3

Fibre fineness and transverse dimensions

3.1 Fibre dimensions

The essential dimensional features of fibres are their fineness and length. Flexibility comes from fineness and length provides coherence. A fabric is a discontinuous solid, which is held together by friction and utilises the strength of the millions of separate fibres. Whereas two-dimensional assemblies of one-dimensional particles (powders) are just loose coatings and three-dimensional assemblies will flow, integrated two-dimensional assemblies of fibres are strong flexible sheets and three-dimensional assemblies are solid blocks.

The three 'ones' in bold type in Table 3.1 are a convenient order of magnitude of fibre dimensions, though they are at the low ends of fineness, length and density. The table includes calculated values for other quantities. Approximate ranges from these values are also indicated. Fineness is best expressed by linear density (mass/length).

Table 3.1 Fibre dimensions

	'Typical'	Approximate range
Linear density	**1 dtex**	to 20 dtex
Length	**1 cm**	staple fibres to 10 cm; filament to infinity
Density	**1 g/cm^3**	polymer fibres to 1.5 g/cm^3; others to 10 g/cm^3
Mass	1 μg	20 dtex, 10 cm, 1.5 g/cm^3 → 300 μg
Diameter	11.3 μm	20 dtex, 1 g/cm^3 → 50 μm
Aspect ratio	1000:1	to ~ 10 000:1 for staple → infinity for filament
Specific surface	355 m^2/kg	20 dtex, 1 g/cm^3 → 80 m^2/kg
Assembly	10^9 fibres/kg	
1 square metre at 100 g/m^2	10^8 fibres	
Fibre elements	10^{12} per kg	

tex = g/km dtex = decitex = g/10 km

Although the use of tex (g/km), which was adopted in 1960 and is recognised for use in the SI system, and millitex (mtex) are preferred for scientific orthodoxy, the decitex (dtex) value is commonly used because it is close to the value for denier (g/9000 m), which was the standard measure for silk[1], was adopted by the manufactured fibre industry and was used for most of the 20th century[2]. When the linear density exceeds about 20 dtex (circa 50 µm diameter), the 'fibres' are commonly regarded as bristles or monofils and generally lie outside the scope of this book. At the other extreme *microfibres* were produced later in the 20th century and are now important in textiles. Even more recently, *nanofibres*, produced by electrospinning and in other ways, are entering the industry.

As shown in Table 3.1, fibres have an enormous specific surface and a fibre assembly contains vast numbers of fibres. Even a small piece of a lightweight fabric might contain 100 million fibres. Interactions of fibre elements, as illustrated in Fig. 3.1, may occur over lengths comparable to the diameter. Hence the number of interactions may be of the order of 10^{12}. These facts have a major influence on the performance of textiles and the study of the mechanics of fibre yarns and fabrics.

Historically, the overwhelming importance of fineness in determining quality and commercial value was recognised in the worsted industry, where a short fine wool is known to be much more valuable than a long coarse one. Synthetic fibre producers also appreciate the value of fineness, with microfibres commanding a premium price. With cotton, particularly before the worldwide adoption of improved varieties, length was a more important quantity than fineness in giving strength to yarns. Furthermore, fineness mostly correlated with length. Consequently, length, which was easily estimated by cotton classers by preparing a *staple*[3], was given much of the credit that should more properly have been accorded to the fineness. Since W. E. Morton was a Professor in Manchester, the heart of the cotton industry, it was therefore natural for fibre length to precede transverse dimensions in the first edition of this book. Now fineness is recognised as a more important indicator of fibre quality.

Some standard test methods for measuring fineness are listed in Appendix III.

3.1 Interaction of fibre elements.

[1]The origin of the word *denier* is interesting. It is the name of an old French coin (Latin *denarius*). The fineness of silk yarns was specified by the weight (number of coins) in denier of a standard hank. This gives a direct measure of linear density. In the cotton and wool industries, various indirect measures (counts) were used based on the number of standard hanks making up a given consignment weight.

[2]An approach to rational units in the 1950s adopted the name *grex* for g/10 000 m, but this was displaced by *dtex* and is only found in some older literature, such as the book by Kaswell [1].

[3]A lock or tuft of fibre, characteristic of a bulk sample, prepared to demonstrate fibre length [2].

3.2 Terms and definitions

3.2.1 Linear density

The accurate measurement of very small lengths requires considerable expertise and care and, for fibres with irregular shapes, *thickness* defined as the apparent width of a fibre is an ill-defined quantity. Consequently, the most useful and unambiguous measure of *fibre fineness* is the *linear density*, namely mass per unit length, sometimes called *titre*. As mentioned above, the preferred unit is tex = g/km. This has the advantage that it is applicable with appropriate prefixes to all the one-dimensional structures from polymer molecules to yarns, cords and ropes. The linear density is additive in terms of the number of units in the cross-section, making allowance for any obliquity. There is no uncertainty associated with density of packing, as occurs when fineness is expressed as thickness.

The widespread use of *denier* has been mentioned and micrograms per inch has also been used for cotton. For staple yarns, the indirect term *count* (length/mass) was based on the number of skeins with a given number of turns making up a given weight. Many different systems were used for different fibres in different places. Fibre fineness was sometimes expressed by the finest count that could be spun from a given sample.

3.2.2 Transverse dimensions

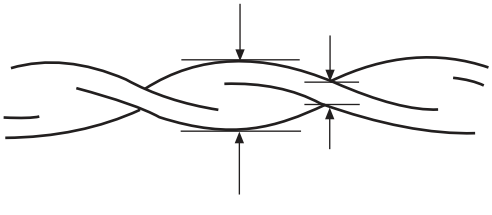
For continuous filament yarns and the tows cut to make staple fibre, the total linear density is easily measured by weighing a given length, and the fibre linear density is given by dividing by the number of fibres in the cross-section. For natural fibres, it is necessary to measure the length and mass of many individual fibres, in order to determine the average linear density. This is difficult and time-consuming. Other measures of linear dimensions are therefore used. For cotton the *micronaire value*, which is an arbitrary measure of fibre specific surface, discussed below, is used. For wool the apparent diameter in micrometre (μm), often referred to by the old name of *micron*, is used. In addition, there are many problems in fibre and textile research and performance evaluation where other linear dimensions have to be taken into account. We must therefore consider the various quantities, their meanings and definitions. For circular fibres, area, circumference, diameter (or radius) are the only parameters. For other fibres, there are more complicated descriptions.

- *Diameter.* In the early literature of textile science, the quantity invariably used for defining the fineness or coarseness of a fibre was the diameter. For wool, which is not so very far from circular and which, except for lamb's wool, does not vary in thickness systematically along its length, this was reasonable enough. For many synthetic fibres, which are even more perfectly cylindrical, fibre diameter is clearly defined. For other fibres, however, which are of irregular cross-sectional shape or which taper towards one or both ends, the term diameter has no real meaning.
- *Width.* What was frequently referred to as fibre diameter in early books about

cotton was really the maximum width as viewed under the microscope. The convoluted fibre varies in apparent width over a wide range throughout the length of each convolution, and either the maximum or the minimum may be measured (Fig. 3.2). If the cross-sectional shape were elliptical, these dimensions would correspond to the major and minor axes of the ellipse. In the general case, for the purpose of characterising a raw material, mean fibre width suffers from the disadvantage that it is too dependent on fibre shape.

- *Perimeter* is a quantity that is perhaps familiar only to the technologist and is important mainly as a link between other dimensions. For circular or oval fibres, it is usually called the *circumference.*
- *Area of cross-section* is the most clearly defined transverse dimension. For a given type of fibre, area is proportional to the linear density, and, if the fibre density is known, the one may be calculated from the other. It is important to note, however, that, whereas the former is usually, and more easily, measured somewhere around the middle of the fibre, the latter has to be measured over an appreciable length of the fibre, maybe over its entire length, so that the relationship between the two is upset if taper is present. For hollow fibres it is necessary to distinguish between the area within the outer perimeter and the area of fibre material.
- *Specific surface* may be defined in two ways: either as the surface area per unit volume or the surface area per unit mass of the fibre. The former is the more useful from the technical point of view and is the more commonly encountered. Defined in this way, provided that there is no major variation in area, specific surface is given by the area of cross-section divided by the perimeter.
- *Fibre shape* takes a variety of forms, discussed in Section 3.10. As the shape departs from circular, the specific surface increases. A *modification ratio* can be defined as the ratio of the perimeter to the circumference of a circle of the same area.
- *Hollow fibres* are characterised by the ratio of the void area to the whole area of the fibre.
- *Wall thickness* is a dimension that has relevance only to hollow fibres.
- *Maturity* (see Section 3.10.2), which is a term only relevant to cotton, is not a direct measure of a transverse dimension, but is relevant because the wall thickness of cotton increases as the fibre grows to maturity.

Relations between these quantities are presented in the next three sections in consistent units, which eliminate the need for numerical factors. In particular, they



3.2 Cotton fibre major and minor axes.

apply in strict SI units, namely linear density in kg/m, length in m, area in m^2, density in kg/m^3, specific surface on volume basis in m^{-1}. specific surface on mass basis in m^2/kg. Alternative relations with more convenient units are also included; some equations are unchanged, others contain numerical factors.

3.2.3 Solid fibres of circular cross-section

Area A is related to diameter D and radius r by the equations:

$$A = \pi r^2 = \pi \frac{D^2}{4} \tag{3.1}$$

also valid with A in $10^{-12}\,m^2$, pico(metre)^2, r and D in μm.

Linear density c can be related to area A and density ρ or specific volume v but is more usefully related to radius or diameter:

$$c = A\rho = \frac{A}{v} \tag{3.2}$$

$$c = \pi r^2 \rho = \frac{\pi D^2 \rho}{4} \tag{3.3}$$

or with c in dtex, r and D in μm and ρ in g/cm^3.

$$c = \frac{\pi r^2 \rho}{100} = \frac{\pi D^2 \rho}{400} \tag{3.4}$$

The inverse relations are:

$$r = \left(\frac{c}{\pi\rho}\right)^{1/2} \tag{3.5}$$

$$D = 2\left(\frac{c}{\pi\rho}\right)^{1/2} \tag{3.6}$$

or with c in tex, r and D in μm and ρ in g/cm^3:

$$r = 10\left(\frac{c}{\pi\rho}\right)^{1/2} \tag{3.7}$$

$$D = 20\left(\frac{c}{\pi\rho}\right)^{1/2} \tag{3.8}$$

The perimeter (circumference) P is given by:

$$P = 2\,\pi\, r = \pi\, D \tag{3.9}$$

also valid with P, r and D in μm.

For a length L, surface area = PL and volume = AL. Hence, on a volume basis, specific surface S_v is given by:

$$S_v = P/A = 2/r = 4/D \tag{3.10}$$

also valid with S_v in $(\mu m)^{-1}$ and r and D in μm.

It follows that, other things being equal, the finer the fibre, the greater is the specific surface.

For the length L, the mass is cL. Hence on a mass basis, specific surface is S_m is given by:

$$S_m = \frac{P}{c} = \frac{2\pi r}{c} = \frac{\pi D}{c} = 2\left(\frac{\pi}{\rho c}\right)^{1/2} \tag{3.11}$$

or with S_m in m^2/kg, r and D in μm, c in dtex and ρ in g/cm^3:

$$S_m = 10^5 \frac{P}{c} = (2 \times 10^5)\frac{\pi r}{c} = 10^5 \frac{\pi D}{c} = 20\left(\frac{\pi}{\rho c}\right)^{1/2} \tag{3.12}$$

3.2.4 Solid fibres with cross-sections other than circular

The volume enclosed by a given surface diminishes according to the degree of departure from circularity of section. It is still correct to write $S_v = P / A$ and $S_m = P / c$, but the value for S_m given by equation (3.12) must be multiplied by a shape factor k greater than one. Thus the greater the ellipticity of section, as in wool, or the greater the extent of indentation in the sectional shape, as in viscose rayon, the greater is the specific surface for a given linear density.

The equations above in r and D are meaningless for non-circular fibres, except when equivalent values are used to match the area. Relations for elliptical cross-sections are given in mathematical textbooks.

3.2.5 Hollow fibres

For hollow fibres of circular cross-section, denote the outer edge by a subscript [o], the inner edge by [i], and the wall by [w]. With A for area and r for radius, we have:

$$A_o = \pi r_o^2 \tag{3.13a}$$

$$A_i = \pi r_i^2 \tag{3.13b}$$

$$A_w = A_o - A_i = \pi r_o^2 - \pi r_i^2 \tag{3.13c}$$

$$\text{Void percentage} = 100\left(\frac{A_i}{A_o}\right)\% \tag{3.14}$$

$$\text{Wall thickness} = (r_o - r_i) \tag{3.15}$$

The value of A_w should be substituted in equation (3.2) to give the linear density. Outer values should be used for perimeter and specific surface values. The effective fibre density $= (A_w/A_o)\,\rho = [(r_o^2 - r_i^2)/r_o^2]\,\rho$, where ρ is the density of the fibre

material. These relations may be used for hollow manufactured fibres, which are used for bulky fillings and for liquid separation.

Cotton fibres as grown are hollow tubes, but they collapse on drying, as discussed in Section 1.4.3. Geometrically, maturity[4] has been defined by Peirce [3] as the ratio θ of the cross-sectional area, A_w, of the cell wall to the area, A_o, of a circle of the same perimeter P. Note that A_o is the area of the fibre before collapse, though the change in material area due to drying must be taken into account. Hertel and Craven [4] prefer the reciprocal of this, which they call the *immaturity ratio*, I. Thus:

$$\theta = \frac{1}{I} = \frac{A_w}{A_o} = \frac{4\pi A_w}{P^2} \tag{3.16}$$

For the fully collapsed fibre, the total fibre area A equals the wall area A_w. Hence:

$$S = \frac{P}{A} = \left(\frac{4\pi}{A}\right)^{1/2} = 2\left(\frac{\pi\rho}{\theta c}\right)^{1/2} \tag{3.17}$$

$$\theta = \left(\frac{S^2}{4}\right)\left(\frac{c}{\pi\rho}\right) \tag{3.18}$$

3.3 The technical significance of fibre fineness

3.3.1 Stiffness, handle and drape of fabrics

For cylindrical rods or wires of homogeneous and isotropic materials, the resistance to bending varies as the square of the cross-sectional area. Textile fibres are rarely homogeneous, never isotropic and only in certain cases circular in cross-section. Even so, it still remains true that, as fineness varies and other things are equal, resistance to bending increases more rapidly than fibre linear density (see Section 17.2.1).

From this it follows that, for a yarn of given count or a fabric of given mass per unit area, made from a given type of raw material, the resistance to bending diminishes as the fineness of the fibre increases. Fibre fineness is thus an important factor in determining the stiffness of a fabric or, alternatively, its softness of handle and its draping quality.

3.3.2 Torsional rigidity

From similar considerations, it can be shown that, as fineness varies and other things are equal, resistance to torsion increases more rapidly than fibre linear density (see Section 17.3.1). Hence fineness plays a part in determining the ease with which fibres can be twisted together during yarn formation.

Considering the situation from another angle, it can be shown that the torque generated in a yarn of given count by a given amount of twist increases as the linear density of the fibres increases. Thus internal stresses capable of producing kinks and

[4]Referred to by Peirce and Lord [5] as the *degree of thickening*.

snarls in a yarn are greater when the constituent fibres are coarse than when they are fine. This is obviously a matter of considerable importance in the design of crêpe fabrics and in twist texturing.

3.3.3 Reflection of light

The finer the fibres incorporated in a fabric, the greater is the number of individual reflecting surfaces per unit area of the fabric. Fibre fineness therefore affects the character of the lustre of the fabric. In descriptive terms, fine fibres produce a soft 'sheen', whereas coarse fibres give rise to a hard 'glitter'.

Practically all textile materials are, however, translucent to a greater or lesser degree. A substantial part of the light reflected from a fabric is therefore reflected from internal surfaces, and in dyed fabrics the intensity of the light so reflected, i.e. the apparent depth of shade, depends on the mean path length of the light rays through the coloured substance. This in turn depends on the number of fibre surfaces, both internal and external, per unit depth of the structure. Hence, other things being equal, the finer the fibre, the lighter is the apparent shade [6–8], and fibres having central canals or medullary cavities will appear lighter than those that are solid.

3.3.4 Absorption of liquids and vapours

The rate at which dyes are absorbed into a fibre obviously depends on how much surface is accessible to the dye liquor for a given volume of the fibre substance, i.e. it depends on the specific surface [9, 10]. It therefore follows that the time required to exhaust a dye bath is shorter for fine fibres than for coarse and for fibres with strongly indented cross-sections than for those which are smoothly cylindrical.

It might be expected that, in a similar way, specific surface would also influence the rate of sorption of water vapour, but, except where fibres are exposed almost singly, the effect is negligible, since the rate of conditioning is overwhelmingly determined by the rate of diffusion of the vapour through the air bounded by the fibre mass and by the associated heat effects (see Sections 9.2 and 9.3).

3.3.5 Fibre cohesion and twist

In a spun yarn, fibre cohesion depends on interfibre friction developed as a result of twist. It has been shown by Gurney [11] that the critical tension, above which slippage takes place, depends on $p\mu S$, where p is the pressure normal to the fibre surface and depends on the degree of twist, μ is the coefficient of friction between the fibre surfaces, and S is the fibre specific surface. Fuller analyses and experimental data for fibre slippage in twisted yarns are given by Hearle [12].

It follows from this that the finer the fibres, the less is the amount of twist necessary to prevent the occurrence of slippage. It should be added, however, that this is only strictly true provided that the shape of the fibre surface remains substantially invariant. Much depends on the extent to which intimate interfibre surface contacts can be established. Fibre length plays its part here too.

3.3.6 Yarn uniformity

More important to the spinner than any of the aspects of fineness mentioned above is the fact that the uniformity of a yarn is very largely determined by the average number of fibres in the cross-section [13–15]. For a given yarn count, therefore, the finer the fibres, the more uniform is the yarn. Improved yarn uniformity is a desirable characteristic in its own right on the score of appearance, but it brings in its train also a number of other second-order consequences of great importance: greater strength, extensibility and lustre; fewer end-breakages in spinning, winding, warping, and weaving; and greater resistance to surface abrasion.

It also follows that the finer the fibre, the finer is the count that can be spun before the irregularity becomes so great that neither acceptable strength nor reasonable end-breakage can be maintained. Fineness is therefore seen as the dominating factor in determining the limiting count to which a raw material can be spun[5].

3.3.7 Shaped and hollow fibres

Shape influences fibre performance in a number of ways. Light is transmitted and reflected in different ways, altering fabric appearance. Flatter surfaces, as in triangular fibres, have a higher lustre. Indentations in fibres act as capillaries and give good wicking behaviour. Ribbon-like fibres bend more easily than their circular equivalents and so give softer fabrics. The *scroop* of silk is partly due to the triangular shape and similar effects can be achieved in manufactured fibres. Other forms lead to soil hiding in carpet fibres.

