uniformly distributed geographically; they tend to occur along her borders. The majority, about 60 percent, come from the Kurile Islands and the Kamchatka Peninsula region, and that so many events are coastal is very important. First of all, by using records from ocean-bottom seismometers it is possible to apply identification techniques applicable to records obtained at angular distances of less than 10°. Secondly, many of the earthquakes probably occur sufficiently far out from land that, if there is no evidence of an underwater explosion, they can be eliminated as possible explosions. No evidence is available about location accuracies in this region, but there is nothing to suggest that teleseismic methods give less accurate results here than in other areas.

Summary and Conclusions

I have tried to describe some current research trends in seismology which are specifically directed toward solving the problem of detecting, locating, and identifying underground nuclear explosions. Attention has been directed specifically toward problems which arise in efforts to obtain information at distances in excess of 2500 kilometers. The main scientific advantage which accrues from working at such distances is that the seismic signals suffer minimal distortion by the geological complexities of the earth. Extrapolation of the data to the question of an international test ban is not within the scope of this article. Suffice it to note that all of the parameters must, in the final resort, be resolved in terms of probabilities. In some cases the seismological probabilities can be estimated with reasonable degrees of accuracy, but the future of the test ban question depends not only on seismology but on such questions as inspection and what probabilities are acceptable.

The current research program has produced revolutionary advances in the science of seismology. By far the greater part of the work has been directed toward obtaining a fuller understanding of seismic propagation paths within the crust and upper mantle, and relatively little of it has been aimed at achieving a deeper understanding of earthquake mechanism. With a concentration of effort on interpreting the character of earthquake signals as seen through the "seismic window" it has become possible to think in terms of actually defining the motion at the source from the seismic records it creates. Despite the fact that only a small section of the source can be viewed through the "window," its definition would undoubtedly mark a big advance in our knowledge of how earthquakes occur—one which could lead, possibly, to a realization of the seismologist's dream of accurate prediction of earthquakes.

References and Notes

1. A large amount of background material, including a relevant bibliography, is contained in the "Congressional Hearings," particularly in "Hearings before the Joint Committee on Atomic Energy, 88th Congress, First Session, on Developments in Technical Capabilities for Detecting and Identifying Nuclear Weapons Tests, March 1963."
2. H. Jeffreys, *Geophys. J.* **7**, 212 (1962).
3. B. Gutenberg, *Proc. Natl. Acad. Sci. U.S.* **39**, 849 (1953).
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6. I am grateful for the help and guidance of my colleagues at Blacknest—in particular, Dr. H. I. S. Thirlaway. Nevertheless, the views expressed are my own and should not be taken as necessarily representing the views of the United Kingdom Atomic Energy Authority.

Spandex Elastic Fibers

Development of a new type of elastic fiber stimulates further work in the growing field of stretch fabrics

Elija M. Hicks, Jr., Arnoldus J. Ultee, John Drougas

Vulcanized rubber, from which the first elastic fibers were made, has found wide application in the manufacture of elastic fabrics. For many years fiber chemists have sought to develop materials superior to rubber in recovery force, resistance to abrasion, and chemical stability. Several such fibers have now been produced within the field of urethane chemistry and are being manufactured commercially, under various trade names. The generic name of these fibers is spandex, which is defined as a segmented polyurethane (*1*). In this article we discuss the synthesis and structure of segmented polyurethanes and the properties of spandex fibers made from these polymers.

The classical theory of elastic behavior is called the kinetic theory of elasticity (*2*). The theory requires kinetically active, long molecular chains with characteristics of liquids, joined by tie-points to provide for recovery from deformation (see cover).

In an ideal rubber there is no change in internal energy during stretching, and the retractive force, being solely dependent upon entropy change, is proportional to the absolute temperature. The retractive force of a deformed elastomer depends also on the molecular weight of the polymer and on the average distance between the tie-points. Statistical considerations (*3*) lead to the relationship

$$f = RTd\left(\frac{1}{M_c} - \frac{2}{M}\right)\left(\alpha - \frac{1}{\alpha^2}\right)$$

where f is the force per unit initial area of cross section, R is the gas constant, T is the absolute temperature, d is the density of the polymer, M is the molecular weight of the polymer, M_c is the average molecular weight between tie-points, and α is the

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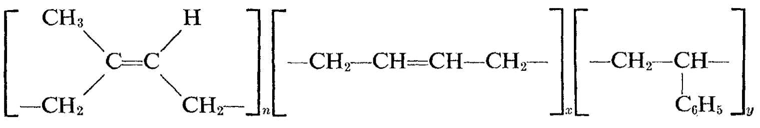
The authors are affiliated with E. I. duPont de Nemours & Company. Dr. Hicks is director of the Orlon-Lycra Technical Division of the Textile Fibers Department, in Wilmington, Delaware; Dr. Ultee is a research associate in the Benger Research Laboratory of the Textile Fibers Department, in Waynesboro, Virginia; Dr. Drougas is a research chemist in the Textile Research Laboratory of the Textile Fibers Department, in Wilmington.



$$\left[-CH_2-CH=CH-CH_2-\right]_x\left[-CH_2-\underset{C_6H_5}{\underset{|}{CH}}-\right]_y$$

cis-1,-4-Polyisoprene, crystallizes under stretch

Copolymer of butadiene and styrene, does not crystallize under stretch

Fig. 1. Structural formulas of natural rubber and a synthetic rubber.

stretch in one direction [elongation (expressed as percentage) = 100 (α − 1)].

