Carothers had been employed by Du Pont at the Experimental Station to direct a group on exploratory chemical research and had elected to examine the preparation and nature of high polymers. After a period of research which laid the base for the first synthetic rubber, the group started work with condensation polyesters and found that by application of the high vacuum of the molecular still high molecular weight ( $> 10,000$ ) esters could be prepared. These polyesters behaved differently than lower polymer. They were labeled "superpolymers."

The polyesters were too low melting to be of interest as commercial fibers so the work was turned toward polyamides. Attempts were made to polymerize  $\epsilon$ -aminocaproic acid, but the results were not satisfactory. However,  $\omega$ -aminononanoic acid did form a superpolymer, melting at  $195^{\circ}\text{C}$ , and was spun into cold-drawable fibers with good properties. The melting temperature was still somewhat low

TABLE 1. Chronology of Commercially Produced Synthetic Fibers [ 1-5 ]

United States generic class	Trademark	Maker	Date of first fibers <sup>a</sup>	Date of commercial or plant production
Glass		E. D. Libby	1893	
	Fiberglas	Owens-Corning		1938
Nylon	6-6 Nylon	Du Pont	1935	1939 [ 6-10 ]
	Perlon L (6-Nylon)	I. G.	1938	1939-41 [ 8, 11-13 ]
	Qiana	Du Pont		1968
Acrylic	-	H. Rein [ 14 ]	< 1938	
	Orlon	Du Pont	< 1942	1950 <sup>b</sup> [ 15, 16 ]
				1952 <sup>c</sup>
	Acrilan	Monsanto		1952 [ 16 ]
Modacrylic	Vinyon N	Union Carbide		1948 <sup>b</sup>
	Dynel	Union Carbide		1949 <sup>c</sup>
	Verel	Eastman		1956 [ 1 ]
Polyester	Terylene	Calico Printers	1941 [ 18 ]	
		ICI		1954 [ 19 ]
	Dacron	Du Pont	1945	1953
	Kodel II	Eastman		1958

Fluorocarbon	Teflon	Du Pont	1954 [ 20]
Spandex	Lyera	Du Pont	1958 [ 21]
Olefin	Meraklon	Montecatini	1957 [ 22-24]
	Herculon	Hercules	1959
Aramid	Nomex	Du Pont	< 1957
	Kevlar	Du Pont	ca. 1965
Graphite	Thornel	Union Carbide	~1959 [ 30]
	Modmor	Morganite R. & D.	
Novoloid	Kynol	Carborundum	< 1969
			1970 [ 31]

<sup>a</sup>From published statements and patent dates.

<sup>b</sup>Continuous filament.

<sup>c</sup>Staple.

and the work was turned to AA-BB type polyamides. It must be recalled that at this time one did not have on hand the wide range of organic intermediates available to the chemist today. Synthesis of high purity intermediates was a key part of the research.

On February 28, 1935 [6], 6-6 polyamide was synthesized. It melted at 263°C. Out of the various polymers examined, 6-6 polyamide was chosen for scale-up and a pilot plant was in operation by late 1937. The decision to build a full-scale plant at Seaford, Delaware, was announced on October 27, 1938. This plant was in operation by December 1939 [8, 9].

As to public product offerings, experimental stockings were evaluated in April 1937 [7]. Hosiery was on display at the New York World's Fair in the summer of 1939 [10] and was test marketed in six Wilmington, Delaware, stores in the fall of 1939. Nylon hosiery was available nationwide by May 15, 1940 [6, 8]. The Seaford plant capacity was planned at 4 million lb/yr, but was changed to 8 million before completion. A second plant was built in Martinsville, Virginia, and was in operation in 1942 with a capacity of 8 million lb/yr.

The public sale of nylon was short-lived, for with the entrance of the United States into World War II in late 1941 nylon production was turned to military applications such as balloon cloth, glider tow ropes, airplane tire cord, and military apparel.

Five years from the first polymer preparation to full plant scale is a remarkably short development time. Furthermore, this was done at a time when there was no monomer supply and there was no past commercial experience in melt condensation polymerization and spinning. The skills of several company departments were called upon. Plants for diamine and diacid preparation were built.

