7 New high-tech fibers and *Shin-gosen*

Synthetic fibers were first produced as imitations of natural fibers. The desire to create a fiber with a silk-like touch was the trigger in the production of many new kinds of synthetic fibers. Today, the technique of imitating nature (biomimetics) has improved to such an extent that not only can the basic structures of living things be duplicated, but the more precise functions of living organisms can also be copied. Using the concept of biomimetics, synthetic fibers with specific properties have been produced, which in turn have enriched our lives.

Rayon was invented in 1884, nylon in 1938 and *Shin-gose*n with silk-scrooping sound emerged during the 1980s. All three types of fiber arose because of the desire of the researchers to create silk artificially. Despite the changes in society over the years, the appeal of natural silk has remained, which has led to the production of better silk-like artificial fibers.

The success of the products which have been based on the natural system is driving an even more intensive utilisation of biomimetics. Nature will continue to be challenged in the quest for new fibers to meet the evolving needs of society. High-tech fibers are, therefore, continually moving on. Although previously described, in this chapter the newer technologies and developments will be given.

7.1 Various categories of high-tech fibers

In the spring of 1985 a book entitled *High Technology Fibers* was published in the USA, resulting in the term "High-tech fiber" being adopted. A high-tech fiber can be defined as a fiber produced by high technology, namely, new fibers having superior properties to ordinary fibers, and can be split into three categories: high-performance fibers, high-function fibers and high-sense fibers.

7.1.1 High-performance fibers

Fibers need to possess mechanical properties such as tensile strength and modulus in some degree, as well as thermal resistance, good dyeing property, weather and chemical resistance. High-performance fibers by definition need to have improved properties compared with ordinary fibers. High-performance fibers with extremely high tensile strength and modulus are referred to as super-fibers. These can be used as ropes by themselves, but are more often used as reinforced fibers in ACMs in the field of aerospace industry, for tennis rackets, golf shafts. Typical examples of super-fibers are PAN-based carbon fibers, *para*-type aramid fibers, high-tenacity and high-modulus polyethylene fibers, and polyphenylene bisoxazole (PBO) fibers. The tensile strength of fibers is shown in Fig. 7.1. It illustrates how many kg/mm^2 cross-section of super-fibers can sustain, in comparison with ordinary fibers. More than a ten-fold increase in strength can now be achieved.

7.1.2 High-function fibers

Fibers that utilise special morphological characteristics to function are termed basic function fibers, or primary function fibers. They are designed to fulfil a specific functional need such as being moisture permeable or water repellent, highly absorbent to water, antibacterial and deodorant. When they are ultraviolet resistant or heat storing, they are sometimes referred to as secondary function fibers. Of course, these terms are not mutually exclusive.

The technologies that add high function to fibers are shown in Table 7.1. These are often used in combination, particularly technologies (1) and (4). *Shin-gosen* is a name given to fibers that combine all the technologies from (1) to (4), which are combined also with innovative sewing methods.

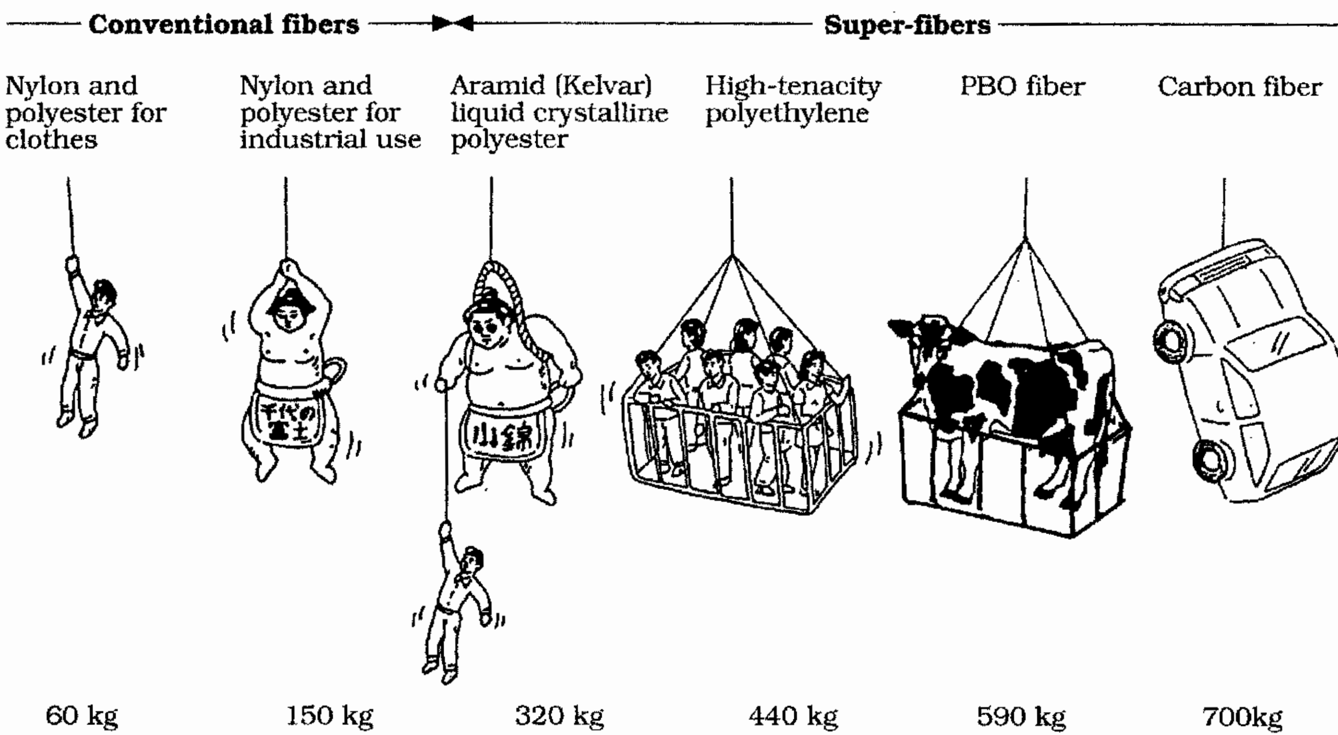
7.1.3 High-sense fibers (or aesthetic fibers)

High-sense fibers are fibers that are extremely comfortable to wear, are highly

Table 7.1. Technologies to introduce "high functions" into fibers

Technology to modify fibers	Functions introduced
1 Modification and improvement in materials	Antipiling, antistatic, hydrophilic, flame-retardant
2 Innovation in spinning	Hollow fiber, non-circular cross-section, composite fibers, ultra-fine fibers
3 Improvement of fabrics*	Bulkiness
4 Modification and improvement during processing	Anti-static, sweat-absorbent, waterpermeable/waterproof, flame-retardant, antibacterial/deodorant

* Textile, knit, and non-woven fabrics



7.1 Super-fibers: how many kilograms can a fiber with 1 mm2 cross-section hold?

Table 7.2. Various aesthetic fibers produced by changing the cross-section

Trade mark	Producer	Cross-section	Basic technology	Specialities of the products
Solo Sowaie	Asahi Chemical Industry Ltd		Hollow, triangular, thick and thin	Higher bending stiffness, mild colour
Fontana μ	Asahi Chemical Industry Ltd		W-shaped, self-crimping	Bulky, crispy, dry and cool to touch
Soielise N	Kanebo Ltd		Pentagonal cross-section	Mild lustre, dry to touch, water-absorbent
Vivan	Kanebo Ltd		U-shaped cross-section, thick and thin	Mild lustre, dry, spun-yarn-like, higher bending stiffness
Dephorl	Kuraray Ltd		Flat cross-section, self-crimping	Deep colour, bulky, higher higher bending stiffness
MSC	Unitika Ltd		Arrow-like cross-section	Dry and cool to touch
Mixy	Unitika Ltd		Random and multishaped cross-section	Dry to touch, natural appearance, higher bending stiffness

fashionable, with superior aesthetic and sensual factors due to their hand feel properties. Owing to their ultra-fine character and non-circular cross-section, these fibers provide fineness, fullness and softness, lustre, crispness and drapability comparable to silk. *Shin-gosen* is one of the high-sense fibers. "Sense" here is used to indicate that the new *Shin-gosen* has added an aesthetic quality, not previously achieved. Examples of how are shown in Table 7.2. Changing from the conventional circular cross-section can change the overall properties of the fiber. Non-circular cross-sections give the fiber, not only a different lustre, but also a remarkable change in bending stiffness and handle. A regular triangular cross-section gives a fiber with 1.2 times larger bending stiffness.

7.2 Development of *Shin-gosen*

The word "*Shin-gosen*" was introduced by the media in Japan during the latter half of 1988 to describe a completely new generation of textiles based on synthetic fibers. Thereafter, there was a "*Shin-gosen* boom" and the term was adopted elsewhere, without translation or clear definition. Such fibers must also be regarded as High-tech, produced by high technology. Micro, random and a combination of all available technologies were used to produce these fibers, which have a different quality and performance from those of ordinary fibers.

7.2.1 *Introduction of* Shin-gosen

The reasons for the "*Shin-gosen* boom" are as follows:

1 Consumers were demanding change in fashion and the changes that had started in the early 1980s had reached the limit of the development of the materials.
2 Every synthetic fiber manufacturing company tried to develop highly value-added new materials, such as high-sense materials, with unique quality and taste and produced new materials, particularly for women's clothes.
3 The development and combination of technologies ranging from fiber production to processing of silky polyester produced *Shin-gosen.*

Peach-skin-like materials became a trigger for the boom because of their new appearance and hand touch. Next, fabrics made of strongly twisted composite fibers were used for suits and jackets, which had usually been made from wool. Finally, high quality, fine texture and bulkiness of new silky materials made of polyester became popular for blouses and dresses. The success of *Shin-gosen* came from the enlargement of this market, not only in blouses and dresses, but also for jackets and suits. Common features of three types of *Shin-gosen* are peach-skin quality, new silkiness and a worsted character giving fullness and drapability, which provided a high quality awareness and gained consumers' satisfaction.

7.2.2 *Technological features of* Shin-gosen

Shin-gosen is produced by combining several established and new technologies ranging from polymer production to sewing (See Table 7.3). Three areas of progress can be identified. The first is the production technology for specific polymers, which could be new co-polyesters, and as such were designated "new polyesters" to distinguish them from the ordinary polyesters. The second covers spinning, weaving and dyeing technologies, to produce non-circular cross-section fibers, ultra-fine fibers, mixed spinning and surface treatment. The third one is new sewing technology to produce completely new fabrics. Therefore, *Shin-gosen* may be defined as fabrics for clothes that have completely different taste and functions compared with those prepared from conventional synthetic and natural fibers. Additionally, the development of *Shin-gosen* required not only the application of a set of new combined textile technologies, but also another technology to evaluate overall sensitivity of need, combined with the engineering skills to achieve a fabric with its own in-built aesthetic sense.

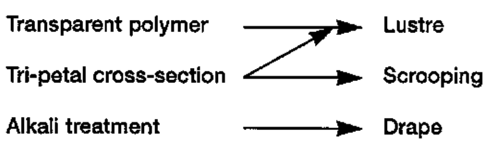
Table 7.3. Established technologies and new technologies to produce *Shin-gosen* fabrics

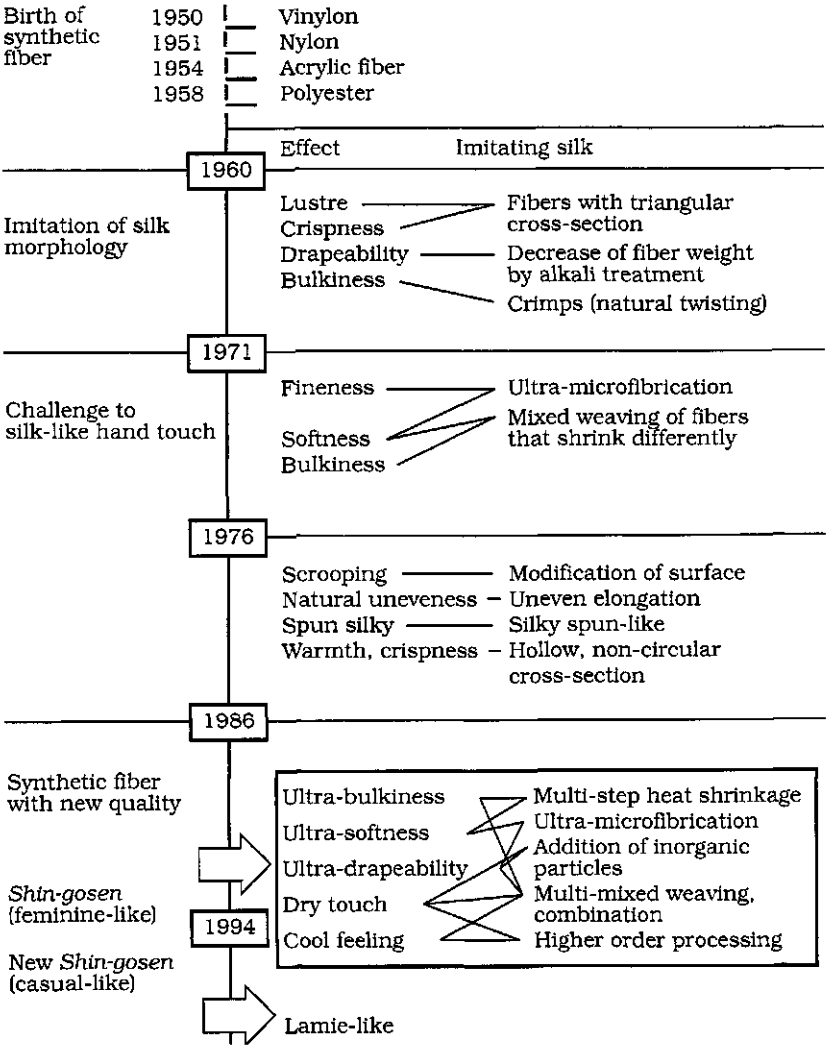
Process	Previous technologies for first and second generations	Newly developed technologies for the third generation: the "*Shin-gosen*"
General	Single technology or its simple combination	Combination of the plural technologies to create highly refined products
Polymerisation	Bright (non-pigment) Dull (pigment) Cationic dyeable polymers (sulphonate group)	High-shrinkable copolymers, high-gravity polymers, unevenly degradable polymers Easily-degradable polymers
Spinning and drawing	Trianguar cross-sections Thin fibers	Specialised, uneven and randomised cross-sections Self-extensible fibers, super-low shrinkable fibers, high-shrinkable fibers, specialised conjugated fibers, super-fine fibers
Blending filaments	Simple combination of heat treated and untreated filaments	Combination of super-low shrinkable filaments, super-less-shrinkable filaments and self-extensible filaments
Texturing	Specialised false-twisting	Composite (mixed) false twisting sheath-core or double-layer false twisting
Dyeing and finishing	Alkaline reduction	Splitting conjugated fibers Heat treatment of high-shrinkable fibers, less-shrinkable fibers and self-extensible fibers, mild pile raising, surface treatment of fiber, randomising

7.2.3 Development of technologies to produce silk-like fibers

Synthetic conventional melt-spun fibers produced in the 1950s had a circular cross-section, which gave the fabrics a flat hand touch like paper. To improve the hand feel, technological developments led to silk-like, cotton-like and wool-like fabrics. Figure 7.2 outlines the stages in these developments, from the birth of synthetic fibers to silk-like fibers and eventually *Shin-gosen.*

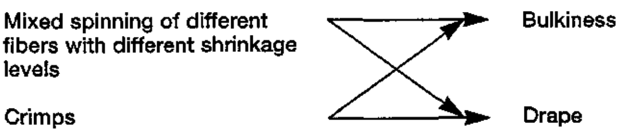
The first generation started around 1964 by reproducing the silk triangular cross-section, which imparts a silk-lustre and silk-crispness to the fibers. During the production of natural silk fibers, sericin is removed from the raw silk thread by alkali treatment, leaving only the fibroin. To mimic this process, the polyester fabrics were reduced in weight (*ca.* 25%) by caustic alkali treatment. As a result the pressure between fibers within fabrics decreased, so that silk softness, and drape were introduced into the fabrics. The steps as in Fig. 7.3 can be represented as:



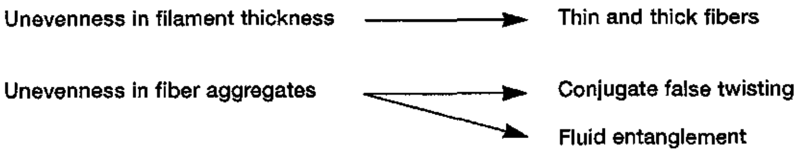


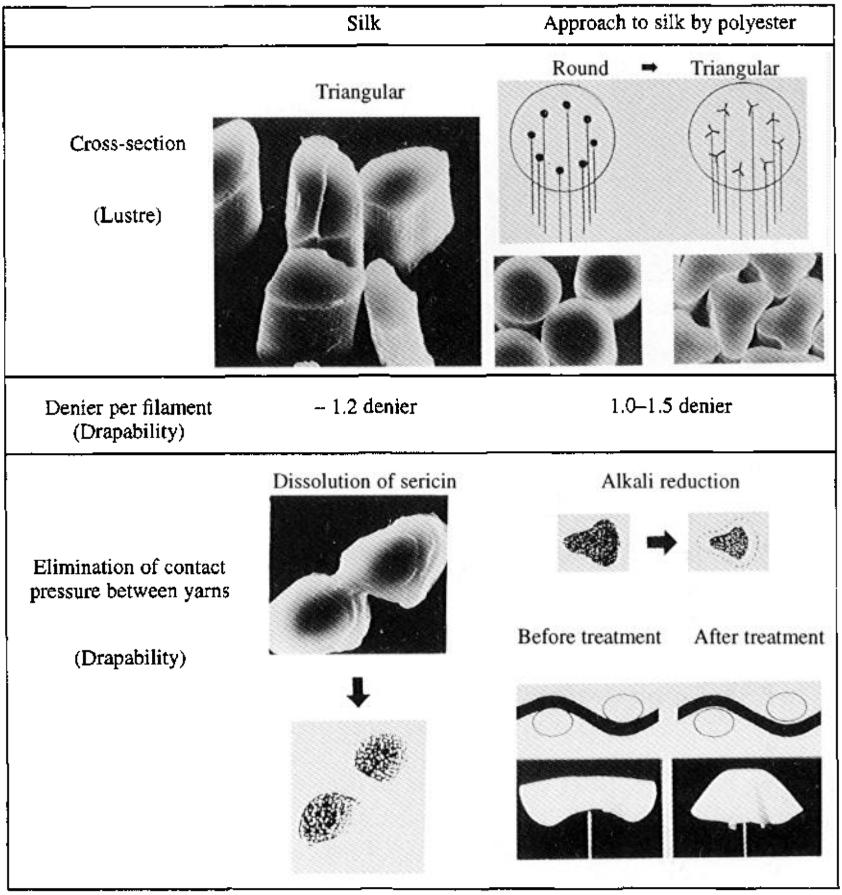
7.2 From silk-like fiber to new *Shin-gosen*.

The second generation, to reproduce silk hand-touch started around 1975. Here new technology gave bulkiness and softness to the fiber by the development of mixed spinning with different types of fibers having different shrinkage levels.