While no rubber behaves exactly according to the prediction for an ideal elastic fiber, the recovery force achieved with the best conventional rubbers is of the calculated order of magnitude. The tie-points in this case consist of covalent cross-links introduced by vulcanization, in which, normally, the unsaturated polymer reacts with sulfur. In vulcanization the average distance between tie-points can be controlled, but distribution of the tie-points along the chain cannot.

The calculation of elastic force applies, for natural rubber, to deformations of up to about 200 percent. At higher elongations the long, flexible molecules which provide the elasticity tend to crystallize (*4*), and the crystallization leads to a considerable increase in tensile strength. This phenomenon of stretch-induced crystallization is a sign of a regular polymer structure and is usually destroyed by copolymerization (see Fig 1).

For most practical end uses for rubber, such as tires, a lack of stretch-induced crystallization is acceptable, but for thin fibers, where breaking strength is very important, the reinforcement achievable through crystallization is very desirable. The fibers made from natural rubber have, characteristically, (i) long molecules of low melting point but crystallizable at high elongation, with areas of unsaturation in the molecular chains, and (ii) random, primary, chemical bonds cross-linking the chains.

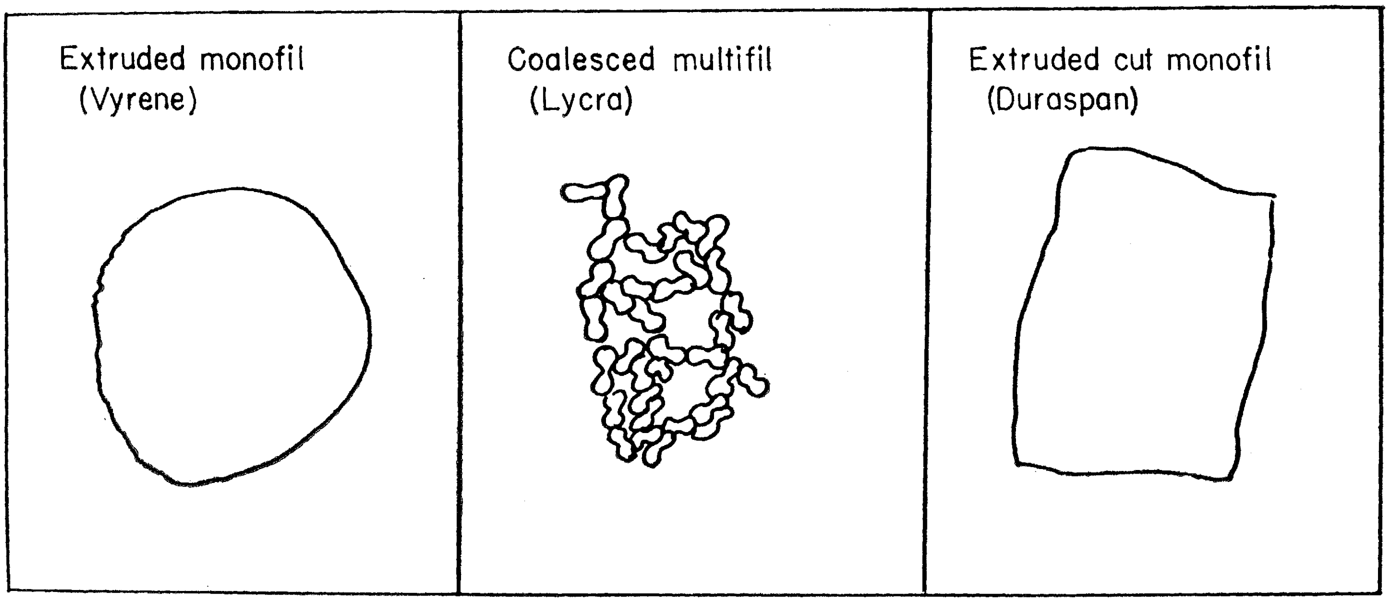
Elastic fibers made from natural rubber are usable, but they have several limitations. While the elasticity of the fibers is good, the tensile strength and the force of recovery from stretch have been less than are required in fibers for making light-weight garments. In addition, the residual double bonds in the structure impart chemical reactivity, particularly with oxidizing agents. Finally, the hydrocarbon nature of the polymers results in a relatively low acceptance of dye.

New Elastomer Fibers

In research aimed at developing improved elastic fibers it was soon established that simple extension of the hydrocarbon rubber approach did not give the desired results. Consequently, work was undertaken to develop quite new structural concepts and to select wholly different kinds of molecules in order to achieve the desired properties. The general principles of obtaining elasticity through changes in entropy, induction of crystallization to provide reinforcement on stretching, and joining by tie-points to provide recovery from deformation were retained, but the application of these principles was vastly different.

It was already known that in certain cases secondary bonds could supplement covalent tie-points. The reinforcement of stretch-induced crystallization, for example, results from such secondary bonding, the crystallites in stretched rubber acting as additional tie-points increasing the modulus of elasticity on further stretching. The forces that hold rubber molecules together in a crystal lattice are relatively weak; stronger forces between polar groups—more specifically, hydrogen bonds—should, it was believed, provide stronger tie-points which could not only supplement but completely replace the covalent bonds in vulcanized rubber.