The first patents on polyamides were granted to Carothers and co-workers in 1938-1939 [33]. The state of the polymer art was so simple at that time that several of the claims contain only two words. Claim 12 of U.S. Patent 2,130,523 reads, "I claim: Polyhexamethylene adipamide."

At the end of World War II, applications of 6-6 nylon fibers were expanded from hosiery to many other textile and industrial uses. Some of these uses today are in apparel of many types, ropes and cables, carpets, monofilaments and tire cord, and chopped fibers for resin reinforcement.

In 1937 Paul Schlack of I. G. Farbenindustrie, A.-G., polymerized caprolactam to 6-nylon. In January 1938 he was successful in preparing fibers and a patent application was filed in June [9, 12]. I. G. began production of monofilaments in the fall of 1939 [9, 13] and large-scale production of 6-nylon fiber began in 1941. After World War II, 6-nylon production was reestablished by Vereinigte Glanzstoff Fabrik, A.-G., at Obernburg.

In the United States commercial production of 6-nylon was begun by Allied Chemical Co. in 1955. Production by other companies followed.

6-Nylon is lower melting than 6-6 nylon but has the advantage of a simpler manufacturing process. It finds many uses such as those listed for 6-6 nylon.

In order for nylons and other classes of man-made fibers to hold or improve their position in the marketplace, changes are made in polymerization processes, polymer composition, in additives and finishes, and in fiber processing. The purpose may be to reduce cost, improve strength, dyeability, color, or light durability. Some general developments, such as variation of fiber cross-section, conjugate spinning of two polymers, bulking processes for yarns, and formation of nonwoven fabrics have had broad fiber applicability.

In the nylon field the continued search for fibers with improved aesthetic qualities led to Qiana fiber and fabrics put in production by Du Pont in 1968. Qiana fabrics have a bulky silk-like hand and high luster yet also provide comfort and high wash-wrinkle recovery and ease-of-care.

After 40 years nylons have the second highest production and consumption rates among synthetic fibers in the United States with excellent prospects of continuing in this position. The 1979 United States production for nylon plus aramid fibers was over 2.7 billion pounds.

## POLYESTERS

J. R. Whinfield and J. T. Dickson, working in the laboratories of the Calico Printers Assoc. in England in 1940, began a study of the esters of phthalic acids [18]. This led to the preparation of poly(ethylene terephthalate) in high molecular weight. The ester melted at 264°C, formed fibers from the melt which were cold-drawable, was crystallizable, and was surprisingly resistant to hydrolysis. The name Terylene was coined. Patent specifications were not published because of the war, and no development work was undertaken for the same reason. In 1947 an arrangement was made with ICI for the latter to explore development of intermediates synthesis and polymer and fiber production in Great Britain. This was successfully done, and a plant with a capacity of 11 million lb/yr was put in operation in early 1954.

In the meantime the Du Pont Co. had undertaken an independent research program on polyesters and by 1945 had developed a practical method for preparing poly(ethylene terephthalate) (PET) from dimethyl terephthalate and ethylene glycol. The U.S. patent application on PET, based on the work of Whinfield and Dickson, was purchased by Du Pont from Calico Printers, and the patent was subsequently issued with assignment to Du Pont [34, 35]. A plant for the manufacture of PET fiber started up in Kinston, North Carolina, in 1953.

After the work of Whinfield and Dickson and the commercial introduction of Dacron and Terylene polyester fibers, there was extensive further exploration of polyesters for fibers, films, plastics, and other uses. This past and continuing research includes intermediates, catalysts, polymerization processes, and all aspects of production and uses of shaped products.

Although PET is the principal textile polyester fiber worldwide,



others have been introduced. One of these is poly(1,4-cyclohexanedi-methylene terephthalate), introduced by Eastman in 1958 under the trademark Kodel II polyester [ 5, 36 ].

The polyesters have shown great versatility in textile applications. More polyester fiber is produced and used in the United States and the world than any other single type of synthetic fiber. Nearly 4.2 billion pounds of fiber was produced in the United States in 1979.

In addition to general textile uses, PET finds application in non-woven fabrics, fiberfill insulating fiber, ropes and cordage, and in tire cord. A major use is in blends with other fibers such as cotton and wool. With cotton and rayon, polyester fiber has provided the tensile strength and abrasion resistance which have made the wide use of permanent press treatments practicable.