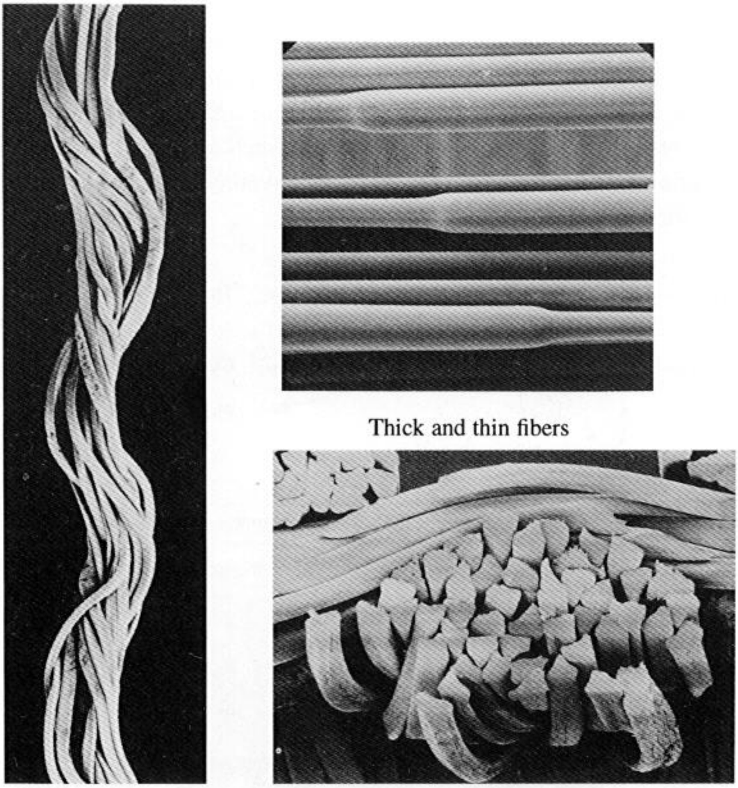


The third generation to seek natural taste and unevenness started around 1979. Demands for variability and higher quality stimulated research to produce materials with a more natural appearance and touch. As a result, fibers were produced with complex unevenness, such as multi-grooves with thick-and-thin, and uneven cross-sections, which synthetic fibers did not have because of their uniformity (Fig. 7.4):





7.3 Triangular fine denier weight reduction.



Thick and thin fibers

Irregularly shaped fibers

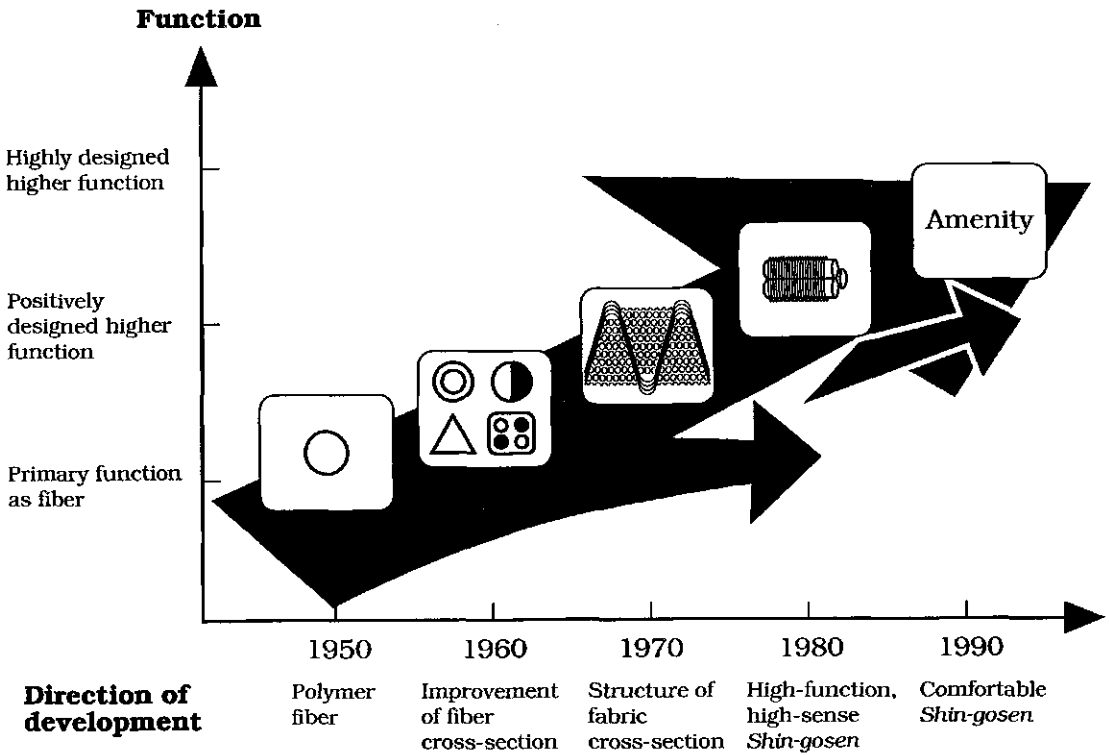
Fabrics of irregularly shaped fibers

7.4 Irregular shape fibers.

Motivation of the fourth generation was to produce synthetic fibers with a unique touch, dyeability and function, and this activity started around 1986. Within a short time, manufacturing of *Shin-gosen* started on a full scale. These were synthetic fibers whose quality and touch could not be provided by normal synthetic fibers and natural fibers, and which introduced a new dimension to fiber design.

7.2.4 Shift of paradigm in the development of Shin-gosen

Looking back, it appears that concepts in fiber development have changed about every 11 years, which has been the result of long-term research, a limit reached in the development introduction of new technology to produce new materials and the changing needs of society. These changes are outlined in Fig. 7.5. The various milestones are worthy of note here.



7.5 Paradigm shift of *Shin-gosen* development.

7.2.4.1 Production of fibrified polymer during the 1950s

Production of fibrified polymer started in Japan in 1950, 1951, 1954 and 1958 for vinylon, nylon, acrylic fibers and polyester, respectively.

7.2.4.2 Improvement of cross-section of fibers during the 1960s

The fibers with triangular cross-section were developed to imitate the cross-section of silk. Research on bilateral structure of wool fibers led to the production of composite fibers by composite spinning technology (bound type and core–sheath type), and fibers based on the structure of cotton and hollow fibers were devised. Following these developments, important new fiber materials were developed.

7.2.4.3 Improvement of cross-section of fabrics during the 1970s

The hand touch of fabrics is controlled not only by the cross-section of fibers, but also by the distance between fibers in fabrics. Artificial leather with a suede touch was developed in the 1970s. The technologies to produce bimetal-type composite fibers and core–sheath composite fibers are used for the production of such fine microfibers. A sheet of microfibers can be produced by "sea–island" technology, when in a multi-component system, one of the components ("sea component") is dissolved away. When the fabric has been formed, the surface of another component can be removed to give silk-like fibers. The technology to reduce the weight of fabrics and mixed spinning technology of fibers that shrink differently are the basic technologies.

7.2.4.2 Production of fabrics using a new concept during the 1980s

Natural fibers are limited in the type of processing which they can be subjected to. Synthetic fibers, on the other hand, have no such limitation in molecular planning and processing. Inevitably, therefore, during the 1980s, research was concentrated on developing new synthetic fibers with a new aesthetic sense and functionality that could not be provided by the normal fibers, using the accumulated technologies during the past decades as already described. Thus came *Shin-gosen*, which does not refer to a specific material such as nylon or polyester. It is a new category of fiber. Some of the basic technologies that have been built upon to produce *Shin-gosen*, particularly conjugated or mixed spinning combined with surface treatment, are shown in Table 7.4.

Table 7.4. Examples of the products of conjugated or mixed spinning combined with surface treatment technology

Trade mark	Producer	Fiber	Cross-section	Cross-section, surface after finishing	Speciality of products
Treview	Kanebo Ltd	Random conjugated finishing			Dry, spun-like natural feeling
Fontana	Asahi Chemical Industry	Mixed or conjugated spinning			Dry-spun silk-like natural feeling
SN 2000	Kuraray Co.	Inorganic particle mixing			Dry-hand, deep colour
Sillook Royal	Toray Industries Inc.	Radial conjugated spinning			Bulkiness, silk sound
Sillook chatelaine	Toray Industry Co.	Inorganic particle mixing			Dry hand, rayon-like
Louvro	Toyobo Ltd	Inorganic particle mixing			Dry-hand, rayon-like, higher bending stiffness
Rapitus	Teijin Ltd	Copolymer or mixed spinning			Natural feeling, crispy, spun-silk-like

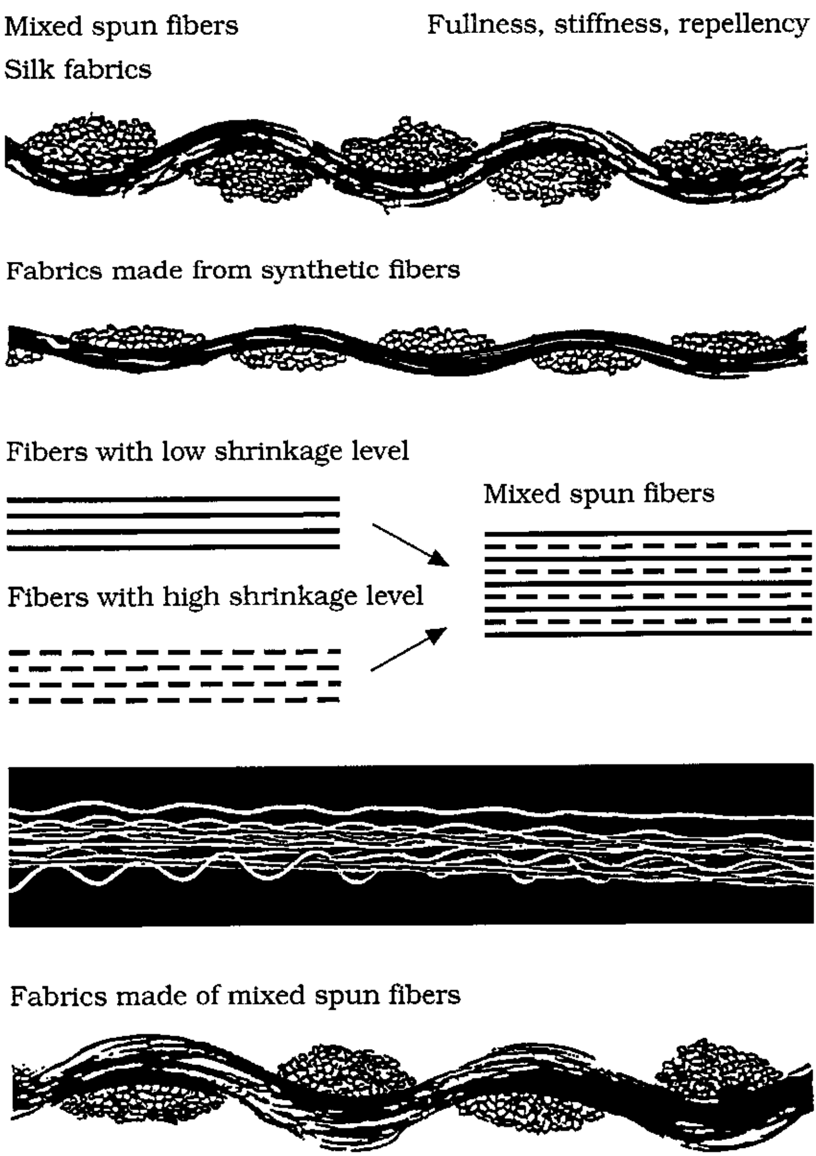
7.2.5 *Feminine* Shin-gosen

7.2.5.1 High shrinkable levels

Mixed spinning of fibers with different levels of shrinkage yields fabrics with fullness. With the appearance of super-high-shrinkable fibers and self-elongation fibers, a highly improved fullness was possible. The previously high-shrinkable polyester fibers had shrinkage levels of 15% in boiling water. However, super-high-shrinkable fibers give 30–50% shrinkage levels. Extremely bulky material can be given by the mixed spinning of fibers with highly different shrinkable levels as illustrated in Fig. 7.6. Self-elongation fibers are obtained by drawing and shrinking the fibers at a lower temperature to give a low crystallinity. Then treating the fibers at a higher temperature during the dyeing process will crystallise and elongate the resulting loops on the surface of fabrics and give an additional fullness to the fabrics. The stages are illustrated in Fig. 7. 7.

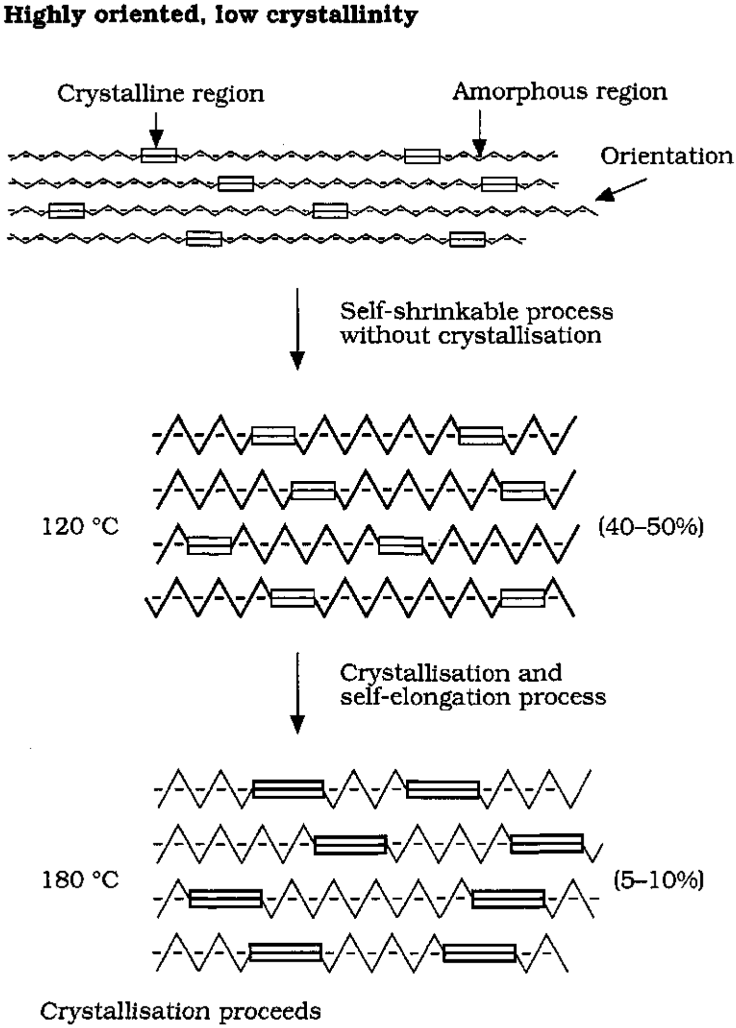
7.2.5.2 Strongly twisted composite fibers as basic for the production of new worsted

Composite fibers are bulky fibers provided by mixed spinning of filaments with different levels of elongation, and then false twisting. The fibers thus



7.6 Ultra-bulky material made of mixed spun fibers with different shrinkage levels.

obtained have complicated crimps, and therefore provide a highly wool-like appearance with better fullness compared with the ordinary fibers. Worsted produced by the *Shin-gosen* concept produces awareness of high quality, and has good drapability, with improved fullness, because the crimps in the fiber are of complex design. Such fullness and excellent hand feel cannot be



7.7 Self-elongation fibers by temperature change.

produced using conventional fibers because the crimps of necessity have to be simple.

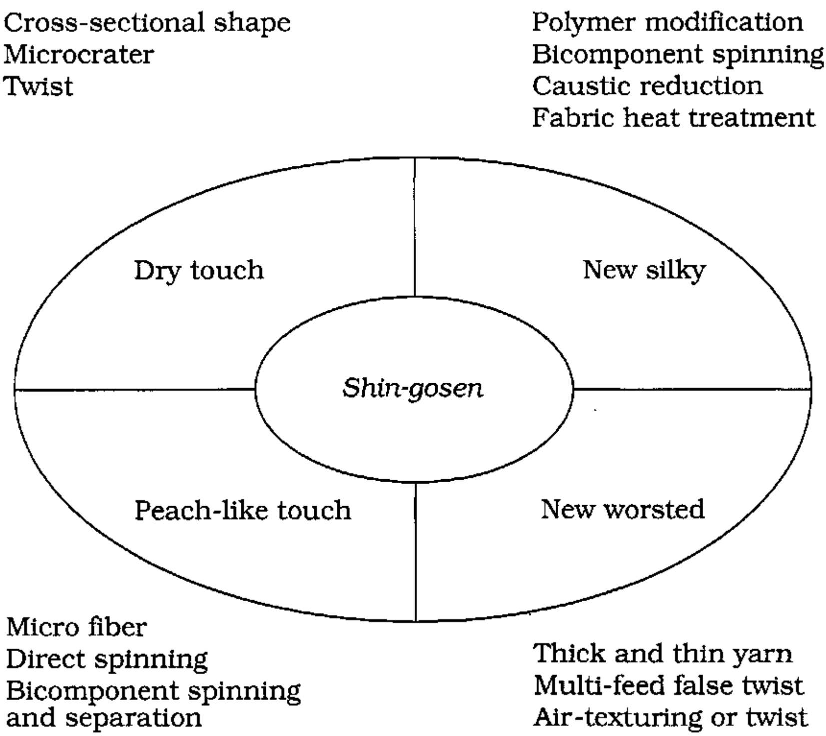
7.2.5.3 Preparation for the weaving and dyeing processes

Having used strongly twisted fabrics to give good drapability, the loose filaments must be woven in a way that would not have been considered previously, so that during the weaving the new characteristics of the filaments are not lost. Designing of the dyeing process thereafter is an important step to bring out the properties of the fibers.

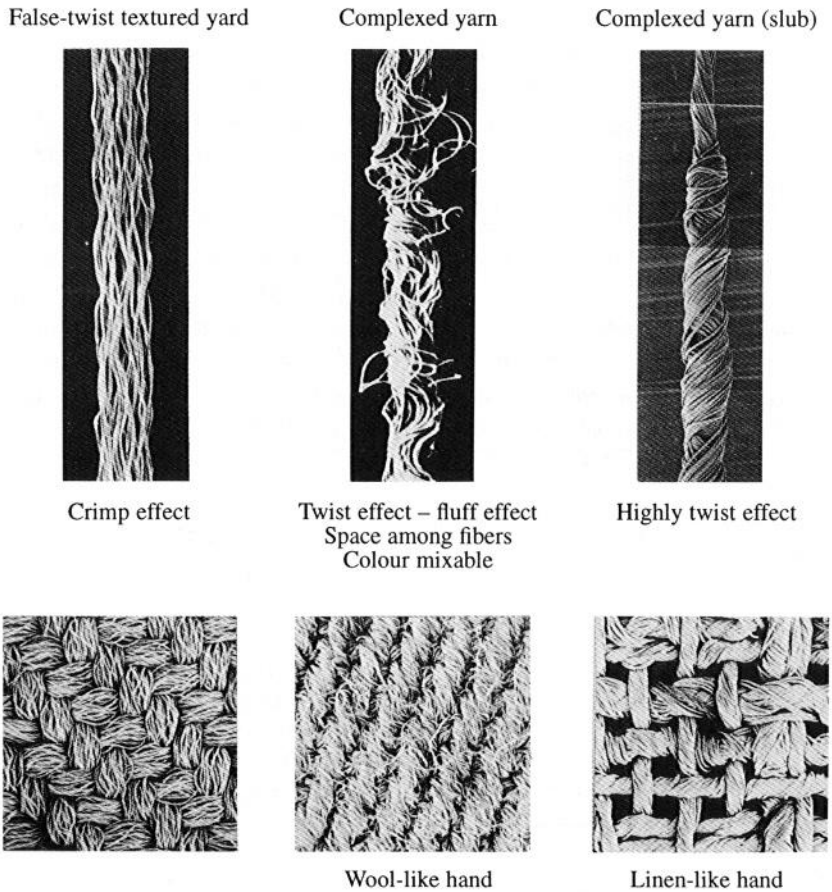
7.2.5.4 Extension of variation of hand touch

A new technology was also needed to introduce a variation in hand touch of *Shin-gosen*. In addition to mixed spinning of fibers with different levels of shrinkage and strongly twisted composite fibers, new rayon-like fabrics with a dry touch and high drapability could be produced by blending fine inorganic particles into polymer in the mixed-spinning process. One of the objectives of the mixed-spinning is to increase the specific gravity of the fiber and to improve the drapability, which the inorganic particles can achieve because they have a high specific gravity. Generally, the mixing is carried out in the polymerisation process, but it can also be done in other stages. The content of inorganic particles should be less than 10% by weight to avoid damage during processing. Extremely fine fibers are also incorporated to give a fine touch to the fabrics. Such fibers can be used in combination with other fibers or not, according to the requirement of the consumers for the type of hand feel.

The share of *Shin-gosen* is about 50% for new silky fabrics (mixed spinning of fibers of different shrinkage), 30% for new worsted (composite fibers), 20%



7.8 Classification of technologies to impart the various types of hand feel to *Shin-gosen*.



7.9 Complexed textured yarn.

for new-rayon fabrics (dry-to-touch) and 10% for fabrics using ultra-fine fibers (as used for the production of artificial suede). The classification of technologies to impart the types of hand feel of *Shin-gosen* is shown in Fig. 7.8. Generally, the term "microfiber" is used in Japan for artificial suede. *Shin-gosen*, in this regard, may be considered as fabrics made by the use of microcraters. Figure 7.9 illustrates the various methods used for textured yarns to achieve variations in hand-feel.