It was actually found that elastomers could be made from *linear* copolymers capable of hydrogen bonding in certain areas along the chains. For example, a polyamide from a dicarboxylic acid and a mixture of two diamines, one of which had substituted (secondary) amine groups, was elastic in behavior (*5*). Such a polymer contained the two elements necessary to



Extruded monofil (Vyrene)

Coalesced multifil (Lycra)

Extruded cut monofil (Duraspan)

Fig. 2. Lateral cross-sections of spandex fibers. Vyrene is the trademark of the U.S. Rubber Company for its spandex fiber; Duraspan is the trademark of the International Latex Company for its spandex fiber. (About × 74)

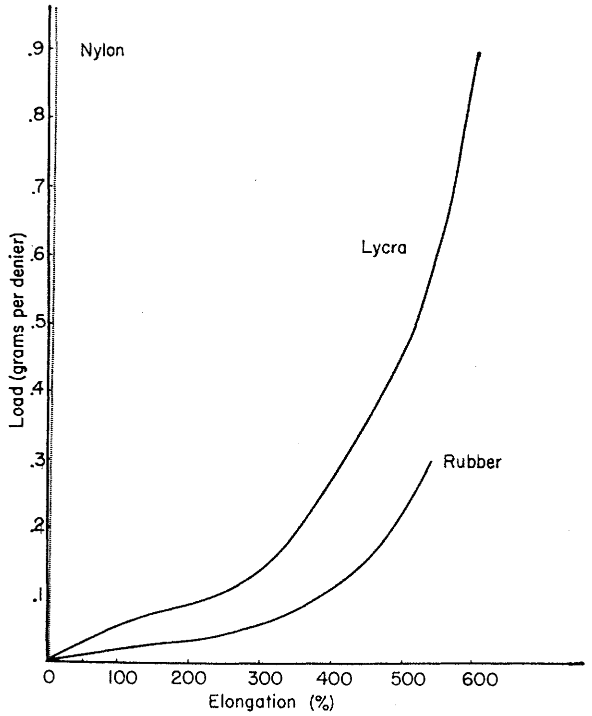


Fig. 3. Load-elongation curves for spandex and rubber fibers.

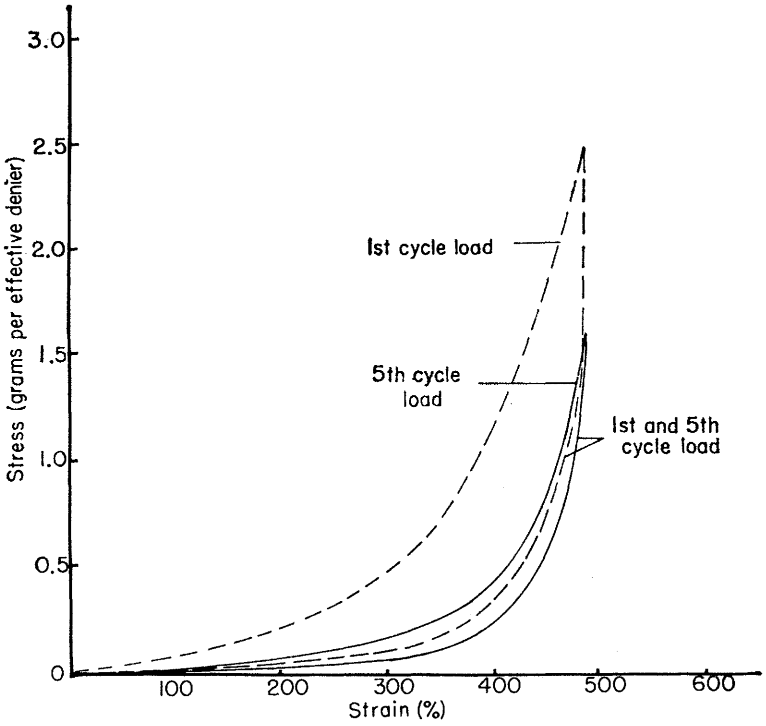


Fig. 4. Typical stress-strain curves for spandex fiber. ("Effective denier" is the denier at the point of measurement.)

elasticity: (i) a pliable constituent of low melting point with poor interchain bonding force (the N-substituted polyamide), and (ii) an interchain bonding constituent (the unsubstituted polyamide with its hydrogen-bonding capacity).

In these random copolymers, however, the average length of the two constituents was rather small. Specifically, the sequences of N-substituted polyamide units were too short for developing the chain flexibility required for high rubber elastic force, while the sequences of unsubstituted polyamide units were too short to prevent rupture during stretching or during heating (rupture during stretching causes flow; rupture during heating results in a low softening point). These problems have been solved by deliberate tailoring of segments of the molecule to perform the desired function.

The problem of lack of flexibility of the pliable constituent (with low melting point) of linear elastic copolymers was solved through the use of preformed blocks of considerable size ("soft segments") for these constituents. The problem of low cohesion of the interchain bonding constituents ("hard segments"), on the other hand, was solved through the use of structures of higher melting points, such as urethane or urea groups. The use, in the final synthesis of the segmented polymer, of large soft-segment blocks rather than ingredients of low molecular weight does not affect the melting point of the hard segments, since, as has been shown by Flory (*6*), the depression of the melting point depends on the mole fraction, as opposed to the weight fraction, of the soft-segment reactants. Thus, with a mole ratio for soft-segment blocks to hard-segment monomers of 1 : 1, it is possible to arrive at compositions having a corresponding weight ratio of 4:1 or higher. The behavior of such linear, "virtually cross-linked" (*7*) copolymers makes them superior elastomers for the manufacture of fibers.