### ACRYLIC FIBERS

Acrylic fibers by definition contain 85% or more of acrylonitrile.

Polyacrylonitrile was known for some time as an unmeltable white powder with solubility in only a few special solvents. It was not considered suitable for commercial fiber spinning. An intensive search for solvents by R. C. Houtz [ 15 ] was undertaken with the discovery of a range of solvents and solvent mixtures which included dialkyl-amides that could be used for dry or wet spinning. The outcome was a development program in Du Pont's Textile Fibers Dept. and the introduction of Orlon acrylic fiber in 1950. Today acrylic fibers are produced in several forms by various companies. A few trademarks are Acrilan (Monsanto), Dralon (Bayer), Zefran (Dow), and Creslan (Cyanamid). The fiber has excellent resistance to sunlight and outdoor exposure. The original intent aimed the product at outdoor uses as in awnings, convertible automobile tops, and so on. However, it soon found high acceptance in knitwear, sweaters, and shirts where its warmth and wool-like hand were welcome. Copolymers and dyes were developed to provide a range of lightfast and bright colors.

### MODACRYLIC FIBERS [ 17 ]

Along with acrylics were developed a class of fibers now designated modacrylics. Modacrylics are by definition synthetic copolymer fibers containing less than 85% but more than 35% acrylonitrile by weight. Some modacrylics produced in the United States are Dynel fiber by Union Carbide (from 1949), Verel fiber by Eastman (from 1956), and Acrilan and Sef fibers by Monsanto.

Modacrylic fibers often contain a high proportion of vinyl chloride, vinylidene chloride, or vinylidene cyanide. The halogen comonomers provide flame resistance. The use of these fibers has grown steadily in pile fabrics, imitation furs, blankets, draperies, and in blends with other fibers.

## POLYOLEFINS [ 22-24 ]

The fourth major organic fiber to be developed was polypropylene. The discoveries of Karl Ziegler in Germany and Julio Natta in Italy on catalysts for the preparation of stereoregular vinyl polymers led to isotactic, solid polypropylene in 1954. Other laboratories appear to have been carrying out related investigations and to have made similar discoveries.

The first commercial production of polypropylene fiber was in 1957 from a plant in Italy built by Montecatini Societa Generale. Their trademark is Meraklon. By 1962 production there had reached 7 million lb/yr.

In the United States, Hercules began polymer production in 1958 and acquired know-how and fiber production facilities from Industrial Rayon Corp. in 1959 [ 24 ]. The trademark Herculon was adopted in 1962. Presently polypropylene fibers are manufactured in more countries around the world than any other fiber, although the total volume of production is much lower than nylons and polyesters (Table 2).

Polypropylene is the least expensive of all organic synthetic fibers. Compared to other fiber materials, it has a low melting point (165°C unstressed). However, the fibers are hydrophobic, resistant to chemicals, and stable to air and sunlight when stabilized. These fibers have found extensive use in ropes and cordage, indoor and outdoor carpeting, upholstery, and other applications.

Polyethylene fibers, primarily because of their low melting point, have found limited uses. These fibers and split film are produced for cordage and netting, car upholstery, tarpaulins, and related applications. Exceptionally high tenacity fibers have been made from polyethylene [ 37, 38 ], and there is much current research activity

TABLE 2. Production of Major Synthetic Fibers in the United States<sup>a</sup> (millions of pounds)

Year	Nylon- aramid	Polyester	Acrylic- modacrylic	Olefin	Textile glass
1950	90	0	1	0	23.5
1960	411	75	136	14	177
1970	1355	1477	492	259	467
1975	1857	2995	525	487	547
1978	2550	3800	725	691	928
1979	2722	4146	770		

<sup>a</sup>Textile Organon, 1979.

in this area. The low thermal transition temperatures and the possibility of slow flow under stress (creep) will be deterrents to many applications.

## DEVELOPMENT OF POLYMERIZATION METHODS AND SOLVENTS

Synthetic fiber developments have frequently depended upon the discovery or working out of new methods of polymerization and of the discovery or application of new solvents and spinning techniques. Nylon depended upon the work of Carothers and Hill on melt polycondensation and the development of melt spinning and drawing processes. Whinfield and Dickson's work on polyesters built on the principles of Carothers and Hill and found that high molecular weight polyesters could be formed with one volatile intermediate in excess. Polyolefins as fibers derived from stereoregular polymerizations arising from the research of Ziegler and Natta. Likewise the exploration of low temperature interfacial and solution polycondensation procedures in the 1950s paved the way for the introduction of several high temperature resistant polymers and fibers, the recent high tenacity, high modulus fibers, and spandex elastic fibers [39].