7.2.6 Casual (comfortable) Shin-gosen

"Comfortable" *Shin-gosen* arose with the change of fashion trend and consumer pressure. The development went along two paths: one is the development of water/sweat-absorbent or easy care materials, and the other is

Table 7.5 Methods to produce "comfortable" *Shin-gosen* materials

Basic technology				Materials	
Cross-section	Added particles	Polymer	Fiber processing	Name	Producer
Circular	Ceramics	Regular		Alteene Estmoule Xye	Toray Teijin Kuraray
Micro-slit			Differently shrinkable	Ceo	Toray
Cross	Ceramics		Thick and thin	Space-master	Kuraray
Circular, hollow			Spinning	Aero-capsule	Teijin
Triangular, hollow	Ceramics		Thick and thin	Gulk	Asahi Chemical Industry

Table 7.6 Methods to prepare water/sweat-absorbent and easy-care materials

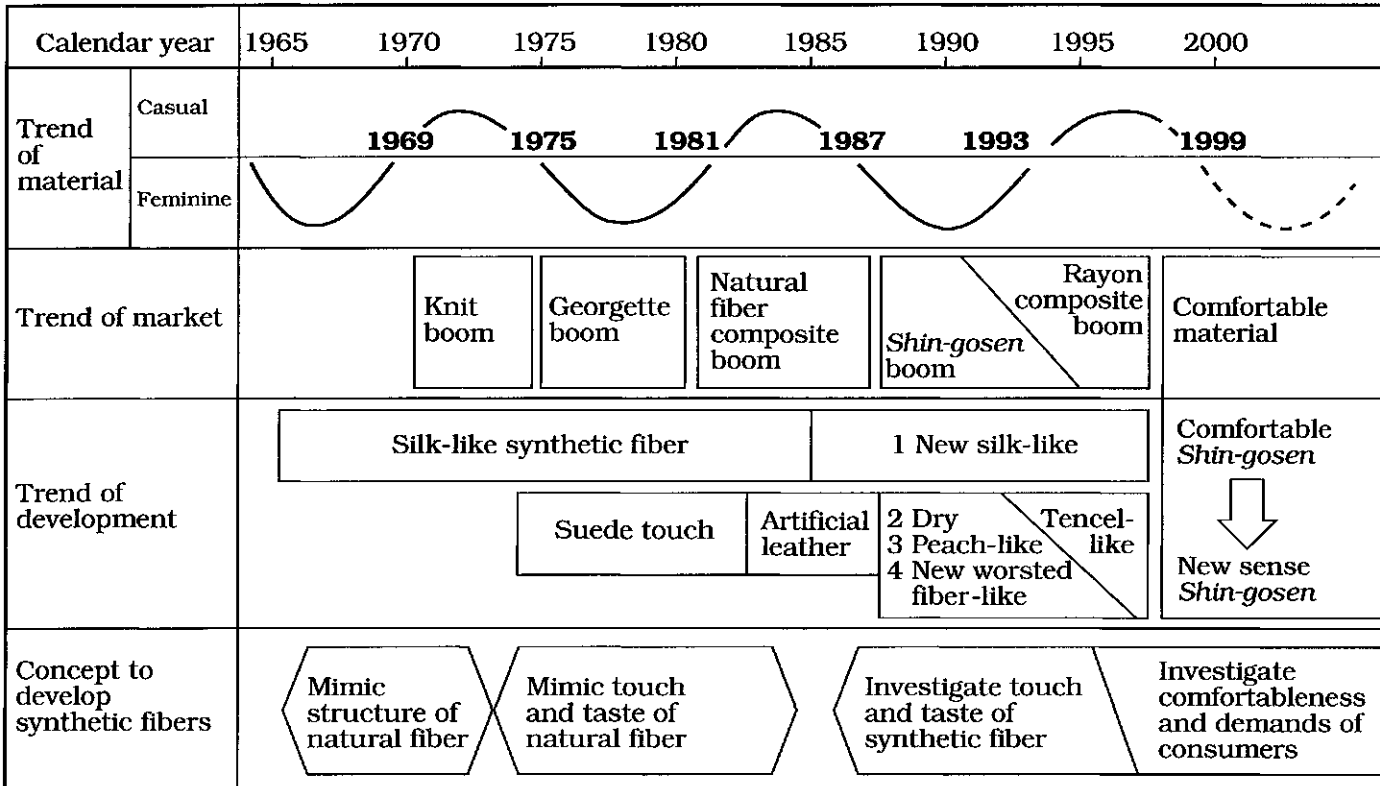
	Basic technology			Materials	
Cross-section	Added particles	Polymer	Processing of fibers	Name	Producer
Circular, hollow				Wellkey	Teijin
Circular, hollow			Conjugate Thick and thin	Aege	Mitsubishi Rayon
Circular, hollow		Dissolution		Kilatt P	Kanebo

the development of composite fiber materials with a new hand touch. The basic technologies are summarised in Table 7.5.

Since polyester is hydrophobic, it lacks moisture and water absorbency. Therefore, efforts to improve its hand-feel and other functionalities, such as water absorbency and easy care, must begin at conception. This started first with polymer modification and processing, then changes in cross-section, surface modification and structure. However, all these needed to be combined to give water/sweat absorbency and easy care, as described in Table 7.6.

7.2.7 "Comfortable" Shin-gosen using composite materials

The movement to develop a specially "comfortable" *Shin-gosen* using composite materials started with the polyester manufacturing companies at the end of 1992. Composite materials include not only the mixed spinning of wool or rayon with polyester, but also composite materials made up of



7.10 Change in market and direction of fiber development.

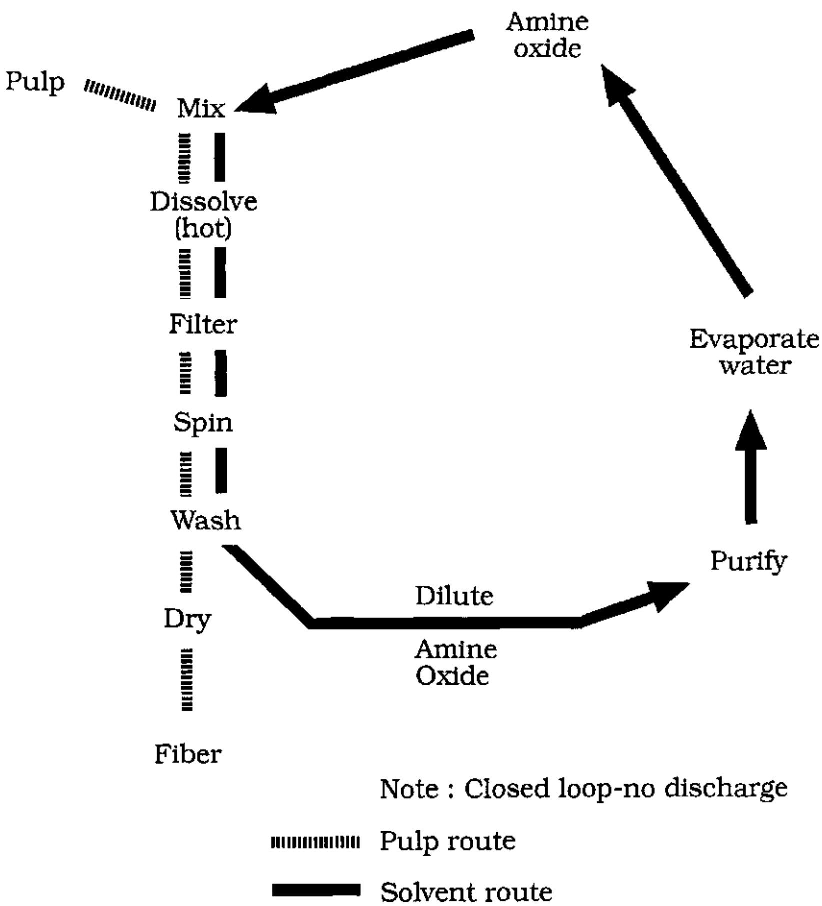
Next page

8 Cellulosic fibers

Since Count Chardonnet first developed rayon as a silk-like fiber, there have been many developments in the field of synthetic cellulosic fibers that give cellulose, once again, an opportunity to challenge the synthetic fibers in their applications and environmental effects. At the beginning of the 20th century the world demand for textile fibers was 3.9 million tonnes, made up almost entirely of cotton (3.2 million) and wool (0.8 million). By 1950 the total demand had risen to 9.4 million tonnes of which 6.6 tonnes was cotton, 1.1 million wool and 1.6 million tonnes the synthetic cellulosics. In 1980 the production of synthetic cellulosics peaked at 3.6 million tonnes, but declined to 2.8 million tonnes by 1993. This drop can mainly be attributed to the collapse in demand in Eastern Europe following the political changes there.

Meanwhile the world population over the same period increased from 1.6 billion to 4.04 billion. It is clear that over this time the cellulosics could not provide the same flexibility that the synthetics had achieved. During the same 50 year period the demand for synthetic fibers had reached 18.6 million tonnes with cotton accounting for 18.5 million tonnes in consumption. The main reasons for this lack of competitivity was the inability of the synthetic cellulosics to achieve a built-in functionality; they could not match the variety of applications of the synthetics or their price. Whereas the price of cotton dropped because of the increase in world production, and the synthetic fibers' prices fell because of over-capacity and lower production costs, the price of the cellulosics continued to increase. This was mainly due to the greatly increased costs associated with pollution control associated with the old chemical pulping processes.

The world population is growing fastest in the regions of the world with a warm climate. It is likely that by the year 2000 the total world textile requirement will be of the order of 50 million tonnes. If the present 56% demand for absorbent fibers is maintained, as is likely, then there will be a call for 28 million tonnes of absorbent fibers. The production of this category at



8.1 Outline of the Tencel process.

present is 18.6 cotton, 1.6 wool, 2.8 cellulosics and 1.6 viscose staple, which is 24.6 million tonnes in all. It is unlikely that cotton production can be greatly increased because the area for planting has remained stable for the last 40 years. The need to use land to produce food has taken precedence. Undoubtedly there is an opportunity for the cellulosics, and it is for this reason that innovative developments have taken place recently to overcome the shortcomings of the past.

8.1 New solvent systems

If processability is to be improved for the cellulosics, then new solvent systems are needed. Research has yielded many which are promising:

paraformaldehyde–dimethyl sulphoxide cyclic amine oxides; nitrosyl chloride dimethyl formamide; chloral dimethyl formamide, for example. The two that have won through into actual commercial processing are sodium hydroxide and *N*-methyl morpholine *N*-oxide (NNMO).

8.1.1 Courtaulds' Tencel, Lenzing's Lyocell and Akzo Nobel's NewCell

These new fibers are synthetic cellulosic fibers produced from morpholine *N*-oxide solvent systems. Tencel is the new cellulosic fiber developed by Courtaulds, one of the pioneer companies in rayon production. It is produced from natural cellulose in wood pulp using a special technique to spin from NNMO solution. It is an environmentally clean process with virtually total recycling of the solvent as shown in Fig. 8.1. The project code-named "Genesis" started on 1981 and a semicommercial plant was built in Grimsby, UK in 1988. A full-scale production facility was commissioned in Alabama, USA, in 1992. The basic patent is entitled "Process for Shaped Cellulose Article prepared from a solution containing Cellulose Dissolved in a Tertiary Amine N-Oxide Solvent", and the inventor was Clarence C. McCorsley, III. The patent was filed on 2 March 1989 and was assigned to Akzona Inc. Asheville, now Akzo Nobel. It gave the licence to produce staple fibers to Lenzing, Austria, in 1988 and to Courtaulds, UK in 1990.

The various terms and developments with this new fiber can be confusing, so identification of the progress made is important:

1. "Lyocell" is a synthetic cellulose fiber produced by spinning from a solvent made of wood pulp in amine oxide.
2. "Tencel" is the first commercialised Lyocell (staple) fiber by Courtaulds, UK.
3. Courtaulds constructed its semi-commercialised plant in the UK in 1988, and went into full production via its commercial plant in the USA in 1992.
4. Lenzing took a licence on the basic patents in 1988, and since 1990 has been running a pilot plant, with a view to going into commercial production in 1998. Its staple fiber is termed "Lyocell".
5. Courtaulds and Akzo Nobel announced a feasibility study of Lyocell filament yarn which was completed in 1996. The filament yarn will be termed "NewCell".

Courtaulds were, therefore, the first to establish a production process and has sold all over the world with great success. Production of Tencel at the end of 1998 will be 90,000 tonnes per year.

Table. 8.1. Fiber properties of Tencel compared with other fibers

	Tencel	Modal	Viscose	Cotton*	Polyester**
Titre(dtex)	1.5	1.7	1.7		1.7
Tenacity (cN/tex)	40–42	34–36	22–26	20–24	55–6
Elongation (%)	14–16	13–15	20–25	7–9	25–30
Wet tenacity (cN/tex)	34–38	19–21	10–15	26–30	54–58
Wet elongation (%)	16–18	13–15	25–30	12–14	25–30
Tenacity (@ 10% ext)	35	23	16		26
Wet modulus (@ 5% ext)	270	110	50	100	210
Moisture regain (%)	11.2	12.5	13	8	0.5
Water imbibition (%)	65	75	90	50	3

* US middling.
** High tenacity.

Lyocell long fibers are being produced in a pilot plant in Germany, in cooperation between Akzo and Courtaulds. Akzo provide the technique to produce long fibers, with Courtaulds inputing the production technology developed for Tencel. Early 1998 saw the start of production in a semi-commercial plant. Marketing and application is being introduced under the leadership of Akzo. The great attraction of the Lyocell type of fiber is its considerably greater strength and versatility compared with rayon and other cellulosics. Its production process also is environmentally sound. It is Tencel that has taken the lead, and currently Lenzing's Lyocell staple (short) fiber has only a third of the production capacity compared with Tencel. The main attention will, therefore be given to Tencel.

Tencel retains all the natural properties of a cellulosic, with good moisture absorbency, comfort, lustre and biodegradability, with coloration characteristics similar to rayon. The properties of Tencel are summarised in Table 8.1. It has high strength, with only 15% loss of strength in the wet state. Exceptional wet modulus results in very low fabric shrinkages. Tencel has a round cross-section and a good open fiber appearance for ease of subsequent processing. It is an ideal fiber for blending with other fibers to give very strong yarn, even at low blend levels.

Tencel produces apparel fabrics with good aesthetic versatility. It satisfies a wide range of fabric needs from fine fashion ladies' lightweight blouse- and dress-wear through moderately heavy skirting and suitings. Its versatility also extends from active leisure wear through to performance fabrics, denims, work-wear and industrial apparel. Tencel produces more luxurious drape effects than cotton. Either alone or in blends with other fibers it provides a variety of handling effects, allowing fabric finishers to demonstrate their skills. Like rayon, Tencel has a very efficient dye uptake and provides natural, bright, vibrant colours. It has a dyeing compatibility with other rayon fibers, which allows a wide range of options for substrate fabrics.

The high strength, rigidity and wet modulus of Tencel translate through fabric structures that show exceptional strength, especially when wet, and very low shrinkage. Additionally, the cellulosic character provides very good thermal stability and low creep. These good physical characteristics allow a broad range of technical applications, particularly spun industrials, disposables and durables. Additionally the environmentally favourable nature of the manufacturing process, combined with comfort levels and biodegradability, give this new fiber a good opportunity to carry the fight back to the synthetic competitor. The development offers an opportunity of having the processing advantages of the synthetics combined with the benefits of the natural fiber.

Although the basic technology to produce Tencel and Lyocell staple fibers is the same, there are subtle differences. Lyocell was improved in its degree of crystallinity and orientation and targeted for use in clothes. Tencel is washed and purified directly after spinning as bundles of long fibers, whereas Lyocell is washed after cutting into short fibers. The treatment gives fibers of different strength. The tensile strengths are:

Lyocell 4.0–4.5 g/denier (Dry); 3.5–3.0 g/denier (wet)

Tencel 4.5–4.8 g/denier (Dry); 4.0–4.3 g/denier (wet)

The Young's Moduli are:

Lyocell 900 kg/mm^2

Tencel 1300 kg/mm^2

Consequently, Tencel finds application not only for clothes but also for industrial materials.

NewCell, as noted, is the name given for the first Lyocell filament yarn being developed by Akzo. It is meant to complement the spun yarns produced from Tencel staple fiber. A NewCell pilot plant has been erected at Obernburg, Germany, to carry out process engineering in preparation for upscaling to a production plant. As with the other fibers produced by NMMO technology, NewCell is able to offer the same advantages as the existing cellulosics, such as wear comfort, moisture absorption and versatility in applications. Its characteristics are:

1 It can be spun in very fine total deniers, and so can find new uses as it is a cellulosic microfilament yarn.
2 It has a tenacity in the dry state that is twice that of existing cellulosic filament yarns.
3 It has excellent dimensional stability in the fabric and the garment due to the low non-continuing shrinkage of the yarn and its reduced water retention.

4 It can be texturised and it has the ability to fibrillate.
5 Garments made of NewCell are machine washable, but unfortunately still have to be ironed.

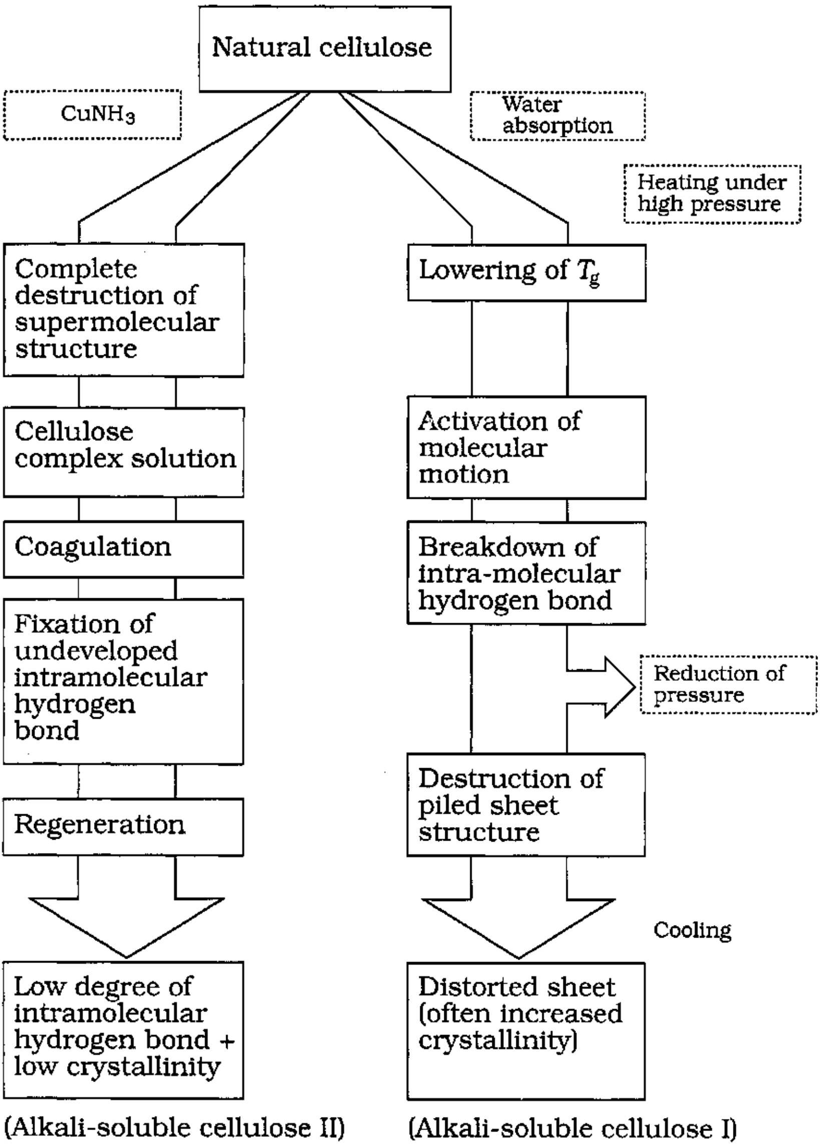
There is still some way to go in market development and it will be approaching the next century before the full potential can be elucidated.