It may be seen from the foregoing discussion that segmented polyurethanes have two characteristic features which may explain their superior physical properties relative to conventional rubber structures.

First, because the long-chain polyurethane molecules are synthesized from preformed, soft-segment polymer blocks, the hard segments, and therefore the tie-points, are spaced more regularly along the chains than those in randomly vulcanized rubber (*8*). Specifically, the occurrence of tie-points close together, which limits the flexibility and hence the elasticity effectiveness of the in-between soft-segment chain, is avoided. Furthermore, a more regular network should result in greater elongation before breaking, by minimizing the number of chains stretched prematurely to the breaking point.

The second characteristic is the occurrence of tie-points which may be broken *and re-formed* during stretching (*9*). Although the classical theory of elasticity (which deals with tie-points of the same strength as the main chain) is not applicable in this case, it is easy to see that this behavior will minimize the concentration of points of stress and lead to an even more regular network structure, with the advantages outlined above. Finally, it should be realized that the hard-segment bonding is not necessarily limited to the tying together of molecules two-by-two, as is the case with covalent cross-links, and that the effect of multiple hard-segment "packages" may be to give additional "reinforcement" similar to that obtained in conventional rubbers by the use of active fillers, such as carbon black.

Formation of Spandex Polymers

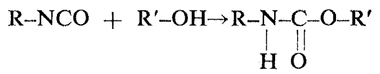
One of the most convenient ways of joining hard and soft segments to produce a polymer is through the formation of urethane linkages. Although there are many possible ways of forming urethane linkages, the preferred

Table 1. Physical properties of spandex, natural rubber, and nylon fibers.

Fiber	Tenacity (g/denier)	Elongation (%)	Modulus of elasticity (g/denier)	Recovery from 100-percent stretch (%)
Spandex (Lycra)*	0.9	550	0.05	95
Natural rubber	.3	540	.02	97
Textile nylon	4.2	26	25	

* Lycra, the first of the spandex fibers, is typical of these fibers.

way is by reaction between isocyanate and hydroxyl groups:



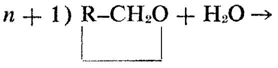
$$\mathrm{R{-}NCO + R'{-}OH \rightarrow R{-}\underset{H}{N}{-}\underset{O}{C}{-}O{-}R'}$$

R and R′ represent either alkyl or aryl groupings.

This reaction was discovered more than 100 years ago (*10*), but it was not used for making polymers until the late 1930's (*11*). In addition, isocyanates are used extensively in the formation of the hard segment, hence spandex chemistry is primarily isocyanate chemistry.

Preparation of the soft segment is the first step in the synthesis of a spandex. Two classes of compounds, polyesters and polyethers, are being used for the rubbery soft segment. The materials involved are polymers of low molecular weight (500 to 4000) with reactive hydroxyl groups at each end. These so-called macroglycols can be made by normal polymerization methods. Polyesters are made by condensation of dicarboxylic acids with a slight excess of a glycol; polyethers, by ring-opening polymerization of epoxides or cyclic ethers:

$$\mathrm{n\,HO_2C{-}R{-}CO_2H + (n+1)\,HO{-}R'{-}OH \rightarrow HO{-}(R'{-}O_2C{-}R{-}CO_2)_n{-}R'{-}OH + 2n\,H_2O}$$

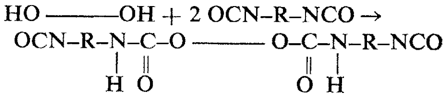


$$\mathrm{(n+1)\,\underbrace{R{-}CH_2O} + H_2O \rightarrow}$$

$$\mathrm{HO{-}(R{-}CH_2O)_n{-}R{-}CH_2OH}$$

The choice of soft-segment ingredients depends on many factors having to do with the properties of the resulting chain molecules, such as melting point, flexibility, and chemical stability, and, it also depends, of course, on availability and cost.

The next step in building a spandex polymer is to introduce, into the urethane, linkages between soft and future hard segments by reacting the macroglycols with an excess of diisocyanate. Using, for example, two moles of diisocyanate per mole of macroglycol, we obtain

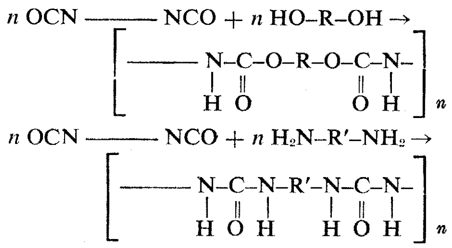


$$\mathrm{HO{-\!-\!-}OH + 2\,OCN{-}R{-}NCO \rightarrow OCN{-}R{-}\underset{H}{N}{-}\underset{O}{C}{-}O{-\!-\!-}O{-}\underset{O}{C}{-}\underset{H}{N}{-}R{-}NCO}$$

The product is an isocyanate-terminated prepolymer.

The reactivity of the diisocyanate depends on its structure. In general, the aromatic diisocyanates are more reactive than the nonaromatic, and, since aromatic diisocyanates are also the ones which are commercially available, they are used predominantly for building spandex polymers.

