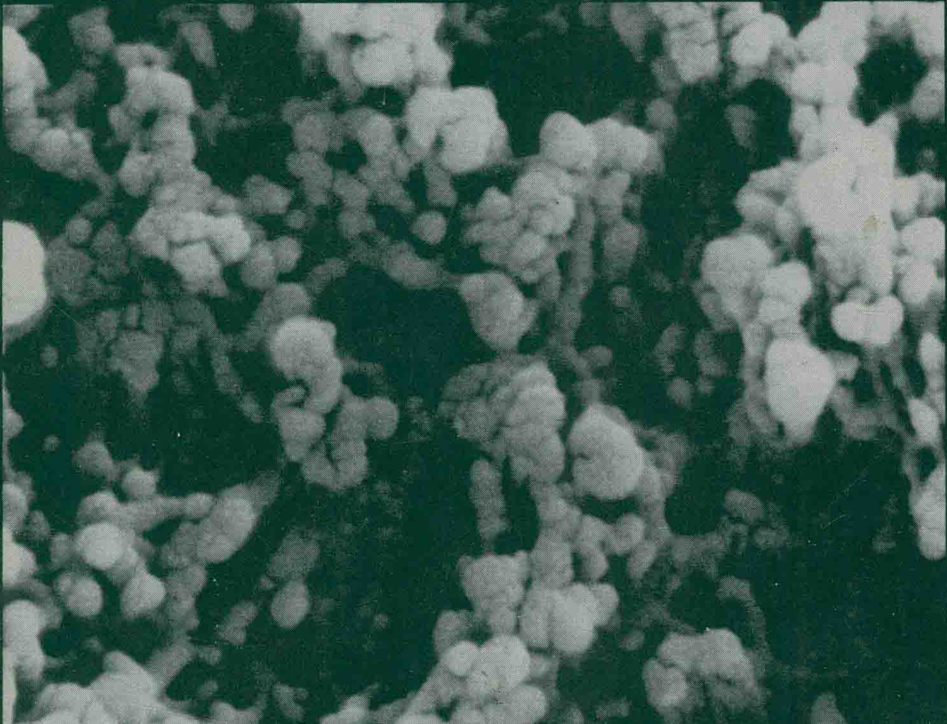
APPLICATIONS OF POLYMERS



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FOREWORD

Natural polymers, such as proteins, starch, cellulose, hevea rubber, and gum which have been available for centuries, have been applied as materials for food, leather, sizings, fibers, structures, waterproofing, and coatings. During the past century, the use of both natural and synthetic polymers has been expanded to include more intricate applications, such as membranes, foams, medicinals, conductors, insulators, fibers, films, packaging and applications requiring high modulus at elevated temperatures.

The topics in this symposium which are summarized in this book are illustrative of some of the myriad applications of these ubiquitous materials. As stated in forecast in the last chapter in this book, it is certain that revolutionary applications of polymers will occur during the next decades. Hopefully, information presented in other chapters in this book will catalyze some of these anticipated applications.

It is appropriate that these reports were presented at an American Chemical Society Polymer Science and Engineering Division Award Symposium honoring Dr. O.A. Battista who has gratifying to note that Phillips Petroleum Company, which has paved the way in applications of many new polymers, is the sponsor of this important award.

We are all cheerfully expressing our thanks to this corporate sponsor and to Distinguished Professor Raymond B. Seymour of the University of Southern Mississippi who served as the organizer of this symposium and editor of this important book.

H. Mark

CONTENTS

COMMERCIALIZATION OF NEW COLLOIDAL POLYMER MICROCRYSTALS*

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Commercial uses of single colloidal polymer microcrystals were first demonstrated in 1955, using cellulose as the raw materials. A world-wide, multi-million, pounds-per-year industry emerged from this discovery. The market is still growing in annual demand more than 30 years later. Today, this specialized field of polymer science is undergoing a major new surge of commercialization based on past as well as never-before-available colloidal polymer microcrystals.