Lenzing AG is putting its faith in Lyocell fiber and decided in May 1995 to install a 20,000 tonne per year production line which will go into operation step-by-step in 1998. Many technological hurdles needed to be overcome. Each of the companies is attempting to place its particular product in a market sector where its properties can be exploited. Lenzing emphasises the softness of Lyocell, which is not equalled by cotton, even when treated with enzymes and softeners. The dyeing behaviour too is comparable to other cellulose fibers. The basic high strength of this fiber makes it possible to treat it at different stages in the textile chain in a dry and wet state. A range of handle and look variations can be produced, the most popular being those that resemble wool or silk. The nature of the fiber offers considerable innovative potential, and clearly the race is on to gain the best from these new fibers.

8.1.2 Sodium hydroxide as a solvent

Sodium hydroxide has proved an interesting and important new solvent for cellulose. The dissolution process, however, cannot readily be achieved without some pre-treatment of the raw material. To utilise wood cellulose, lignin and other non-cellulosic materials need to be separated from it. Delignification of wood is carried out by a sulphite and prehydrolysed sulphate process. The end-use of the pulp determines the degree of signification required. Usually it is necessary to remove at least 50%, of the lignin, which then results in removal of at least 50% of the hemicelluloses and 10–15% of the celluloses from the wood also.

Several methods have, therefore, been tried to open up the wood structure and so make the cellulose more available for solvent systems. Preference, of course, is given in a practical situation to using various types of dissolving pulps, such as softwood prehydrolysed and hardwood sulphite pulps which can be made soluble in 9% sodium hydroxide by a combination of mechanical shredding and enzymatic treatments. These pulp fibers originating from the cell wall form ether and hydrogen bonded systems and contain cellulose with different degrees of polymerisation. The final reactivity and aqueous alkaline solubility of cellulose depends a great deal on the pulping process.



8.2 Underlying principle of the preparation of alkali-soluble cellulose (T_g = glass transition temperature).

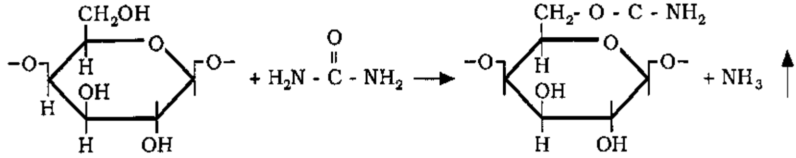
Generally, the enzyme systems that degrade native cellulose require a combination of individual enzymes which either randomly or systematically from the chain ends hydrolyse the polymeric chains. Such a combination of enzymes from well-known *Aspergillus niger* and *Trichoderma reesei* have been used for the cellulose activation in the Celsol method of directly solubilising pulp in 9% alkali. However, the most successful method to open up the structure to solvent is that developed by Professor Kanji Kamide and co-workers at the Fundamental Research Laboratory of Fibers and Fiber-Forming Polymers at the Asahi Chemical Company in Takatsuki, Japan. These workers used steam explosion on a commercial scale, but only after establishing exactly what changes were induced in the cellulose to enable it to become wholly soluble in alkali.

The principle of preparing alkali soluble cellulose is shown in Fig. 8.2. First using the steam explosion process cellulose in the cellulose I crystal form can be prepared. The solubility towards aqueous alkali is governed by the degree of breakdown in the O—H——O intramolecular hydrogen bond. Once in solution, a whole new world opens up and another processable fiber with cotton-like properties can be produced. The fiber produced in this way by Asahi is a triumph for basic cellulosic research, and demonstrates that once the nature of a chemical process is understood, then the potential for commercial exploitation s is considerably greater.

8.2 New cellulosic fiber derivatives

The Institute of Chemical Fibers, Lódź, Poland, has developed an original technology to manufacture fibrous cellulose carbamate, which has a range of potential uses. The chemistry is very simple as illustrated in Fig. 8.3. It is important for fiber making that the cellulose carbamate be specially tailored. The average degree of polymerisation of the cellulose should be lowered to about 400 and adjusted so that the carbamate groups are evenly distributed along the cellulose chain. A research group at Nesteoy, Finland, achieved these two preconditions by employing a liquid ammonia treatment to activate its structure including a change in its crystallinity and enabling the even intercalation of urea into the cellulose structure. The group also used ionising radiation to reduce the degree of polymerisation. The Polish process did not use the liquid ammonia step, and was replaced by other chemical activators to modify the super-molecular structure of the cellulose.

A small pilot-industrial manufacturing plant has been set up in Zaaklady Chemiczne "Viscoplast" S A, Wrocław, Poland, and as a result substantial quantities of the product are available for trials, and practical applications such as fibers, film and other technical products. This technology presents many advantages. Several types of pulp are suitable for manufacture of cellulose carbamate. Good spinning solutions can be prepared. Solution of 9 wt% in sodium hydroxide can be produced which are extremely stable. Moreover, it can be well blended with viscose to prepare stable and good



8.3 Scheme of reaction of cellulose with urea.

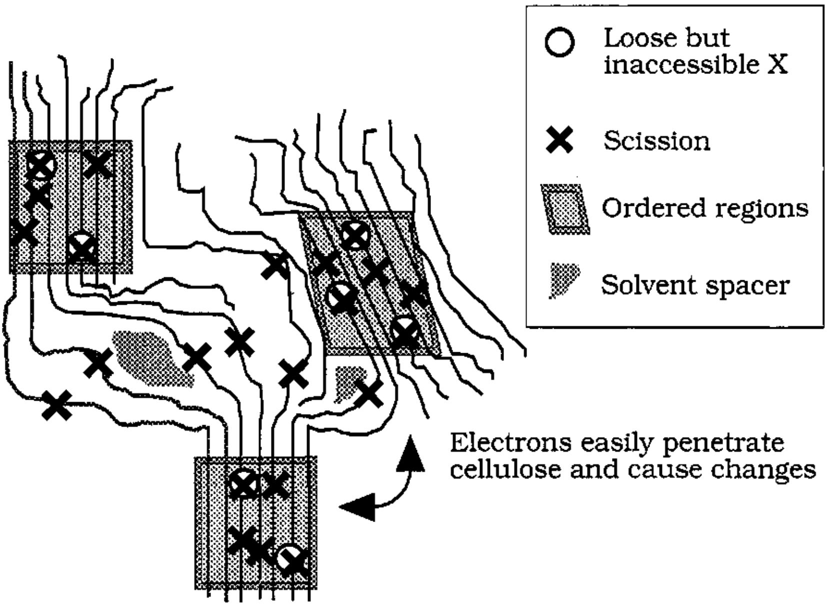
spinning solutions. The main objective for using the cellulose carbamate is to make fibers, which are spun by a wet method using coagulation as well as regeneration baths. The carbamate also has good film-forming behaviour. The major advantage is to allow this new process to replace the existing environmentally difficult viscose process in Poland. Most of the existing viscose fiber manufacturing equipment can still be used with the new technology. Moreover, cellulose carbamate is miscible with cellulose xanthate in the viscose process which enables a step-wise and safe introduction of the carbamate to the viscose process. It is of particular benefit to introduce greater water retention and produce high absorbent blended viscose fibers.

8.3 New environmental and cost saving developments

8.3.1 Electron processing technology

Chemical and physical changes are induced in cellulose when subjected to high-energy radiation. Degradation occurs due to chain scission and certain carbonyl and carboxyl groups are introduced into individual glucose units. The tertiary structure is also opened up, making the individual chains more accessible to solvents. Over the years such changes were regarded as harmful to the properties of cellulose, as for example cotton, which lost strength by this treatment. Recent work by Atomic Energy of Canada Ltd has demonstrated that the use of high-energy electrons, produced by an electron accelerator can induce changes in wood pulp which make it easier to process when used to prepare viscose. The changes are illustrated diagrammatically in Fig. 8.4. This new technology has considerable cost and environmental benefits and is now being considered by the major viscose manufacturers either for introducing on-line in their own viscose process or by having their pulp pre-irradiated at a central facility.

The changes and benefits that the electron process can introduce in the viscose process are illustrated in Fig. 8.5. Owing to the greater accessibility introduced by the radiation, the concentration of sodium hydroxide necessary can be reduced from 19% to 16%. The ageing step can be eliminated

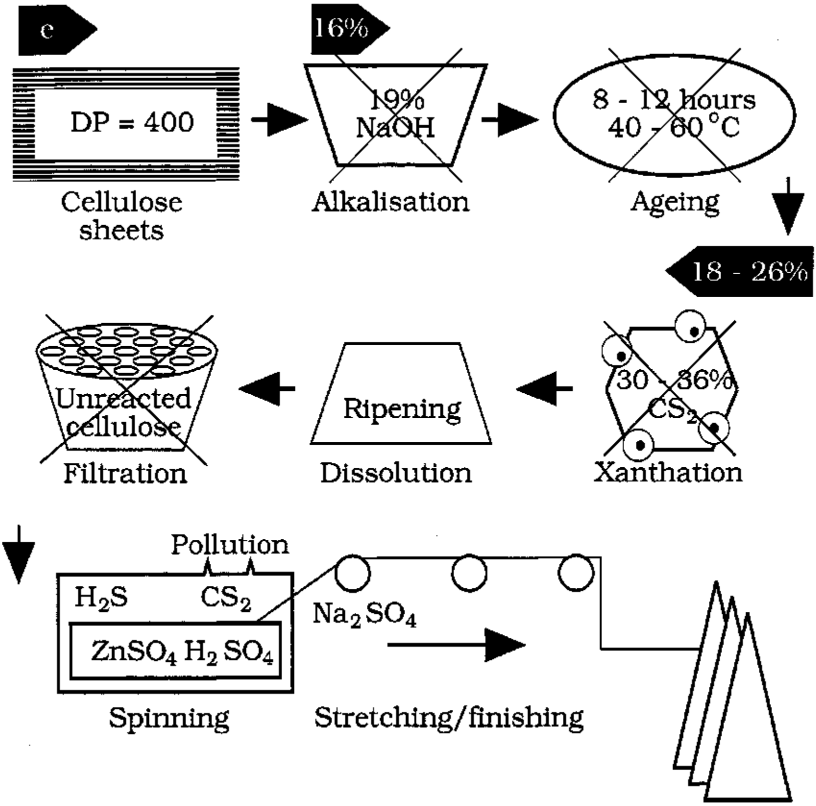


8.4 Supermolecular changes induced by electron processing (lateral view).

completely and the concentration of carbon disulphide reduced from the norm of 30–36 down to 18–26%. The unreacted cellulose which in the traditional process causes filtration problems is also removed. Figure 8.5 compares the effects of the electron treatment on each of the steps in the traditional viscose process. The benefits, therefore, are:

1 Significant chemical saving on carbon disulphide, sodium hydroxide and sulphuric acid.
2 Better product due to homogeneous xanthation.
3 Better process control.
4 Great environmental advantages.

In short, electron processing enhances cellulose reactivity, increases filterability, improves viscosity and allows the utilisation of a greatly reduced concentration of chemical reagents. These chemical savings amount to US$6 million per plant (60,000 tonnes per year) for carbon disulphide and US$0.5 million for alkali per year. Even greater, perhaps, in the current climate towards chemical pulping and viscose plants are the reduction of 40–50% in sulphide emissions, which also greatly reduce the clean-up costs. There is elimination also of the traditional ageing step. Undoubtedly, there are important advantages to be gained from introducing this new technology.



8.5 Changes to the viscose process induced by electron processing.

Note: cross through step indicates either elimination of the step or reduction in concentrations used after electron processing.

8.3.2 A total chlorine-free pulping process

According to public opinion, the production of pulp and viscose fibers is associated with heavy pollution of air and water by emissions of sulphur dioxide, hydrogen sulphide, carbon disulphide, chemical and biological oxygen demands (COD and BOD), and halogenated organic compounds (AOX). This aspect has proved the Achilles' heel of the man-made cellulosic fiber industry compared with synthetic fibers and the natural fibers. On a raw material basis, the variability in physical properties using fiber engineering and the problems associated with disposal, the new cellulosics are now approaching the stage where they can hold their own with their competitors. The pollution problem is, therefore, fundamental for their future well-being in the market-place. Reduction of emissions, the avoidance of hazardous chemicals, the economical use of limited resources and the development of new environmentally sound technologies present an important challenge in order to improve the position of viscose within the inter-fiber competition.

The Lenzing Company of Austria has shown the way forward. No other company could possibly have faced such stringent regulatory requirements as were imposed upon it in Austria. In response, Lenzing developed a unique strategy to meet the very strict requirements of the Austrian authorities. A waste-water project and a clean air programme were started in the early 1980s to reduce pollution drastically. But in the new circumstances that was not good enough. New technologies, unavailable at the time, had to be invented. Lenzing invested US$300 million and had to reduce its workforce by a third from 3,800 to 3,000 to retain its competitiveness. Now new key technologies are in place: the vapour condensate extraction, the medium-consistency ozone bleaching, and the thermal monosulphite splitting process all had to be developed *ab initio.* As a result Lenzing is now able to produce viscose fibers, which are totally chlorine-free and create a minimum of pollution during the production process. Such fibers are now considered to be the optimum raw material for medical and hygienic products.

The transformation has been remarkable. In 1982 Lenzing's waste-water load from pulp, paper and viscose production still equalled a population equivalent of more than 1 million, which was an acceptable value at the time. Within a decade it has been possible to reduce the waste-water load to 3,000 population equivalences, which is less than 1% of the initial value. Recovery of all materials used has been the key. For example, investment in a new recovery boiler with highly efficient flue gas desulphurisation reduced sulphur dioxide emissions from the pulp mill, energy and sulphuric acid production to about 20% of the 1985 value. The improvement was even more dramatic with regard to the odour-intensive component hydrogen sulphide. After starting up a new Sulfosorbon plant for carbon disulphide and sulphur recovery from lean gases and utilisation of hydrogen sulphide-rich strong gases for sulphuric acid production, hydrogen sulphide emission dropped to 2.5% of the 1985 value.

Energy savings too have been dramatic. Owing to the interlinked power economy of the pulp and the viscose factory and the thermal utilisation of residual substances from the process, such as bark, thick liquor, biological sludge, it is almost possible to eliminate the need for the use of fossil fuels.

The elements in this clean production process are:

1 Closed loop operation of spin bath and stretch bath.
2 High-yield recovery of sodium sulphate.
3 Steeping-lye purification by dialysis.
4 Incineration of waste lye with soda recovery.
5 Carbon disulphide and sulphur recovery in sorbon plants.

6 Production of sulphuric acid from hydrogen sulphide-rich gases.
7 Chlorine-free fiber bleaching.
8 Biodegradable additives.
9 Removal of zinc from effluents by precipitation.
10 Biological waste-water treatment.

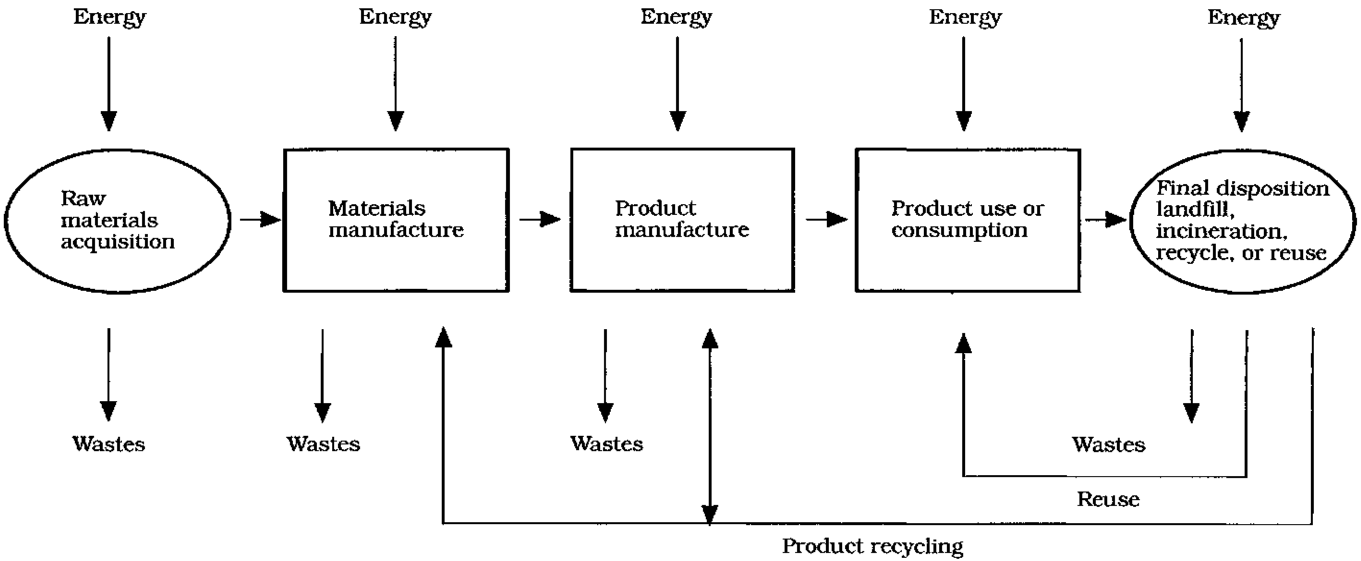
The overall consequence is a chlorine-free viscose fiber produced with environmentally sound technology. It meets the requirements of hygienic fiber consumers, and it is part of an ecologically closed life cycle based on the natural, replenishable raw material wood. This praiseworthy development points the way forward for the industry as a whole. The problems remain enormous in developing countries, particularly where the sulphate pulping Kraft process remains the most viable option with chlorine dioxide used to bleach the pulp. Increased environmental awareness will surely demand that all countries approach pollution control in global partnership.

8.4 Life-cycle assessment

The growing public and industrial interest in environmental issues has led to the development of different methods for the assessment of the environmental impacts from materials, products, processes and activities. A widely used method is the so-called life-cycle assessment (LCA). The purpose of an LCA is to quantify the environment burden from cradle to grave for a production system, including extraction of raw materials, processes, transports, use and final waste disposal, as illustrated in Fig. 8.6.

The Akzo Nobel AB Company has carried out an assessment of the environmental friendliness of the man-made cellulosics in comparison with the polyolefines. The amount of detail required for this analysis is quite extraordinary. It must be emphasised that the results are only relevant to the particular production system and the conditions pertaining to that country and site location. First, a flow chart of the life-cycle system for each product must be drawn up, starting with the initial natural resources.

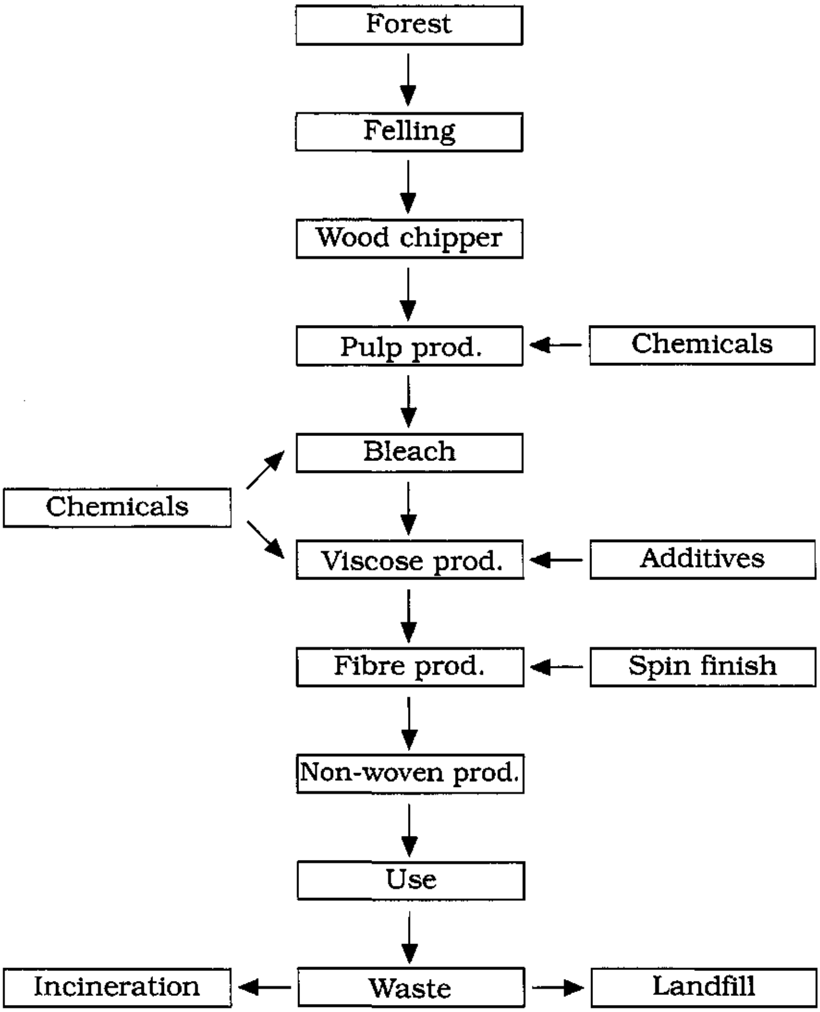
It is tempting to ask whether the cellulosic fibers are more environmentally friendly than the polyolefines. The Akzo Nobel AB study carried out this comparison, starting from the crude oil for polypropylene fibers and in the forests for viscose. From these natural resources, raw materials are extracted and used in various formulations to produce consumer products, some of which can be refused or recycled before being converted into waste. All stages in this life cycle contribute to the total environmental burden and must be taken into account. For an LCA, a standard structure laid down by SETAC, the Society of Environmental Toxicology and Chemistry, must be adhered to.