Hollow fibres provide more bulk at lower weight and so are used in fillings. They can also be used for filtration or to hold chemicals for release.

3.3.8 Fibre end diameter

Thick fibre ends have been shown to be a cause of prickle in wool fabrics [16]. Mahar and O'Keefe report on the relation between comfort factor and fibre end diameter [17].

3.4 Variation in fineness

3.4.1 Variation within and between fibre types

The most convenient basis of comparison between different samples is the mean linear density, which among the natural fibres can often be used to distinguish between raw materials obtained from different sources. Some breeds of sheep invariably bear coarse wool whereas others bear fine. Some types and strains of cotton produce fine

[5]The results of certain experiments, notably with short Indian cottons, suggested that in some cases fibre length is more important, but it may reasonably be argued that this arises from the increasing mechanical difficulty, as staple length is reduced, of maintaining satisfactory drafting conditions and effective fibre control.

fibres whereas others produce coarse. The mean linear density of the fibres from even a pure strain of plant or animal is not, however, always exactly the same. It varies to some extent from time to time and place to place according to environment and so cannot be used as a precise means of identification. Some strains that are recognisably different are capable of producing fibres that in fineness are the same. Nevertheless, measurements of linear density, in association with other tests, can often be used to identify the origin of a sample with a fair degree of confidence.

Fibre fineness is a major factor in determining the value of wool [18]. Fine Merino wools are mostly in the 18–21 µm range (3.4–4.6 dtex), with superfine wools from 14 to 17 µm (2.0–3.0 dtex) and small amounts of expensive ultra-fine wools down to 12 µm (1.5 dtex). New Zealand carpet wools are typically in the 30–38 µm range (9–15 dtex). Asiatic carpet wools may be as coarse as 20 dtex. Cashmere ranges from 12 to 20 µm (1.5–4.1 dtex). In a similar way, the figures for cottons range from about 1.0 dtex for a St. Vincent Sea Island to about 3.4 dtex for a coarse native Indian cotton, with the dominant American-type cottons around 2 dtex. The mean linear density of the single filament of silk ranges from about 0.95 dtex for Canton to about 1.6 dtex for Japanese.

Nearly all the manufactured fibres can be made to cover a very wide range indeed according to requirements. For many years, 100 mtex (1 dtex) represented about the lower limit. Microfibres have reduced the limit. Development of direct spinning methods have taken polyester filaments to 0.1 dtex [19]. Conjugate spinning of two components, which then split into finer fibres, and islands-in-a-sea fibres, which have ultrafine components in a soluble matrix, give even finer fibres [20]. There is no strict upper limit, but 15 denier nylon (1.67 tex), which can be knitted singly as as a monofil, is about the coarsest before there is a step jump to bristles and plastic monofils with diameters of the order of a millimetre.

3.4.2 Variation of fineness within a sample

In 1956, Morton [21] determined the between-fibre variation in 18 different samples of fibre using a vibroscope method (see Section 3.9) on 2 cm specimens. Several of the fibre types are no longer made. Wool samples showed coefficients of variation of 29 and 36%. Most manufactured fibres had coefficients of variation between 11 and 14%, but *Fibro* (viscose rayon staple) was more uniform at 8.9% and *Terylene* (polyester) was more variable at 21.4%. Improved quality control will have reduced the variability since then. The dry-spun manufactured fibres had near normal distributions, the melt-spun and wet-spun materials mostly had distributions that were positively skewed.

It has already been shown that different samples of the same kind of natural fibre can differ widely in their mean linear densities (see Section 3.4.1). This is also true as regards the variation among the fibres within a sample. The above figures should not therefore be taken as anything more than an indication of the order of variability that might be encountered. Another set of values, which were measured in 1945 in connection with mechanical tests, is given in Table 14.6 on page 335.

3.4.3 Within-fibre variation

Only with manufactured fibres is it reasonably safe to assume that the cross-sectional dimensions remain constant throughout their length. Even then, although variations are negligibly small over the comparatively short lengths of staple fibres, they may in some cases be quite appreciable over the much longer lengths represented by filaments. Thus, for example, over a 1·83 m (6 foot) length of a 4·4 dtex (4 denier) acetate filament, Lord [22] found the linear density to vary from 407 to 460 mtex. Again the degree of variability depends on the standard of quality control of the manufacturer.

Silk filaments show long-range variations throughout the length on the cocoon. In the part that can be reeled for use, the linear density increases to a maximum of about 1.75 dtex some 300 m after reeling has commenced and then falls off to about 1.0 dtex before the cocoon has to be replaced. But variations over short lengths can also be considerable. Thus Goodings and Turl [23] reported variations in cross-sectional area of up to 20% of the mean and in a particular instance noted a change from 81 to 108 μm^2 within an interval of only 180 μm.

The ultimate fibres of flax invariably show a marked tapering from the middle to the two extremities, and to this is due, in very large measure, the great variation in cross-sectional area seen in the transverse section of a flax fibre bundle. It is therefore to be expected in tensile tests that, unless the test specimens are very short, they will tend to break mostly at the grips.

With wools, systematic tapering from the root towards the tips is only evident in lamb's wool, but appreciable random variations in cross-sectional area are liable to be found in any sample [24], as shown in Fig. 3.6 on page 113, depending on the changing vigour and health of the sheep while the wool is growing. For example wool from Western Australia shows thin places from the time of dry summer growth.

The cotton fibre has a tapered tip extending over about 15% of its total length, tapers more sharply near the root end, and frequently also shows considerable variation elsewhere [25–28]. The extent and the pattern of variation evidently differ from one sample to another. Thus, apart from the tapered extremities, Turner [26] found comparatively little variation in a sample of Cambodia 295, whereas in a sample of Surat 1027 ALF he found the mean linear density to change from 215 to 318 mtex in adjacent 6–4 mm ($^1/_4$ in), lengths. From evidence at present available, it would seem that in most cases, though not in all, there is a tendency for the area of cross-section to be a maximum about one-quarter or one-third of the distance along the fibre from the base. In the region of the tip of the fibre, the area of cross-section may in some cases be as little as one-half of what it averages elsewhere.

3.5 Measurement of linear density

3.5.1 Conditioning the specimen

Measurements of the dimensions of any moisture-absorbing fibre must take account of its state. A dry fibre has a lower linear density and a smaller diameter than a wet

one. The normal procedure is to condition the fibre in a standard atmosphere of 65% relative humidity (r.h.), 20 °C (see Section 7.2.1).

3.5.2 Continuous filament yarns

The fibre linear density in continuous filament yarns is easily measured, although the manufacturer's specification is usually accepted as correct. A controlled length is obtained by winding a given number of turns on a reel of given diameter and then the skein is weighed on a standard balance. Dividing by the number of turns and by the number of filaments gives the fibre linear density.

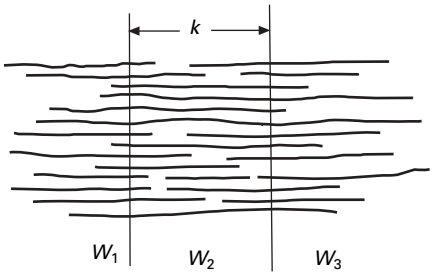
3.5.3 Staple fibres

When fibre length is determined by an individual-fibre method (see Section 4.6) the linear density of a sample of fibres is readily determined. One has only to preserve all the fibres measured for length and weigh them. The mass divided by the total length then gives the required information with a minimum expenditure of time and effort. This is the standard method prescribed by BISFA for all manufactured staple fibres [29], and, since the contribution that each fibre makes to the final result is proportional to its length, it gives a length-biased mean.

In the ASTM standard method for cotton [30], the procedure is essentially the same, though the necessity for individual fibre measurement is avoided by the use of a comb sorter. As described in Section 4.7, the sorter is used to fractionate the sample into groups of known length ranges. From each group, except the two shortest and any of which the weight of fibre is less than 2 mg, a bunch of approximately 100 fibres is taken, weighed and counted. The length of every fibre in the bundle is assumed to be the mid-length of the group from which it is taken, so that if L = the group mid-length, n = the number of fibres in the bunch and M = the mass of the bunch, the linear density of the bunch is nL/M. From the values so obtained, the linear density of the sample as a whole is calculated in such a way as to give here also what is, for all practical purposes, a length-biased mean.

Yet another method giving a length-biased mean is that based on the cutting-and-weighing method of length determination described in Section 4.9. For obtaining the mean fibre length, sections I and III of the tuft (Fig. 3.3) are weighed. To get the whole-fibre linear density in addition, it is only necessary to weigh section II of length k between the clamps, giving a mass M_2, and to count the number of fibres N in section I. Then the total weight of the tuft $M_1 + M_2 + M_3$ divided by the total length NL gives the desired result. Neither this method nor the ASTM method described above is suitable for fibres that are strongly crimped because of the error thereby introduced into the length measurement. It is scarcely necessary to add that, with all hydrophilic materials, the fibres should be conditioned in a standard atmosphere before being weighed.

The CSIRO Cottonscan measures length on a weighed sample of snippets and so gives a direct measure of linear density [31].



3.3 Müller's method for fibre length measurement.

3.5.4 Cut-middles method

The earliest [32] form of gravimetric fineness test involves cutting known lengths from the middle of bundles of parallelised fibres, counting out a suitable number of those lengths, and weighing them. Alternatively, the desired number of fibres can be counted first and their middles then cut out for weighing.

In either event, the operation is most readily carried out by straightening the parallel bundle over a piece of cork linoleum or similar material and slicing through its middle with a cutter consisting of two parallel razor blades, set the desired distance apart in a holder. The lengths cut should be as long as possible, but not so long that an appreciable number of short fibres has to be rejected.

With cotton, for which this technique is most commonly employed, a length of 1 cm is the most suitable for general use, and it is better to cut before counting because short cuts can then be readily seen and discarded. In the Shirley Combined Stapling Test, where the fibres are sorted for length on a comb sorter, the mean weight per centimetre is obtained by weighing 100 lengths of 1 cm taken from each of five different places, evenly distributed over the Baer diagram. In this way, the variation of linear density with length is satisfactorily allowed for. By weighing only the middle (thickest) parts of the fibres, this method gives for cotton a result that is too great by an amount varying according to the mean profile of the fibres concerned. On the average, the cut-middles linear density is about 8% greater than that of whole fibres, though in some cases it is considerably more than this. Maximum differences ranging from 15 to 26% have been recorded by various workers [33–35]. It is to be expected, therefore, that from time to time appreciable divergences will be found between the results given by this form of test and those obtained by the rapid, whole fibre methods described in the following section.

3.6 Direct measurement of transverse dimensions

3.6.1 Width and diameter

For all fibres of cylindrical shape, and especially if the between fibre variation is small, so that only a comparatively modest number of observations is called for, the mean diameter is a very satisfactory measure of fineness. The technique of measurement is simple and straightforward involving the use of a microscope, with a micrometer

eyepiece, or a projection microscope with a scale. The scanning electron microscope (SEM) gives greater precision. If the density of the fibres under examination is known, all other transverse dimensions and quantities can be readily calculated; in addition, since individual readings are recorded, the variability of the sample can be obtained, which is sometimes an important consideration.

Provided that suitable precautions are taken, the same method can also be used for measuring the fineness of fibres of somewhat oval or flattened section. The width of a fibre of oval section can assume any value from a minimum across the minor axis to a maximum across the major axis, according to the orientation of the fibre with respect to the observer. If things are so arranged that the mean of all possible widths can be obtained, the result is a quantity that is virtually equal to the diameter of a cylinder of the same cross-sectional area and therefore proportional to the mean linear density [36].

In the projection microscope method [37], this objective is achieved by cutting the sample of fibres into 0.8 mm lengths, dispersing them in a suitable mounting medium on a microscope slide, and observing the width at one point selected at random along the length of each piece examined. If the pieces are too short, they tend to lie on their flat sides so that only their major axes are presented for measurement, but if they are 0.8 mm long or more, the position they assume is determined by the general curvature along the length of the fibre piece, and this has been shown to have no particular orientation with respect to the axis of cross-section [36].

Errors due to swelling must also be avoided. Fibre pieces should therefore first be conditioned in a standard atmosphere and then mounted for measurement in a medium that does not change their moisture content on immersion. Liquid paraffin and cedarwood oil are suitable for this purpose.

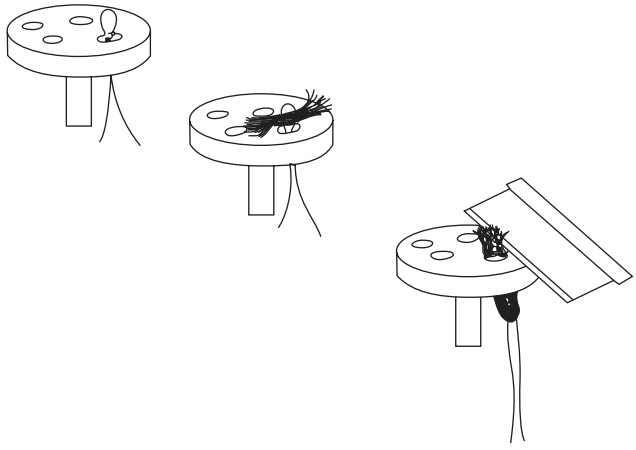
When the short pieces are obtained direct from a section of top, sliver or yarn, the sample is, of course, biased for length. This, however, is an advantage in most contexts, because the length-biased mean width gives an estimate of the fineness of the mass of fibre as a whole, each fibre contributing to the width measurement according to its length. In this respect, the method is then comparable with the more rapid methods of fineness-testing described in Sections 3.7 and 3.8.

For measurements of the width of microfibres and nanofibres, SEM would be used. Digital processing would compute values of diameter from the image.

3.6.2 Measurements on fibre sections

Measurements made with optical microscopes on transverse sections were used for special research purposes to obtain maximum information on the transverse dimensions of a sample of fibres. They are, however, laborious and time-consuming, call for considerable skill in section-cutting and subsequent measurement, and, unless carried out by someone of experience, can lead to misleading results.

The use of the SEM simplifies the problem with the adaptation of the method of preparation described by Ford and Simmens [38], using small holes cut in a standard specimen holder. As illustrated in Fig. 3.4 a bundle of fibres is pulled through a hole by a loop of thread and cut across with a razor blade. The specimen holder can then



3.4 Preparation of fibre cross-sections for viewing in SEM [39].

be placed in the SEM and directly observed. Originally, prints were made and measurements made, but digital processing would now allow computerised determination of the transverse dimensions.

3.7 Optical technology for high-speed testing

3.7.1 Laser scanning and digital optical analysis

The use of microscopic methods is laborious and has been mainly used in research. Advances in lasers, optical sensors, and digital detection and processing have changed the methodology.

Computerised optical analysers speed up the operation and enable large amounts of data to be collected with minimum time and effort. The underlying optics is discussed by Glass *et al.* [40]. The technology is particularly suitable for circular or near-circular fibres and was developed for rapid wool testing. It was readily extended to manufactured fibres. The first step in determining fibre diameter by these rapid methods is to guillotine a test sample of snippets of about 2 mm length.

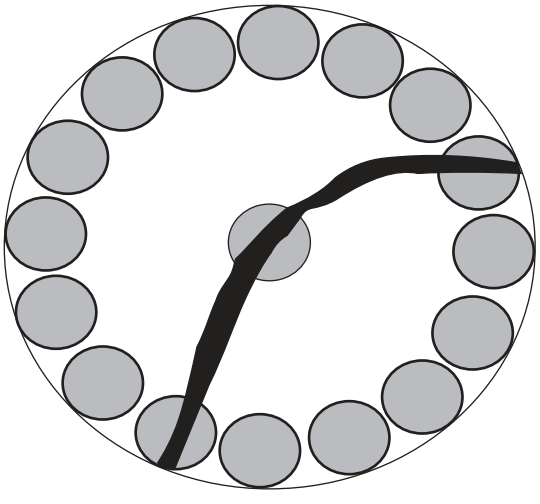
In the Laserscan [41], developed by CSIRO, the snippets are dispersed in an isopropanol–water mixture and then flow through a measurement cell, where they intersect a thin beam of light from a laser. The signal received by an optical detector is reduced in proportion to the width of the intersecting fibre, and is calibrated in diameter values by comparison with samples measured on a projection microscope. It is necessary that snippets fully intersect the beam and that only one snippet at a time is included in the measurements. An optic discriminator, consisting of a ring of detectors round a central detector, ensures that signals that do not meet the criteria are rejected. The information passes to a computer, so that mean and variability of diameter can be calculated. In addition to the usual statistical parameters, a 'comfort factor' is given by the percentage of wool fibres greater than 30.5 μm in diameter. The effect of medullation is discussed by Butler and Glass [42]. The discriminator

also enables curvature to be determined, as indicated in Fig. 3.5, which gives a measure of crimp (see Section 4.5). Some 1000 fibres can be measured in 40 seconds.

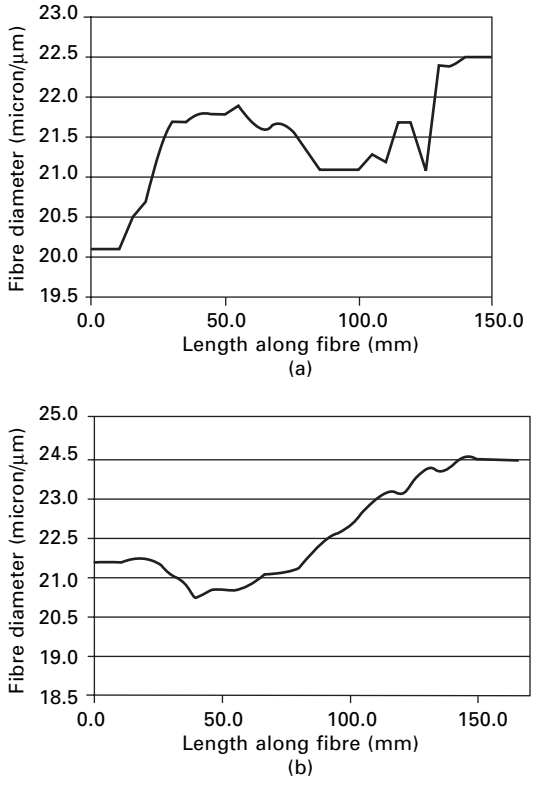
Although Laserscan is still widely used, advances in information technology (IT) are so rapid that the technology is becoming obsolescent. Detectors with multiple pixels, as in digital cameras, are used in the video-microscopes of the optical fibre diameter analyser, first introduced as OFDA100. Fibre snippets are imaged and analysed [43]. In contrast to Laserscan and to the indirect methods described later, digital imaging gives absolute values of linear dimensions, and so does not need to be calibrated by older microscopic methods. More information can be used in research studies. The OFDA100 measures fibre diameters and curvatures on 2 mm snippets of wool scattered on a glass slide [44]. The later OFDA 4000 [45], which is discussed in Section 4.11.2, was primarily developed to measure length by scanning across a beard of fibres. The digital image can be processed to give fibre diameters, curvatures, diameter distributions, diameter profiles, as illustrated in Fig. 3.6, and comfort factors (see Section 3.3.8). The OFDA 5000 [46], which is designed for synthetic fibres, makes 20 000 measurements per minute on fibre snippets in a diameter range of 0.5–60 μm, with a typical standard deviation of less than 0.05 μm. Mean and coefficient of variation are automatically calculated, histograms can be saved in a spreadsheet, and images saved in Windows format. The process of preparing slides by cutting snippets on a guillotine, automatic spreading and insertion in the microscope takes 1–2 minutes.