Expanded commercialization of single colloidal-sized polymer microcrystals is underway. Production has already progressed past the pilot-plant stages for polymer microcrystals other than cellulose microcrystals.

One particularly new broad-based opportunity that is being developed has to do with the conversion of hundreds of millions of pounds of waste polymer products into new colloidal aqueous suspensoids or dry colloidal particles. Some of these new forms have greater value than their natural or man-made polymer precursors.

For example, conservative estimates based on 1986 data project that at least 700,000,000 pounds of waste polymer products will be available in the U. S. A. alone as a reservoir of acceptable, reusable, polymer, raw materials. The toxicity and environmental hazards created by the incineration of waste polymer materials have become of national concern. The cost of burying them in "graveyards" many miles from the site of their origin has been estimated conservatively at 15 cents a pound! A new industry designed to give a "second life" to these valuable natural materials and man-made waste polymer forms - an industry to recycle particular waste polymer forms - is about to leave the heel of an exponential growth curve.

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*American Chemical Society's Award Lecture, Applied Polymer Science Award sponsored by Phillips Petroleum Co., delivered on April 6, 1987, at the 193rd National Meeting in Denver, Colorado.

What are the raw materials of primary commercial interest?

They are: waste cellulose (rayon, cellophane, alpha cellulose, and cotton), nylons (especially nylon -6 and nylon -66), polyesters (in fibrous, textile, and structural forms), crystalline amylose, and even silk and wool wastes! In addition, millions of pounds of valuable discarded cotton, nylon, and polyester fabrics are hanging in the household closets of America - not to mention all of the rest of the world.

From the late thirties through the discoveries of Carothers and countless others up until today, conventional polymer science has focused its thrust largely on making molecules longer and from which stronger and tougher fibers, films, or plastic structures could be manufactured. Conventional polymer science has been remarkably successful. It has spawned products with sales in excess of $70,000,000,000 a year in the United States alone.

Microcrystal polymer science is the antithesis of more conventional polymer chemistry. It requires using as raw materials fibers, films, resins, or plastics that have already had the "genetics" of their microcrystalline regions fixed in place with predetermined dimensions and degrees of perfection. Carefully controlled, selective chemistry is used to break up and/or loosen the more disordered networks of interconnecting molecules within which polymer microcrystals are embedded in a molecular matrix fixed by linear, covalent, and molecular bonds. After using chemistry to disconnect the covalent, molecular linkages between regions of high molecular order (microcrystallites) and interconnecting regions of lesser molecular order, appropriate mechanical energy is used to provide high sheer forces to liberate the polymer microcrystals into single virus-sized, highly-crystalline particles. This process requires that the chemical treatment must be controlled carefully so that the size of the microcrystals will remain as close as possible to their dimensions as they existed in the precursor polymer raw materials. The "liberated" polymer microcrystals, depending on their respective precursor raw material, may range in size from 4,000 angstroms in maximum dimensions to as small as 200-300 angstroms.

The commercial potential of recycling waste polymer materials in colloidal forms is not a "pie-in-the-sky" projection. Producing countless millions of pounds of microcrystalline cellulose from a single polymer raw material - wood pulp alpha cellulose - is a proven reality worldwide. You would be hard put to find anyone in the food and/or pharmaceutical industry from New York to Paris to Moscow or to Tokyo who has not used or at least heard of AVICEL Microcrystalline Cellulose. A recent computer printout of literature references about microcrystalline cellulose stunned me! It contained about 4,000 separate publications. More than ten new plants have been built in recent years to manufacture cellulose microcrystals alone.

Even so, as a consultant to eight major polymer-oriented corporations, I am constantly puzzled by the almost naive understanding that many chemists still have of the science of colloidal polymer microcrystals.

Two unexplored avenues for each of the newer colloidal polymer microcrystal species are:

1) Commercialization of much smaller microcrystals by selective use of new and/or chemically modified precursor raw materials and

2) Topochemical derivatization at very low degrees of substitution of derivatives of polymer microcrystals.