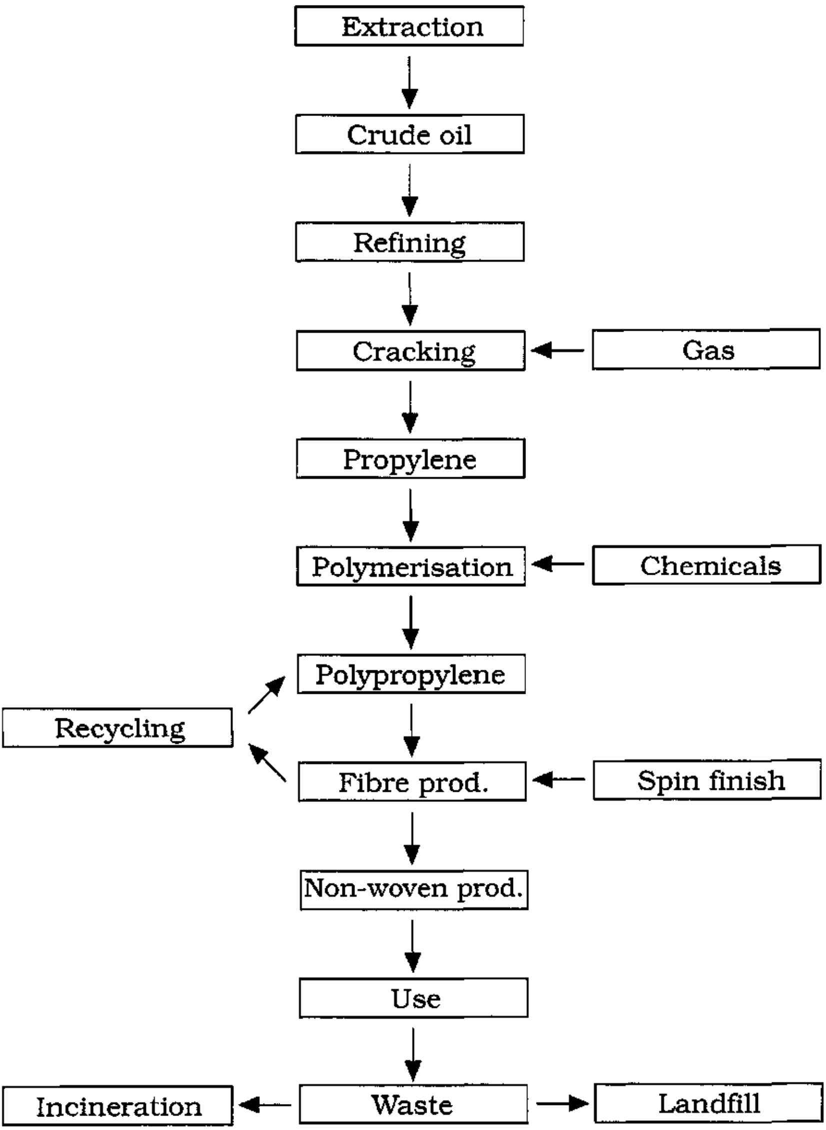
8.6 General materials flow for "cradle-to-grave" analysis of a product distribution system.

The individual components that must be quantitatively considered for the production systems of viscose and polypropylene are shown in Fig. 8.7 and 8.8.

Only the preliminary results are available, since the study has not yet been completed. It is not possible to answer the basic question unequivocally and decide which of the two products is most environmentally friendly in all aspects. However, the initial results are indicative of the different environmental impacts of the two products, and then, it must be emphasised, only for site-specific conditions in Sweden for the viscose data and an average value for European conditions adopted for polypropylene.



8.7 Stages in the production of viscose.



8.8 Stages in the production of polypropylene.

The total energy consumption is comparable for the two systems, including inherent energy of feedstock materials, but for viscose fiber almost half the total energy is based on renewable materials. For carbon dioxide which originates from renewable resources there is no net effect on the *global warming potential*, which is the situation that pertains for viscose, but not for polypropylene. Viscose, on the other hand has a greater impact on acidification owing to the emission of hydrogen sulphide, carbon disulphide and the sulphur and nitrogen oxides. However, greater amounts of nitrogen oxides and hydrocarbons are generated by polypropylene production. Undoubtedly, polypropylene production has a greater impact on photochemical oxidation. On the basis of the Swedish management it is more advantageous to incinerate both polypropylene and viscose with energy recovery than to deposit in landfills. However, since polypropylene has a higher heat of combustion than viscose, the energy recovery is higher. Overall, however, when considering the environmental impact based on global warming potential that might be expected over the next 20 and 100 years, the *photochemical ozone creation potential* caused by outlets of hydrocarbons, eutrophication brought about by emissions of nitrogen oxides and *acidification* brought about by sulphide, nitrogen and sulphur oxides emissions, it is the polypropylene that imposes the greatest environmental impact.

This type of analysis will inevitably be required for most products in the future as concern for the environment grows. Here the natural and modified cellulosics have a built-in advantage which they must energetically exploit commercially. The information can be used for fulfilling the need for eco-labelling criteria and as a basis for strategic planning for future product developments.

8.5 Cellulose: the renewable resource

It is important to recognise that the available resources of cellulose from wood represent a major supplement to oil-based polymers, and could well provide a means of tackling the inevitable critical problem of clothing the world in the future when oil is becoming depleted. There is now very active and successful research into developing fast-growing trees. From these, new fiber materials could be produced. The features of cellulose which can support such a development can be summarised:

1 Rigid segments that give good fiber-forming ability and high Young's modulus.
2 Various functionalities can be introduced by the controlled rearrangement of hydrogen bonds.
3 Moderate wettability and humidity-retaining ability provide comfortable clothing for the human body.
4 Superior biodegradability is a built-in factor when considering environmental protection.
5 The cellulose structure lends itself excellently to chemical derivatisation and so allow the ability to introduce special qualities.

Table 8.2 illustrates the already extensive range of applications, which will surely multiply in the years ahead.

Table 8.2. Cellulose and its derivatives

Type	Material	Application
Celluloses	Cotton, linen	Fiber, non-woven fabrics
	Powdered cellulose	Filter
	Micocrystal cellulose	Medical, chromatography
	Microfibril cellulose	Foods, cosmetics
Regenerated cellulose	Viscose	Fiber, tyre yarn
	Benberg	Fiber, dialyser
	Tencel	Fiber
	Spherical cellulose	Chromatography, cosmetics
	Cellophane	Food-wrapping film
	Sponge, non-woven fabrics	Domestic goods
Esters	Cellulose acetate	Fiber, film
	Cellulose nitrate	Paint, gunpowder
	Cellulose acetate phthalate	Medical (masking)
	Cellulose acetate buthylate	Plastics
Ethers	Methylcellulose	Cement mixture, sizing agent
	Ethylcellulose	Lacquer, paint
	Hydroxyethylcellulose (HEC)	Paint, latex
	Hydroxypropylcellulose (HPC)	Medical (adhesive), cosmetic
	Carboxymethylcellulose (CMC)	Foods, binder, adhesive
Etheresters	Various	Medical (masking)

9 Fibers for the next millennium

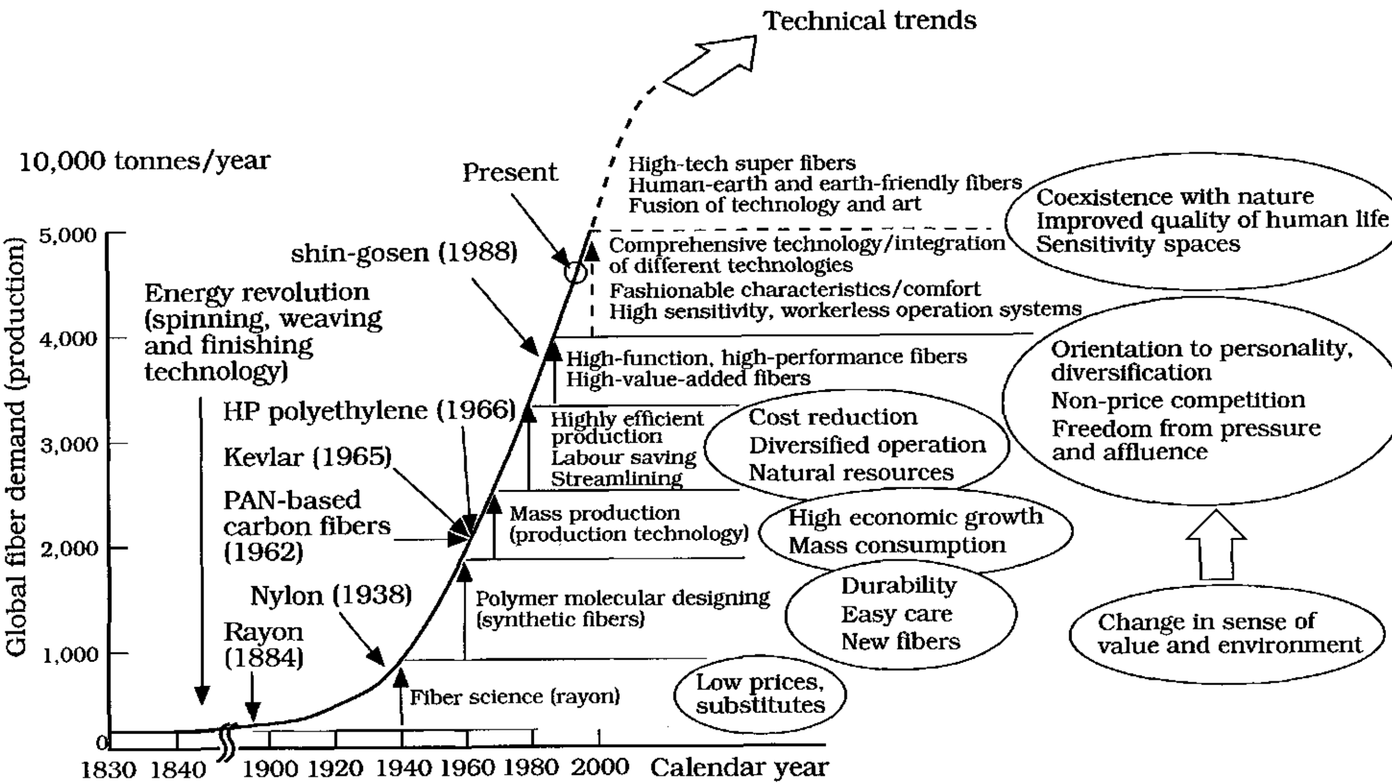
To look forward, it is necessary to look back and summarise the fiber developments that have been described in previous chapters. These are illustrated in Fig. 7.5. The key objectives have been to improve the performance, function and productivity of fibers. To achieve these aims, innovative technology was required. For the development of fibers with strength, super-high tenacity, and super-high modulus, new technologies needed to be developed. To reach the ultimate in fineness, a radically new approach was required. Since these will need to be the springboard for new innovations, the principles used should be identified.* On this foundation, the leap into the next millennium can be taken (Fig. 9.1).

9.1 High-tenacity and high-modulus fibers

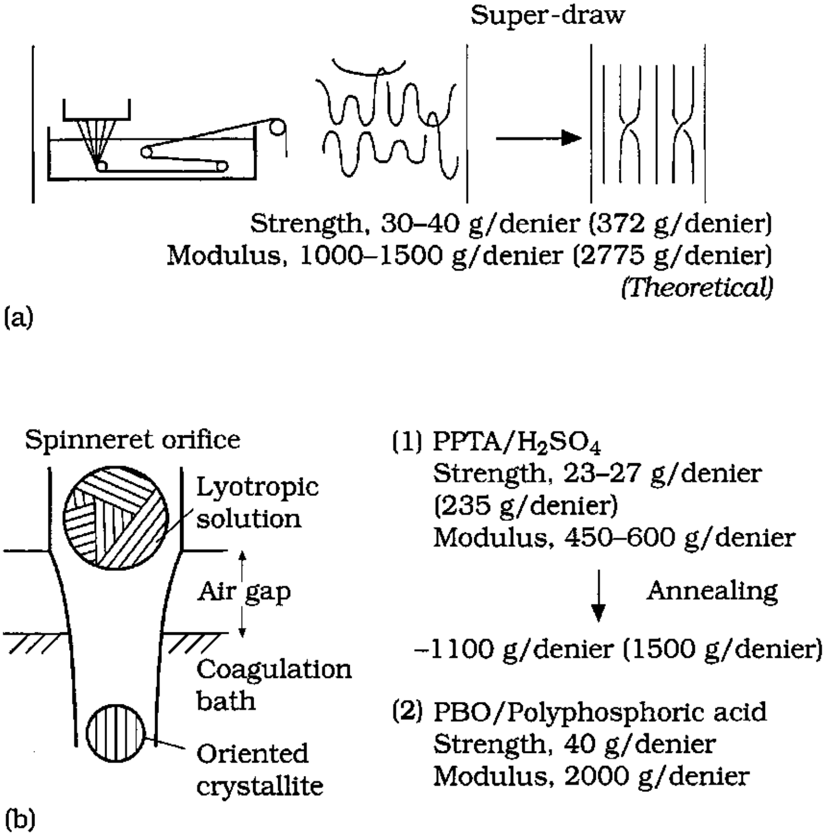
Four new fiber-making technologies have produced the "super-fibers", which need to have a tenacity of at least 20 g/denier, to qualify for this category. First is gel-spinning, super-drawing fiber-making technology that, after forming gel-like fibers by wet-spinning a super-high molecular weight polyethylene solution, draws out the fibers at a very high draw-ratio (Fig. 9.2a). Fibers produced by this process have greater tenacity and a higher modulus than any other organic fibers currently commercially available. Because of their low melting point, however, these fibers have only limited uses.

The second technology is a liquid crystal spinning process (Fig. 9.2b), which spins a liquid crystal solution of rigid polymers in a semi-dry and semi-wet state and then produces highly oriented crystallisation of rigid polymers by a spinning draft. The process uses a high concentration of sulphuric acid, as a solvent. Among typical examples of products using this process are the

* We acknowledge the material and illustrations from Teijin Ltd which have been incorporated into this chapter.



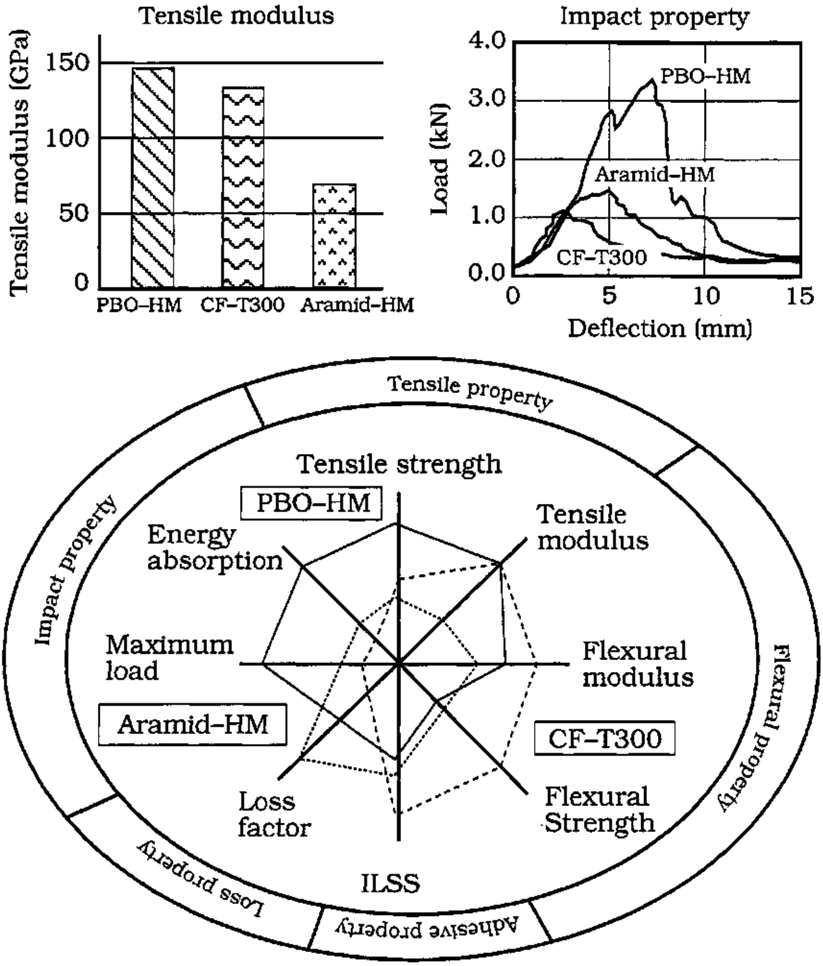
9.1 Factors of fiber technology and trends of fiber demand (production).



9.2 (a) Advanced technology for molecular orientation (gel-spinning and super-drawing). (b) Spinning of anisotropic polymer solutions.

para-aramid fibers such as polyparaphenylene terephthalic amide (PPTA). Aramid fibers have high tenacity and great heat resistance.

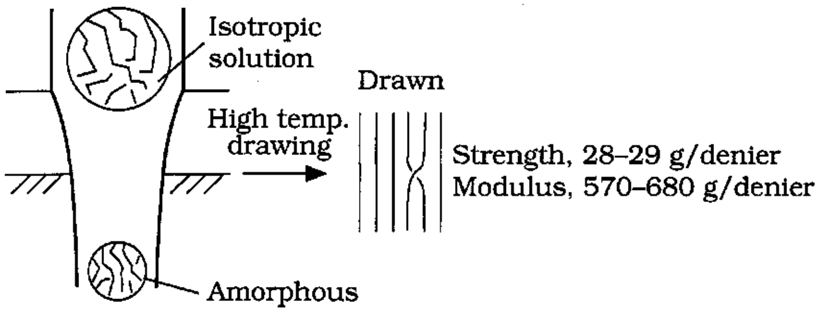
Another new product using this process is poly-*para*-phenylene bisoxazole fiber (PBO fiber), which has ultimate values in the modulus and tenacity. This can be regarded as one of the products for the 21st century. Stanford Research Institute acquired the basic patent, and Dow Chemical (USA) purchased the patent, and have enlisted the Toyobo Company (Japan), who now have developed a pilot plant for its production. It is a wonder fiber, stronger than steel, superior to carbon fibers, with twice the strength of Kevlar. A single fiber, a mere 1 mm in diameter is strong enough to lift 400 kg (the weight of a cow). Commercial production will start in 1998. PBO is polymerised from diaminoresocinol dichloride and terephthalic acid in polyphosphoric acid. PBO's second outstanding feature is its high Young's modulus, exceeding twice that of Kevlar. Most materials of high strength and Young's modulus,



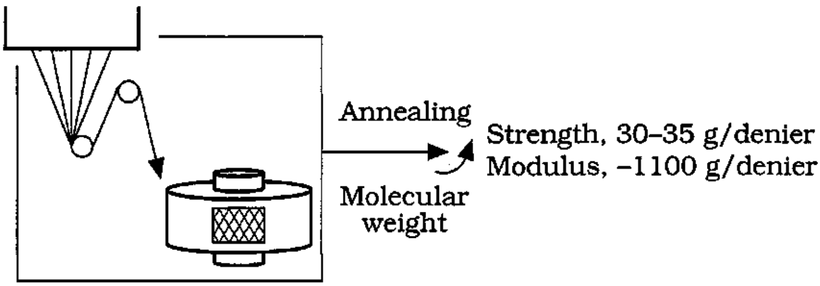
Advantages	Application
High tensile strength	Light-weight tension member
High tensile modulus	Pressure vessel
High impact property	Hybrid composite

9.3 Properties of PBO-reinforced composite.

like carbon fiber, are quite brittle, but PBO is strong, yet flexible. Its third important characteristic is its flame resistance. Flame resistance is measured by the limiting oxygen index, which is 56 for PBO, markedly greater than polybenzimidazole, the former record breaker at 42. Applications, well into the 21st century, could be as a heat-resistant cushion for aluminium and glass manufacturing processes, tension members for optical cable and cord,



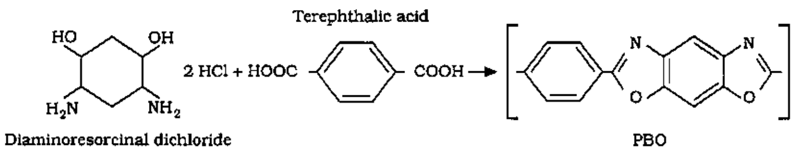
9.4 Spinning of isotropic polymer solutions.