An interlaboratory comparison of measurements of wool fibre diameters was presented to IWTO [47]. This compared Laserscan and OFDA with projection microscope and air-flow methods. Butter and Glass [42] report that medollation does not affect the accuracy of *Laserscan* diameter measurements.

SIFAN [48] monitors cross-sections of fibres and produces profiles of fibre diameter. It was adapted to be mounted on a tensile tester. The width is measured from several directions at intervals along the fibre, so that three-dimensional models of fibres at



3.5 Fibre-optic discriminator in Laserscan.



3.6 OFDA 4000 fibre diameter profiles from two wool tops: (a) autumn shorn; (b) spring shorn.

increasing strain can be produced. Image processing gives cross-sectional area and maximum and minimum diameters at each point along the fibre. Mean fibre diameter in µm and, knowing fibre density, linear density in dtex can be computed, together with variability.

3.7.2 Application to cotton testing

For cotton, the complicated shape and its variation with maturity make the digital techniques more difficult to interpret. The industrial acceptance of air-flow methods in HVI testing, which give micronaire values, means that there has been less incentive to change. However, the dependence of micronaire on both fineness and maturity gives misleading information, with negative effects on the control of breeding and choice of fibres for spinning. As Gordon and Naylor point out: 'varieties of fine, mature cotton have been wrongly discounted because low micronaire values were taken as indicating immature cotton' [49].

The advances in affordable digital imaging and algorithms for rapid image processing have led CSIRO to adapt the testing of snippets of wool to the development of *Cottonscan* as a rapid method for the determination of the linear density of cotton

fibres [31, 49, 50]. A measured mass of snippets is placed on a slide and digitally imaged. The total length is then computed. Division of the mass by the length gives the average linear density of the cotton sample. If a micronaire value is also known, an estimate of maturity is then given by the use of the relation found by Lord [51]:

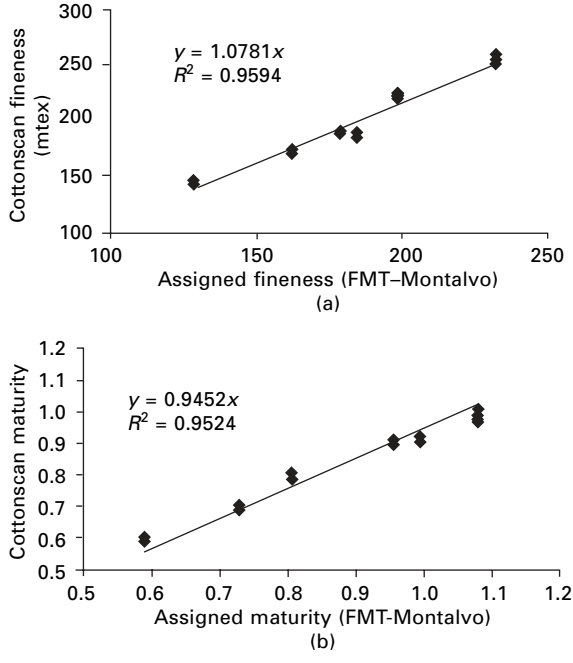
$$\theta c = 3.86\, X^2 + 18.16\, X + 13 \tag{3.19}$$

where θ = maturity, i.e. degree of thickening as defined by Peirce and Lord [5] (see Section 3.2.5), c = linear density in mtex and X = micronaire value.

With a knowledge of the fibre density, the area of the fibre wall could be computed. If the maturity is also known, either from the empirical link to micronaire value or from other measurements, algorithms could be developed to determine other transverse dimensions, such as perimeter and fibre shape, if these are needed.

Figure 3.7 shows that Cottonscan gives good agreement with other methods of measuring fineness and maturity. The early tests of Cottonscan were carried out on sliver samples, but an automated method now enables samples of ginned cotton to be tested [50]. Cottonscan is a fast test method, which could be incorporated in HVI lines.

Although it is not a direct method of measuring maturity as a geometrical feature, it is convenient to mention here another CSIRO development, *Siromat* [49, 53, 54]. This estimates maturity from the interference colours produced when the fibre is viewed in polarised light. This is an old technique, which is discussed in Sections 3.10.6, but colour digital cameras and colour analysis have made it possible to have an automated computerised test. The test involves placing a collection of fibre snippets



3.7 Comparison of values obtained by Cottonscan and from Montalvo's upgrade of the FMT test [52]: (a) fineness; (b) maturity [31].

on a glass slide and immersion in castor oil. The image in a polarisation microscope is digitally recorded and the snippet colours analysed to give a distribution of maturity values. Test times are of the order of two minutes per sample, which is not fast enough for an HVI line, but is useful in quality assurance laboratories and for research purposes.

Finally, developments in sample preparation and digital imaging, together with advances in computer hardware or software, may lead to new direct methods of determining the transverse dimensions of cotton and other non-circular fibres. If fibre sections could be rapidly produced and deployed on a slide, then image analysis would give a full statement of the transverse dimensions. Alternatively, tomography might give a way of obtaining the information from observations of snippets or whole fibres.

3.7.3 Advanced fibre information system

Although air-flow methods dominate routine, high-speed testing of cotton, fineness is measured as one part of the comprehensive Uster Advanced Fibre Information System, (AFIS), which also provides information on fibre length (see Section 4.11.1), neps, trash and dust. Fibres from a tuft are transported individually in a fast air stream past a beam of light, which falls on an electro-optical sensor. Measurement of the direct intensity indicates the amount of attenuation, which is related to the linear density of the fibre. Measurement of the light scattered at 40° is related to the shape of the fibre. Calibration against known cottons enables values of micronaire, maturity ratio and per cent immature fibre content to be recorded. Gordon *et al*. [55] compare AFIS measurements with those by other methods and note that there are differences in predicted distributions of transverse dimensions. Bradow *et al*. [56] compare AFIS measurements with X-ray fluorescence spectroscopy.

3.8 Air-flow methods

3.8.1 Indirect methods

The older direct methods of measuring transverse dimensions suffer from the objection that a great deal of time and labour, as well as eye-strain, is involved. Only with the advent of digital imaging and computer software is that changing. In the second half of the 20th century, indirect methods were developed to get the desired results more quickly and with less trouble. The most successful of these endeavours has been the development of air-flow fineness testers, which contain a suitably prepared porous plug. It is important to note, however, that the quantity measured is the specific surface, not the linear density. The first use of this principle for measurements on fibres was in the Porometer devised by Balls in the late 1920s [57].

3.8.2 Flow relations

An analysis of air-flow through fibre plugs was given by Lord [58]. Kozeny's equation for the laminar flow of air through a porous plug under a small pressure gradient is usually written as:

$$Q = \left(\frac{1}{k}\right)\left(\frac{A\Delta P}{S^2\mu L}\right)\left[\frac{\varepsilon^3}{1-\varepsilon^3}\right] \tag{3.20}$$

where Q = volume rate of flow through the plug, k is a proportionality factor depending on the shape of the voids and fibres and on their orientation with respect to the direction of air-flow, A = cross-sectional area of the plug, ΔP = pressure difference between the ends of the plug, S = specific surface of the fibres constituting the plug (surface area per unit volume of material), μ = coefficient of viscosity of air, L = length of the plug, and ε = porosity of the plug (volume of voids/total volume of the plug).

The porosity of the plug of fibres is given by:

$$\varepsilon = 1 - \frac{m}{\rho AL} \tag{3.21}$$

where m = total mass of the plug and ρ = density of the fibre.

The flow equation can therefore be rewritten to give a resistance to flow R as:

$$R = \frac{\Delta P}{Q} = \frac{k\mu m^2 \rho S^2 L^2}{(\rho AL - m)^3} \tag{3.22}$$

If the plug consists of a fixed mass of fibre uniformly compressed in a cylinder of fixed dimensions, then, for a given type of fibre, A, L, m and ρ are constant, and the coefficient of viscosity of the air, μ, is also sensibly constant over the range of normal room temperatures. Thus, if a fixed pressure drop, ΔP, is part of the experimental conditions, and provided that k can also be maintained constant, the rate of flow of air through the plug, Q, is inversely proportional to the square of the specific surface, S. This is the basis of the design of two of the air-flow instruments described briefly below, namely, the Micronaire Cotton Fibre Fineness tester and the WIRA Fibre Fineness Meter.

Alternatively, ΔP can be measured at constant Q or, as in the Arealometer[6], measurements can be made by adjusting the length, L, of the plug so that it offers a fixed resistance, R, to the flow of air.

It is a simple matter to control all the conditions of the experiment save one. The factor k depends on the shape, orientation and distribution of the sizes of the channels through which the air flows, on the porosity of the plug, and possibly also on the character of the fibre surfaces. Thus the value to be assigned to k can only effectively be obtained by empirical means. The relation between specific surface and L, ΔP or Q, as the case may be, will differ according to the type of fibre being examined, e.g. wool, cotton, viscose rayon, and also according to the manner in which the fibres are prepared and arranged in forming the plug. Thus, when the technique of sample preparation has been determined, it is necessary to make experimental calibration of the flow-meter, by using a range of tested samples of varying fineness for each class

[6]The Arealometer, developed by Hertel and Craven [4] is no longer manufactured, but is still used in some research studies [59, 60].

of fibre [58]. The dependence on fibre shape is particularly important for cotton, since it means that the value of R depends on cotton maturity as well as fineness.

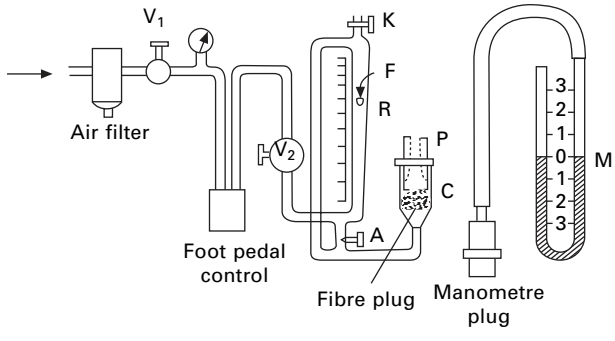
3.8.3 The Micronaire

The Sheffield Micronaire [51], the first commercial instrument to be marketed for the measurement of fibre fineness by air-flow methods, is now a standard method for evaluating cotton. Indeed, although it depends on fineness and maturity, the word 'micronaire' is now used as a term to characterise a cotton sample, along with length and other grading features. Micronaire values influence price. Too much attention to selecting for high yield, neglecting selection for micronaire, has been counter-productive by reducing the return to cotton growers for fibres with lower micronaire [61]. However, as discussed below, the interpretation of micronaire values is not a simple one. Low micronaire indicates fineness, which is good, but also immaturity, which is bad.

The operation of the Micronaire is illustrated in Fig. 3.8. In this instrument, air at a pressure of 41.3 kPa (6 lbf/in^2) is made to flow through a plug of fibre, of mass 3.24 g, enclosed in a chamber, C, (25.4 mm (1 in.) long and 25.4 mm (1 in.)) in diameter. The floor of the chamber and the bottom of the annular plunger, P, are perforated so that, although the sample is confined within a space of fixed dimensions, L and A in equation (3.19), the air can flow freely through it. The rate of air-flow is indicated by the rotometer, R, which consists of a tapered tube, wider at the top than at the bottom, in which a light metal float, F, is airborne at a level depending on the airvelocity.

The standardised air pressure is controlled and adjusted by inserting the manometer plug shown in place of the plunger P in the otherwise empty chamber C and making adjustments at V_1 and V_2 until the manometer, M, registers 41.3 kPa (6.lbf/in^2). Calibration of the flowmeter at the top and bottom of its range is effected by adjustments at A and K when the outflow of air from the chamber is restricted by standardised orifices.

On the mistaken assumption that the resistance offered by the plug to the flow of air could be regarded as a unique function of the linear density of the fibres, the flowmeter scale was calibrated against a set of Upland American cotton, the linear



3.8 Micronaire.

densities of which had been determined by the standard ASTM gravimetric method, to give a reading in the mixed units of micrograms per inch. It is a matter of great regret that, when this instrument was first introduced, it was calibrated in gravimetric units. It is not surprising, therefore, that, when the instrument came to be used for testing Egyptian and other types of cottons, the results failed to agree with those of the gravimetric test. Now the micronaire value is regarded as a measure of cotton quality in its own right, loosely and inversely related to fineness, but also affected by maturity.

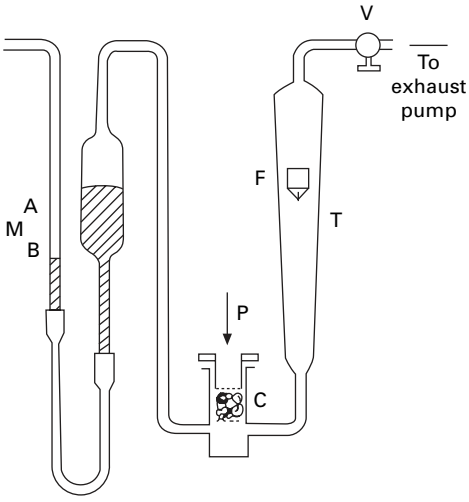
Being extremely rapid in operation, the micronaire test was quickly taken up by the American cotton spinning industry, where it was found to be extremely useful for the purpose of quality control in blending. So long as only Upland cotton was used, it was the general experience that, if the micronaire reading fell below about 3.3, neppy yarn and excessive ends down were to be expected, and that mixing bales so as to give a blend of constant micronaire led to more consistent and better running conditions in the mill. This gave rise to the quite widely held but completely false notion that the finer the cotton (low micronaire), the poorer was the performance. As has been shown, the rate of air-flow depends on the specific surface, which can be expressed as the ratio of the perimeter to the cross-sectional area. If the perimeter remains constant, changes in the rate of air-flow will reflect changes in the area of cross-section or linear density, which arise from changes in the thickness of the wall, namely the maturity. All American Upland cottons have roughly the same perimeter and what was being shown by a low micronanire was poor maturity, which caused poor spinning performance.

To obtain consistent and reliable results, the method of preparing the specimen must be standardised. Any pieces of stalk, seed or other major impurities must be removed, and, after the standard amount of cotton has been weighed out, the fibres must be well teased and fluffed with the fingers while being packed into the sample chamber. The conditions to aim at are uniform density of packing but random arrangement of fibres.

The Micronaire can also be used for testing wool, in which case the standard mass of the sample is 5.9 g and the air-pressure is 31.0 kPa (4.5 lbf/in^2). Removal of oil or grease by means of a suitable solvent is necessary before the sample is conditioned, weighed, fluffed up and packed into the chamber. The flow meter is empirically calibrated for direct reading in diameter in μm, and, although different wools vary somewhat in their ellipticity, the results obtained for non-medullated samples are nearly always found to agree very closely with the mean diameter as measured by the method described in Section 3.6.1.

3.8.4 The WIRA Fibre Fineness Meter

The WIRA Fibre Fineness Meter [62], which was developed for wool testing and is shown in Fig. 3.9, operates on the same principle as the Micronaire and incorporates the same simple flowmeter-tube method of measuring the rate of air-flow. It has, however, certain advantages over the Micronaire; in particular, it is simpler in design, and the air, instead of being pumped through the system by a compressor, is drawn



3.9 WIRA Fibre Fineness Meter.

through it by a suction pump. By this means is avoided the difficulty of controlling the temperature and humidity of the air passing through the specimen and consequently the errors that could arise owing to swelling of hydrophilic fibres. Although superseded by the automated optical methods described in Section 3.7, the air-flow method is still used in textile mills.

There are two models, one for wool and one for cotton, differing in the dimensions of the sample chambers and the weight of the sample. As with the Micronaire, the sample is required to be well teased out and fluffed up, so that the fibres are in a substantially random condition, and for cotton it is convenient to use a Shirley Analyser for this purpose. Both models can be obtained with the tube graduated in flow units, litres per minute, in which case there can be no misunderstanding about what the instrument is really measuring. To give results in terms of more commonly recognised textile units, the instrument should be calibrated by means of specimens of the kind for which the instrument is to be used and of which the required fineness characteristics have already been determined by independent methods. Either a calibration chart can be used or a calibrated scale may be fixed alongside the flowmeter tube T for direct reading. If the material to be tested is wool, the calibration will naturally depend on whether the fibres are in the greasy, oil-combed or scoured (or extracted) condition, and the presence of sand, dust or other foreign matter could be a source of error.

As with the Micronaire, it is convenient to calibrate the wool instrument in terms of mean fibre diameter. With cotton, the calibration can be in terms of specific surface or, regrettably, in maturity ratio or micronaire scale units. For the latter purpose, physical standards consisting of samples of cotton of known fibre properties are available.

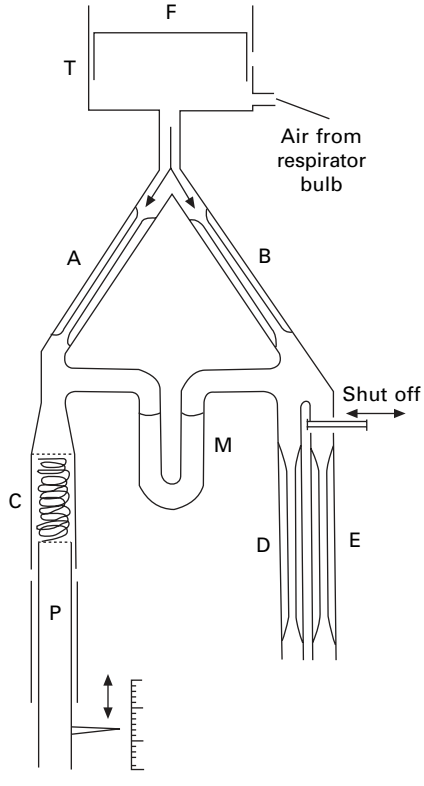
Operation is extremely simple. With the instrument levelled so that, with no air flowing, the level of liquid in the manometer tube M is at A, and with the perforated lid P placed on the weighed and uniformly packed specimen in the chamber C, the

valve V is gradually opened until the pump suction lowers the liquid level to B. Then, at the standard pressure represented by the difference in liquid levels in the manometer, the rate of air-flow (or the corresponding measure of fineness) is given by the height of the float F.

With slight modifications to the size of the sample chamber, to the weight of the sample, and to the range of the flowmeter, the wool model can also be used at a constant rate of air-flow. In that case, the valve V is opened until the flowmeter registers a fixed rate of flow, and the fineness is then measured in terms of the pressure drop indicated by the manometer M. In this case, it is, of course, the latter that has to be calibrated in the required fineness units.