The final step in making a segmented polyurethane is the synthesis of the hard segment by "chain extension," or coupling of the isocyanate-terminated prepolymer by reaction with a bifunctional compound of low molecular weight, such as a glycol or diamine. The reaction product is a polymer having hydrogen bonding sites in the form of urethane or urea groups, at least two of which will occur in each resulting "hard segment":

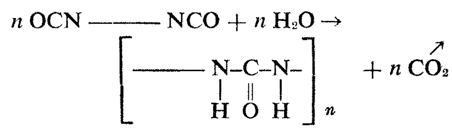


$$\mathrm{n\,OCN{-\!-\!-}NCO + n\,HO{-}R{-}OH \rightarrow \left[{-\!-\!-}\underset{H}{N}{-}\underset{O}{C}{-}O{-}R{-}O{-}\underset{O}{C}{-}\underset{H}{N}{-}\right]_n}$$

$$\mathrm{n\,OCN{-\!-\!-}NCO + n\,H_2N{-}R'{-}NH_2 \rightarrow \left[{-\!-\!-}\underset{H}{N}{-}\underset{O}{C}{-}\underset{H}{N}{-}R'{-}\underset{H}{N}{-}\underset{O}{C}{-}\underset{H}{N}{-}\right]_n}$$

Actually, since the isocyanate-terminated prepolymer usually contains unreacted diisocyanate initially, many hard segments will contain longer sequences of hydrogen bonding sites; that is, the hard segments can be considered to consist of polymers of low molecular weight and high melting point.

Water can also be used as a chain extender:



$$\mathrm{n\,OCN{-\!-\!-}NCO + n\,H_2O \rightarrow \left[{-\!-\!-}\underset{H}{N}{-}\underset{O}{C}{-}\underset{H}{N}{-}\right]_n + n\,\overset{\nearrow}{CO_2}}$$

This reaction gives only one urea group for each two isocyanate groups and produces carbon dioxide as a by-product. Gas evolution during chain extension may be desirable in the manufacture of urethane foams but, in general, it is not desirable in the manufacture of elastic fibers.

Table 2. Set induced by various degrees of stretch in 420-denier Lycra spandex.

Stretch (%)*	Permanent set (%)†
200	10
300	20
500	58
600	78

* Fiber cycled five times on "Instron" tensile tester to designated stretch. † Expressed as increase in original length of fiber.

Through the chain extension reaction the polymer attains its final molecular weight, with a corresponding increase in viscosity. As in the case of conventional polymers, it is often difficult to maintain throughout the reaction system the delicate balance of reactants required to attain high molecular weight. In the case of linear, soluble polymers, the viscosity can be reduced by carrying out the reactions in a solvent. If it is desired to make insoluble, cross-linked polymers through the use of multifunctional reagents, the chain extension can be delayed until after fiber formation.

Fiber Formation

A polymer can be made into fibers in many different ways. In the case of spandex fibers, however, there are some limitations. The reversibility of isocyanate reactions at high temperatures (*12*), for example, limits conditions of melt extrusion or spinning, since high temperatures are required to melt the hard segments. Spinning from a solution into a coagulating bath ("wet spinning") or into an evaporative atmosphere ("dry spinning") is possible, provided the polymers are linear and can be dissolved (*13*). When this is the case, spinning can be accomplished by the well-known techniques, allowance being made for the elastic nature of the product. Another method, which is also applicable to insoluble polymers made from moderately branched prepolymers, is "chemical spinning" (*14*). In this case, the isocyanate-terminated prepolymer, which often has a bulk viscosity which permits spinning, is spun as a thread line into an environment containing a chain extender which diffuses into the fiber and reacts.

The specific form that the fiber takes depends on the process used. Procedures for spinning synthetic fibers (melt, dry, or wet spinning) can be used to produce either a monofilament yarn or a multifilament yarn (many coalesced filaments). Sheet-extrusion procedures, followed by curing and slitting—processes developed earlier for making rubber thread—result in a monofil generally of square cross-section (Fig. 2).

Spandex fibers may be made very fine. This is an important feature. Whereas the finest rubber yarns are about 150 denier, spandex fibers as fine as 40 denier are now produced commercially, and finer spandex fibers are being developed.

Physical Properties of an Elastic Fiber

An elastic fiber is characterized by a high breaking elongation (in excess of 100 percent and usually 500 to 800 percent), a low modulus of elasticity (about 1/1000 that of a conventional "hard" fiber, such as nylon or cotton), and both a high degree and a high rate of recovery from stretching. Table 1 lists typical properties of spandex fibers, rubber, and nylon.

Spandex fibers, because of their segmented structure, can be made stronger than rubber fibers. To achieve a given stretch, spandex fibers require a force twice as high, over the entire range of elongation, as the force required by rubber (see Fig. 3). However, in contrast to a hard fiber such as nylon, spandex fibers have a very low modulus of elasticity.