Results
Modulus has almost reached theoretical value (ca. 80%)
Strength is 1/10 of theoretical value
A wide range of applications is expected

9.5 Melt spinning of thermotropic liquid crystal polymer.

composite cables for bridges, turbine engine fragment containing, etc. It is truly a wonder fiber. The properties are summarised in Fig. 9.3.



The third technology reforms the rigid *para*-aramid molecular structure and spins in semi-dry and semi-wet systems by dissolving in an organic solvent. Although the feed stock is in an amorphous state at the spinning stage, this new spinning technology highly orients molecules by hot-drawing at high temperature (Fig. 9.4). This technology uses an organic solvent instead of high-concentration sulphuric acid. The product has a greater tenacity than aramid fibers made by the liquid crystal spinning process, but its modulus is limited.

The fourth process gives super-high-tenacity to the fiber by melt-spin of semi-rigid polymers through heat treatment (Fig. 9.5). This technology, specifically for aromatic polyesters, does not use a solvent.

These new technologies have respective special features, and physically, some of them have provided a means of achieving a modulus closer to the theoretical value (i.e. *ca.* 70–80%), but in terms of tenacity, they have only attained one-tenth of the theoretical value. To achieve the ultimate in strength, more work is needed, but from a practical point of view, it may be argued that super-high-tenacity and high-modulus yarn-making technologies have already been established.

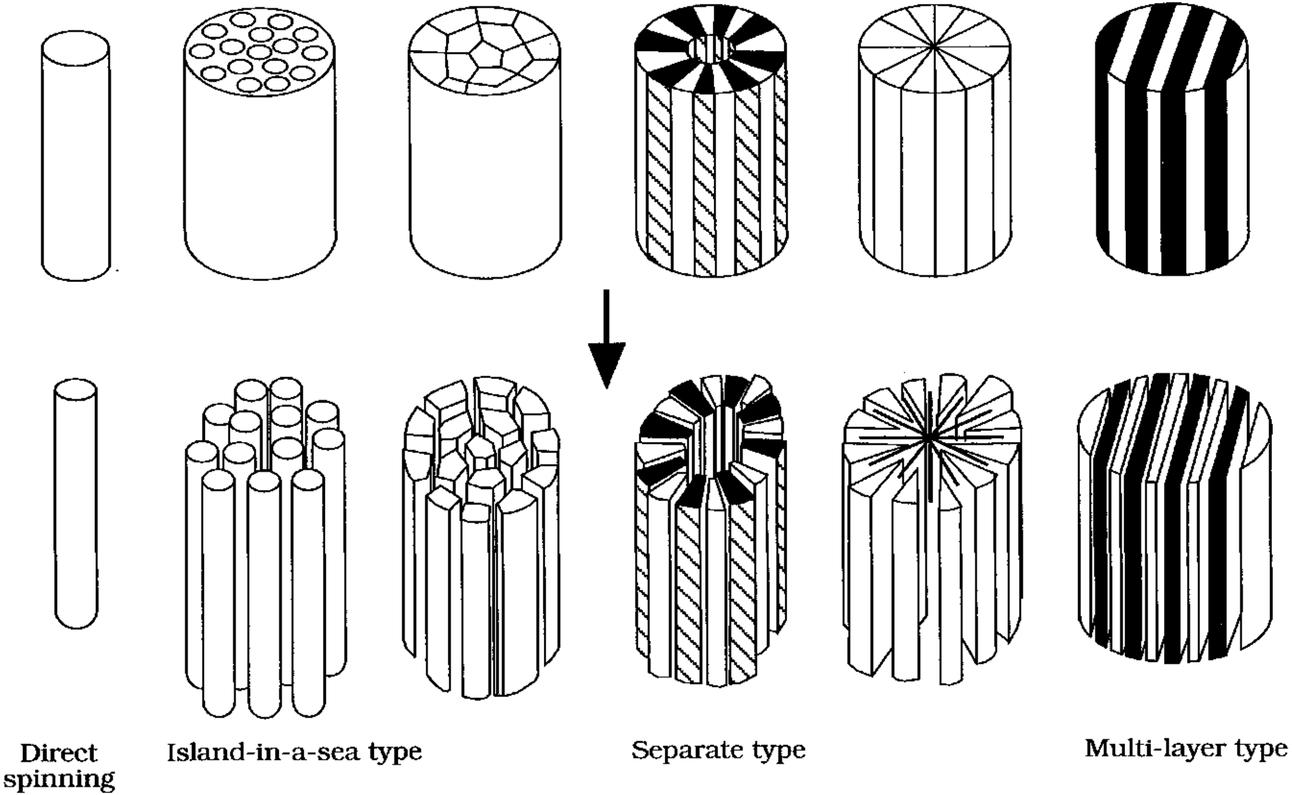
9.2 Microdenier (ultra-fine) fibers and biomimetics

Manufacturing processes can now make fibers of 0.0001 denier. Typical ultra-fine yarn-making technologies available can now be summarised. In this respect, learning from nature (biomimetics) has assisted greatly in planning fiber design. Natural fibers have built into them structures that enable them to perform specific functions within human and animal bodies. By replicating these technologically, high-performance, superior functions and high aesthetics can be achieved.

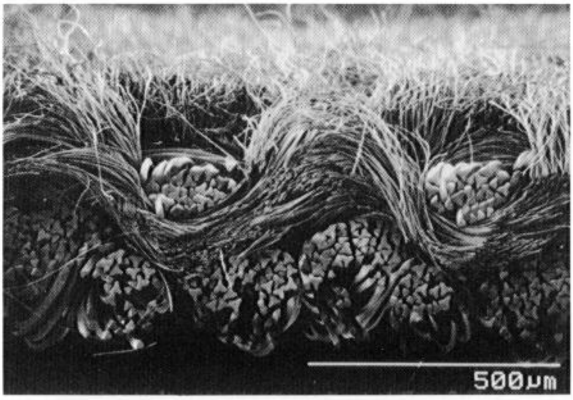
There are four methods to produce ultra-fine fibers as shown in Fig. 9.6. Direct spinning is simply an extension of conventional spinning, and has a technical limit with regard to the denier. The islands-in-the-sea type produces ultra-fine fiber of 0.0001 denier. The separate type allows ultra-fine fiber to be produced with a sharp edged cross-section and the multi-layer produces flat fibers of mixed denier. The elegant fibers that can be produced by these methods are shown in Fig. 9.7, which is a peach-skin type fabric, composed of ultra-fine fiber and trilobal cross-section fiber in filling and warp respectively. Figure 9.8 shows the new spun-type yarn composed of fine fiber as a sheath and thick conjugate fiber as a core.

To produce a synthetic with all the qualities of silk has proved a continuing challenge to the fiber scientist and technologist. It has now been achieved by a variety of technological innovations successively introduced. The silk features that have been replicated in synthetic fibers and the methods used to achieve them are:

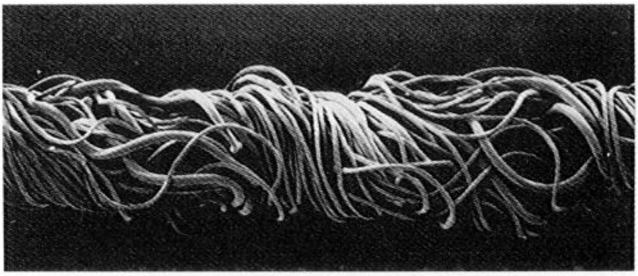
1 Lustre – triangular cross-section.
2 Drapability – lowering contact pressure between yarns by alkali weight reduction.
3 Soft feel – ultra-fine fiber.
4 Bulkiness – Mixed weaving, and combining fibers with self-extensionable yarn.



9.6 Methods to produce ultra-fine fibers.



9.7 Fabric from various ultra-fine fibers.

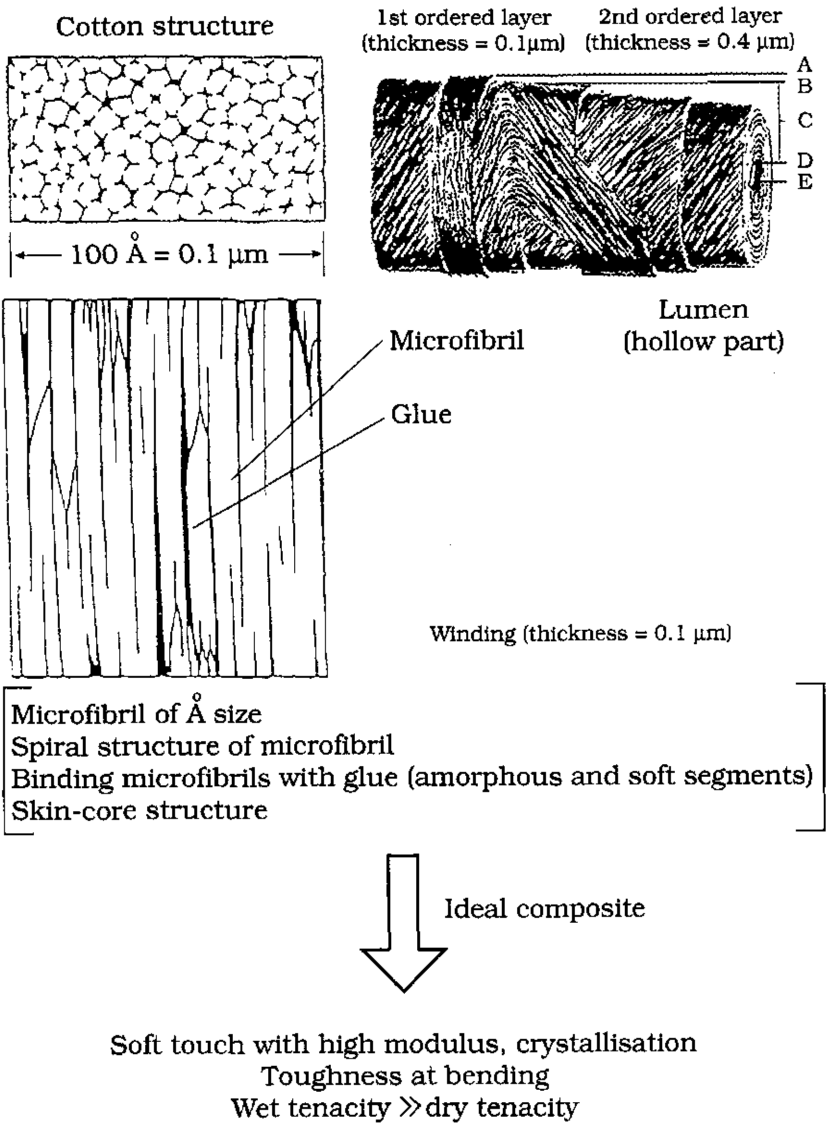


9.8 Yarn from fine fiber sheath and a conjugate fiber core.

5 Scrooping sound – introducing irregular shape and microgrooves.
6 Natural appearance – Combining various deniers and modifying and touching shapes in cross-section and/or combining filaments and staples.

Further improvement can be expected in the future by controlling fibrillar structure and moisture absorbency through amino acid compositional changes and fibrillar structure.

It is the bulkiness of wool that has been emulated, achieved naturally through its macrostructure which comprises crimps and staple fibers, resulting from bilateral structures consisting of *ortho*-cortex and *para*-cortex. To copy the crimps in wool, polyester fibers were similarly crimped using false-twisting technology, making the most of their thermoplasticity. A process was developed to give these polyester fibers a spun-yarn touch similar to wool by forming micro-loops through air texturising or by making the surface fluffy by nap-raising. The most difficult task was to achieve the opposing characteristics of wool, namely stiffness and resilience, but remaining soft to the touch. This was eventually achieved by simultaneously false-twisting



9.9 Future innovations: ideal composite structure – cotton.

filaments with different elongation. Wool also has excellent shape-recovery properties arising from the cuticle structure on its surface and the complex islands-in-the-sea and skin–core structures specific to wool. There are other characteristics, too, that have not yet been fully replicated, such as combined water-repellancy and moisture-absorption.

Cotton remains the most widely used of all fibres, and has posed complex problems in its improvement and duplication synthetically. The water-absorbing properties, which make cotton so desirable in warm climates, arise from micro-holes and lumens in its structure (Fig. 9.9). The challenge in the future is to replicate this structure, which is an ideal composite, as illustrated in Fig. 9.9. Some of these properties can be introduced into synthetics by emulation:

1 Sweat/liquid absorbency – modified cross section, and introducing porous/hollow fiber.
2 Warmth retention – high degree content of hollow filament.

However, synthetics have not been able to replace cotton and the new man-made cellulosics (Chapter 8) appear now to be the best method of obtaining the combined properties of cotton and the synthetics, rather than trying to modify the synthetics to copy cotton. There have been other properties introduced into synthetics not provided by the natural fibers, but these can be combined with those features that have been described. They include combined moisture permeability and waterproofing, electrical conductivity, antibacterial and odour-preventive qualities, fragrance and wood-aroma, stretchability, ultraviolet radiation resistance, intra-hospital infection capability and ultra-light weight.

9.3 The next stage: technological improvements

Certain technological innovations can be envisaged, although they are not yet fully achieved. The reduction in cost and improvement in productivity are two tasks that must be successfully addressed. Already much has been accomplished. In polymerisation, for example, continuous processes have expanded production from 100 tonnes in 1986 to 300 tonnes in 1996. Speed of filament spinning has increased from 4,000 m/min in 1986 to 7,000 in 1996. In the staple fiber sector, the main progress has been in the expansion of capacity, rather than in spinning speed, and capacity has been raised from 70 tonnes per day in 1986 to 130 in 1996. Meanwhile, the texturing speed for draw-textured yarn has increased from 700 m/min to 1000.

Rationalisation of the manufacturing process is a vital part of reducing production costs. Previously, polymerisation, spinning, drawing and texturing were performed by four independent processes. Now, continuous spinning and direct drawing technology consolidate the spinning and drawing processes. Production of textured yarn is now rationalised, with either the polymerisation and spinning stages directly connected or with unified drawing and texturing processes. Meanwhile a large-capacity spinning process, directly connected with continuous polymerisation, has been adopted for staple fiber production, resulting in significant cost reductions. The manufacturing process for filaments has already been developed into a continuous polymerisation, direct spinning and direct-drawing technology that has all three stages linked. Now, also, an integrated process comprising polymerisation, drawing and texturing has been developed in nylon carpet production.

Simplification of manufacturing processes has been achieved, particularly in high-speed spinning and direct fabrication of sheet fabrics. Spun bond and melt blow technologies are now available which directly gather spun filaments or fibers on the net and directly fabricate them into non-woven fabrics. These processes will surely be extended further in the years ahead.

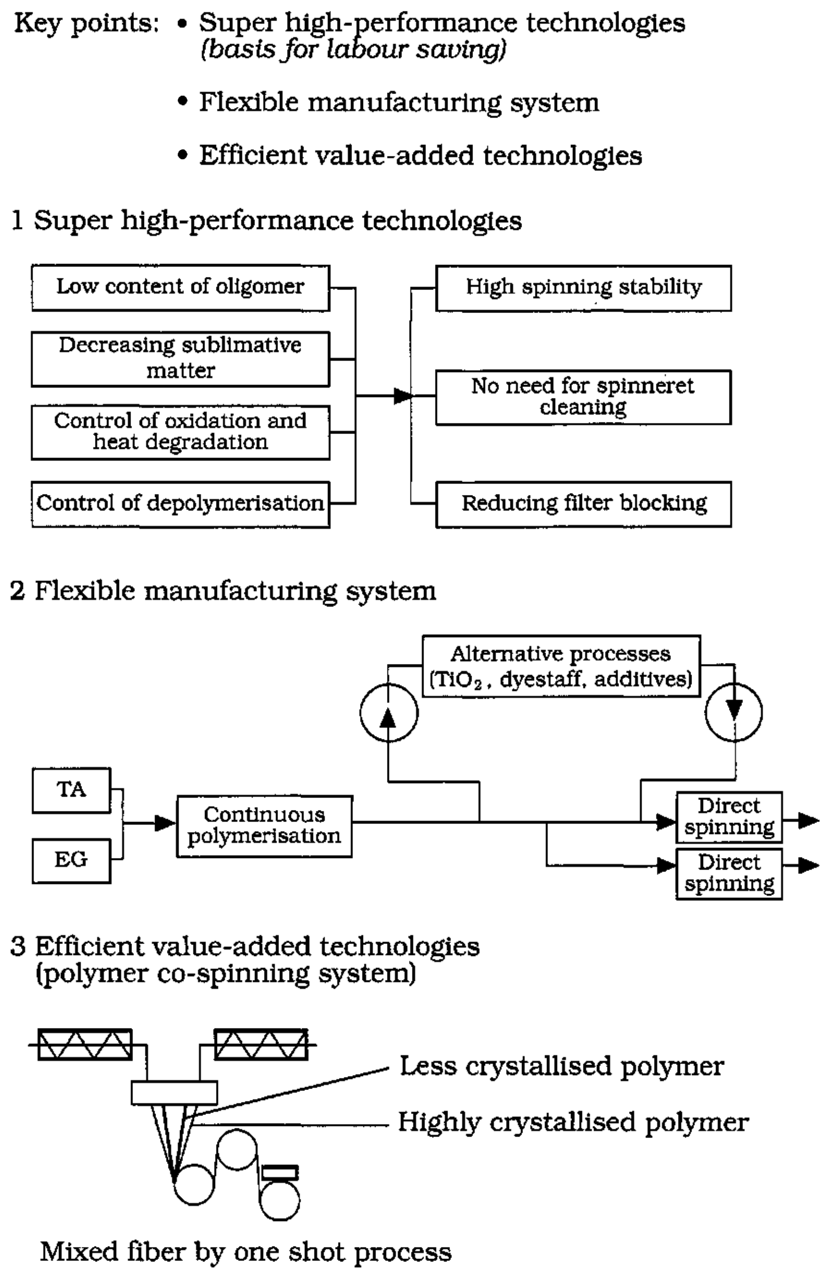
Further possible improvements in the manufacturing technologies are illustrated in Fig. 9.10, which push forward the improvements already evident. Automation and a stable trouble-free technology, with flexibility, will be required.