3.8.5 The Arealometer

The Arealometer [4, 34], shown schematically in Fig. 3.10, works essentially on the principle of the Wheatstone bridge. Air at a low constant pressure is made to flow through a branched pair of resistance tubes, A and B, as shown. The air in branch A flows into the atmosphere through the sample chamber C in which the plug of fibres is inserted, while the air in branch B also escapes into the atmosphere through the standard resistance tubes, D and E. The tubes A and B offer equal resistance to air-



3.10 Arealometer.

flow. In operation, it is the object, by suitable compression of the fibre plug in C, to adjust its resistance to air-flow so that the pressure drop across C is equal to that across D and E combined, as recorded by the manometer M. The length to which the fibre plug has to be compressed to achieve this balance is then a measure of the specific surface of the fibres.

The desired degree of compression of the fibre plug is obtained by advancing the hollow piston P into the chamber, the crown of the piston and the inlet end of the chamber being perforated to permit the necessary flow of air. Advancement of the piston is by means of a handle on the end of a micrometer screw carrying a scale on which direct readings of specific surface can be read off in units of square millimetres per cubic millimetre.

The pressure of the air admitted to the system is determined by the weight of the freely floating piston F in the pressure tank T. This arrangement has the advantage of enabling the instrument to be small, compact and completely self-contained.

The sample chamber is only 0.8 cm in diameter, and the instrument has been so designed that the correct size of sample is one in which the volume of the fibre substance is 0.1 cm^3. This is obtained by taking a quantity of fibre of mass (in grams) equal to one-tenth of the density of the material in g/cm^3. Thus, for cotton, the correct test-sample mass is 152 mg, and, instead of the aim being a random orientation of the fibre, the sample is prepared by a special technique such that the fibres are made to lie in coils transverse to the direction of air-flow, and the instrument is calibrated accordingly. Unfortunately, with this technique, the time required per test is appreciably longer than with the Micronaire and WIRA instruments, and it is rather more difficult to secure concordance among different operators. For these reasons, in a later and portable version of the Arealometer, known as the Port-Ar, the makers reverted to a teased and randomised sample of much larger size, of mass 8 g. With this change and the inclusion of a built-in weighing device, specially designed for rapid weighing, it is claimed that an experienced operator can easily run 60 samples an hour, provided that the samples are accessible. With the Arealometer, the corresponding time required per test is approximately 10 minutes, but it is also possible at the same time to obtain a measure of maturity by making a measurement at another level of compression (see Section 3.10.7).

3.8.6 SDL Micromat

The SDL Micromat is a stand-alone, high-speed tester, which includes an electronic balance, a computer and a monitor to display results. It operates on the double compression principle (see Section 3.10.7) to measure fineness and maturity. The SDL operating procedure specifies a mass of 3.8 to 4.2 g, which has been opened and cleaned in a Fibreblender or Shirley Analyser, but Gordon *et al*. [54] recommend a consistent weight of 4 ± 0.005 g. The specimen is compressed to two different volumes in the test chamber. It is subject to a flow of 4 litre/minute at low compression, and 1 litre/minute at high compression, giving pressure differences P_L and P_H respectively. Fineness (mtex), micronaire, maturity ratio and percentage maturity values are computed from P_L and P_H by a set of empirical equations, with constants

derived from calibrations.

3.9 The vibroscope method

The vibroscope method, originally put forward by Gonsalves [63], is a non-destructive test, which can be used in combination with a tensile test on the same specimen. Although not too suitable for measurements on cotton or wool because of the within specimen variability, it is useful for manufactured fibres.

For a perfectly flexible string of linear density c and length l, under tension T, the natural frequency of transverse vibration f is given by:

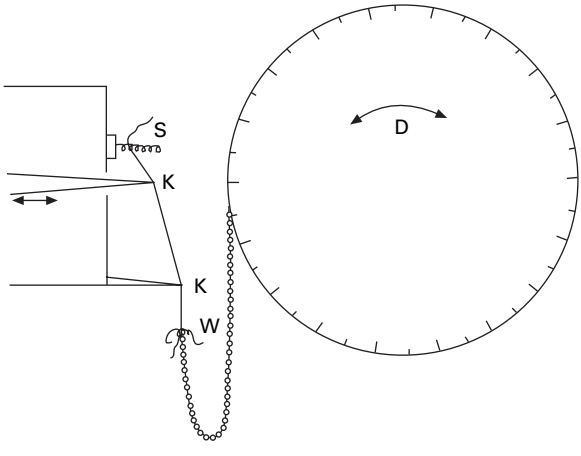
$$f = \tfrac{1}{2}(1/l)\left(\frac{T}{c}\right)^{1/2}(1 + a) \tag{3.23}$$

whence:

$$c = T\left(\frac{1}{2}\,lf\right)^{2}(1 + a)^{2} \tag{3.24}$$

where a is a correction factor involving the elastic modulus of the material. If a can be made negligibly small as compared with unity (see below), then m can evidently be found for a specimen of fixed length l in one of two ways: either by finding what frequency of vibration f corresponds to a given tension T, or by varying T until a given natural frequency f is obtained.

In the apparatus used by Morton [21] (see Fig. 3.11), the fibre specimen is clamped between two springs S and W and stretched across two knife-edges KK under a chainomatic tension adjustable by rotation of the drum D. The knife-edges are 2 cm apart, and one of them is caused to vibrate in a direction normal to the fibre axis with a fixed frequency of 1.640 kHz. When the natural frequency of the specimen coincides with this applied frequency, resonance occurs. The fibre is therefore observed through



3.11 Vibroscope.

a low-power microscope, and the tension T is adjusted until the fibre is seen to vibrate with maximum amplitude. Since d and T are linearly related, the drum readings may be calibrated directly in the units of linear density desired. The specific stress on the fibre T/c depends only on the value of l and f, which were chosen to give a value of 8·83 mN/tex (0.1 g/den).

For fibres of circular cross-section, the correction factor a is given by:

$$a = \left(\frac{r^2}{l}\right)\left(\frac{\pi E}{T}\right)^{1/2} \tag{3.25}$$

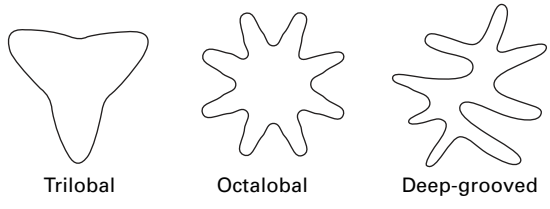
where r is the fibre radius and E the Young's modulus.

In most cases, a does not exceed 0.03 and can be neglected, but, if necessary, it can be calculated with sufficient accuracy from an approximate value of E. An alternative method suggested by Gonsalves is to compare, for a single specimen, the value of m given by the vibroscope with that determined by direct weighing on a delicate torsion balance. The percentage difference is then taken as the correction to be applied to all other specimens from the same sample.

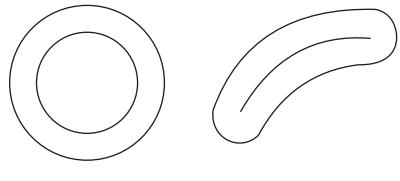
3.10 Fibre shape and cotton maturity

3.10.1 A variety of shapes

The simplest melt-spun fibres, which are extruded through a circular spinneret, are circular in cross-section. The use of shaped spinnerets has enabled fibres of different shapes to be made. Sharp edges are rounded to an extent dependent on time in the thread-line and melt viscosity. Typical examples of fibre shape are shown in Fig. 3.12. As discussed in Chapter 1, solution-spun fibres, such as rayon and acrylic fibres, have shapes that result from the formation of a skin and then the loss of solvent from the core. Wool only slightly departs from being circular, though some hairs are more elliptical, but at higher resolution surface scales determine the shape of the perimeter. Silk has a triangular cross-section.



3.12 Examples of melt-spun fibre shapes.



3.13 A cotton fibre, which is not fully mature, before and after collapse.

Fibre shape has a major effect on cotton quality. As shown in Fig. 3.13, cotton grows as a circular hollow tube, but collapses on drying to a ribbon or, when mature, kidney-shaped fibre (see also Section 1.4.3).

3.10.2 Cotton maturity

Whereas the mean perimeter of a raw cotton is mainly a hereditary characteristic, the degree of development of the cell wall is very largely determined by environment. If a fibre has a thick and well-developed wall, it is said to be mature. If, on the other hand, its wall is thin and poorly developed, it is said to be immature. Correspondingly, if a cotton, because of unfavourable growing conditions, contains a considerable proportion of immature fibres, it is referred to as an immature cotton. As stated in Section 3.2.5, the degree of thickening, which is a measure of maturity, is given by the ratio of wall area A_w to total fibre area, which equals $4\pi A_w/P^2$, where P is the fibre perimeter. For a solid fibre, $\theta = 1$. A *maturity ratio* is defined as the ratio of the actual degree of thickening to a standard degree of thickening equal to 0.577. Mature cottons have average values of θ greater than this, but immature cottons may have average values below 0.3. In any given sample of cotton, there will be a range of maturities, which, for a mature cotton might go from 0.15 to 0.96 [64].

There is an optimum degree of maturity for a cotton fibre, above which it tends to be too stiff and bristly for ease of processing, and below which it tends to be too flabby and unresilient. It is not very certain just where this optimum lies, though it is probably somewhere between $\theta = 0.8$ and 0.9. Spinners, however, are not usually worried about fibres that have abnormal wall thickening: they are much more concerned about those that have little or none. Cottons that are classed as immature are objectionable mainly because of their liability to the formation of neps, which are small, tightly rolled-up entanglements of fibre and which, unless removed by combing, survive all processes through to the yarn, when they appear as unsightly specks. Neps are not of natural occurrence: they are artefacts [65] produced by excessive rubbing against or between surfaces, which tends to roll the fibres into minute knots, and they have been repeatedly shown to consist mainly of very thin-walled, or so-called ‘dead’, fibres [66].

In the spinning of fine yarns from fine cottons, nep formation is at once both more frequent and more deleterious in its consequences. With fine cottons, even the fully matured fibres are more delicate than with coarse cottons, and dead fibres are more delicate still so that neppiness is less easily avoided; the neps that are formed are much more noticeable because in fine yarns their size is comparable to the yarn diameter. On account of the very poor wall thickening of the fibres involved, neps when dyed appear much lighter in shade than a normal sample of fibres given the same treatment, and hence appear as light, or even almost white, specks on the surface of the fabric. Calendering increases their prominence because the knot of flabby fibres is easily flattened and given a bright, glazed appearance. In printed fabrics, somewhat similar faults are produced. If surface neps are removed or dislodged, the underlying normal yarn is relatively unstained over the small area that has been covered by the nep. From the same argument, it will be evident that similar yarns

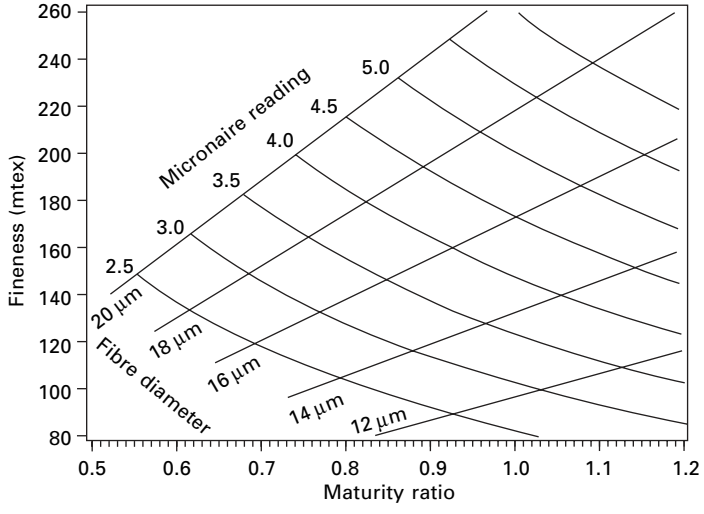
made from cottons differing in average maturity will also give different overall apparent shades and that imperfect mixing of the immature elements in a blend may give rise to streaky dyeing.

3.10.3 Measured maturity

The degree of thickening θ can be directly measured on fibre cross-sections, now made much easier by digital processing. Alternatively, as shown in equation (3.15), θ can be calculated from the mean specific surface S and the mean linear density[7] c of a sample of cotton. In accepting such calculated values, however, while a considerable amount of labour may be saved, it must be remembered that the results are subject to two independent sources of experimental and sampling error. In particular, it should be noted that errors in S are squared in the evaluation of θ. The value of such a procedure therefore depends largely on the reliance that can be placed on the data. Experience suggests that, if the linear density is determined by duplicate tests on each of 500 well-sampled fibres and the specific surface from four air-flow tests, then the calculated maturity is as accurate as is needed for practical purposes and no less reliable than if obtained directly by other means.

3.10.4 Micronaire, fineness and maturity

As already indicated, the micronaire value depends on specific surface and is therefore



3.14 Relations between micronaire, fineness (linear density) and maturity ratio. Diameter values are for an equivalent circular fibre [68].

[7]To be consistent, of course, the linear density should be measured by a whole fibre method.

influenced by both fineness and maturity. A detailed discussion of the relations is given by Montalvo [67]. Figure 3.14 shows relations between micronaire, fineness and maturity for US cottons [68].

3.10.5 Maturity counts

For all except highly specialised research purposes, micrometric methods of measuring maturity are unsuitable, not only because of the technical difficulties referred to in Section 3.6, but also because of the amount of time consumed by comparison with other methods that are available. Among these, by far the most commonly used is that in which the fibres are examined in longitudinal view under the microscope and classified according to the apparent thickness of the cell wall relative to the width of the fibre. In the U.S.S.R., the observations were made on untreated fibres [69], but in most other countries the fibres are first swollen in caustic soda. How thin the wall has to be before it is regarded as potentially nep-forming or otherwise undesirable is impossible to define precisely: hence the criteria by which the fibres are classified are decided to some extent arbitrarily.

In the British version of the maturity count, the test is carried out on the five tufts of fibre that are left from the Baer diagram after the fibre linear density has been determined. Each tuft is laid on a microscope slide so that the fibres are parallel but separated, a cover-slip is placed over the middle of the fibres, and they are then irrigated with an 18% solution of caustic soda until swelling is complete. The dangerous fibres are considered to be those in which, after this treatment, the wall thickness is one-third or less of the apparent lumen width: these are called 'dead' fibres. 'Normal' fibres are considered to be those which have become deconvoluted and rod-like and in which swelling of the wall has virtually obliterated the lumen. Between these two is the third class of fibres, referred to as 'thin-walled'. Classification is carried out with the microscope condenser so adjusted as to give maximum definition of the boundaries of the wall. Observations are made at one place only on each fibre, somewhere about its middle and, where convolutions are still perceptible, at a point where the width is a maximum between two reversals. The slide is first traversed to count the total number of fibres in the mount. It is then traversed again to count the rod-like normal fibres. Finally, it is traversed a third time to count the number of dead fibres. The number of thin-walled fibres, if required, may be obtained by subtraction.

The percentage occurrences of normal N and dead D fibres are calculated, and the means for all the slides are obtained. The sample is then characterised as to maturity by a quantity called the *maturity ratio* M, defined as:

$$M = \left(\frac{N-D}{200}\right) + 0.7 \tag{3.26}$$

The more or less arbitrarily chosen constants[8] are such that a value of unity is commonly obtained for high grades of Egyptian and Sudan Egyptian cottons, irrigation-

[8]For details of how this formula was arrived at, see the work of Peirce and Lord [5].

grown under generally favourable conditions. If the value of M is below about 0.8, the cotton is one which, as a whole, would be regarded as immature. Few samples of commercial crops have values for M of less than 0.7 [70].

The empirical relation between maturity ratio and degree of thickening θ has been given by Peirce and Lord [5] as:

$$\theta = 0{\cdot}577M \tag{3.27}$$

The ASTM standard maturity count is carried out in a similar way on fibres that have been comb-sorted for length and fineness determinations, but, instead of three levels of maturity, only two are recognised, mature and immature. A fibre is taken to be immature if the wall thickness is equal to or less than half the maximum width of the lumen. The fibres (approximately 100) that have been taken from each length group in the sorter array and weighed for fineness determination are mounted and swollen substantially as in the British test, and then traversed once under the microscope to count the two classes, which thus gives the percentage number of mature fibres M on each slide. Since both the number N' and weight W' of fibres on each slide are also known, as well as the weight of fibre W that each slide represents, the number of fibres N in each length group can be calculated as $N = N'W/W'$. The duly weighted mean percentage of mature fibre present in the entire sample is then given by

$$P_M = \sum NM / \sum N \tag{3.28}$$

As in all tests of this kind, doubtful classification may be decided with the aid of a filar micrometer or by means of a wedge-shaped line template. It is to the advantage of the ASTM method that there is only one boundary where doubts may be entertained, and in general it is easier to recognise quickly that one dimension is more than twice another than that it is more than three times another[9].

Although the British and American criteria of maturity are different, the results obtained by the two methods are highly correlated [71], and Lord [70] has given the following conversion formulae:

$$P_M = (M - 0.2)\,(1.5652 - 0.471M) \tag{3.29}$$

$$M = 1.762 - \sqrt{(2.439 - 2.123P_M)} \tag{3.30}$$

and, by combining equations (3.27) and (3.30),

$$\theta = 1.017 - \sqrt{(0{\cdot}812 - 0{\cdot}707P_M)} \tag{3.31}$$

It is, of course, possible to carry out a reliable maturity count without the necessity of first sorting the fibres for length, but, however conducted, the test is unfortunately tedious and time-consuming. The minimum time in which it is possible to obtain worthwhile results is about $1^1/_2$ hours [72].

3.10.6 Interference colours in polarised light

[9]Herein lies one of the main advantages of swelling the fibres with caustic soda. The ratios of lumen width to wall thickness that are of interest are smaller.

Another attempt to measure maturity, which was suggested by Grimes in 1945 [73] is examination of colours seen in polarised light [53], as used in the automated *Siromat* test described in Section 3.7.2. When cotton fibres are examined by means of a polarising microscope, they exhibit different interference colours that are dependent largely on the thickness of the cell walls. A first-order red selinite plate is used to obtain the brighter second-order additive colours and also to permit an additional check by observation of the subtractive colours when the stage is rotated. The fibres are examined at 100 × magnification and classified into four, three or two classes, depending on how fine a differentiation is required, as follows.

Fibres that appear purple or indigo throughout their entire length in the field of the microscope and turn orange on rotation of the stage through 90° are immature. On removal of the selinite, they show parallel extinction. Fibres that appear deep blue or alternatively blue and purple, turn orange-yellow upon rotation of the stage, and show some parallel extinction on removal of the selinite are also classed as immature. Fibres that appear blue-green or alternatively blue and yellow, turn yellow-white on rotation of the stage, and show only slight dimming on removal of the selinite are partially mature. Fibres that appear yellow or yellow-green throughout their entire length and show practically no change of colour on rotation to the subtractive position nor parallel extinction on removal of the selinite are fully mature fibres.