The emerging new technology will provide increasing market opportunities for colloidal water suspensoids and/or dry, colloidal aggregates or clusters of submicron, single, near-perfect, polymer microcrystals.

Among the industrial end uses being evaluated are non-toxic, water-based systems of binders and coatings for paper; board and pulp molded products, including particle and chip boards for the building industries; prime coatings for glass, aluminum, wood, ferrous, and other non-ferrous surfaces; thickeners for water-based paints; etc. In dry form, the colloidal microcrystals may be used for fluid bed and electrostatic coatings, as binders for industrial and agricultural tableting, and as additives for changing the characteristics of existing molding and casting polymers. Some of the more unusual uses will be in concrete products, synthetic ivory, and catalytic substrates - to name a few.

The first commercial plant for recycling waste polymers as single polymer microcrystals is expected to be on-stream in the latter months of 1987. Projections are that the recycling of waste cellulose, nylon, polyester fibers and/or plastics, etc. will spawn a new worldwide industry that will introduce second life products at a profit and, at the same time, reduce the environmental hazards of present ways of disposing of them. This plant will be constructed and operated by MCP's, INC., a subsidiary of MICROTECH INDUSTRIES, INC., Suite 201, 275 MacPherson Avenue, Toronto, Ontario, Canada M4V 1A4.

On the 32nd anniversary of the discovery of commercial uses for polymer microcrystals, the emerging new industry we have described proffers to make a significant future impact in broadening the opportunities of polymer chemistry and in making important improvements to the quality of life on a global scale. It has been an honor and a privilege to have spent over 40 years of my professional career in this science. I am most grateful to each participant in this Symposium and to the Phillips Petroleum Company, sponsor of the Applied Polymer Science Award.

FIBERS

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Fibers,[1-7] flexible and having a high ratio of length to width and cross section, are an important segment of the 100 million tons of polymers manufactured annually in the world.[8] Fibers have been classified[3] as:

Naturally Occurring Fibers

Vegetable (cellulosic), e.g., cotton, linen, ramie.
Animal (protein), e.g., wool, mohair, silk.
Mineral, e.g., asbestos.

Man-Made or Manufactured Fibers

From natural organic polymers, e.g., rayon, acetate.
From synthetic organic polymers, e.g., polyester, nylon.
From inorganic substances, e.g., glass, metallic, ceramic.

The production of natural fibers continues to be a major agricultural activity world-wide; the production of man-made or chemical fibers is a major activity in the chemical industry. The textile and paper industries are the primary converters of fibers into the numerous products needed by five billion humans in our modern society.

Fibers and fibrous products, like food, were critically important to the some 113 billion humans who lived and died over the past 2.5 million years.[9] The fibrous materials of prehistory and ancient times included hides, furs, cords, ropes, mats, nets and baskets. Tying knots might have been an early invention. Inventions of much greater importance, spinning and weaving, might have occurred about 35 thousand years ago; this could be inferred from patterns of weaves found on clay vessels of the Old Stone Age.[6]

The earliest evidence of woolen textiles dates from about 6000 B.C. Bits of linen from Egypt indicate that people there wove flax about 5000 B.C. By 3000 B.C., cotton was grown in the Indus River Valley in what are now Pakistan and western India. The Chinese began to cultivate silkworms about 2700 B.C.[1,6,10]

Advances in technology have had a dramatic impact on the production and processing of fibers and fibrous products. Man-made or chemical fibers, manufactured from synthetic polymers, have replaced the natural fibers in many uses; they also are the basis for new products and new uses.

Table 1. Fiber Consumption by the U.S. Textile Industry, 10^6 t[a]

Fiber Type	1976	1980	1984
cotton	1.54	1.41	1.21
wool	0.04	0.04	0.07
rayon	0.27	0.23	0.18
acetate	0.14	0.14	0.09
polyester	1.50	1.59	1.45
nylon	0.95	1.04	1.09
acrylic	0.27	0.27	0.23
polyolefin	0.23	0.32	0.45
glass	0.04	0.09	0.09
Total	4.98	5.13	4.90

[a]Refs. 3 and 7.