The discovery and the large-scale availability of solvents has been a key factor for some fibers such as the acrylics. Other major factors are progress in analytical techniques and the ability to characterize polymers and fibers. And basic to any success have been the engineering contributions to manufacture and handling of polymers and solvents on a large scale, spinning technology, and the processing of fibers to useful forms.

## SPANDEX FIBERS

The search for a satisfactory synthetic elastic fiber was a long one begun with the work of Wittbecker [40, 41] on N-substituted nylons. This search within the Du Pont Co. for a sheer and stable elastic fiber ended with the discovery that such a fiber could be made from linear, segmented, noncross-linked polymers. In these compositions domains of hard segments in a matrix of soft flexible polymer act as a reinforcing filler or tie points through their crystalline or hydrogen-bonding forces. The soft segments are hydroxyl-terminated polyether or polyester units which are first capped with aromatic diisocyanates. The intermediate prepolymer then is chain-extended with hydrazine or other diamine. The fibers are prepared by spinning from polar solvents.

Fibers from this type of elastomer were introduced under the trademark Lycra in 1958. They are produced in much finer yarn sizes than conventional rubber threads, permitting weaving or knitting

of lightweight garments that are machine-washable and fast drying. They are used, usually in combination with other fibers, in foundation garments, lingerie, swimwear, outerwear, and other elastic applications.

### HEAT- AND FLAME-RESISTANT FIBERS

With the development of low temperature polycondensation procedures there was recognition at the Pioneering Research Laboratory (Du Pont) and elsewhere that methods were at hand to synthesize high- or nonmelting polymers which might have high resistance to thermal degradation. Many compositions were examined [42]. The final selection at Du Pont was a wholly aromatic polyamide which was developed as HT-1 and introduced commercially as papers and fibers in 1961. The trademark Nomex nylon was adopted in 1963 [29]. The products are now reclassified as Nomex aramids. The fibers have low color, good tensile properties, and excellent resistance to thermal aging. The fabrics are used where heat-resistance and flame-resistance are needed, as in filter cloths, protective clothing, and as an asbestos substitute. The papers are used in electrical insulation, in wall paneling, and in other structures.

Related competitive fibers are now produced in Japan and Europe.

There has been widespread synthesis and examination of other condensation polymers based on aromatic and heterocyclic units. Much has been learned about relationship of structure and the limits of thermal stability of organic polymers. Two of the most promising materials for superior heat- and flame-resistant fibers are certain polyimides and polybenzimidazoles. However, both are costly to produce.

Two other specialty heat- and flame-resistant fiber types are the fluorocarbons and cross-linked phenolic resins.

Teflon TFE fluorocarbons are well known in the form of plastics and coatings. Fine fibers were introduced in 1954 by Du Pont for use where high chemical resistance, thermal stability, and low friction are desired; for example, packings in pumps for chemicals, filter fabrics, and protective clothing [47]. The fiber is produced by wet spinning a polymer dispersion mixed with a small amount of cellulose xanthate (viscose). The precursor fiber is heated to coalesce the fluorocarbon particles and burn out the cellulose [4].

A flameproof fiber based on a cross-linked novolac resin was introduced in 1970 by the Carborundum Corp. under the trademark, Kynol. Its proposed uses are in protective clothing and thermal insulation [31, 43]. It has a natural gold to light brown color which is removed by bleaching or by acetylation. The generic name, novoloid, is now applied to this class of fiber.

Much research and exploratory effort has been expended in the United States in recent years in a search for ways to improve the burning resistance of textiles and other organic polymeric materials.

Although the textile industry as a whole has always been concerned with flammability, this special surge of activity was stimulated by the Flammable Fabrics Act of 1953 (which banned easily ignitable fabrics from the market) and other regulations which have followed. Extensive accounts of research, conferences, and reviews on the flammability of fibers, fabrics and other materials have been published (see, for example, Refs. 43-46).