Approximately 1000 fibres are examined, and the whole operation, excluding sampling, takes between 2 and 3 hours, so that in the matter of time it has no advantage over the maturity count and, depending as it does on the colour judgement of the operator, it is, if anything, more subjective. Any attempt to classify a continuous variate (as maturity is) on the basis of colour judgement must inevitably give rise to uncertainties at the class boundaries. Furthermore, a question has been raised as to how far the test is one of maturity and how far it is mainly one of wall thickness. With American Upland cottons, where there is comparatively little variation in cell girth, this would not be a problem, but for world cottons as a whole, it was suggested that the correlation with a maturity count was weaker.

In more recent studies related to the development of Siromat, an examination of the interference colours of different cottons by Gordon and Phair [74] showed no differences dependent on genetic origin or intrinsic fineness. The fibres were classified according to the scheme of Grimes, namely blue to orange for fibres with varying degrees of immaturity and bright yellow for mature fibres.

3.10.7 Other indirect methods

Differential compression

The use of differential compression was first noticed by Hertel and Craven [4] in the course of developing the Arealometer instrument, and is now more widely used in the Shirley Fineness and Maturity Tester (FMT). It was found that, if a sample of cotton was subjected to an air-flow test at two widely differing compressions, the highly compressed condition produced an apparently greater specific surface, and the increase was greater for immature samples than for mature. This led to the idea that the difference in the results obtained at two different porosities might be made to serve

as a measure of immaturity, and for this purpose the Arealometer was designed in its present form. On referring to Fig. 3.10, it will be observed that the standard resistance tube E is provided with a cut-off switch. If, after a normal test has been made, tube E is cut off by this switch, the resistance to air-flow down limb B increases, and the sample has to be further compressed in order to restore the pressure balance as indicated by the manometer M. A second, and spurious, reading of specific surface is therefore taken on a different calibrated scale, which is automatically brought into use by the throwing over of the cut-off switch. The difference D between the two readings is then used to calculate the immaturity ratio I by using the empirical relation[10]:

$$I^2 = 0.0625D + 1 \tag{3.32}$$

Hertel and Craven explain the apparent increase in specific surface by supposing that, when the plug of fibre is subjected to the higher compression, the contact between the fibres is increased considerably and, as a result, the immature fibres are flattened and constrained to rotate about their own axes so that their broad sides are presented, or more effectively presented, to the direction of air-flow. The result is an increased resistance, which the Arealometer reflects by registering an apparent increase in specific surface. In other words, the factor k in the flow equation is changed.

Agreement between the results of the Arealometer test and those of the maturity count is quite good. Webb and Burley [75] found the correlation coefficient to be +0.889 as against +0.752 for the Causticaire test. Morton and Radhakrishnan [34], comparing the Arealometer immaturity with the immaturity calculated from the whole-fibre linear density and the Arealometer specific surface, found the correlation coefficient to be +0.978. The test has much to commend it. Of all the 'bulk' tests proposed, it appeared to be the most reliable and is certainly by far the quickest. Unfortunately, however, for a reason that has not yet been satisfactorily explained, it cannot be used for testing material, such as sliver, that has been mechanically processed.

Differential compression is also the principle adopted in the Shirley FMT [76], which is used in quality control laboratories in spinning mills and some test houses. Values for maturity are calibrated by swelling in caustic soda and for fineness by cutting and weighing. An upgrade of FMT has been made by Montalvo *et al.* [51].

The Causticaire test

This is an adaptation of the Micronaire test by means of which it is possible to obtain a measure of maturity. The underlying idea is that treatment with 18% caustic soda, by swelling the fibre walls, reduces the specific surface. The changes so brought about are more pronounced with immature than with mature fibres, and consequently the difference in the air-flow readings for a sample before and after caustic treatment should be a reflection of its average maturity.

Lord [77] has investigated this test in considerable detail with results that can only

[10]In a later publication, Hertel proposed an increase in the constant from 0.0625 to 0.070, but Morton and Radhakrishnan [34] and Webb and Burley [75] found that this led to immaturity values that were too high for agreement with standard maturity counts.

be regarded as unfavourable. He found that the 'Causticaire maturity index' was biased to an extent partly depending on the fibre fineness but that, even after correction for this bias, the method yielded estimates of maturity that were of low accuracy. Webb and Burley [75], in an investigation involving tests on 319 American Upland samples of the 1951 crop, found the correlation between Causticaire maturity index and percentage of mature fibres, as determined by the ASTM standard maturity count, to be no higher than +0·752. As Lord remarks, the Causticaire estimates for fibre maturity can, at best, only be regarded as providing a rough approximation to the real values.

The differential-dyeing test

This test, originally put forward by Goldthwait *et al.* [78], was used by workers in Ghent and Delft, in the following way. A 3 g sample is introduced into a boiling dye-bath consisting of Diphenyl Fast Red and Chlorantine Fast Green. After 15 minutes, 4% (calculated on weight of fibre) of NaCl is added and, after a further 15 minutes, a further 4% of NaCl. When the sample has been in the bath for 45 minutes, it is taken out and rinsed three times in distilled water. After draining off, the sample is immersed and continually stirred for 30 seconds in a beaker of vigorously boiling distilled water, after which it is centrifuged. The cotton is then rinsed in cold distilled water and carefully dried. The sample is now ground to powder in a mill, thoroughly mixed, and pressed into the form of a pad. The pads are then compared visually with pads prepared from Standard American cottons of known maturity as measured by the standard ASTM maturity count. Mature samples appear predominantly red and immature samples predominantly green.

According to Boulton and Armfield [7], the test depends on two circumstances: (1) that, of the two dyes used, the red diffuses into, and also washes out of, the cellulose of the cell wall much more rapidly than the green; and (2) that immature fibres have a greater specific surface than the mature and so take up dye more rapidly. Thus, because of their greater specific surface, the immature fibres take up more green dye than the mature fibres do and, because of the slow diffusion rate of the green dye, the difference between the two is not greatly affected by the subsequent boiling wash. With the rapidly diffusing red dye, on the other hand, a period of 45 minutes is long enough to cause both mature and immature to take up much the same amount of dye, but, in the 30 second boiling wash, the immature fibres lose much more of what they take up because of their greater specific surface.

From the foregoing, it will be evident that, if the test is to have any success at all, the procedure for dyeing and washing must be precisely defined and rigidly adhered to. It will be equally evident, however, that the test is essentially one of specific surface. It is a test of maturity only in the special circumstances of the American Uplands cottons already noted, namely, that mean perimeter can be assumed substantially constant. It could be used for other types only if in each case a special set of reference pads were prepared for each type. In the matter of time, the test has no advantages at all, and, bearing in mind that it is the specific surface that, in fact, is measured, the same results can be obtained far more quickly and with much less mess by means of an air-flow instrument.

Near infra-red reflectance

This is a fast test method, which has been investigated in connection with HVI testing. The radiation is scattered from the fibre surface and so correlates well with micronaire values and other methods of measuring surface area. Published work on this method of measuring cotton fineness and maturity has been reviewed by Montalvo and Von Hoven [79].

X-ray fluorescence analysis

This is another fast method, which measures the calcium content of the fibres, which can be related to maturity parameters [55, 80].

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4
Fibre length

4.1 Fibre lengths

In continuous filament yarns, the fibres are infinite in length. In the literal sense of the word, it is always possible to increase the length by adding another turn on the package. From a practical viewpoint, the fibre length in a 1 kilogram package of 100 dtex yarn is 10 kilometres, which gives an aspect ratio of 10^9 for a 1 dtex fibre and a negligible number of free ends in any product.

Manufactured staple fibres are mostly cut to a controlled length, so that the length is part of the specification, and the fibres are much more uniform in length than natural fibres, though not perfectly so. A reference from 1950 gives a coefficient of variability of 10% as indicating the degree of length variation likely to be encountered [1]. A part of this is due to imperfections in the stapling machine, which may have been reduced with improved quality control, but a part is caused by fibre breakage. All fibres are liable to breakage during handling and processing, and it follows that length measurements made on the same material in successive stages of manufacture will disclose the presence of a progressively increasing amount of short fibre, except where combing is introduced for the express purpose of removing the short fibres. In principle, manufactured staple fibres may be produced in any length, but since most manufactured staple fibre is blended with natural fibres, or, if used alone, is processed on machinery designed for natural fibres, the lengths available are selected to meet these needs. In nearly every case, the length is intended to be uniform, but it has been suggested that there are advantages for rayon staple in varied lengths when it is intended for blending with natural fibres [2]. In contrast to the genetic associations in natural fibres, length and fineness can be varied independently in manufactured fibres, and, incidentally, without affecting the cost.

An exception to the directly controlled length of manufactured staple fibres is in stretch-breaking of tows. A length distribution then depends on the quasi-random location of breaks in the filaments trapped between rollers running at increasing speeds.

For natural fibres, the length and the length distribution are critical properties, which influence processing, performance and price. In common with most of the physical properties of the natural textile raw materials, fibre length varies very greatly within any one sample. Thus, for example, the coefficient of length variation, itself differing appreciably from sample to sample, is of the order of 40% for cotton and

50% for wool [1]. This variability is biological in origin, and there is no practicable way of avoiding it, mainly because the major component of variance is to be found in the single seed of cotton or the single lock of wool. Some marginal improvement may still be possible by breeding for greater length uniformity, but, for the rest, the most that can be done is to adopt such farming, harvesting and marketing methods as will keep the other components of variance down to a minimum.

An impression of the magnitude of length variation in the natural fibres may be obtained from the fibre array shown in Fig. 4.1(a), while a comparison of (b) and (c) shows an increased tail of short fibres in a lot of $1\frac{7}{16}$ inch (3.7 mm)[1] *Fibro* viscose rayon staple as a result of breakage during processing.

In wool and cotton, length and fineness are correlated, negatively in the case of wool and positively in the case of cotton. Thus, among the wools of the world, the longer types are generally also the coarser, and the same kind of association between length and fineness is also found among the individual fibres of a given sample. Among cottons, the longer types are generally the finer, but there is no corresponding correlation for the fibres within a sample. Fineness does vary throughout the length range within a sample, but not systematically. Sometimes the longest fibres are the coarsest, sometimes the shortest, and sometimes those of intermediate length, as illustrated in the data by Clegg [3] in Table 4.1. Variations greater than those shown in Table 4.1 are not likely to be encountered very often. Sometimes, as shown by the figures for the Maarad sample, fineness is practically independent of length.

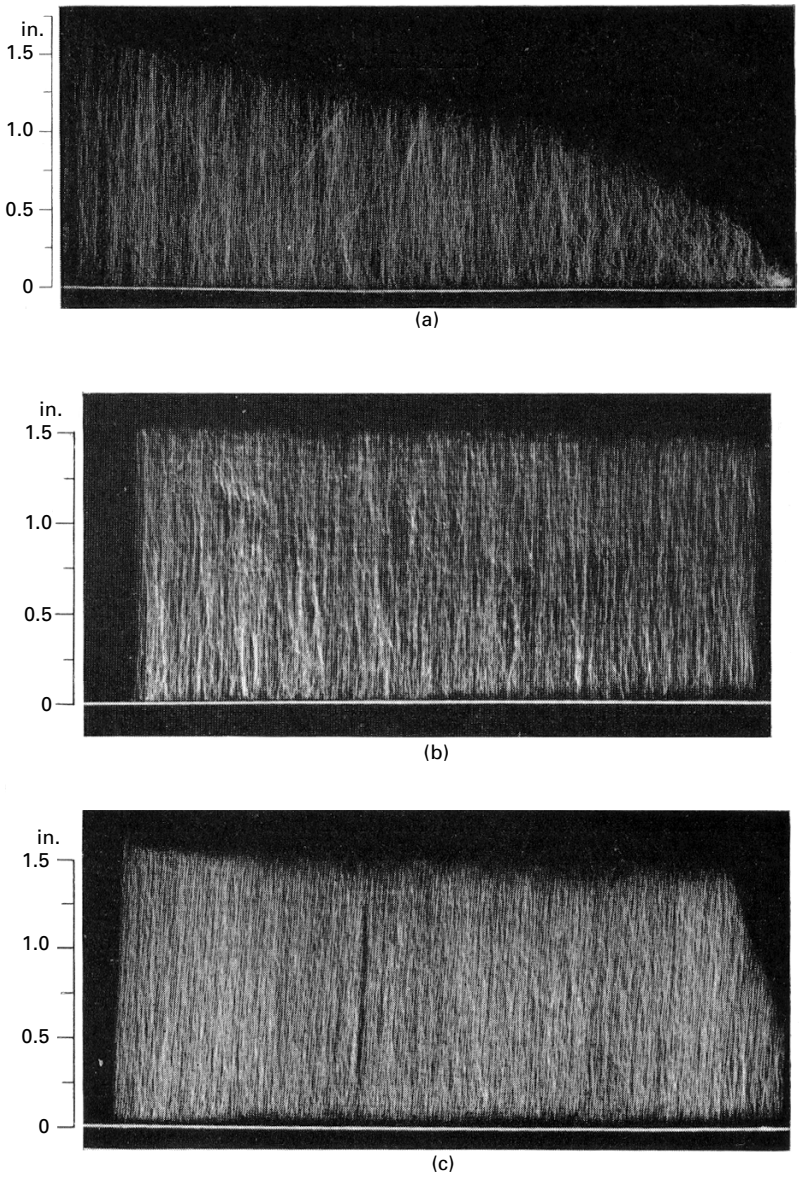
The lengths of wools and cottons are usually referred to in terms of staple length, a quantity which, so far as cotton is concerned, is discussed in some detail in Section 4.4.2. For present purposes, it is sufficient to say that the staple length of a wool is the average overall length of the natural locks in their normal crimped condition, whereas that of a cotton is somewhere between the mean length and the maximum.

Rough guides to the range of fibre lengths are given by the following examples. Coarse Indian cottons had staple lengths as low as $\frac{1}{2}$–$\frac{5}{8}$ inch, (13–16 mm) but short fibres below 1 inch (25 mm) have mostly been replaced by improved varieties. American Upland varieties (*G. hirsutum*), which now account for 90% of world cotton production, are 1–$1\frac{1}{4}$ inch (25–32 mm) *G. barbadense*, which has 8% of world production and includes Sea Island and long-staple Egyptian cottons, are $1\frac{1}{4}$–2 inches (32–50 mm). Australian Merino wool is typically 65–75 mm ($2\frac{1}{2}$ to 3 inches) but a coarse Lincoln

Table 4.1 Cotton length and fineness

Type of cotton	Linear density of fibre group millitex Longest ⟶ Shortest				
Brazilian São Paulo	194	225	236	256	283
Egyptian, white	158	160	166	180	173
Sea Island	138	124	131	117	108
Sudan Sakel	131	132	148	132	116
Egyptian, Maarad	141	134	131	137	134

1. Inches are given as the primary unit because that is cotton industry practice. The wool industry now uses mm.



4.1 Fibre arrays (Baer diagrams): (a) cotton; (b) raw Fibro viscose rayon staple; (c) Fibro from card sliver (1 inch = 25.4 mm).

wool would be 250–300 mm (10–12 inches). Strands of flax, hemp and jute may be between 15 and 90 mm (5 and 35 inches) in length.

4.2 Technical significance of fibre length

Fibre-processing machines, and especially those incorporating roller-drafting, are designed to operate efficiently only on a comparatively narrow range of staple lengths.

Furthermore, within that range, adjustments have to be made with some care to suit the material being processed if the best results are to be obtained. Therefore, once the machinery has been set up and adjusted, to avoid repeated and costly alteration, it is desirable to maintain optimum processing conditions by ensuring that raw material supplies do not vary by more than minimal amounts from some established length standard.

Where combing is involved, it is necessary, too, to control not only the length but also the variation in length of the material put into process. The amount of short fibre present influences the amount of 'noil' or waste extracted and thus has an important bearing on the economics of manufacture.

In rovings and yarns, the longer the fibre, the longer is the overlap among the fibres over which they can be made to cohere by means of twist. It follows, therefore, that the twist can be less without sacrificing essential strength and that, as a corollary, the longer the fibre length, the lower is the end breakage rate, other things being equal.

It should be mentioned that, when the material to be processed is short, the machine designer is presented with special problems inasmuch as roller settings must be correspondingly close. Consequently, smaller, high-speed, and less robust rollers must be used and less space is available for accommodating devices capable of controlling the motions of the short fibres present. It is therefore not surprising that the longer the fibres, the finer and the more uniform is the yarn that can be spun, other things again being equal.

Hence, for most purposes, longer fibres are preferable. From the point of view of cloth characteristics, however, short fibres have the advantage where it is desirable to produce a soft, hairy and warm-handling surface. Here a large number of projecting fibre ends are desired, and, although the number of ends can be strongly influenced by the method of spinning employed, under any given set of conditions it must obviously vary inversely as the mean fibre length.

4.3 Length distributions and fibre diagrams

4.3.1 Frequency diagrams

Table 4.2 relates to a hypothetical sample of fibrous material on which 100 length measurements have been made and the results arranged in the usual way for statistical calculation. For the sake of simplicity and to avoid the compilation of a cumbrous table, it is here assumed that 100 observations are enough to make a sufficiently reliable test, though in practice so small a sample would be quite inadequate. The overall range is 20 length units, divided at equal intervals of 2 units into ten classes, the mid-points l of which are given in column (1). The frequencies f given in column (2) relate to a numerical sample, and, when these are plotted as ordinates against the corresponding values of l, the usual form of frequency diagram is obtained as a histogram, polygon or curve (see Fig. 4.2). It is evident that the smooth curve derived from the frequencies represents the probability p that any fibre taken at random will have a length lying between l and $(l + \delta l)$ (see Fig. 4.3).

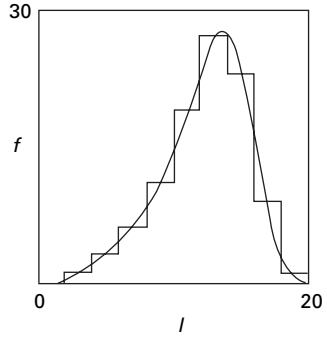
Table 4.2 Hypothetical fibre length distribution

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Class mean l	f	$\sum_{i}^{l_m} f$	$lf = f'$	$l^2f = lf'$	$\sum_{i}^{l_m} f'$	$\sum_{i}^{l_m}\sum_{i}^{l_m} f'$
1	0	100	0	0	1236	8692
3	1	100	3	9	1236	7456
5	3	99	15	75	1233	6220
7	6	96	42	294	1218	4987
9	11	90	99	891	1176	3769
11	19	79	209	2299	1077	2569
13	27	60	351	4563	868	1516
15	23	33	345	5175	517	708
17	9	10	153	2601	172	191
19	1	1	19	361	19	19
Totals	**100**	–	**1236**	**16 268**	–	–

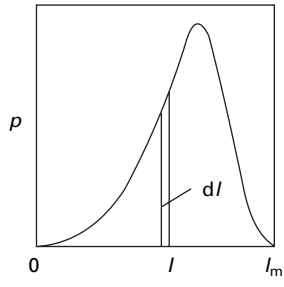
Mean length = $\bar{L} = \dfrac{\Sigma(lf)}{\Sigma f} = \dfrac{1236}{100} = 12.36$

Standard deviation = $\sigma^2 = \dfrac{\Sigma(l^2f)}{N} - \bar{L}^2 = \dfrac{16\,268}{100} - 12.36^2 = 9.92$

Length biased mean length = $\bar{L}' = \dfrac{\Sigma(lf')}{\Sigma f'} = \dfrac{16\,268}{1236} = 13.16$



4.2 Frequency histogram.



4.3 Frequency curve.

To calculate the mean length, $\bar{L}$, we proceed in the usual way to find, by column (4), the total length of fibre $\Sigma(lf)$ whence

$$\bar{L} = \frac{\Sigma(lf)}{\Sigma f} = \frac{\Sigma(lf)}{N} \tag{4.1}$$

where N is the total number of fibres.