The production of manufactured fibers has greatly increased in both the U.S. (Table 1) and the world (Table 2).

Textile products now include woven and knitted goods, draperies, blankets, towels, felts, laces, nets, braids, and an incredible variety of fabrics. In the United States, the textile industry manufactures about

Table 2. World Fiber Production 10^6 t[a]

Fiber type	1974	1976	1978	1980	1982	1984
Natural fiber						
cotton	14.05	12.48	12.97	13.99	14.63	16.48
wool	1.53	1.49	1.53	1.61	1.63	1.67
silk	0.04	0.05	0.05	0.06	0.06	0.06
Synthetic fiber						
cellulosics	3.53	3.21	3.32	3.24	2.94	3.08
synthetic polymer	8.20	9.45	11.04	11.56	11.35	13.19

[a]Refs. 3 and 7.

25 billion square yards (21 billion square meters) of fabric a year. About 70 percent of this output is used in making clothing and household goods.[1] Textiles are also used in thousands of other products. These products include basketball nets, boat sails, bookbindings, conveyor belts, fire hoses, flags, insulation materials, mailbags, parachutes, typewriter ribbons, and umbrellas. Automobile manufacturers use fabrics in the carpeting, upholstery, tires, and brake linings of cars. Hospitals use adhesive tape, bandages, and surgical thread. Surgeons replace diseased heart arteries with arteries knitted or woven from textile fibers.[1]

Natural Fibers

Only natural fibers were available during most of history. Natural fibers--from plants, animals, and minerals--still account for more than half the fibers produced annually in the world.

Cotton, the most widely used natural fiber, is processed into numerous apparel, home furnishings, and industrial products. Flax, a strong, silky fiber from the stems of flax plants, is used in making clothing, napkins and other linen products. Hemp, jute, and sisal are coarse fibers used in cords, ropes, and rough fabrics.

Animal fibers include fur and hair. Wool, the hair sheared from sheep and certain other animals, is popular in clothing and home furnishings. Rough surfaces on wool fibers give bulk and warmth to wool clothing and blankets. Silk is the strongest natural fiber. Manufacturers unwind silk filaments from silkworm cocoons and make silk yarn for clothing and household fabrics.

Various minerals--chiefly serpentine and amphibole--that occur in fibrous form are called asbestos. They resist high temperatures and are used in insulation, shingles, and fireproof products.

Man-made or Manufactured Fibers

The chemical or manufactured fibers (Tables 3 and 4), products of 20th century technology, account for more than two-thirds of the fibers processed today in U.S. textile mills. Manufactured fibers consist of two broad groups. The first group, of which rayon and acetate are examples, are produced by modifying natural polymers such as cellulose. The second group, frequently called synthetic or man-made, includes fibers such as polyester and nylon that are made from chemical intermediates. Unlike most natural fibers, manufactured fibers are produced in long, continuous lengths called filaments. Many manufactured fibers also have certain qualities superior to those of natural fiber. The most widely-used manufactured fibers are the polyesters, nylons, polyacrylics, and polyolefins.

Rayon fibers, particularly staple fibers, serve in a wide variety of uses, alone and in combination with other fibers. High-tenacity, high total tex (denier) filament is used in tire cord and other industrial uses. Rayon staple is produced in a variety of types, including polynosic and high wet-modulus types, these retaining greater strength and dimensional stability when wet. Rayon staple is used in apparel, household goods, and various nonwoven fabrics.

Cellulose acetate fabrics have attractive appearance, pleasant hand, and excellent thickness. Women's apparel, draperies, and upholstery are major uses. Cigarette filters represent a major and still growing use for acetate tow.