9.4 The next century: respect for people's quality of life and harmony with nature

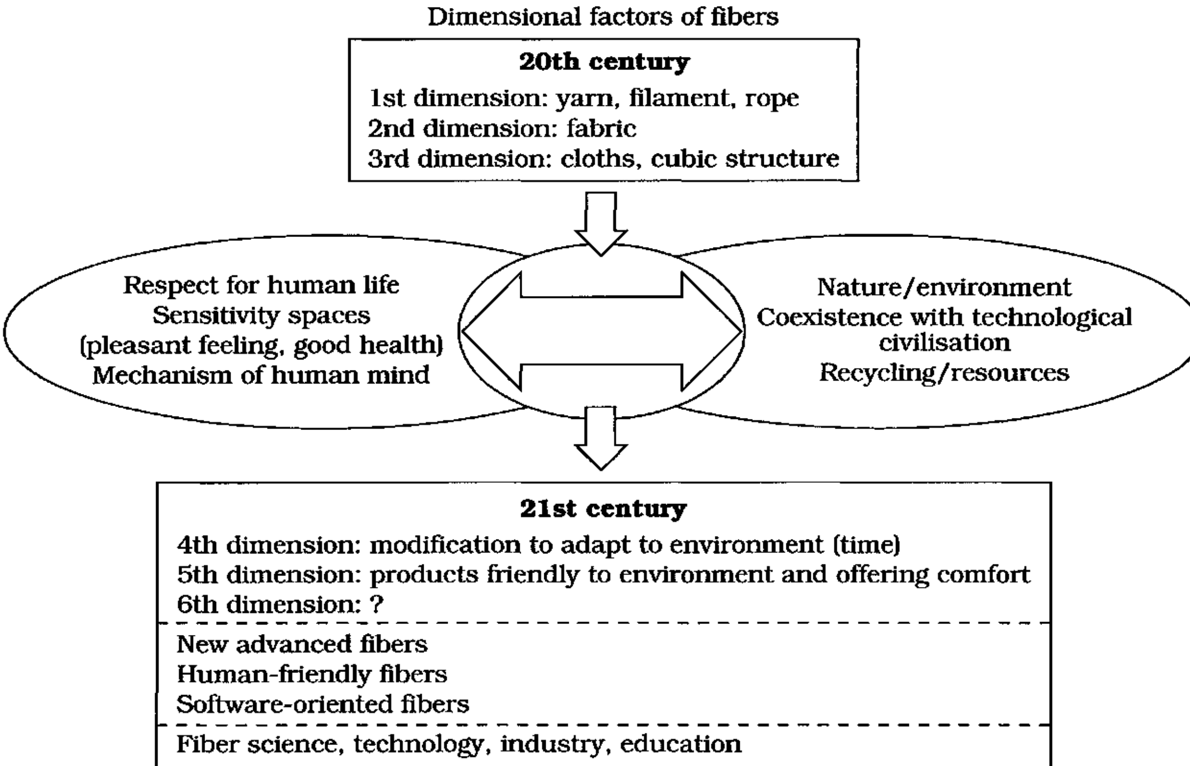
In the past, priority was given to the objectives of manufacturers, including highly efficient mass production, but in the future, more attention must be given to consumers' interest and the quality of people's life. Harmony with nature should also be taken into consideration. A problem to be solved is how to incorporate those factors into business. Research emphasis will inevitably be shifted from hardware to software. Figure 9.11 illustrates the concept of the dimensional factors for the next generation of fibers. Essential to progress is a partnership between fiber science and technology, industry and education. Figure 9.12 illustrates the fundamental directions that fiber science must encompass in the next generation if the new concepts are to be introduced into fiber design and manufacture.

9.4.1 Dimensions and structural control of fibers

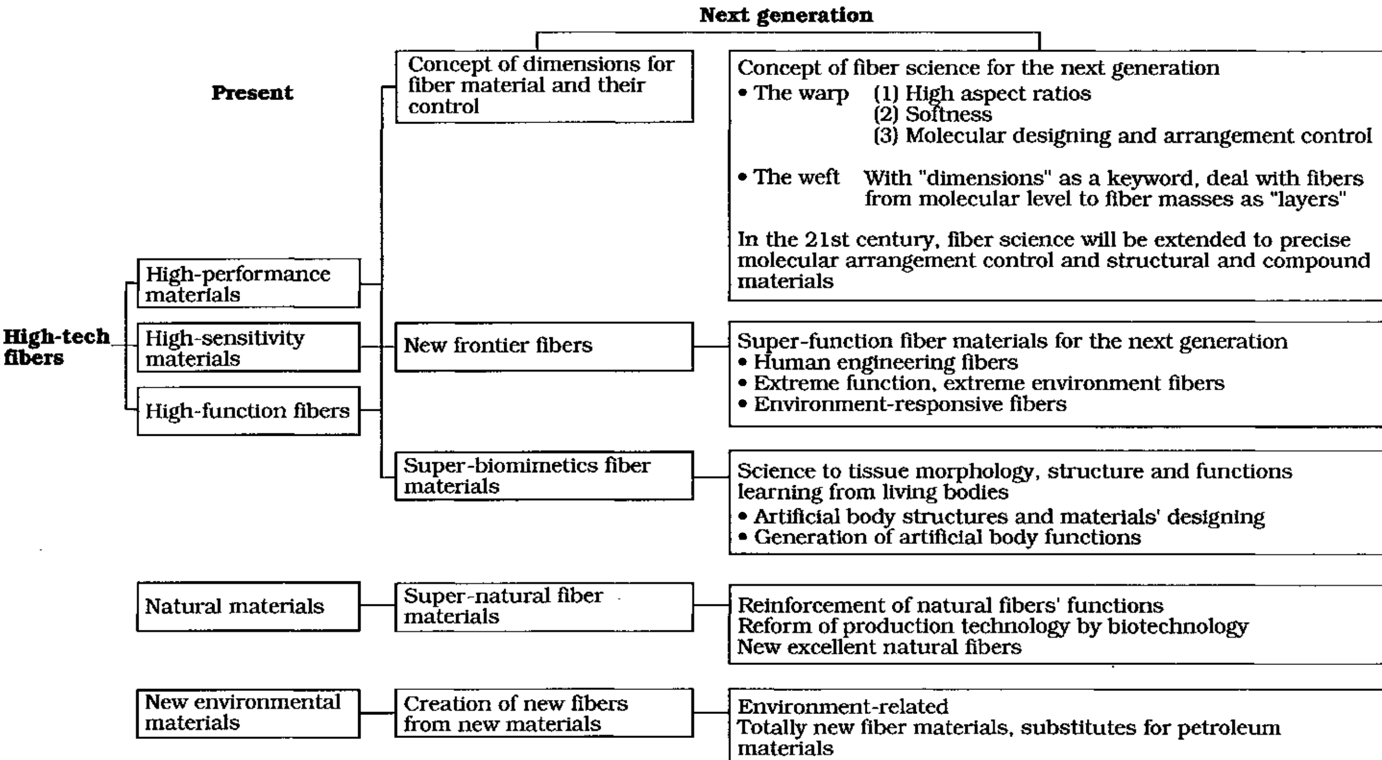
A fiber can presently be defined as the unit composing yarn, fabric, etc. which has a sufficient length relative to thickness and is thin and easy to bend. This agrees with the macroscopic definition of fibers that are used, not only for clothing, but also for medical and industrial purposes. For example "dietary fiber" consists of a staple so minute that it cannot be seen with the naked eye; artificial kidneys use hollow fibers. Super-fibers stronger that steel wire have been developed and are used in the fields of sport, recreation and aerospace. The word "fiber" encompasses not only a mass of threads but nerve and



9.10 Future improvements of production technologies.



9.11 Concept of dimensional factors of next-generation fibers.



9.12 Fundamental directions of fiber science for the next generation.

muscle fibers also. Thus the element of "size" from the term "fiber" can be removed and enable redefinition of the term as "a thin and long substance with strength and elongation of a certain level or greater". Because it is by definition thin, the fiber is able to bend (degree of freedom). To characterise the thin and long character of fibers numerically the ratio (*L*/*D*) of their length (*L*) to their diameter (*D*) is useful; this is known as the aspect ratio. The fiber can be defined as a material that has an aspect ratio of 100 or more.

The diameter of existing fibers ranges from a few to scores of μm. If we apply the definition of fiber with aspect ratios down to molecular levels, we can consider the possibility of fibers with a diameter of the order of an angstrom. Such fibers are represented by linear polymers, such as cellulose and polyethylene which are referred to as molecular fibers. DNA is similarly referred to as a nano-fiber. Thus, the term fiber can adequately describe a range of thicknesses ranging from molecular polymers (1–10 Å) to the thinnest fibers that can be spun (1 μm) to twine (1 mm) and hawsers for ships (100 mm).

Within this broad fiber definition, three targets must be set: (1) exploitation of the morphological characteristics of fibers, (2) scientific and technological pursuit of softness; and (3) extend the performance and function of fibers by molecular design to control the warp and dimensional structure.

9.4.2 Next-generation fibers and dimension

9.4.2.1 Fibers as first-dimensional materials

Because fibers have the morphological characteristics of being thin and long, they are referred to as the first-dimensional materials. To exploit the characteristics of these first-dimensional materials thoroughly is one of the directions fiber science must take in the future. For example, an extremely fine filament has been experimentally produced, which can reach the moon (384,400 km) with a total weight of only 4.16 g. Other new filaments can envelop the Earth with a weight of only 1 g. Researchers, however, have not yet controlled the boundary between the macroscopic fiber structure and chain-like high polymer molecules composing it, nor have they established the technology for isolating molecular chains and dealing with them as independent fibers. We still do not know what characteristics will emerge in the property of the fiber materials when the fibers become much finer and increase their surface and interface.

9.4.2.2 Fibers as high-dimensional materials

The techniques for providing fibers with a higher-dimension aspect has been exploited for the production of synthetic fibers, where cross-section is modified into a non-circular shape or is made of multiple components. For example, non-see-through white bathing suits are made of the new fabric produced by combining several different materials and modifying the shape of fiber cross-section. By applying the idea of higher dimensions to the structure, like the scales of wool, it might be possible to create a synthetic fiber with a different frictional coefficient according to the direction of the force. The higher dimension of fibers can be realised by modifying the molecular arrangement in a specific manner. If the molecular arrangement can be modified specifically according to the location of molecules in the cross-section, the mechanical property of the fiber can be designed at its molecular level.

In future, new fiber materials could be produced where the cross-section has a slanting or non-continuous layer structure by arranging molecules specifically in a radial direction of the fiber cross-section or by combining structure-controlled fiber materials.

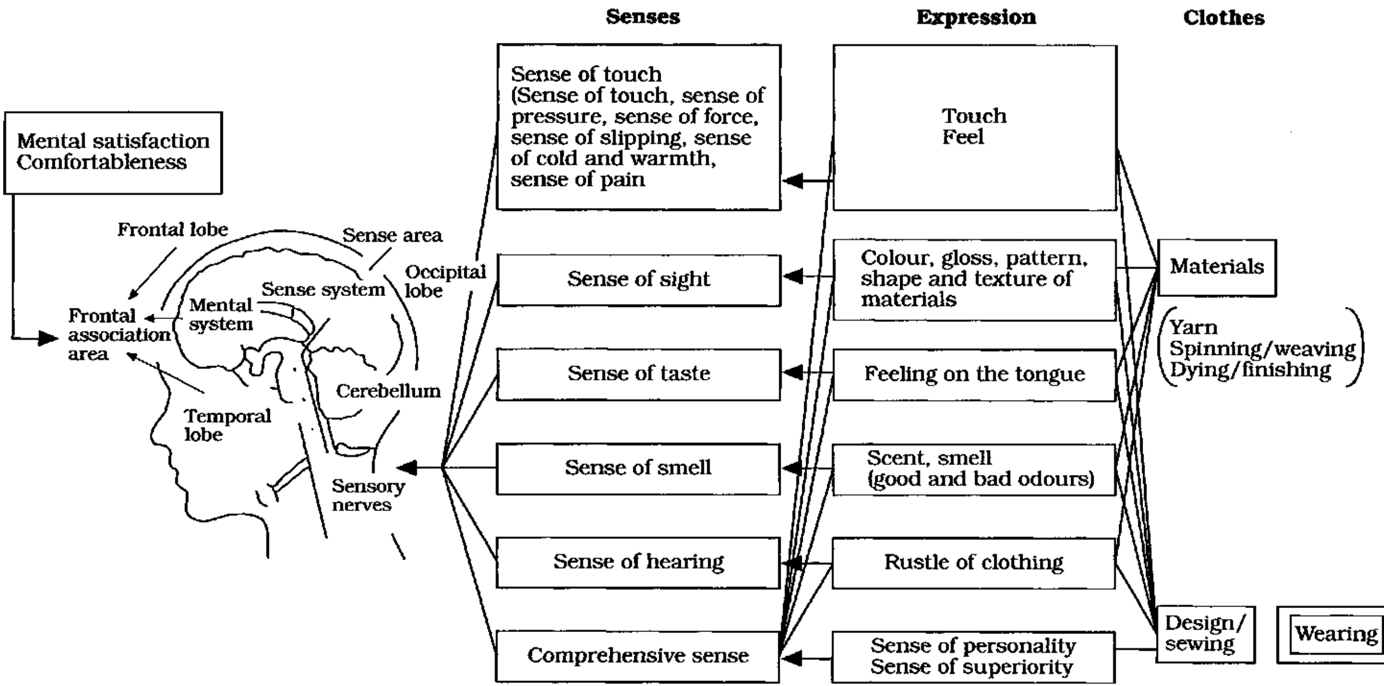
9.4.2.3 Super-dimensional fiber science

It is also important to expand the potential of fiber materials by introducing the concept of time and space dimensions. The ultimate goal is to provide fibers with intelligence that could introduce sensor-actuator function to fibers. To do this, a system with a particular purpose must be built into the fiber materials. Here we need to integrate a broad range of knowledge and technology, covering the research areas of molecular design, molecular composites and high-order structural control of fiber materials.

Since fibers are regarded as the materials of sensibility, a new type of technology should be developed to exploit the full capacity of fibers. Here human *Kansei* (*Aesthetic*), corresponding to aesthetic engineering must be evaluated quantitatively, and then correlated with physical quantities specifying fiber characteristics. Conventional physical quantities will not be sufficient to specify the fiber characteristics fully, and a new concept such as fluctuation, fractal or chaos will be required to extend the range of observable physical quantities. In other words, the technological strategy should be shifted from hardware-oriented to software-oriented. The software-oriented technology may be able to create novel fibers of high sensibility which we cannot fully conceive at present.

9.4.3 Systemisation of software fiber science

Today's consumers demand more of what will enrich their life. They desire new standards in areas such as health, amenity and education. In the next

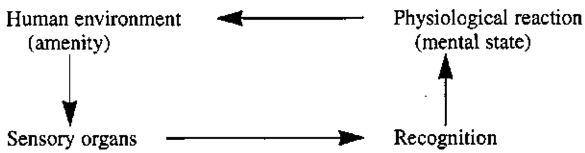


9.13 Mechanism by which a suit is felt comfortable to wear.

generation, such unprecedented new aspirations may determine the quality of fiber materials, so that a new system needs to be developed urgently to evaluate human sensibility.

"*Kansei* (Aesthetic) engineering" has now become a full-fledged field of science in Japan in order to deal with human mental activities such as the appreciation of beauty. People are becoming more interested in the pursuit of sensibility. Technology and art became two independent subjects with the development of modern industries, but now they are expected to amalgamate to create new commercial values.

The scientific study of the mechanism of the human mind includes mental activities for appreciating aesthetic beauty. We interact with the environment through sensory organs, which input outside information, conveyed by the nervous system to the brain to be processed and fed back. We feel comfortable when such processed information is recognised as being agreeable, but there seems to be no definite criterion which fluctuates according to the mental state. So it becomes important to develop a system for value judgement through the analogous cycle:

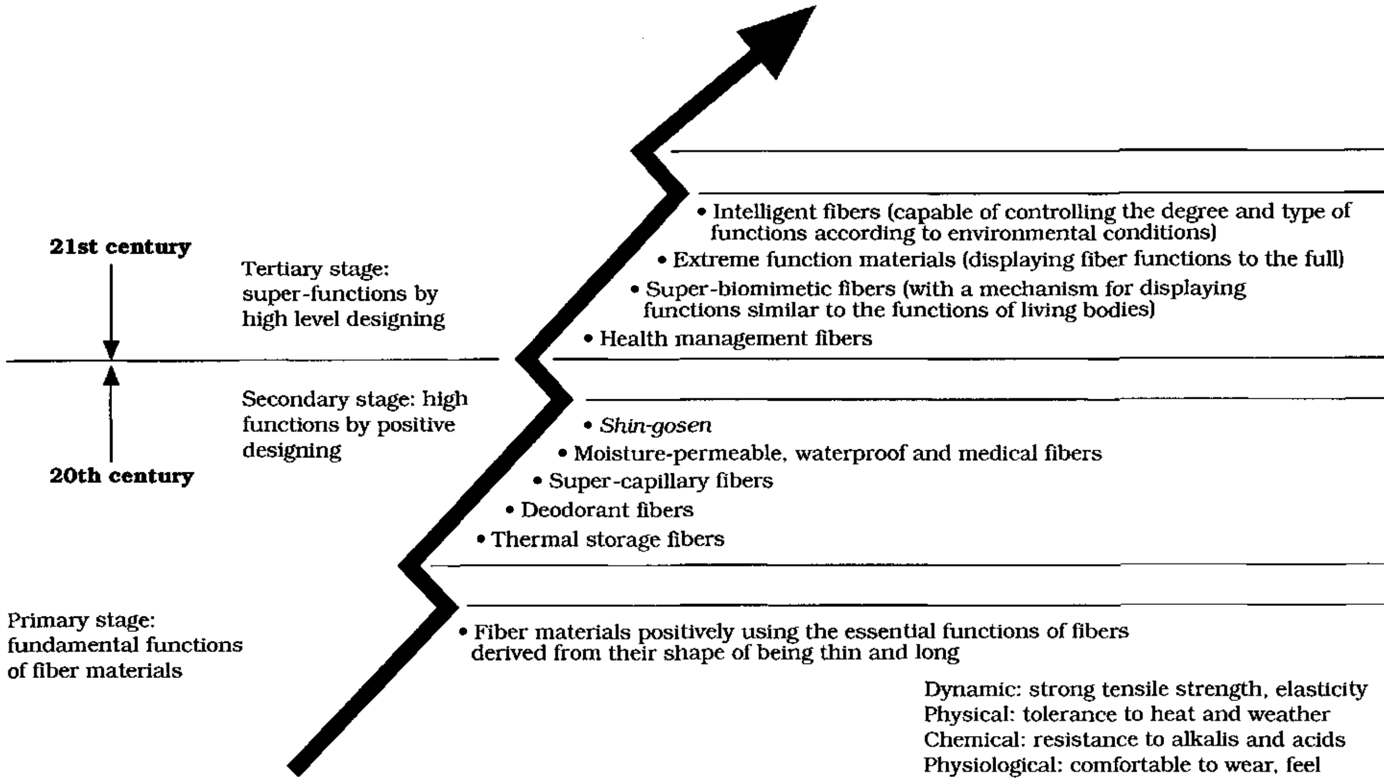


This cycle may be a model of the mechanism by which we feel when a suit is comfortable to wear. If we understand the mechanism, we can evaluate the comfort of clothes and other environmental factors quantitatively. Figure 9.13 illustrates this mechanism.

9.5 New frontier fibers (super-function fiber materials, etc.)

The term "new frontier fibers" implies opening up a new area of advanced high-tech fibers. These next generation fibers should be those products whose functions are highly designed and controlled by the fusion of fiber science and other fields and should have tertiary functions, that is, super-functions. Examples include intelligent fiber materials that can control their own functions according to the environment and "super-function fiber materials," such as optical fibers, in which functionality is incorporated into the fiber. Figure 9.14 shows the development steps necessary to produce such functional fibers for the next generation.

In a society where human needs have priority, attention must be paid to



9.14 Development steps of functional fibers for the next generation.

possible impact on the global environment in developing super-function fiber materials, with such performance as strength, elasticity, heat resistance and environment tolerance and having optical, electronic and magnetic properties. In addition, a broad range of problems, including harmony between people and fibers, between communities, fibers and human mental activities, should be addressed. Mind, sensibility, health, animal and plant systems and comfort should be dealt with as the subjects of human engineering. Figure 9.15 gives examples of the research areas and social infrastructure for such *Kansei* (aesthetic) engineering.