As has been pointed out, materials with good to high inherent resistance to burning are available. In addition to those discussed, there should be added the vinyons, modacrylics, and chelated polyacylamidrazones [45]. Many of the commercially available, inherently nonflammable fibers suffer for general textile use in terms of comfort and hand, dyeability, abrasion resistance, or high natural coloration. Cost is also a deterrent to acceptance for general use.

No fully satisfactory additive or comonomer for appreciable improvement of flame resistance and burning characteristics of the major fibers from wholly synthetic polymers has yet appeared. The search continues but at a less frantic pace.

### HIGH STRENGTH, HIGH MODULUS FIBERS

One of the most exciting and recent developments is that of fibers with exceptionally high strength and modulus [25-29]. In rayon fiber evolution in the pre-nylon period a "high strength" rayon had a tenacity of 2.5 to 4 gpd. Cordura rayon tire cord, announced in 1934 and in plant production by 1936, had a tenacity of about 3 gpd. Cordura and other viscose rayon fibers were gradually improved to the range of 5-6 gpd. Cellulose fibers formed by saponification of steam-stretched cellulose acetate fiber, with a tenacity of 7 gpd, were made on a pilot-plant scale by British Celanese as early as 1935. These fibers were made for military use during World War II and introduced in England and the United States after the war under the name Fortisan. Nylon and later polyester cords in the range of 8-10 gpd were developed and have gradually displaced much of the rayon cord. Although tenacities as high as 23 gpd had been demonstrated for "flash spun" polyethylene, the range of 10-11 gpd was considered to be the practicable upper limit of fiber strength for many years. Then in the middle 1960s research was begun at Du Pont by Kwolek, Bair, and the author on extended-chain aromatic polyamides [25-28] and at Monsanto by Preston, Black, and others on aromatic polyamide-hydrazides [48].

The Du Pont research resulted in the discovery of liquid crystalline solutions of aromatic polyamides which when spun yielded fibers with tenacities of 20-30 gpd and initial moduli of 400-1400 or more (Fig. 1). This breakthrough led to the development of Kevlar aramid fibers for a variety of uses in ropes and cables; ballistic and other protective fabrics; reinforcement of resins for automotive, marine,

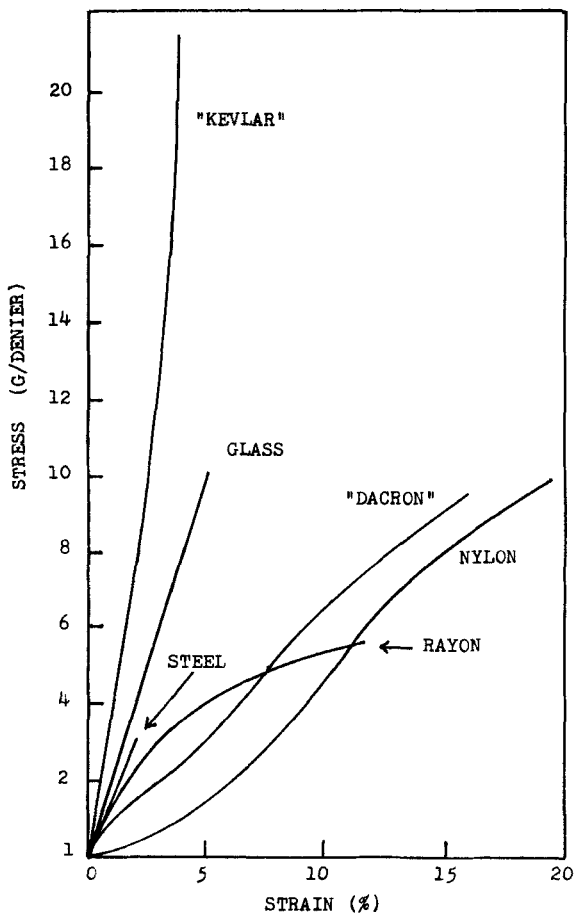


FIG. 1. Tire yarn stress-strain curves.

air and aerospace vehicles; and in rubber for tires, hoses, and belts. A 15 million lb/yr plant was started up in 1971 and expansion to 45 million lb/yr is planned for 1982.