Table 3. Generic Names for Manufactured Textile Fibers[a,b]

Generic name	Definition of fiber-forming substance[a]
acetate	cellulose acetate; triacetate where not less than 92% of the cellulose is acetylated
acrylic	at least 85% acrylonitrile units
aramid	polyamide in which at least 85% of the amide linkages are directly attached to two aromatic rings
azlon	regenerated naturally occurring proteins
glass	glass
modacrylic	less than 85% but at least 35% acrylonitrile units
novoloid	at least 85% cross-linked novolac
nylon	polyamide in which less than 85% of the amide linkages are directly attached to two aromatic rings
nytril	at least 85% long chain polymer of vinylidene dinitrile where the latter represents not less than every other unit in the chain
olefin	at least 85% ethylene, propylene, or other olefin units
polyester	at least 85% ester of a substituted aromatic carboxylic acid, including but not restricted to substituted terephthalate units and para-substituted hydroxybenzoate units
rayon	regenerated cellulose with less than 15% chemically combined substituents
saran	at least 80% vinylidene chloride
spandex	elastomer of at least 85% of a segmented polyurethane
vinal	at least 50% vinyl alcohol units and at least 85% total vinyl alcohol and acetal units
vinyon	at least 85% vinyl chloride units

[a]All percentages are by weight.

[b]Ref. 4.

Table 4. Man-made Fibers: Their Properties And Uses[a]

Fiber	Trade Names	Characteristics	Uses
Acetate	Acele, Celaperm, Estron	Resists mildew, shrinking, stains, and stretching	Clothing; draperies; upholstery
Acrylic	Acrilan, Creslan, Orlon, Zefran	Soft; resists mildew, sunlight, and wrinkling	Blankets; carpeting; clothing; upholstery
Aramid	Kevlar, Nomex	Resists heat, chemicals, and stretching	Bulletproof vests; electrical insulation; rope; tires
Glass	Beta, Fiberglas, PPG, Vitron	Resists chemicals, flames, mildew, moisture, and sunlight	Draperies; electrical insulation; ironing board covers
Metallic	Brunsmet, Chromeflex, Fairtex, Lurex, Metlon	Resists insects, mildew, and tarnishing	Decorative trim for bedspreads, tablecloths, and upholstery
Modacrylic	Verel	Soft; resists chemicals, flames, and wrinkling	Artificial furs; blankets; carpeting; wigs
Nylon	Antron, Cumuloft, Enkaloft, Quiana	Strong; elastic; easy to launder; dries quickly; retains shape	Carpeting; hosiery; lingerie; parachutes; upholstery
Olefin	DLP, Herculon, Marvess, Vectra	Light-weight; resists insects, mildew, moisture and sunlight	Automobile seat covers; filters; indoor-outdoor carpeting
Polyester	Dacron, Encron, Fortrel, Kodel	Resists wrinkling; easy to launder; dries quickly	Blankets; carpeting; clothing; fire hose; sewing thread
Rayon	Avril, Fibro	Absorbent; easy to launder; dyes easily	Carpeting; clothing; draperies; upholstery
Rubber (Synthetic)	Contro, Lactron, Lastex	Strong; elastic; repels moisture	Mattresses; support hose; swimwear; underwear
Saran	Rovana, Velon	Resists acids, insects, mildew, moisture, and stains	Draperies; outdoor furniture; rainwear; upholstery
Spandex	Glospan, Lycra, Numa	Elastic; lightweight; resists sunlight and and perspiration	Fitted sheets; slipcovers; support hose; swimwear; underwear
Triacetate	Arnel	Resists shrinking, stains, and wrinkling; dries quickly	Draperies; sportswear; blended with other fibers

[a]Ref. 1.

Cellulose triacetate filament became a useful specialty fiber in the 1950s. Unlike regular cellulose, it can be heat-treated to induce a degree of crystallization, which produces dimensional stability and related "ease-of-care" characteristics. As a result heat-treated triacetate resembles such fully synthetic fibers as nylon or polyester.

Alginate and protein fibers are two additional textile products that have been made from natural polymers. Their commercial success has been limited.

Polyester fibers are now the largest-volume man-made or chemical fiber. These are manufactured from poly(ethylene terephthalate) and from the polymer made by condensing terephthalic acid with 1,4-dimethylolcyclohexane. The latter type of fiber melts higher than the first-mentioned polyester and has a lower specific gravity and excellent recovery from stretch.