The standard deviation σ is conveniently calculated by working with deviations from the arbitrary value zero, in which case the values of l are treated as deviations, squared and multiplied by the corresponding values of f, giving l^2f in column (5). The total variance is given by $\Sigma(l^2f) - N\bar{L}^2$, and the standard deviation by:

$$\sigma = \left(\frac{\Sigma l^2 f}{N} - \bar{L}^2 \right)^{1/2} \tag{4.2}$$

from which the standard error of the mean and the coefficient of variation are readily calculated. The maximum and the mode, with equal numbers shorter and longer, of the distribution can usually be estimated with reasonable accuracy from the frequency curve.

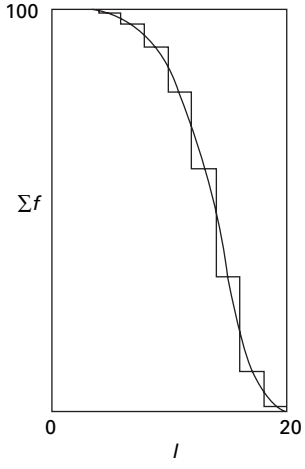
4.3.2 Survivor diagrams

An alternative way of graphically representing the fibre length distribution is to construct a survivor diagram, in which, for a numerical sample, the ordinates represent the number of fibres, expressed as a percentage or any other suitable basis, whose lengths exceed any given length, l. The most convenient way of obtaining such a diagram from frequency data is to find the cumulative totals of f, from the maximum, l_m, to zero, l_0, as shown in column (3) of Table 4.2, and plot these totals in histograph form against l. The survivor curve can then be obtained by drawing a smooth curve through the mid-points of the horizontal steps as shown in Fig. 4.4.

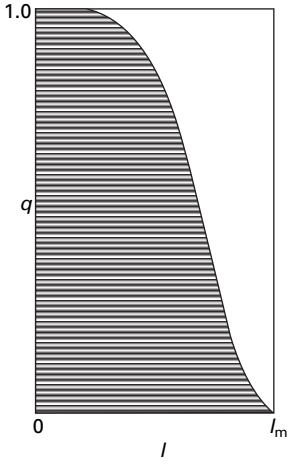
Another form of survivor curve is that given by the outline of a Baer diagram (see Section 4.7.2). In this case, the sorted fibres extend vertically from a common base-line, the longest on the left and the shortest on the right, as in Fig. 4.1(a). If, instead, they were arranged horizontally with the longest at the bottom and the shortest at the top (Fig. 4.5), the outline of the survivor curve of Fig. 4.4 would be obtained.

It is obvious that the curves of Figs 4.4 and 4.5 represent the probability q that any fibre taken at random will be longer than any given length l, and further that:

$$q = \int_{l}^{l_m} p \cdot \mathrm{d}l \tag{4.3}$$



4.4 Survivor diagram.



4.5 Baer diagram.

4.3.3 Distribution for length-biased samples

It is possible, and sometimes most convenient, to take as the sample for measurement a length-biased Wilkinson tuft. The length distribution of such a sample can be related to that of a numerical sample.

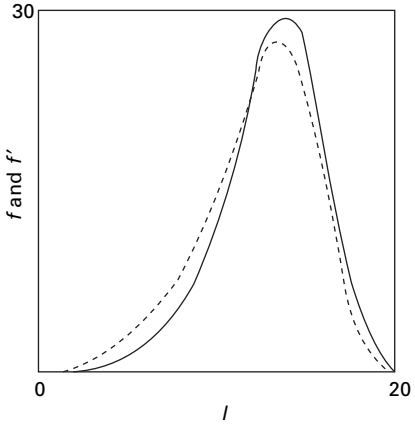
Consider a length-biased sample taken from the same population as in Table 4.2. In that case, as we have already seen, the probability of the occurrence of a fibre of length l is proportional to the product of its length and the frequency with which that length occurs in the population, or in the numerical sample, which we here assume accurately represents the population. Hence the relative length-biased frequencies, f', are given by $f' = lf$.

These quantities are given in column (4) of Table 4.2. With suitable adjustment of scale, they can be plotted as in Fig. 4.6 to show how a length-biased distribution compares with its numerical counterpart. Similarly, by taking cumulative totals of f' from l_m to l_0, we can obtain, as in column (6), the ordinates for a survivor curve for the length-biased sample. This is shown in full line in Fig. 4.7. Such is the curve that would be obtained if a Baer Sorter test (see Section 4.7.2) were made on a length-biased sample. For the infinite population, the equation corresponding to equation (4.3) is:

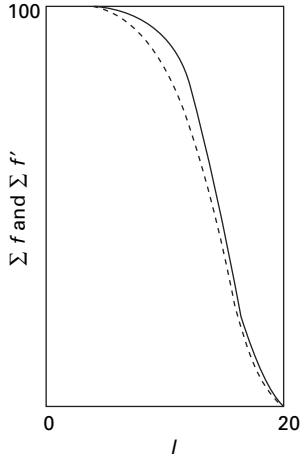
$$q' = \int_{l}^{l_m} p' \cdot \mathrm{d}l \tag{4.4}$$

To calculate the mean length, $\bar{L}'$, of the length-biased sample, we treat the values of f' as frequencies and proceed as usual to find $\Sigma(lf')$. But, since $f' = lf$, this quantity is the same as $\Sigma(l^2 f)$, which has already been found by column (5) of the table. Hence:

$$\bar{L}' = \frac{\Sigma(l^2 f)}{\Sigma(lf)} \tag{4.5}$$



4.6 Length-biased (full line) and numerical distributions (dashed line).



4.7 Cumulative length-biased (full line) and numerical distributions (dashed line).

But $\sum(lf) = LN$ and, from equation (4.2), $\sum(l^2 f) = (L^2 + \sigma^2)N$.

We have, therefore:

$$\bar{L}' = \frac{(\bar{L}^2 + \sigma^2)N}{\bar{L}N} = \bar{L} + \frac{\sigma^2}{\bar{L}} \tag{4.6}$$

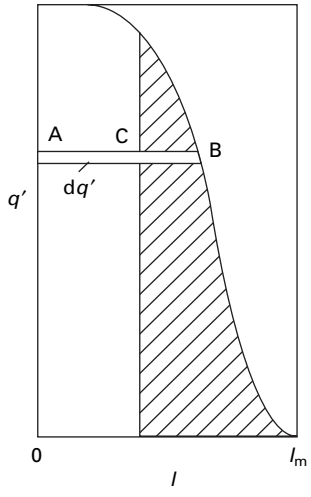
Thus, if the mean and standard deviation of a numerical sample are known, the mean of the corresponding length-biased sample can be calculated [4].

4.3.4 Beard diagrams

If a sliver of straight and randomly overlapping fibres is clamped across a section and all loose fibres are combed away on one side, a beard of fibres is left projecting. The distribution of lengths of the fibres in the beard will be the same as the distribution of distances from fibre ends to points randomly selected along the fibres. The length characteristics of the beard are of great technical importance [4, 5]. It is such a beard, for instance, that is held by a pair of drafting rollers or by the nippers of a rectilinear comb. The fibres held by the clamp, including the lengths on the other side, which have not been combed away, constitute a Wilkinson tuft, the nature of which has been discussed in Section 2.3.2, but here we are concerned with a semi-Wilkinson tuft, the composition of which is quite different.

Consider a beard formed by the left-hand ends of a length-biased population of fibres represented by the survivor diagram shown in full line in Fig. 4.7, and reproduced in Fig. 4.8. For convenience, let us refer to that part of a fibre that contributes to the beard as a beard element, or simply an element.

In the formation of the beard, every fibre that is held at all may be held at any point along its length with equal probability; so fibres of length l will contribute to the beard every length of element from zero to l in equal proportions. From the population



4.8 Clamp diagram.

as a whole, therefore, beard elements can arise varying in length from zero to l_m, the maximum length of fibre present.

Consider the probability r' that a beard element will be longer than l. For this to happen, it is clear that a fibre must be clamped at a distance > l from its left-hand end. Hence no fibre shorter than l makes any contribution. On the other hand, every fibre longer than l contributes to r' in a measure depending on how greatly its length exceeds l.

Take, for example, the fibre AB in Fig. 4.8, the probability of whose occurrence in the length-biased population is dq'. The probability that it will form a beard element longer than l is the probability that it will occur at all multiplied by the probability that the point where it is clamped will fall between B and C.

Since it is equally likely that the clamping point will be anywhere between A and B, the probability that it will fall between B and C is obviously BC/AB, and a similar condition holds for every other fibre longer than l. The total probability of an element longer than l occurring in the beard is therefore the ratio of the shaded area to the entire area under the curve, i.e.:

$$r' = \int_l^{l_m} q' \cdot dl \Big/ \int_0^{l_m} q' \cdot dl \tag{4.7}$$

But, since, substituting from equation (4.4), and noting that $\int_0^{l_m} q' \cdot dl$ is a constant for a sample, we have:

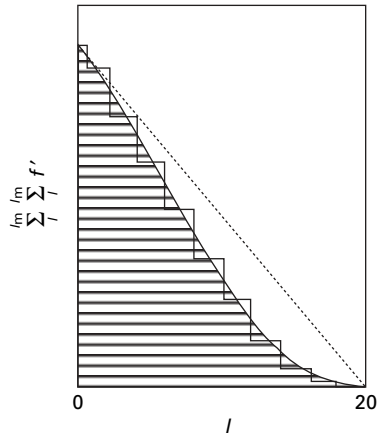
$$r' = \int_l^{l_m} dl \int_l^{l_m} p' \cdot dl \tag{4.8}$$

From this it is evident that all we have to do to obtain the distribution of beard elements from the length frequencies of a numerical sample of fibres is first to find the length-biased frequencies, $f' = lf$, and then to obtain the second successive cumulative totals of these frequencies, i.e.: $\sum_l^{l_m} \sum_l^{l_m} f'$. This is done in column (7) of Table 4.2. When these values are plotted against l, the diagram shown in Fig. 4.9 is obtained. Horizontal and closely spaced lines are here drawn in to convey more graphically what the composition of a beard diagram is really like and to emphasise the striking difference between it and the corresponding Baer diagram. The dotted line shows what the beard diagram would have been if all the fibres had been of the same length l_m.

4.3.5 Distributions by mass

In some of the techniques of fibre-length measurement, the fibres of a sample are sorted into length groups; and the fibres in each group, instead of being counted to enable the frequencies to be obtained, are weighed.

Referring to Table 4.2, it is evident that, if f is the number of fibres in a group having a length l, then (f l) is the total length of fibre in that group. If the linear



4.9 Beard diagram.

density of all the fibres is c, then ($c\ f\ l$) is the mass of the fibres in the group. Thus, since c is a constant factor, the figures in column (4) also represent the proportions by mass of the different lengths.

For this to be true, it is not necessary that every individual fibre should have the same linear density: it is sufficient if c varies randomly so that its mean value shows no appreciable variation over the entire length range. Given these conditions, it is possible to transform a numerical distribution into a mass distribution, or vice versa, simply by multiplying or dividing by l, as the case may be. It is further evident that, given these conditions, the proportions by mass of a sample are the same as the proportions by number (i.e. proportionate frequencies) of a length-biased sample.

The necessary conditions can be assumed to hold good for all manufactured staple fibres, but not for wool or cotton, since fineness varies between fibres usually with length bias (see Section 4.1). When, therefore, as a result of using certain measuring techniques, mass distributions of length are obtained directly, they are best left and interpreted as such, without any attempt at transformation, unless c is actually measured for each group and the values so found are used in the computations (see Section 3.5.3).

A distribution can also be given in terms of the proportion biased by fineness (linear density or titre). This is mass-based in the sense that it depends on mass per unit length, but is not biased by the mass of the whole long fibre.

4.3.6 Measures of fibre length

The frequency distributions described above give a full picture of the fibre lengths in a sample. However it is also useful to give values for particular parameters. *Mean fibre length, variance, standard deviation* and *coefficient of variation*, whether on a numerical or a biased basis, are standard statistical parameters. A number of other terms have particular connotations [6]. *Staple length* is a characteristic length, usually estimated by subjective visual assessment. For cotton, it corresponds closely with the

modal (most frequent) length when the fibres are straightened; for wool it is usually taken as the length (extent) of the longer fibres in the crimped state in a hand-prepared tuft. *Short fibre content* is the percentage by number or weight of fibres shorter than a specified length, $\frac{1}{2}$ inch (13 mm) for cotton, typically 25 or 40 mm for wool.

For cotton, *effective length* is given by a series of approximations, usually two, to the upper-quartile length with elimination of short fibres by a procedure described below. The *fibrogram* is a particular form of length distribution obtained on modern automated instruments. Statistically, it is the second summation of the numerical distribution, which is column (7) of Table 4.2. *Upper-half mean (UHM) length* is the mean length by number of fibres in the longest half by weight of the fibres in a cotton sample, usually measured from the fibrogram. *Uniformity index* is then the ratio of mean length to UHM length expressed as a percentage. *Span length* is the length exceeded by a stated percentage of cotton fibres in the fibrogram. *Uniformity ratio* is the ratio of the 50% span length to the 2.5% span length, expressed as a percentage.

For wool, *hauteur* is defined as the mean length in sliver or roving from a titre (linear density)-biased distribution; *barbe* is the equivalent quantity from a mass (whole fibre) biased distribution. Because of the greater influence of longer fibres, barbe B is always greater than hauteur H. If the coefficient of variation of hauteur is V:

$$B = H\left(\frac{1 + V}{100}\right) \tag{4.9}$$

4.4 Wool and cotton

4.4.1 Wool fibre length

Because wool fibres are relatively long, length is a less important property. The twists needed in yarns are less and, in woollen yarns, entanglement is effective in giving strength. The low twist preserves yarn bulk, though sometimes at the expense of a propensity to pilling. Length was not a factor in traditional wool grading. However as Simpson [7] notes: 'Objective testing of fine Merino wools [which are shorter] has come to include measurement of wool staple length and strength (IWTO-30 test method) applied to greasy wool samples.' For long staple New Zealand wools, the reduction in length in carding of wool that has become entangled in scouring is a more important consideration. Data on short fibre percentage, mean fibre length and coefficient of variation of hauteur for *length after carding* can be provided for *sale-by-sample.*

4.4.2 Cotton staple length

From the earliest inception of roller drafting, it must have been recognised that there was a very strong association between the optimum spacing of the rollers and the length characteristics of the cotton being processed. It is therefore not unreasonable to assume that the values assigned to the so-called 'staple lengths' of the different cottons in use corresponded fairly closely with the roller settings that each demanded. But the concept of staple length came into use long before satisfactory methods of

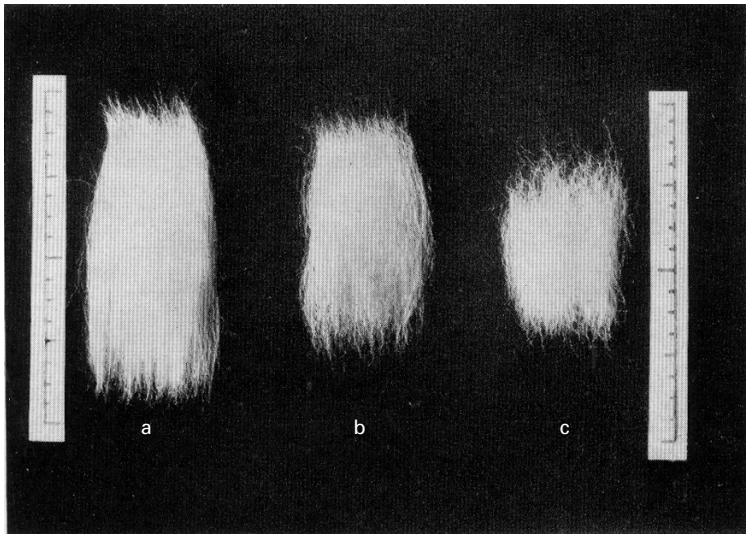
measuring fibres had been developed, so that merchants, spinners or graders in doing business with one another, had to be content with estimates of length made by personal judgement of the appearance of a hand-prepared staple such as is shown in Fig. 4.10. Thus, being arrived at by judgement and not by measurement, staple length was never formally defined in terms of any statistic of length distribution.

Continuous commercial intercourse has naturally resulted in a substantial measure of agreement throughout a business community as to what the staple length of any particular sample of cotton is, and, in the United States, at least, stability in the standards of judgement of Upland staples was greatly helped by the setting-up of physical reference standards, in the form of actual cotton samples, by the Department of Agriculture in 1918. Nevertheless, individuals differed in extreme cases by as much as 3 mm in their judgement, and furthermore, there is evidence to show that in Britain, if not also elsewhere, the whole level of judgement shifted with the passage of time. Whereas, in the 1920s, Lancashire estimates of Uplands staple tended to be about 10% over the American, by 1950 they had changed so as to fall into line. It was obviously desirable to give greater definition to this somewhat elusive quantity.

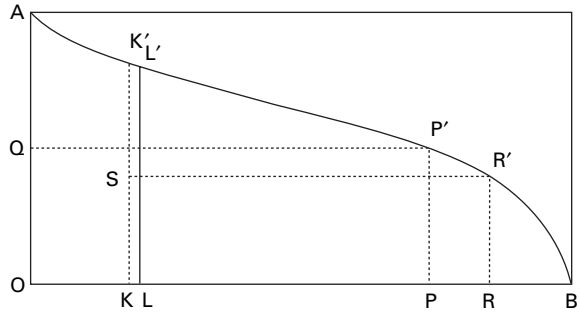
The earliest attempt to do this was that made by Clegg [3], who, starting with the outline of the Baer Sorter diagram (see Section 4.7.2), devised a geometric construction to give a quantity that she called the *effective length*. She found this to agree fairly well with the grader's estimate of staple length as judged on the Liverpool raw-cotton market at that time (1930). The construction is as follows (see Fig. 4.11):

$$OQ = \tfrac{1}{2}OA = PP'$$

$$OK = \tfrac{1}{4}OP$$



4.10 Hand staples from around 1960: (a) Egyptian cotton of $1\frac{7}{16}$ inch (37 mm) staple; (b) American cotton of $1\frac{1}{8}$ inch (29 mm) staple; (c) Indian cotton of $\frac{7}{8}$ inch (22 mm) staple.