Since, in many applications for elastic fibers, the important property is recovery force after stretching and partial relaxation, attention must be given to both the "load" and the "unload" cycles in the stress-strain curves. There is a time-dependent difference in stress between load and unload cycles resulting in a loss of energy which is dissipated as heat (Fig. 4). This hysteresis results from a stress decay which reaches a constant value after repeated cycling, no change being noted beyond the fifth cycle. The hysteresis affects not only recovery force but also degree of recovery. The lack of recovery, usually referred to as "set," is only partially permanent. If the fiber is allowed to relax completely, the set gradually diminishes with time, a behavior which is speeded up by an increase in temperature. Thus, a high rate of recovery from a moderate stretch indicates that little flow of molecules has occurred; rather, there has been a temporary deformation as a result of the viscosity of the system. "Permanent set" is induced by stretching the fiber so far that rupture of some of the interchain tie-points occurs. These bonds reform after molecular flow and cause an unrecovered strain. As may be seen in Table 2, set increases with degree of stretch, particularly above stretch of 300 percent.

Because of stress decay and set as factors in recovery force, it is necessary to assess yarns under conditions which approximate the degree of stretch and cycling the yarn will undergo during manufacture into fabrics and during wear. The extent of stretch required in elastic yarns varies according to the type and required elasticity of the fabric into which it is to be manufactured. Figure-controlling garments, such as women's girdles, are designed to have stretch 50 to 100 percent greater than the elongation during wear. The restraining force of such garments is directly related to the recovery force of the elastic fiber at its elongation when it is in use. The term "effective power" has been used for the recovery force per unit of linear density of a yarn at a given elongation. Figure 5 shows the "effective power" of the DuPont spandex fiber Lycra and of rubber over a range of available stretch (*15*). The spandex fiber has about twice the "effective power" of rubber at the important elongations at which additional stretch of 50 to 100 percent is available.

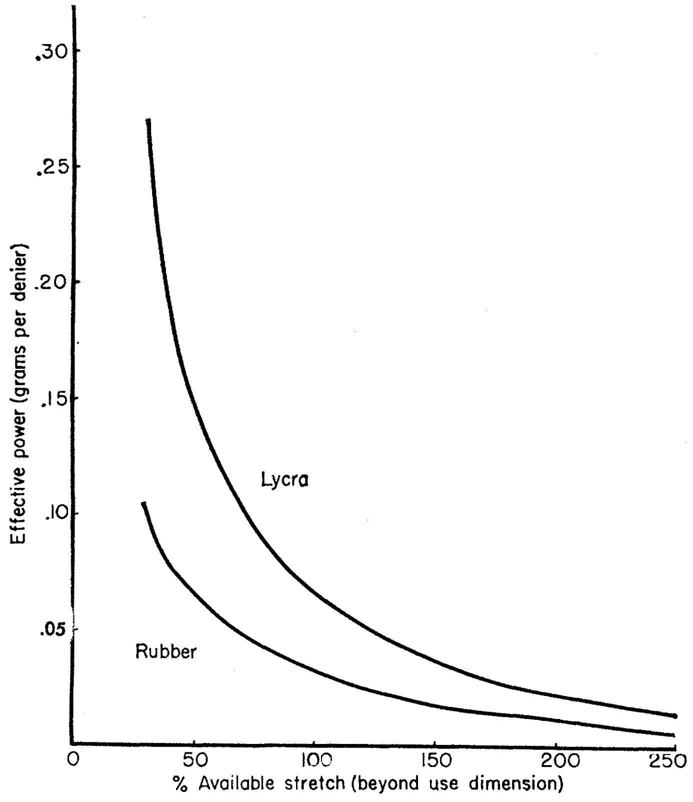


Fig. 5. Relationship of "power" to stretch beyond the use dimension.

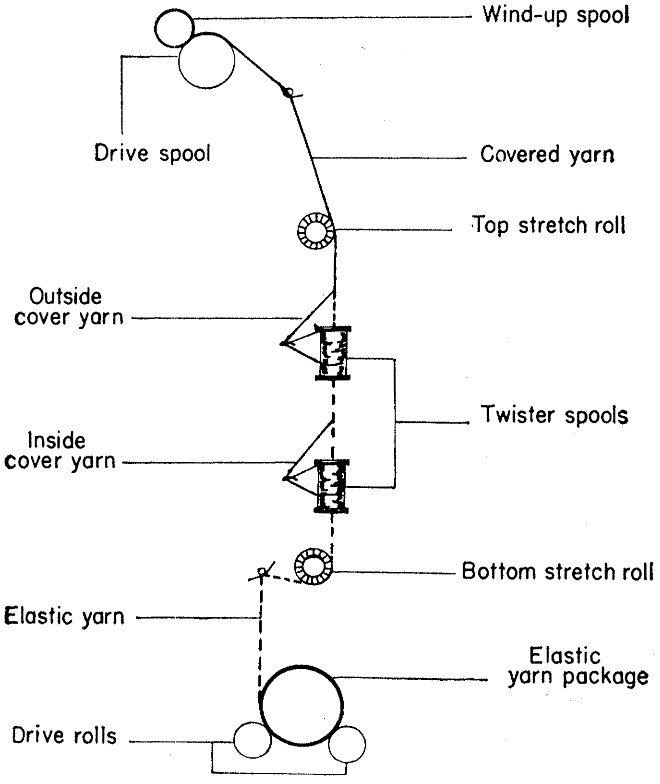


Fig. 6. Schematic diagram of a machine for covering elastic fibers.

Table 3. Correlation of effective power of yarn and of woven fabric.