Polyester fibers are produced in both staple and filament form. The fiber is remarkably versatile. It is strong, abrasion resistant, relatively stable, higher in modulus than nylon, and of lower moisture regain.

Uses range widely over the apparel, home furnishings, automotive, and industrial fields. Enormous quantities of polyester staple are blended with cotton, rayon, or wool in spun yarns used for apparel. Good abrasion resistance also suits polyester to use in carpeting. Continuous filament yarn finds wide use in apparel; much of it is textured to produce bulk and opacity for this use.

Polyester is used in tire cord. Other industrial uses include belts, ropes, and filter fabrics.

The principal aliphatic polyamides are nylon-6,6 (made from adipic acid and hexamethylenediamine) and nylon-6 (made from caprolactam).

Nylon-6,6 is a strong, tough, abrasion-resistant fiber that is relatively stable and relatively readily dyeable. Nylon-6,6 has a wide spectrum of uses. Textile nylon is used in hosiery, apparel, and home furnishings. Most of this fiber is multifilament, but monofilament nylon is used in sheet women's stockings. The high strength of nylon permits manufacture of lightweight and very sheer fabrics. Because of good abrasion resistance and resilience, nylon dominates the U.S. carpet market. Strong, durable nylon monofilaments are used in fishing lines and fishnets; high-strength nylon multifilament has a variety of automotive and industrial uses ranging from belting to filter fabrics. Tire cord is a major use.

The fiber properties and uses of nylon-6 are generally similar to those of nylon-6,6.

Quiana, a polyamide containing alicyclic rings, is silk-like in appearance and resilience. Quiana fabrics are used mainly in apparel, particularly dresses, blouses, and shirts.

Aromatic polyamides (aramid fibers) are made from aromatic intermediates. They are high melting, high in thermal stability, and generally possessed of high performance properties. The aramid fibers are higher in price, and find use in applications where exceptionally high strength, high modulus or high resistance to heat, or both, are required.

Commercial aramid fibers are trademarked Nomex and Kevlar by DuPont. Nomex, based on meta-linked isophthalic acid and m-phenylenediamine, is used in specialty papers for electrical insulation and aircraft structures, in protective garments, and in other applications requiring high thermal stability. Kevlar is an aromatic polyamide containing para linkages. It melts at over 500°C, is expectionally high in strength with a tenacity more than twice that of high strength nylon or polyester, and a very high modulus. It finds use in heavy duty conveyor belts, and in composite structures with casting resins such as epoxies. It competes with steel in radial tire reinforcement.

Acrylic fibers, based primarily on acrylonitrile, have good tenacity, although less than polyester or polyamides, excellent stability to sunlight, good dye acceptance as a result of the copolymer system used for this purpose, and a soft, pleasing hand of wool-like characteristics. Abrasion resistance, although well below that of nylon or polyester, is nevertheless good, and superior to that of wool. The acrylics find widespread use in both indoor and outdoor furnishings, including awnings and draperies, and in blankets, sweaters, and carpets. Blending low- and high-shrinkage yarns and shrinking the blend produces a bulky yarn.

The modacrylic fibers are acrylonitrile copolymers or terpolymers with significant comonomer contents. Among the comonomers used are vinylidene chloride and vinyl chloride. The fiber-forming modacrylic polymers are more soluble than the acrylics and have various textile uses, including fake fur pile fabrics and protective garments. Modacrylics, because of their flame-resistant characteristics, are used also in wigs and doll's hair.

Polypropylene fiber is relatively low melting for a chemical fiber. Offsetting this and other relative deficiencies are low cost, high strength, great chemical inertness, and, because of the low density, high yardage of fiber of a given tex per kilogram (den/lb). Because of the chemical inertness, dye acceptance is inadequate. For uses where color is requisite, either the base polymer is modified to provide dyeability or the fiber is spun-colored. Because of oxygen and light sensitivity, suitable stabilizers are incorporated. Textile uses include upholstery and carpeting, particularly indoor-outdoor carpets. In addition to face yarns for carpeting, polypropylene fiber, particularly that produced from film, is used for woven carpet backings. The low melting point and the fabric hand have largely precluded polyolefins from application in apparel fabrics. Other uses include rope and cordage, fishnets, and filter media. Negligible moisture adsorption, resistance to decay by organisms, and low density, which causes the fiber to float make polyolefins particularly suited for some uses.