4.11 Baer diagram analysis.

$$KS = {}^1/_2KK' = {}^1/_2RR$$

$$OL = {}^1/_4OR$$

and LL′ is the effective length.

It will thus be seen that the effective length is the upper quartile of a numerical length-distribution from which some of the shortest fibres (to the right of R) have been eliminated by an arbitrary construction. As has been remarked above, however, Lancashire judgement of Upland staples changed. Hence, so far as American cottons are concerned, the effective length must be divided by 1.1 in order to obtain the staple length. For Egyptian-type cottons, the effective length still corresponded fairly closely to the grader's estimate of staple according to Morton in the first edition of this book in 1962.

With the standard American methods of testing, the staple length is claimed to be given by the UHM length of the distribution by weight, though unfortunately there are no extensive data available by which the closeness of the agreement can be judged. If Egyptian-type cotton is tested with the Balls Sorter (see Section 4.7.2) to give a weight distribution, the staple length is said to be given by the 71st percentile [8].

An extensive investigation of this subject was carried out by Lord [9], who subjected a large number of samples of cotton from all over the world both to repeated judgement and to measurement. His results showed that, except for Egyptian cottons, the best measure of staple length for general application is that given by the modal, or most frequent, length of a numerical distribution, and he designed an instrument to measure this quantity rapidly and accurately (see Section 4.10.4). For Egyptian cottons, the modal length must be multiplied by 1.1 to obtain the commercial staple length.

4.5 Crimp

A characteristic feature of practically all staple fibres, which cannot be neglected in any discussion of fibre length, is crimp. Crimp, which in general terms may be defined as the waviness of a fibre, is of technological importance in several contexts. In brief, it determines the capacity of the fibres to cohere under light pressure and so in turn determines the cohesiveness of card webs, the amount of fly liberated during

processing, and the hairiness of the resultant yarn. It is also the principal feature governing the bulk of a textile material and so influences the specific volume of yarns and fabrics, through the dependence on packing factor.

It may be measured in terms of either the number of crimps or waves per unit length or the percentage increase in extent of the fibre on removal of the crimp. With strongly crimped fibres, the force necessary to straighten a fibre may be enough to cause some actual elongation of its axial length, but this is not likely to be of any moment unless the fibre is exceptionally extensible. Cotton has a relatively low crimp associated with the convolutions. In wool, the bicomponent structure gives rise to a helical crimp, which if lost in processing is regenerated on wetting. Crimp can also result from asymmetric forms in manufactured fibres, either in the skin of viscose rayon or in bicomponent synthetic fibres. In manufactured staple fibres, crimp is imposed by serrated rollers as an aid to processing, which may or may not survive into the final product.

For continuous filament yarns, a number of texturing processes lead to the filaments taking up forms, which may be pig-tail snarls in high-stretch yarns or alternating helices or other forms in low-stretch yarns [10]. However, detailed discussion of this type of crimp is outside the scope of this book, though the discussion of setting in Chapter 18 is highly relevant to the processes.

4.6 Individual fibre length measurement

4.6.1 Direct methods

The most obvious and most reliable method of fibre length measurement is to straighten the fibres from the sample, one by one, over a suitable scale and to measure their lengths directly. It is tedious and involves a certain amount of eye-strain. On the other hand, the results it yields are completely comprehensive, and it is superior to any other for accuracy, especially where the short-fibre components of a sample have to be accurately delineated, as in studies of fibre breakage, for example. It is essentially a research worker's method and is that by which the accuracy of other methods may be tested. By suitable illumination of the working plane, combined with a contrasting background and the use of a large lens when necessary, eye-strain may be reduced to a minimum; with practice, especially where it is possible to use a semi-automatic device such as is described in Section 4.6.3, measurements may be made surprisingly quickly.

If individual fibres can be selected, optical analysis of digitised images speeds up the direct measurement of length. However, automated methods are not as easy to develop as the use of snippets for fineness measurements. Recent advances are described in Section 4.11.

4.6.2 Oiled plate method

For cotton and short manufactured staple fibres, a convenient form of scale to use is a sheet of glass, of about quarter-plate size, which has a centimetre scale photographed or etched on its underside. The surface of the glass is smeared with liquid paraffin,

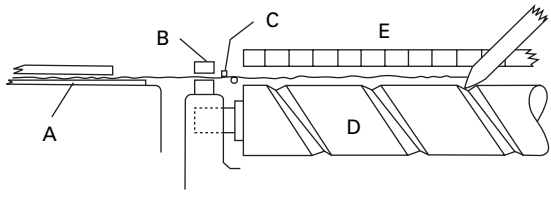
and a bunch of about a dozen fibres from the sample is placed on the far left-hand corner. Then, with the tips of the little fingers of each hand, the fibres are drawn one at a time over the scale and smoothed out straight, and their lengths are noted. The paraffin serves to keep the fibres from blowing about and assists in making them lie flat and straight on the scale when brought into position. As each fibre is measured, it is drawn off into a bunch at the right-hand side of the slide and its length is recorded. The measurements may be written down in columns in the ordinary way, or, more conveniently, the readings may be entered as individuals directly into the appropriate length groups of a frequency table.

If the scale is placed on a dark grey background of matt card and the whole is suitably illuminated, both the fibres and the graduations of the scale may be clearly observed without any difficulty. Up to 300 fibres per hour may be measured in this way, so that, even with cotton, a test may be completed in $2–2\frac{1}{2}$ hours. It is worth noting, too, that, if it is required to know also the mean linear density of the fibres, this may be obtained with very little extra work. All that is necessary is to weigh the entire sample before bringing the oiled plate into use. If one knows the total weight and the total length, a short calculation provides the answer, which would otherwise have to be found separately at the expense of considerable labour.

4.6.3 Semi-automatic single-fibre testers

For measurements on wool and manuifactured fibres of comparable length, a purely manual procedure similar to the foregoing may be used, in which a black velvet-covered board is used instead of the oiled plate. To speed up the operation for wool tops, Anderson and Palmer [11] devised the semi-automatic WIRA Fibre Length Machine, and a special cotton version for measuring lengths down to 5 mm (0.2 in.) has been described by Wakelin, *et al*. [12].

The WIRA instrument [13, 14] is illustrated in Fig. 4.12, where the material under test is shown in the form of a 'squared' top spread out under a glass plate resting on a cloth A, ready for sampling. Each fibre to be measured is gripped at its extremity with forceps and drawn to the right successively under the light tensioning arm C, and the point of the forceps is pressed gently into the groove of the revolving screw shaft D. This causes the forceps to traverse smoothly sideways and draw the tensioned fibre after it until the tail end emerges through B. Thereupon the detector wire drops and makes an electric contact, which stops the revolving shaft and indicates by the position of the forceps the length of the fibre being measured. The operator then raises the forceps vertically, thus lifting one of the keys E, which in turn registers the



4.12 WIRA fibre length machine.

observation on the appropriate one of a drum of frequency counters at the back. The counters are spaced at 5 mm intervals, so that, by reading off the numbers on the counters at the end of the test, the frequency distribution of the results is obtained, classified in 5 mm groups. An experienced operator using this instrument can measure wool fibres at the rate of 500 per hour. Here again, by collecting the measured fibres and weighing them, the average linear density may be obtained with very little extra labour.

The drag of the fibre through the tensioning arm B is such as effectively to remove the crimp without stretching the fibre. There is a small consistent error of about 1 mm in the mean, owing to the fact that each fibre can be gripped not at, but only near, its end. This may be neglected in measuring wools but assumes some importance in dealing with short fibre materials.

4.7 Comb-sorter methods

4.7.1 Fibre sorters

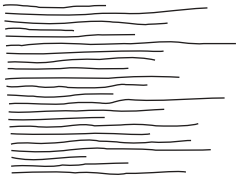
In order to avoid what was regarded as the too laborious measurement of individual fibres, and to expedite the handling of larger and therefore ostensibly more representative samples, a variety of mechanical or semi-mechanical 'sorters' were devised for the purpose of fractionating the sample into a suitable number of groups or of grading the fibres in the order of their lengths.

In all cases, the operation involves two steps: (i) the preparation of a fringe or tuft of fibres, all of which are aligned at one end as shown in Fig. 4.13 and (ii) the withdrawal of the fibres from the fringe in the order of either their increasing or their decreasing length.

4.7.2 Comb sorters

The commonest type of sorter in use is the comb sorter, which, in a variety of forms, can be used for measurements of most kinds of fibres. Only where strong crimp presents difficulties are comb sorters unsuitable.

The principle of operation is the same for all, though there are differences in matters of detail. The essential element is a bed of upright and parallel steel combs in which the fibres are embedded for control during manipulation. The pitch and fineness of the needles and the spacing of the combs vary according to the kind of fibre for which the instrument is designed. For cotton, the comb spacing is usually 5 mm, while for

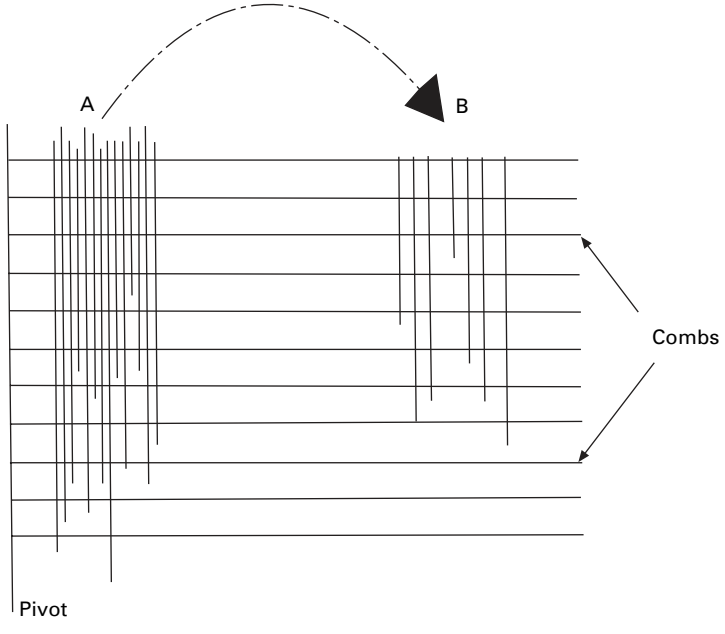


4.13 Fibres aligned for sorting.

wool it may be 1 cm or $\frac{1}{2}$ inch (1.25 cm). The following is a brief description of the manipulation of the Baer Sorter as used for raw-cotton testing [15, 16].

A sample weighing approximately 15 mg is first prepared by one of the zoning methods described in Section 2.5.2, and, by repeated drawing and doubling, it is formed into a narrow bundle of fibres, which are as straight and parallel as possible. This bundle is impaled in the combs with a short fringe protruding, as illustrated in the left-hand side of Fig. 4.14. With the aid of special tweezers, the fibres are taken successively in small groups by their extreme ends, withdrawn from the bundle, and transferred to the right-hand side of the needle bed, so that they lie straight and parallel with their near ends almost flush with the rearmost comb. When the entire sample has been thus transferred, the sorter is turned round and a set of hinged intersecting top combs is swung over into position to aid in controlling the fibres during the final, sorting, stage. In this, again by using the special tweezers to grip the fibres only at their extremities, the fibres are withdrawn in small groups in the order of their diminishing lengths, the combs being successively dropped or lifted out of the way as required.

From this point onwards, the procedure varies according to the method of analysis that it is proposed to adopt. In the United Kingdom, the usual practice is to prepare what is known as a Baer diagram (Fig. 4.1). To do this, the succession of small groups of fibres withdrawn from the tuft in the combs is deposited on a black velvet pad so that all their ends are conterminous with a base-line, which may conveniently take the form of a piece of white thread tied round the pad. When complete, the 'diagram' consists of an array of all the fibres in the tuft, arranged in order of their lengths; the longest, drawn first, is on the left and the shortest, drawn last, on the right, with any



4.14 Operation of a comb sorter.

neppy remnants from the first stage of manipulation gathered in a cluster on one side. The outline of the fibre array may then be traced on suitably graduated transparent paper to give a survivor, or cumulative-frequency, curve, which can be analysed to obtain any of the desired length parameters.

If, however, the results are to be at all reliable, considerable skill is required on the part of the operator in preparing the fibre array. In the analysis of the traced outline, two things must be assumed: (i) that, at any point on the trace, the vertical distance between the curve and the base-line represents the straightened length of the fibre at that point and (ii) that distances measured along the base-line are proportional to the number of fibres present. It is unnecessary to elaborate on the care and precautions that must be taken to justify these assumptions. Failure to straighten the fibres properly in preparing the array can alone give rise to an error of as much as $\frac{1}{16}$ inch (1.6 mm) [16], and errors of similar magnitude can also arise from failure to space the fibres along the base-line with uniform density. Appreciable subjective errors are thus involved, and, even with only one operator, it is usually thought desirable to make two diagrams to obtain a sufficiently reliable result. The time taken by an experienced worker in making a single Baer Sorter test, excluding sampling and analysis of data, ranges from about $\frac{3}{4}$ hour for a short-stapled Indian cotton to $1\frac{1}{2}$ hours for long-stapled Egyptian or Sea Island cotton. It will be seen, therefore, that, although it may be less of a strain, the Baer Sorter method has by no means a great advantage over the oiled plate method described in Section 4.6.2 as far as time is concerned.

An alternative and less subjective method of using comb sorters is to sort the fibres into groups at predetermined length intervals, weigh the groups, and so obtain a mass distribution for the sample (see Section 4.3.5). One way of doing this [17] is to withdraw, a few at a time, all the fibres whose proximal ends lie between each comb and the next, form them into convenient bundles, and weigh them on a micro-balance of suitable capacity. In this procedure, the group intervals are determined by the spacing of the combs, which must therefore be such as to provide at least ten groups from the sample of material under examination and must extend over at least the length of the longest fibre. For this reason, the Baer Sorter, with its nine combs spaced 5 mm apart, would be unsuitable for cotton. Accuracy depends on the thorough straightening of the fibres as they lie in the comb-bed, and appropriate allowances must be made for the facts that (a) the distal, conterminous ends of the fibres inevitably project a short distance behind the rearmost comb, and (b) it may not be possible, according to the type of gripping tweezers used, to withdraw all the fibres right up to the edge of each comb.

With the Schlumberger Analyser [18], which is designed for the sorting of wool and other long fibre materials, the operations just described are carried out semi-automatically, and a complete test on a wool top can be made in $1\frac{1}{4} - 1\frac{1}{2}$ hours. The fibres are laid in the combs in a crimped condition, however, and results for wool are consequently some 10% too low, though consistently so.

For cotton, which presents the greatest difficulties owing to its shortness, the most accurate method of obtaining the length characteristics directly from a distribution by weight is by the Suter-Webb Comb Sorter [19]. Here, the weight of the test specimen is standardised at 75 ± 2 mg, and a three-stage process of combing is prescribed

which ensures that, in the final tuft to be sorted, all the fibres are as straight as possible, with no displaced or straggling fibres breaking the alignment of the more distant fringe. By using the special tweezers, a long succession of small 'pulls' of fibres is now carefully withdrawn from the forward projecting fringe (combs being dropped out of the way as required) and deposited *separately* on plush-covered boards, each capable of holding about ten pulls. If the successive pulls diminish in length by only very small amounts (which is ensured by the requirement that their number should be in the range of 65–100), and if the depositing of the pulls on the plush is carried out meticulously as specified, then it may be assumed with negligible error that each one consists of straightened fibres, all of the same length. It then becomes a simple matter to measure each pull and assign it to its appropriate length group for weighing. A suitable interval between the length groups is $\frac{1}{8}$ inch (3 mm) and the mid-point of the group range is taken to be its mean. From the weights of the groups and their respective lengths, a reliable distribution by weight is obtained, but it is perhaps desirable to repeat that the 'mean' length and other characteristics of the material are derived from what is, in effect, a length-biased sample.

When the material to be examined is in the form of a random sliver of well-straightened and parallelised fibres as, for example, a wool top or a finisher-drawframe cotton sliver, the early stages of manipulating the sorter are modified [17] so that one may obtain a cut-square sample directly. This is done very simply by cutting the top or sliver, impaling it on the comb-bed with the cut end projecting slightly, and squaring back by the removal of all cut fibres.

Comb sorters cannot, of course, be used for card slivers. Even when the fibres are highly oriented, a certain amount of fibre breakage takes place, a fact that should be borne in mind in contemplating the use of comb sorters in experimental work on fibre breakage in processing or length fractionation in combing.

As already explained in Section 4.3.5, distributions by mass can only be transformed into frequency distributions if, within the sample, the linear density of the fibres is independent of, or bears a known relation to, length. With this in mind, it has been suggested in reference to both wool [20] and cotton [21] that the linear density of each length group can be determined by the method described in Section 3.5 and the transformation thus made possible. It should be pointed out, however, that, in some technical contexts, the proportionate weight of the different length groups is the information that is really required and transformation is unnecessary.

Sometimes, the sole interest lies in the amount of short fibre present in the sample. Comb sorters can be used to yield this information in terms of weight proportions quickly and without the necessity for making fibre arrays. All that is needed is to know the weight of the original sample and the weight of the fibres remaining after those longer than the desired length limit have been withdrawn and discarded.

4.8 The Balls sledge sorter

This ingenious semi-automatic instrument was devised by the first great cotton scientist, W. L. Balls, for use in cotton-breeding field stations where electricity was not available [22]. Since it is now very rarely used and is somewhat complex in design and operation,

it will not be described in detail here[1], but it is worthy of brief mention if only to show how far ahead of his time Balls was in recognising the pitfall of length bias.

The sample to be tested was first made up into the form of a short sliver of parallelised fibres, prepared with the miniature drawbox referred to in Section 2.5.2. This was then fed into the machine, which could be comfortably held in the hand and with which, by suitable manipulation, the following operations were carried out.

- The leading end of the sliver was subjected mechanically to a series of squarings in order to eliminate length bias (see Section 2.4.1).
- From the squared fringe, a small tuft, similar to that shown in Fig. 4.13 but containing about 500 fibres, was withdrawn and passed slowly downwards through a pair of delivery rollers. Since the leading ends of the fibres in the tuft were aligned, the rotation of the rollers released the fibres in succession according to their length, the shortest first and the longest last.
- Meanwhile, by manually traversing the sorter on its road wheels over a 180 cm (6 foot) long strip of one-way hatter's plush, the fibres were deposited as they were released, each to its appointed place on the plush according to its length. This was repeated for 20 tufts, the deposit at each traverse being superimposed on those preceding it.
- Finally, the elongated deposit on the plush strip was gathered up into bunches representing 3.2 mm (1/8 in.) intervals of fibre length and weighed on a torsion micro-balance.