Material	Effective power (g/effective denier)*			
	Lycra spandex		Natural rubber	
	50%†	70%†	50%†	70%†
Uncovered yarn (from package)	0.088	0.130	0.041	0.058
Covered yarn	.086	.138	.039	.053
Covered yarn removed from fabric‡	.085	.128	.042	.057
Fabric‡	.075	.125	.048	.061

* "Effective denier" is the denier at the point of measurement. † Percentages indicate actual fabric stretch, or, in case of yarns, simulation of "in-fabric" stretch, of 50 or 70 percent. ‡ Stretchable woven fabric, 100 percent total stretch available.

Analytical procedures, based on the principles given above, have been devised for predicting the performance of a yarn incorporated in a given fabric from measurement of the stress-strain properties of the yarn (*16*). For these measurements, test conditions were established which simulated quantitatively the stretch conditions to which the yarn would be subjected during manufacture of the fabric. Table 3 shows a comparison of "power" for the yarn and for the fabric. The data show good agreement of values for the original uncovered yarn, the yarn in covered form, the covered yarn after weaving and subsequent removal from the fabric, and the fabric itself.

Durability of spandex fiber in garments, where flex, abrasion, and needle-cutting are very important, is high. The durability results from the regularity of polymer structure and the strength of the interchain hydrogen bonding. The "power" of two commercial power-net fabrics (420-denier Lycra and 50-denier nylon) is virtually unchanged after 500,000 flex cycles at elongation of 100 percent.

Table 4 shows the durability and dimensional stability of the spandex-fiber fabric when it is subjected to cyclic flexing at elongation approaching the limit of stretch of the fabric. Spandex-fiber fabrics of two different weights show high resistance to flex and low growth compared to their rubber-fiber counterparts. Moreover, because of the durability of spandex fibers, very fine fibers (40 denier) can be produced. The availability of these fine yarns has opened up new applications for elastic fibers.

Table 4. Flex resistance of elastic yarns in hosiery.

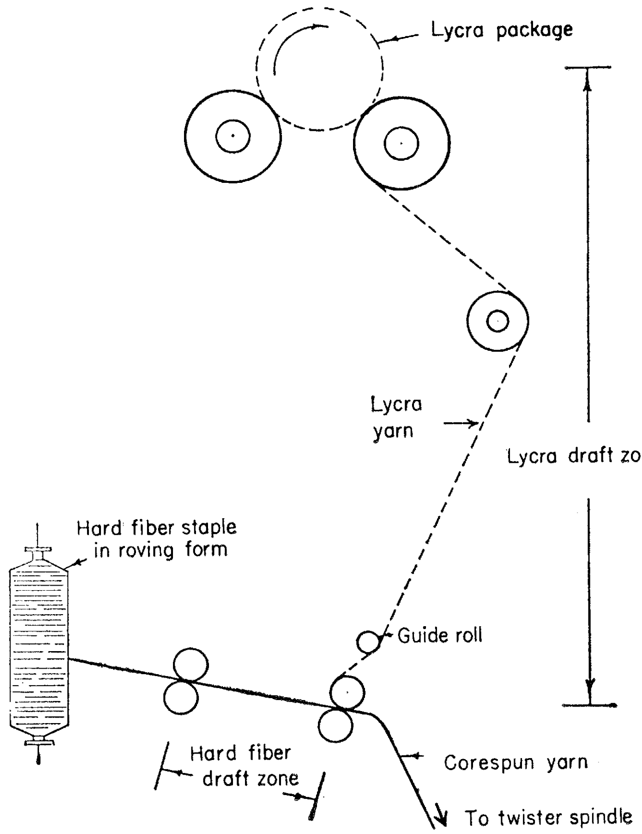
Fiber	Cycles to rupture* (No.)	Washings (No.)	Growth† (%)
Lycra spandex, 280 denier	50,000	18	17
Lycra spandex, 140 denier	50,000	18	10
Rubber, 500 denier	5,000	10	45

* A piece of sock top 2.5 centimeters wide was subjected to cyclic flexing at elongation of 100 percent. † "Growth" means increase in length of the sample subjected to cyclic flexing relative to original length.

Chemical Properties

Spandex fibers are the first elastic fibers to accept dyestuffs readily. Because of this dyeability, which results directly from the chemical nature of the fiber, utilization of elastic fibers in uncovered form has become feasible. Spandex fibers may be colored by virtually all classes of dyes, but color fastness is achieved only with dyes substantive to the fiber (*17*). Basic dye sites in the fiber provide for bonding of the dye molecules through the acid groups in the acid dye. Greater fastness may be achieved by the use of top-chrome acid dyes, but the color obtained with these dyes is less brilliant. Disperse dyes are also used, but only where colorfastness is not critical.