9.6 Super-biomimetic fiber materials

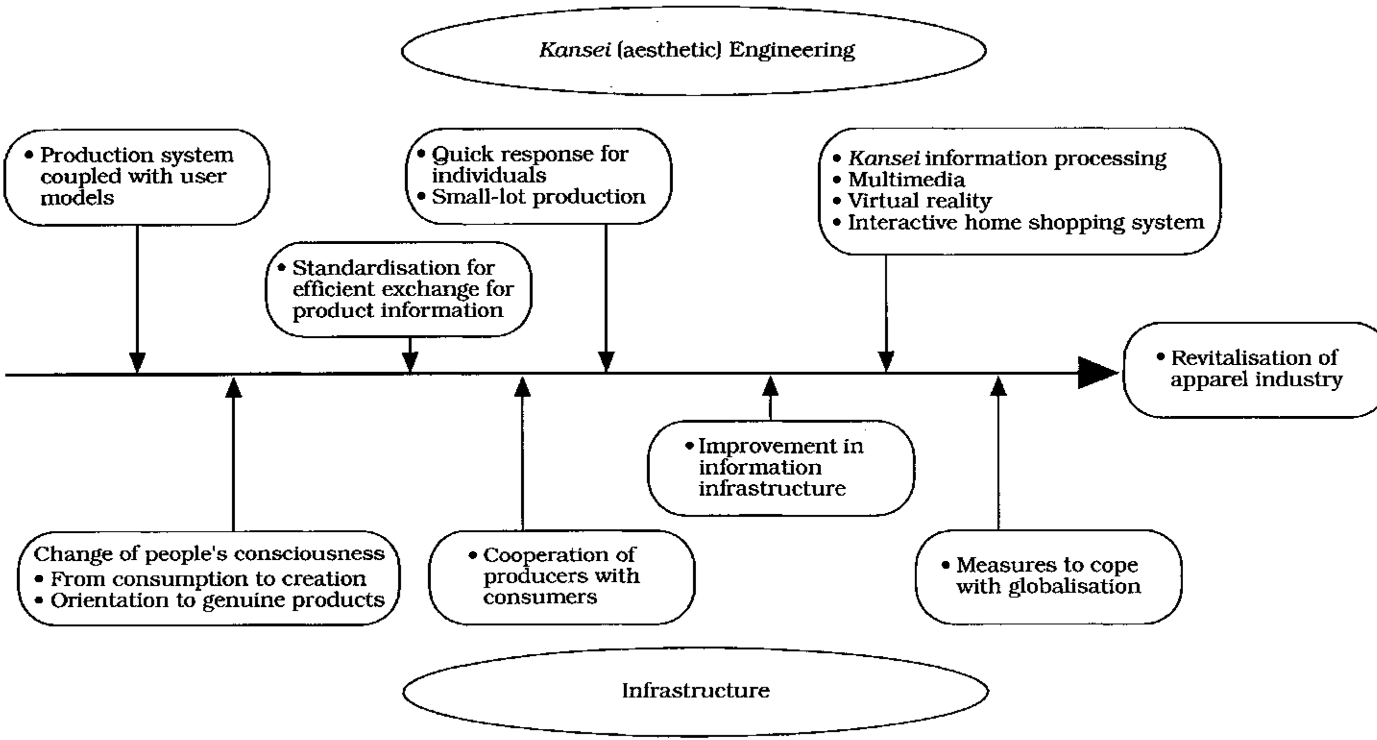
Biomimetics, the design of new fiber materials through the study of living systems, has already achieved a great deal (Fig. 9.16). Because of this, it is certain that learning from the system of living bodies and studying their structures and functions will be important to the development of fiber science and technology in the next generation and will provide a fund of new ideas and concepts. "Super-biomimetic fiber materials" can be developed in this way. However, this does not mean the mere copying of living bodies: it is to make clear their structures and functions, to learn from their high-level mechanism of displaying their functions, and to apply the mechanisms to molecular design and materials design. An interdisciplinary approach will be required to achieve this.

9.7 Super-natural materials

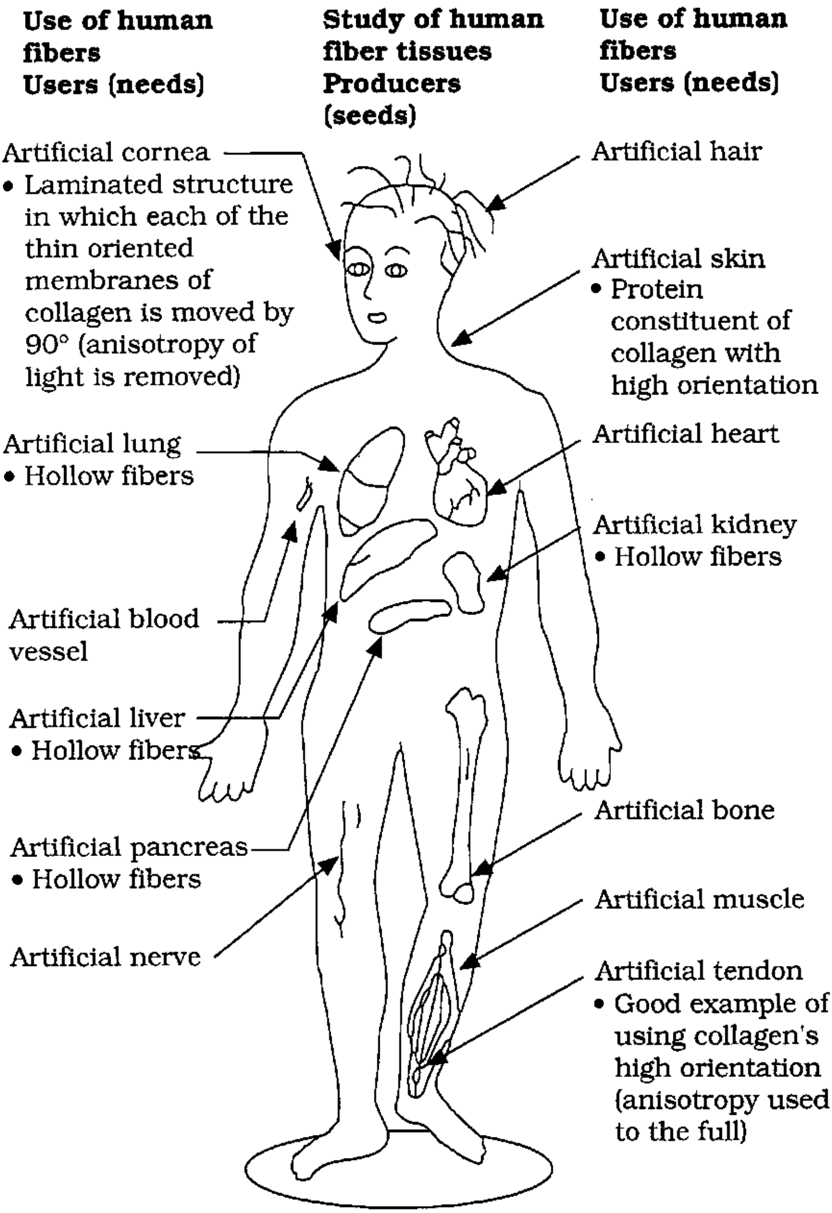
Biotechnology has the potential to produce environmentally friendly fibers from polysaccharides, proteins and other materials found in nature. Figure 9.17 illustrates what can be achieved using polysaccharides.

The research and development of synthetic fiber materials which began to develop in the first half of this century is heavily dependent on petroleum. The world's production of raw fibers is increasing mainly as a result of growth in synthetic fibers and the output of chemical fibers is now nearly half of that of all fibers. However, the reliance of chemical industry on petroleum will reach its limit sooner or later.

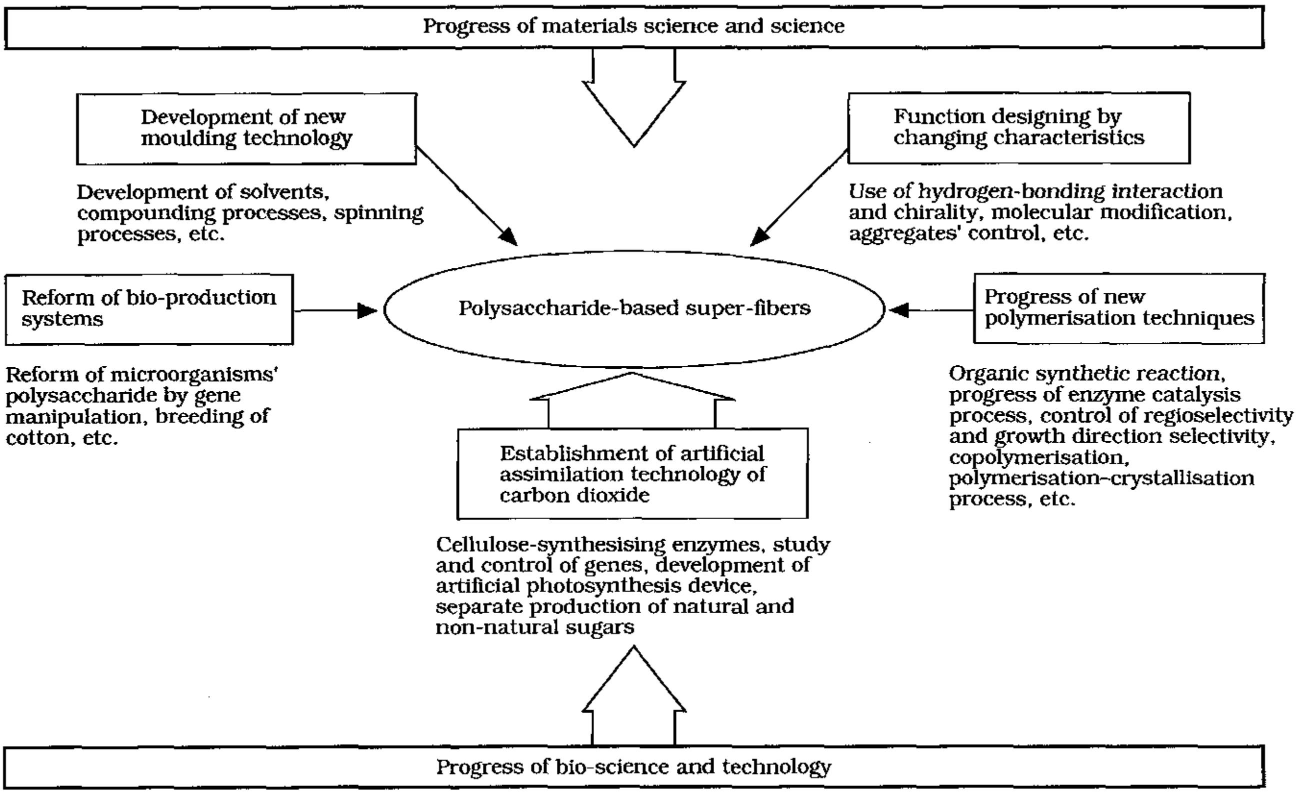
In view of the rapidly increasing global population, it is very important to promote further the recycling of resources and to strengthen efforts to save energy and other resources. It is also essential to continue research and development on new, environment-friendly fiber materials. Potential fiber materials include, for example, wood-based biomass (including wood cellulose), starch, biodegradable polyester, carbon dioxide, coal and amino



9.15 Research areas and infrastructure of Kansei (aesthetic) engineering.



9.16 Designing of materials better than living bodies by learning from them.



9.17 Process of creating new polysaccharide-based super-fibers: four basic approaches and a challenge to realise a dream.

Table 9.1. Forecast of the development of fibers and fiber science in the next generation

(Year) 1995	Super-functions	Super-performance	Raw materials and production technology
2005	● High-sensitivity fibers ● High-performance antibacteria fibers	● Super-strong fibers substituting for asbestos ● New fibers with multiple layers and diverse structure	● After-processing, workerless production of synthetic fibers ● Designing system to cope with consumer preference to personality
2015	● Environmental change responsive fibers (intelligent fibers; having difference in performance) ● Biodegradable fibers	● Super-fibers in the second generation ● Good cost-performance super-fibers	● Fiber recycling technology (having difference in technology) ● Speedy cultivation of natural fibers ● High-speed spinning of 8,000–10,000 m/min
2025	● Optical fibers (GI-type POF) ● Nerve fibers effectively conveying weak electric currents (artificial nerve) ● Motion function retaining fibers (artificial muscle)		● High-performance plant fiber production technology ● Environment-friendly fiber production technology ● More efficient rayon production process
2035	● Superconductive fibers ● Hazardous substance (NO_x, SO_x) absorbing fibers ● Uranium-absorbing fibers	● Carbon fiber expanded into automobile use	● Synthetic fiber materials made of non-petroleum material by carbon dioxide fixation etc. ● Highly efficient production technology of natural fiber materials by biotechnology

acids as well as inorganic-based substances, such as silicon compounds. In the next generation, human needs will be respected much more than at present, and so in those areas where there is a close relationship to organic substances and living organisms, such as clothes and fiber materials for medical use, human-friendly fibers will be required. Therefore, such naturally occurring materials will have a higher potential in the future.

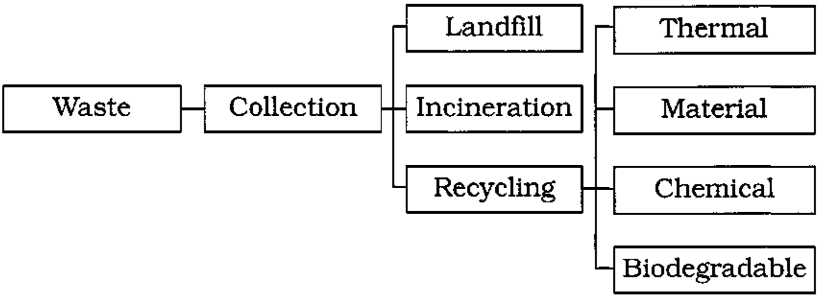
Examples include the use of wood-based biomass and conversion of starch into fibers by the salting-out process. An important theme for the distant future is to fix carbon dioxide into organic materials. Plants fix it to make cellulose (cotton) and other organic substances: petroleum, coal and other organic substances were originally made by the fixing of carbon dioxide by plants, too. Petroleum generates this gas when it burns and if science and technology make it possible to fix it efficiently and to use it as a fiber material, it will make an immeasurable contribution to humankind. The range of applications will certainly increase and new materials with different properties from those presently available will be needed (Table 9.1).

9.8 Resources recycling

From now on, all industries will be required to maintain the balance between economic growth and environmental protection. The fiber and textile industry is no exception. Greater efforts to reduce and reuse industrial wastes are needed from the viewpoint of environmental protection and energy and resources conservation (Fig. 9.18).

The recycling of resources can be broadly divided into thermal, material and chemical sectors. In the fiber and textile industry, thermal recycling is intended to recover heat energy generated from the incineration of fiber wastes as thermal or electrical energy. This method, although easily practicable, does not mean the recycling of resources. Material recycling recovers polymers from fibers or plastics, and at present, the idea of transforming polyethylene terephthalate (PET) into fibers is most economical and widely used for practical purposes. But there is concern about this method which is apt to let impurities mix into recovered polymers, resulting in declined quality and spinning stability. Chemical recycling recovers monomers from waste fibers by polymer decomposition. This is the method of the future. Impurities can be easily removed from recovered monomers, so their quality will be made exactly equal to virgin monomers. An important consideration in all three sectors is to establish an economical collecting system and an efficient recovery technology and to develop commodities using recovered materials. The key point of material and chemical recycling in particular is how to collect and separate wastes. In this context, it may be

1 Waste handling



2 Comparison of recycling methods

Method	Sorting	Applied for	Remarks
Thermal	Not required	Energy recovery • Electric power • Local heating	Efficient recovery system
Material	Required	Fiber or plastics	Proper applications
Chemical	Required	Any products	Economical recovery technologies

3 Future Works

- Economical collecting system from consumers
- Efficient recovery technologies
- Appropriate application development

9.18 Recycling: environment protection, energy saving and resource saving.

argued that the development of those products that can be easily recycled will be an important task to be carried out in the years ahead.

9.9 Fibers for health

The presence of fiber in food is beneficial to health. The subject of such benefits is rapidly expanding, and is worthy of a place in the future application of the fiber concept. Dietary fiber (DF) was originally described as the skeletal remains of plant cells in the diet that are resistant to hydrolysis by the digestive enzymes of humans. This excluded polysaccharides in the diet present as food additives (i.e. exudate gums, modified celluloses and starches), so the definition was expanded to include all polysaccharides and lignin that are not digested by the endogenous secretions of the human digestive tract. Dietary fiber thus mainly comprises non-starch polysaccharides (NSPs) but owing to imprecise methods of analysis it also includes oligosaccharides, polyphenolics (includes lignin), cutin, waxes, suberin, phenolic esters and inorganic constituents. These materials are very diverse, having many different nutritive and physiological properties. The levels of the individual components are also very difficult to measure. This has resulted in DF being defined by some workers, particularly Englyst, as the "polysaccharides which are resistant to the endogenous enzymes of man" (British Nutrition Foundation, 1990). Despite these variations and possible future changes, it is certain that the polysaccharides will remain central to the concept of DF. Such dietary fibre polysaccharides are here classified (Table 9.2).

DF is not digested by the endogenous secretions of the gastrointestinal tract, but undergoes anaerobic fermentation in the colon. The products are non-utilisable gases (for example, hydrogen, methane and carbon dioxide) and organic acids, particularly short-chain fatty acids. These can be utilised in human metabolism after absorption from the intestine.

Health professionals and medical groups now recognise that foods rich in dietary fiber have significant and beneficial effects on human health, mainly as a result of the bulking action in the colon and the products formed there by fermentation. The American Dietetic Association specifically recommends eating 20–35 g of fiber every day. Epidemiological research supports the theory that high intakes of dietary fiber protect against degenerative diseases. High-fiber diets reduce disease risk by increasing faecal bulking, decreased transit time, reduced blood cholesterol levels and assisting in the control of blood sugar levels. It is the "soluble" fibers (more correctly hydrocolloids") that are mainly responsible for reducing blood cholesterol levels, and helping control the rise in blood glucose levels following a meal, thereby reducing insulin requirements in some people with diabetes. The fatty acids, such as propionic acid, are metabolised by the liver, where it inhibits cholesterol synthesis. There is a great deal of evidence too for dietary fiber's role in cancer prevention. The USA National Research Council found colon cancer negatively correlated with high dietary fiber intake. Finally, DF, because it is not broken down in the intestine, has a low calorific value, so contributing to health without adding to obesity.

Table 9.2. Dietary Fiber Polysaccharides

Main source	Soluble in water*	Major groups	Components	Polysaccharide type	Foods
Storage material	Partly	Starch	Amylose Amylopectin	α(1-4)-glucan α(1-4,1-6)-glucan	Fruits, seeds tubers
Structural material	No	Cellulose		β(1-4)-glucan	All cell walls
		Non-cellulosic			
	Yes		Pectic substances	Galacturonans Arabino-galactans	Mainly fruits and vegetables
			Hemi-cellulose		Cereals
	Slightly			Arabino-xylans Glucurono-arabinoxylans β-glucans	Cereals Fruits and vegetables Cereals
Non-structural materials	Yes Yes	Mucilages Gums		Diverse and complex hetero-polysaccharides	Algal seaweed exudates, seeds and fruits

In the next millennium there is a great opportunity to link fiber science and technology with the fabrication of new types of DF, which can function as a result not only of their metabolic behaviour, but also of their physical performance in various organs of the human body.

9.10 Conclusion

The scope of fiber science is very broad. The future of fiber research will be directed to produce only what is needed. Only innovative products will be able to open up new markets and new horizons for the textile industry. Table 9.1 shows a forecast of the development of fibers and fiber science into the new millennium.

As a famous Scandinavian economist said, "It is very dangerous to make predictions, particularly about the future!" It is in this spirit that the predictions are made. New science, not yet developed, can produce products beyond our present perception. This has been the way in the past.

We can give as typical examples the development of *Shin-gosen*, super-fibers, optical fibers and fiber-reinforced plastics, which did not exist at all 30 years ago. In the area of fibers and their surrounding areas, it is expected that there will emerge via innovative science and technology materials that will surpass these fibers.

To realise this, it is essential to invest in future research and researchers. In particular, the education of software researchers will be important, since demand will increase for human-friendly fibers. Fiber science 20 or 30 years from now will depend on development by humans.

What is needed is not simply the conveyance of knowledge but the development of truly creative researchers. The textile industry is required to shift its emphasis from "quantity" to "quality" as the 21st century dawns. The industry must adapt itself to the dynamism of the market economy.