Man-made elastomeric fibers, e.g., Spandex, differ from the usual textile fibers in having high extensibility to break (500-600%) and high recovery from stretching. The fibers, white and dyeable, are stronger and lighter than rubber; they are particularly suitable for use in foundation garments, bathing suits, support hose, and other elastic products.

Vinyon fibers are about 85-90% vinyl chloride and 10-15% vinyl acetate units. The fiber is temperature sensitive, starting to soften, shrink, and become tacky below the boiling point of water. It finds specialty use in applications requiring bonding and heat sealing, in conjunction with other fibers.

Vinyon fibers from vinyl chloride homopolymers have relatively limited thermal stability, tending to shrink at temperatures in the neighborhood of boiling water. They are, however, resistant to moisture and rotting, and inherently nonflammable, suiting them to specialty uses such as filter cloths, nonflammable garments, fishnetting, and felts for insulating purposes.

Saran fibers are based on vinylidene chloride copolymerized with small amounts of vinyl chloride, and still smaller amounts of acrylonitrile. They are characterized by a pale straw color and by resistance to water, fire, and light, and bacterial and insect attack. Their relatively low melting points require excessively low ironing temperature. The fibers find specialty use in certain types of upholstery, filter cloths, and fishnets. The relatively low cost of these fibers is one of their attractions.

PeCe fiber is based on a post-chlorinated vinyl chloride polymer. The post-chlorination raises the chlorine content of the polymer from 57 to 64% and confers acetone solubility. Like many other vinyl fibers, it is low melting and restricted to special applications.

Vinal fibers, based on poly(vinyl alcohol) have reasonable strength, a moderately low melting point (222°C), limited elastic recovery, good chemical resistance, and resistance to degradation by organisms. Vinal is used in bristles, filter cloths, sewing thread, fishnets, and apparel. Production has remained largely in Japan.

Polychal fibers are related to the Vinyon and Vinal types. Polychal fibers have been exported from Japan to the U.S. for use in flame-retardant apparel.

Teflon fibers, based on polytetrafluoroethylene, have uniquely high chemical stability and inertness, no water absorption, low frictional characteristics, and high melting points with decomposition preceding and accompanying melting. Teflon fibers in both filament and staple forms are high priced and find, as would be expected, highly specialized applications, such as packings, special filtration fabrics, and other uses where corrosion resistance, lubricity, and temperature resistance are required.

Kynol, a phenolic-type fiber having fire-resistant properties, is used in protective garments.

Polybenzimidazole fibers are of the high performance type, of very high melting point, good strength and extensibility, nonflammable, and surprisingly for a synthetic fiber, of high moisture regain: 13%. These fibers are of interest for aerospace and industrial applications.

Poly(phenylene sulfide) fibers, produced by the reaction of p-dichlorobenzene with sodium sulfide, are used as engineering thermoplastic polymer. These fibers have good dimensional stability, flame resistance, thermal stability, and chemical resistance. They are used in air filtration applications and as conveyor belts in high temperature drying operations.

Benzoate fibers are made in Japan by the self-condensation of p-(betahydroxyethoxy) benzoic acid to provide silk-like products.

Poly(hydroxyacetic acid) or poly(glycolic acid) fibers are crystalline, and can be oriented by stretching. Because they are absorbable in the body, they have become important in surgical suture applications, where they replace catgut sutures in many such applications.

Polyphosphazene fibers are being developed; the anticipated applications include biomaterials, drug delivery systems, electronics, and separation membranes.[11]

Glass fibers are inorganic, strong, nonflammable, and rather heat-resistant, as well as highly resistant to chemicals, moisture, and attack