These discoveries have stimulated a new era of basic and applied research on stiff chain polymers around the world. Calculations of ultimate strengths of oriented polymers by Mark and others [49] currently project tenacities of 150 and 250 gpd for aramids and polyethylene, respectively. Experimental fibers with tenacities over 40 gpd have now been reported.

Within the realm of high strength, high modulus fibers are graphite fibers [30] and special types of glass fibers (next section). Graphite

fibers are prepared by thermal decomposition of a polymeric precursor to carbon and then a higher temperature conversion to graphite.

Cellulose, polyacrylonitrile (PAN), and petroleum or coal tar pitches are the common starting materials. The conversion of PAN fiber by controlled heat-treatment to a black, highly flame-resistant form was reported by Houtz in 1950 [ 15 ].

Graphite and/or carbon fibers have been produced at several locations since the early 1960s. Companies in Europe, Japan, and the United States are engaged in commercial production. The production level is a relatively modest one. However, the fibers have important and growing use in the reinforcement of resins for automotive, aircraft, and aerospace vehicles and many other special applications where light weight, strength, and rigidity are desired.

### TEXTILE GLASS FIBERS [ 50 ]

Glass fibers occupy a peculiar place in the discussion of synthetic fiber developments in that the base material is inorganic and the polymer structure is a network. However, one cannot deny that the fibers are man-made, they precede nylon in origin, were placed on the market about the same time (1938), and have some outstanding properties which have led to large-scale production (Table 2) and to uses in which they compete with fibers based on organic materials.

Three major composition types are E glass with superior electrical properties, C glass having high corrosion resistance, and S glass having high strength. Glass fibers are used for electrical insulation; liquid and gas filtration fabrics; thermal insulation and protection; fireproof draperies, curtains, and other fabrics; the reinforcement of resins; and as tire cord in the belts of automobile tires. Tensile strength and compressive strength are high (Fig. 1). The intermediate density of glass is an advantage in composites in competition with metals but is nearly twice that of competitive organic high-strength fibers. Production level in the United States exceeds those of acrylic-modacrylic fibers and of olefin fibers (Table 2).

### SOME GENERAL COMMENTS

Such a short review, of course, is a bare outline of some of the happenings in the development of fibers from synthetic polymers. Many polymers produced as fibers have received little or no mention. Examples are polyvinylidene chloride, polyvinyl alcohol, and the homologs of 6-nylon.

There has been little comment on modification of structures for improvement of dyeability, antistatic effects, etc. Of major importance in affecting properties and applications are the manipulations of fiber physical structure and fiber processing. Little mention