As would be expected from the chemical structure, spandex fibers are resistant to hydrolysis (in Lycra, power retention is 100 percent after boiling for 1 hour in water at *p*H 3 to 11). In addition, they have good resistance



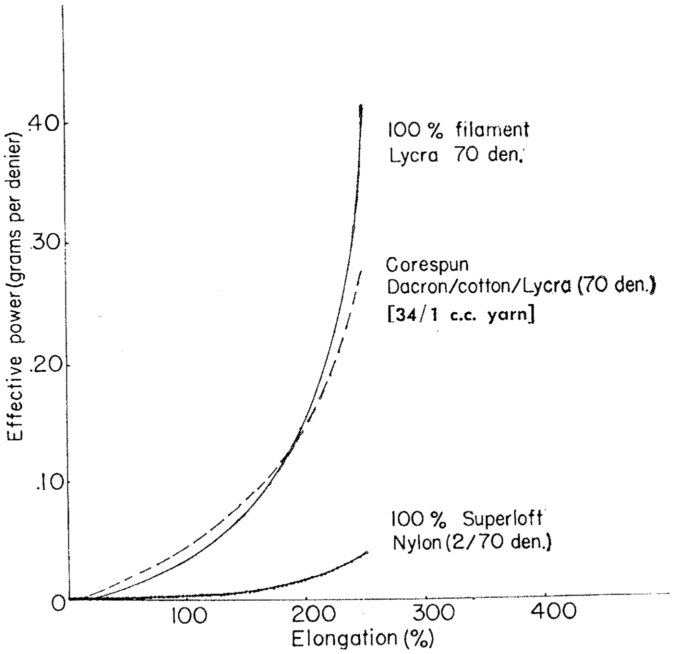


Fig. 7 (left). Schematic diagram of a core-spinning arrangement on a conventional spinning frame.

Fig. 8 (above). Stress-strain curve for core-spun spandex yarn compared with curves for spandex and stretch nylon.

to ultraviolet radiation, oxygen, heat, and oils.

Conventional processes. For most of the textile products now being made from rubber yarn, the yarn is covered in some manner with a hard fiber (*18*). Covering protects the yarn from abrasion, controls the amount of built-in elongation, and provides a base for dyeing. Either continuous filament or spun yarns may be used as covering, and generally two coverings are used to obtain a balanced structure. A typical machine for covering rubber yarn is shown schematically in Fig. 6.

Spandex fibers can be covered, with satisfactory results. Because they are strong, uniform, and resistant to abrasion, they can be processed on standard covering machines. Moreover, their resistance to abrasion is great enough to permit use of fine covering yarns without damage to the elastic fiber.

Processing of uncovered fiber. Because of their resistance to abrasion, their whiteness, their high "power," and their inherent dyeability, spandex fibers can also be used in uncovered form (*19*). Through adjustment of textile-manufacturing processes to achieve an adequate level of elastic-fiber stretch, uncovered spandex fibers can be used for making fabrics for foundation garments. These fabrics have as much stretch and restraining force as fabrics made of conventional double-covered elastic fibers. Uncovered spandex fibers are also used successfully for the manufacture of bathing suits and support hosiery.

Core spinning. "Core spinning" is the process of introducing a continuous-filament yarn together with short-length "hard" fibers onto a spinning frame in such a way that a composite yarn is formed in which the continuous-filament yarn is a core and the staple fibers are a sheath (*20*). This process differs from the conventional covering method, in which a thread is wrapped around the core yarn. The basic requirement in preparing core-spun yarns which are elastic is that the elastic component be stretched before combination with the hard fibers during spinning. In the recommended method of performing this operation (Fig. 7) there is an independent stretching zone (or draft zone) for stretching the elastic component, where the stretch can be varied as required. The hard-fiber staple is passed between drafting rolls and then wrapped around the elastic core, as the yarn emerges from the nip of the front rolls, by the action of twist.

Core-spun yarns, as they come from the spinning frame, have a tendency to relax as the elastic core recovers from the stretch imposed in spinning. By the application of adequate tension, however, the core-spun yarn may be held in the stretched state while it is woven or knit into fabrics. The fabrics develop stretchability through shrinkage after knitting or weaving, the major part of the shrinkage occurring during the steps of hot-scouring and dyeing. The degree of stretchability of the fabric depends upon the degree to which the fabrics are allowed to shrink after weaving or knitting.

The first elastic fabrics made of synthetic yarns were made of nylon yarns, in which the elasticity is provided through fiber crimp and recovery. An entirely different type of stretch is available with spun yarn containing a core of spandex fiber. In these core-spun yarns, elasticity is provided by molecular chain geometry, not fiber geometry as in the case of yarns whose elasticity is based on crimp force. The differences in performance of products made of the two types of yarn are directly attributable to this difference in stretch and recovery mechanism.

A wide range of combinations of elasticity and restraining force can be achieved through the use of core-spun yarns of spandex (Fig. 8). In a typical yarn of Dacron, cotton, and Lycra, from which fabrics of relatively high elasticity and restraining force are made, the spandex-fiber content is only 7 percent. Furthermore, availability of spandex fibers in very fine deniers has made it possible to manufacture very light weight elastic fabrics.

One reason for the versatility of core-spun spandex yarns is the fact that they can be "set" by heat (*21*). Because interchain tie-points involve hydrogen bonding, the bonds may be broken and then reformed upon exposure to heat. Heat setting can be accomplished at temperatures as low as 110°C, with exposure times of about 30 minutes. At higher temperatures, shorter exposures suffice. Heat setting of yarns or fabrics can provide a broad range of effective "power," from zero to the maximum shown in Fig. 9. Core-spun spandex yarns provide an elasticity range from 0 to 450 percent. Heat setting is important since it provides a means of adjusting the elastic properties of fabrics to the requirements of the application.

Summary

A family of synthetic elastic fibers, designated spandex fibers, has been developed, providing new degrees of sheerness and effective "power" in elastic fabrics. These fibers have segmented polyurethane structures. They are durable, they are white and accept dye readily, and they can be set by heat. The development of these fibers has led to new textile technology and to new uses for elastic fabrics.

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