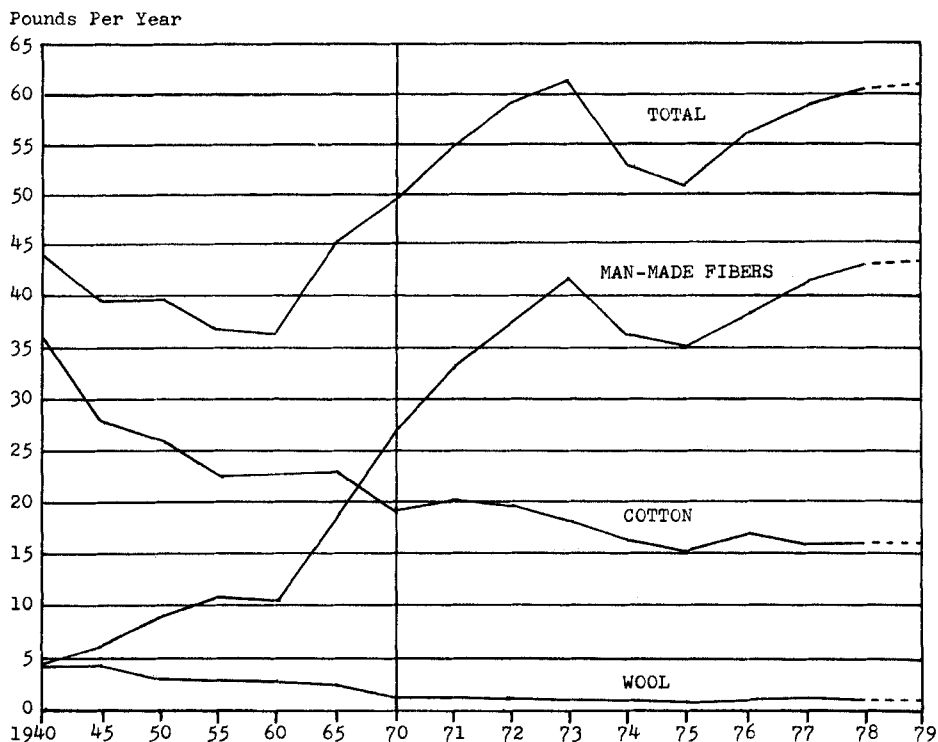


FIG. 2. United States per capita consumption of fibers.

has been made of drawing processes, fiber cross-section variations, sheath-core and side-by-side fibers, crimping, texturizing, finishes, delustrants, and so on. These and still other processing steps have contributed importantly to the successful application and performance of textile fibers.

### THE PRESENT AND FUTURE

The fiber business has had its ups and downs. A look at the plot in Fig. 2 shows that the general trend in per capita consumption in the United States continues to be upward. This is also true worldwide. Part of the reason for the trend in the United States is the increase in the use of fibers in carpets and industrial applications. Today in the United States synthetic fibers dominate the markets in clothing, bedding, carpets and other home furnishings, and in many industrial uses.

Worldwide figures for 1978 fibers production show man-made



TABLE 3. World and United States Production of Textile Fibers in 1978<sup>a</sup> (millions of pounds)

Fiber group	World	United States
Rayon and acetate	7,307	905
Noncellulosic organic:		
Nylon-aramid		2,550
Polyester		3,800
Acrylic-modacrylic		725
Olefin	2,230 <sup>b</sup>	691
Other		19
Total noncellulosic organic	24,163	7,785
Glass	2,002	928
Total man-made	35,474	9,618
Natural (raw fiber)		
Cotton <sup>c</sup>	28,803	5,210
Wool <sup>d</sup>	3,241	101
Silk	110	0
Total natural	32,154	5,311

<sup>a</sup>Source: Textile Organon, 1979 issues.

<sup>b</sup>Totals incomplete because of lack of data for some countries.

<sup>c</sup>1978-79 season ending July 31.

<sup>d</sup>Seasonal basis.

fibers exceeding natural fibers even with glass fibers excluded. The ratio of wholly synthetic fibers to natural fibers was about 3 to 4 or 43% of the sum, whereas in the United States it was 60% (Table 3).

There are influences at work both to increase and decrease the growth of fibers consumption. Countering increased consumption in the United States are decreased population growth, general price inflation, decreased housing starts, the trend to smaller cars and lowered production of cars, increased durability of fibers as in clothing and carpets, and increased conservation-mindedness of the population. Increases in use and demand will be brought about by discovery of new domestic markets such as innovative home applications, industrial and outdoor uses, possible continuance of changes in life styles toward leisure and outdoor living, and replacement of metals and plastics by composites.

For developing countries, greater demand for fibers is to be expected if life styles and standards of living change and to satisfy the needs of those with a lesser share of goods. These markets may be satisfied by import of goods or by the establishment of local factories.

There is presently considerable unused capacity for production of all the major fibers worldwide.

Yale [51] has analyzed current trends in socioeconomic forces and has projected that the United States per capita consumption of fibers for 1988 will be 70 to 75 lb (compare data in Fig. 2). Researchers at Predicasts, Inc., a market study organization, have published a very optimistic report on the future of synthetic fibers in the next decade [52]. World fiber consumption will reach 92 billion pounds and synthetic fibers will comprise 58% or nearly 54 billion pounds.

For polymer and fiber scientists there remain a number of widely recognized goals for new synthetic fibers or modifications of existing ones. Examples are:

1. A truly satisfactory flameproof fiber without sacrifice of properties and without toxic hazards.
2. A low-cost fiber with cottonlike comfort and the durability of polyamides or polyesters.
3. An easy-care fabric with the qualities of the best wools.
4. Highly electrically conductive fibers with good handling and durability properties.

You will recognize that cost is a constraining factor in all of these objectives.

Although goals and guidelines for research are desirable and necessary, discoveries of an unforeseen nature are frequently made in the course of planned exploration. Some of these discoveries will be an important part of the future of man-made fibers.

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