The sample, then, was a numerical sample, but the result was a mean length determined from mass proportions (see Section 4.3.5). Results were very consistent, it being rare for differences of as much as 0.8 mm (1/32 in.) between repeat tests to be encountered. The time taken, however, was what would now be regarded as unacceptably long.

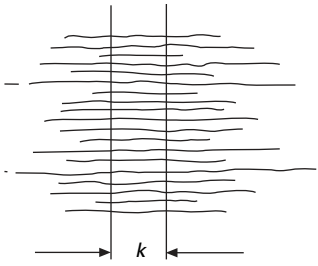
4.9 Cutting-and-weighing methods

4.9.1 Method 1 (Chandler)

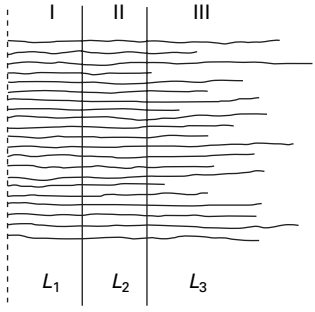
From a representative sample of fibres, a tuft or staple is prepared by repeated drawing and doubling and building it up by successive draws of small quantities, so that the fibres lie straight and parallel and extend approximately equally on either side of the middle of the tuft. The tuft is placed on a surface of fine cork linoleum, or similar material, and clamped across its middle at right angles to the fibres by a metal bar of width k (Fig. 4.15). The projecting fringes are cut off close to the edges of the bar and their combined mass, expressed as a ratio, r, of the mass of the middle portion, is then determined.

If L = mean fibre length, n = number of fibres in the tuft and c = mean linear density, then the total mass of fibre = Lcn, the mass of the middle portion = kcn, the mass of the fringes = $cn(L - k)$, and the ratio, $r = \dfrac{cn(L-k)}{kcn} = \dfrac{L}{k-1}$, whence:

[1] A fuller description is given in the first edition of this book.



4.15 Chandler's method.



4.16 Ahmad and Nanjundayya's method.

$$L = k(r + 1) \tag{4.10}$$

It should be noted that in this method a number of assumptions are made: (1) that all fibres are at least as long as k and extend wholly across the middle portion; (2) that they lie straight and free from crimp; (3) that the fibre linear density is the same for all lengths; and (4) that the fibres are not tapered towards either end. Because of this last assumption, the results for cotton are invariably on the low side. Ahmad and Nanjundayya [23] show that for Indian cottons, if k is approximately $l/2$ as recommended by Chandler [24], the results are too low by about 0.1 inch (2.5 mm) Even if, because of (1) above, k is reduced to $\frac{1}{8}$ inch (3.2 mm), the results are still about 5% too low according to Lord [25].

4.9.2 Method 2 (Ahmed and Nanjundaya)

The following method was devised by Ahmad and Nanjundayya [23] with the object of allowing for tapering fibre tips in measurements on cotton.

A representative sample is first made into a sliver by means of a Balls drawbox. This is placed on a set of four combs, and one end is squared-back as required in the squaring method of sampling (see Section 2.4.1). With a Baer-type tweezer, a numerical-sample tuft is withdrawn and combed free of any stray fibres. The tuft is then cut, as indicated in Fig. 4.16, into three sections, of which the lengths L_1 and L_2 are predetermined and can be varied to suit the cotton under examination. Sections I and III are next weighed, which gives masses M_1 and M_3. L_3 is the mean length of the fibres in section III.

Assuming the fibre linear density in sections I and III to be the same, then $M_1/L_1 = M_3/L_3$, i.e. $L_3 = M_3/M_1 \times L_1$. Hence the mean length of the tuft, L, is given by:

$$\bar{L} = L_1 + L_2 + \left(\frac{L_1 M_3}{M_1}\right) \tag{4.11}$$

The principal assumption, namely that the fibre linear density in section I is the same as that in section III, is justified on the grounds that, since the tuft is drawn from a random sliver, the number of basal and apical ends should be equal in both sections. How far this is true depends to some extent on the dimensions chosen for L_1 and

L_2. In general, since section I contains a length L_1 of all the fibres in the tuft, the fibre linear density in section I might be expected to be slightly greater than that in section III. Hence L_1M_3/M_1 will tend to be too small and $\bar{L}$ will be slightly under-estimated.

The other assumption is that all the fibres are at least as long as $L_1 + L_2$. To the extent that fibres terminate within sections I or II, so will $\bar{L}$ be over-estimated. The two errors tend, therefore, to cancel one another, and it is claimed that for Indian cottons the results obtained are not likely to exceed the true value by more than 0.01 inch (0.3 mm).

As regards the dimensions L_1, L_2 and L_3, it is recommended that the weight ratio, M_3/M_1, should be approximately unity, since otherwise the cut fibres in one section may weigh appreciably more per unit length than those in the other. The middle section should be neither too narrow nor too wide, because in the former case the effect of the tapering ends will be magnified, whereas in the latter it will be diminished.

4.9.3 Method 3 (Muller)

This method, due to Müller [26], can be used only for measurements on slivers, tops, rovings or yarns and gives the mean length of a length-biased sample.

A length of the strand, longer than the length of the longest fibre present, is cut, measured and weighed to determine its linear density C. It is then held near its middle by a suitable clamp, and all loose fibres on one side of the clamp are combed away. The projecting beard that remains is cut off and its mass M determined.

Since the beard is half a Wilkinson tuft, it is evident that, using the symbols n and w as before, we obtain

$$M = \frac{nc\bar{L}'}{2} \tag{4.12}$$

where $\bar{L}'$ is the length-biased mean length. Hence

$$\bar{L}' = \frac{2M}{nw} \tag{4.13}$$

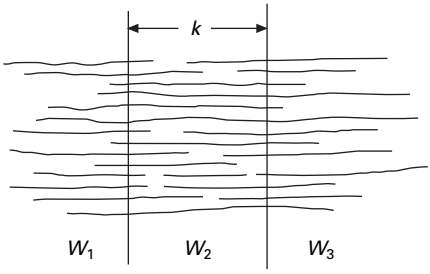
But, assuming uniformity of the strand specimen, $C = nc$. Hence

$$\bar{L}' = \frac{2M}{C} \tag{4.14}$$

Because the fibres in the strand specimen are not stretched out straight, W is over-estimated, and $\bar{L}'$ is given as less than it should be (see Section 4.9.4).

4.9.4 Method 4

This is a refinement of Müller's method and is again applicable only to strands of parallel fibres. Here the strand is held under a clamp of width k, and, after all loose fibres have been combed away on either side, the two projecting fringes are cut off. The combined masses of these, $M_1 + M_3$, and also that of the middle portion, M_2, are then determined (Fig. 4.17).



4.17 Müller's method.

$$M_1 + M_3 = n\,\bar{L}'\,c \tag{4.15a}$$

It follows that

$$\bar{L}' = \frac{M_1 + M_3}{nc} \tag{14.5b}$$

But $M_2 = nkc$; i.e. $nc = M_2/k$. Hence:

$$\bar{L}' = k\,\frac{M_1 + M_2}{M_2} \tag{4.16}$$

According to Lord [25], the results obtained for cotton are about 10% too low because the fibres in the mid-section are not straight, and, in fact, they agree fairly well with the mean lengths of the corresponding numerical samples. In other words, the error is approximately balanced by the bias in sampling. For cotton, it is recommended that k should be $\frac{1}{2}$ inch (12.7 mm), but for worsted tops Huberty [27] recommends 5 cm.

4.10 Automated scanning of fibre tufts

4.10.1 Automated procedures

The physical sorting of fibres into their various lengths is, in general, tedious and slow. To obtain quicker results, numerous devices have been introduced in which a representative tuft of a standard form is prepared and then scanned from end to end for some property more or less linearly related to number of fibres reaching each position. From results obtained in this way, and with suitable calibration, various length characteristics of the material may be derived.

4.10.2 Thickness scanning

Thickness is one way of determining the amount of material at each position in the tuft, but has now been superseded by other methods described below. In the 1960s, the Uster Stapling Apparatus[2], designed for the testing of cotton, is the most notable

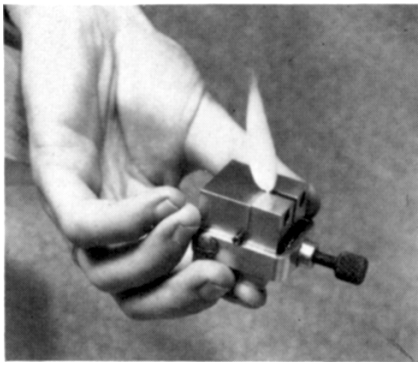
[2] More details are given in 2nd and 3rd editions of this book.

of the devices that operated on the thickness principle. It consists essentially of three parts: (1) an intersecting comb sorter of the semiautomatic Schlumberger type, by means of which a fringe of fibres having the characteristics of that shown in Fig. 4.13 may be rapidly prepared; (2) a tufting apparatus for converting the flattened fibre fringe into a tuft of the form shown in Fig. 4.18; (3) a dial gauge with which the thickness of the tuft can be measured from end to end.

4.10.3 Capacitance scanning

Suitably prepared fibre fringes or 'draws' may also be scanned by traversing them slowly between the plates of a condenser and recording the changes in its capacity. The latter quantity may be assumed with negligible error to be proportional to the weight of the fibres lying between the electrodes, i.e. length × linear density × number of fibres. Therefore, if the mean linear density of the fibres can be assumed constant over all parts of the draw, and if the fibres lie straight and normal to the width of the condenser, then successive readings of capacity lead directly to a cumulative-frequency distribution based on a numerical sample. From this, the various parameters of length may be calculated. The method is particularly useful for measuring fibre length in combed slivers or rovings of wool and other fibres of similar length. The fringe to be examined is of the type illustrated in Fig. 4.13 and is obtained from the top or sliver by the squaring technique, essentially as described in Section 2.4.1.

The Almeter was introduced in the 1960s [28–30], but has since been additionally automated and linked to a computer. An end-aligned sample is produced by a comber device built on the lines of the Schlumberger Analyser (see Section 4.7.2) and is fed at constant speed through the plates of a condenser. The signal is processed by a computer to show a cumulative length diagram and values of hauteur and barbe, their coefficients of variation, percentages of fibres longer or shorter than given lengths and length exceeded by a given percentage of fibres, both of the latter biased by cross-section or weight. Twisting of slivers is necessary to obtain accurate results.

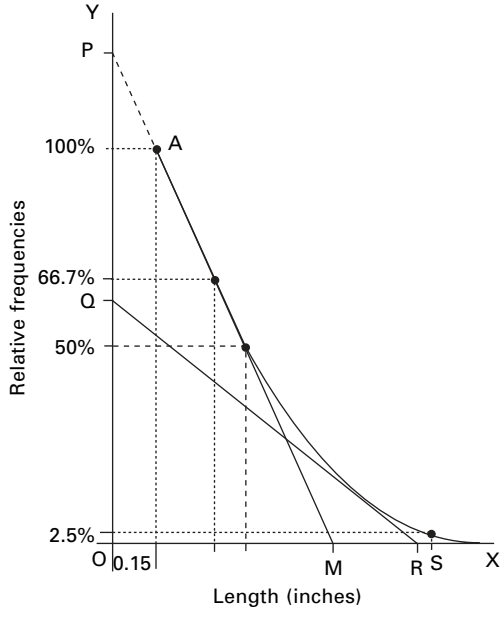


4.18 Uster clamping block with fibre tuft.

4.10.4 Photo-electric scanning

Photo-electric scanning was first developed in the early days of electronics by Hertel in 1940 for the testing of lint cotton [4]. Developments of his method are still the main way of testing cotton lengths. The basic principle is that carefully prepared fringes of cotton are passed through photo-electric scanning, in which the reduction in signal depends on the number of fibres in the cross-section. Current instrumentation for HVI testing of cotton uses automatic preparation and feeding of fringes through photo-electric sensing, with the signal passed to a computer for analysis. The principles of the method can be explained by reference to Hertel's original Fibrograph test.

The sample to be examined is presented for scanning in the form of a pair of fibre fringes, the composition of which is intended to be closely similar to that indicated by the beard diagram in Fig. 4.9. In manual testing, the preparation of the fringes is all-important for consistency of results and inter-laboratory agreement [31], and the makers put considerable stress on the need for a careful following of instructions, repeated checks and the exercise of judgement based on experience. In its original form, the Fibrograph made provision for the changes in the photo-electric current to be recorded graphically by hand against the distance of the slit from the roots of the fringes. The resulting graph, called a Fibrogram (Fig. 4.19), thus shows by an indirect measure the number of fibres surviving in the fringes as they are traversed from root to tip. However, because of the thickness of the lens at the light source, scanning cannot be carried out right at the very roots of the fringes and must start a short distance away. The instrument is consequently insensitive to the presence of very short fibres, and in practice the Fibrogram has its origin at a point representing a length of 0.15 inch (3.8 mm).



4.19 Fibrogram diagram (1 inch = 25.4 mm).

The Fibrogram may be analysed graphically to yield various length parameters of interest to the producers and users of cotton [4]. The tangent to the curve at its starting point A cuts OY at P and OX at M. Then OM is the mean length of the fibres in the original population longer than 0.15 inch (3.8 mm). If OP is bisected at Q and the tangent to the curve from Q cuts OX at R, then OR is the upper-half mean length, UHM (see Section 4.3.6), and the ratio of OM to OR is a valid index of uniformity.

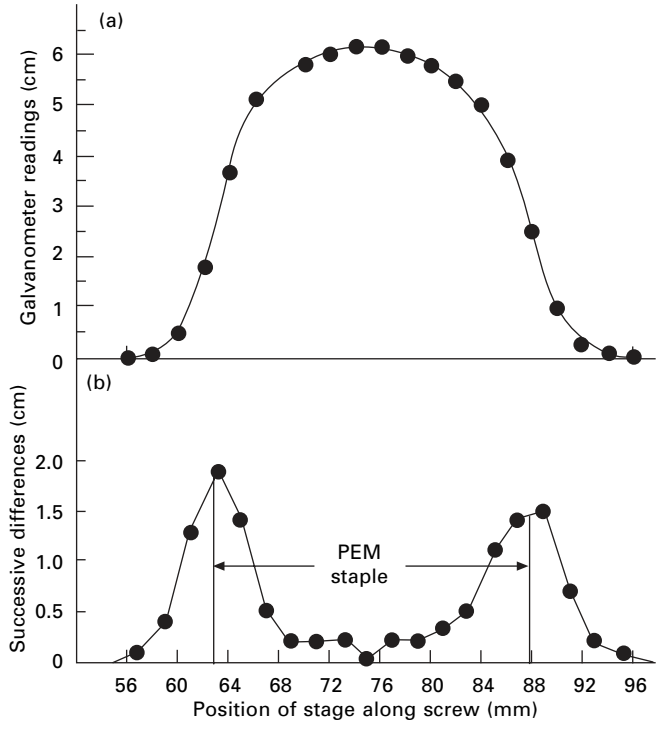
Another significant quantity introduced by Hertel is the 'span length'. As noted in Section 4.3.4, the fibre beard represented by the Fibrogram shows the distribution of fibre lengths that would project on one side of the nip of a pair of drafting rollers. The curve can therefore be used to determine the span or setting between successive pairs of drafting rollers to avoid more than any given proportion of the fibres being clamped in both pairs of rollers simultaneously. A span length found useful in this connection is the 2.5% span length, i.e. the length that is exceeded by only 2.5% of the beard fibres scanned by the instrument. This is shown by OS in Fig. 4.19.

The curve itself is the locus of the various span lengths (abscissae) for the beard scanned, and in computerised versions of the Fibrograph the span lengths are automatically recorded on digital counters throughout the scanning operation. From the scan lengths read off at suitably chosen intervals, the curve can be constructed if desired and the mean, UHM, and other quantities determined graphically. Alternatively, it may be considered that the sample is sufficiently characterised by the span lengths at, say, 66.7, 50 and 2.5%, in which case tests may be made extremely rapidly, several in a minute. With the original Fibrograph, the time required to make a complete test, including preparation of the fringes and analysis of the Fibrogram, is about 10 minutes. In the automated HVI tests, the analysis is computerised and testing is rapid.

The following are possible sources of error:

- The analysis of the Fibrogram is based on the assumption that, in the fringes prepared in the manner described, all points along the length of each fibre have an equal chance of coinciding with the line of the comb teeth. This is not strictly true because the frictional drag of combing tends to displace the fibres outwards somewhat and so leads to an over-estimate of length.
- The fibres in the fringe are assumed to be straight, whereas in fact they are crimped, and length is therefore likely to be under-estimated. This is a source of error held in common with most other methods.
- The tapering of the fibre ends also leads to some under-estimation of fibre length.
- So also does fibre breakage incurred in the preparation of the sample, which must, of course, at all times be minimised, perhaps especially if any mechanical aid to expedite the operation is used.
- Because of personal errors in the drawing of the tangent PM, the estimate of the mean length, OM, is not too reliable, though the UHM length is comparatively little affected. So far as this latter quantity is concerned, it has been found that, for cottons of staple length up to about $\frac{1}{8}$ inch (29 mm), the result given by the Fibrograph is correct to within $\frac{1}{32}$ inch (0.8 mm) but that above that length accuracy falls off considerably [25].

Another early photo-electric tester was the Shirley PEM Stapler [32]. This scanned a hand-prepared tuft, similar to those shown in Fig. 4.10. The measured boundaries are taken to lie where the visual density shows the greatest rate of change[3]. Consequently, the test gave only one statistic of length, namely, the modal length. It did this very rapidly (as regarded in the 1940s), and the quantity so measured agreed very closely with the standard American staple lengths from $\frac{3}{4}$ to $\frac{15}{16}$ inch (19 to 33 mm). The difficulty with hand-stapling lies in the fact that the boundaries of the tuft or staple are ill defined: over a large part of the middle, the visual density of the fibres is fairly uniform, but near the extremities it falls off until the tips of the longest fibres are reached. The light reflected from the surface was focused on a photo-cell, and the current generated was measured with a sensitive galvanometer. In this way, determinations of visual density were made at equal intervals along the length of the tuft, and, when these were plotted, a graph such as that shown in Fig. 4.20(a) was obtained. If, then, the differences between successive readings were plotted, a graph such as (b) was obtained, which indicated by its peaks the positions where the greatest rates of change occurred. These peaks located the boundaries of the tuft, and the distance separating these boundaries corresponded to the modal length of fibres as they lay in the tuft.



4.20 PEM test.

[3] This is evidently also true of the subjective judgement of the hand stapler.

4.11 Scanning individual fibres

4.11.1 Advanced fibre information system

The Uster Advanced Fibre Information System (AFIS), which was described for fineness testing in Section 3.7.3, also provides data on fibre lengths. A fibre individualiser unit opens the sample, typically 0.5 gram, separates individual fibres and transfers them to an air-stream. As each fibre is carried past the photo-electric sensor, its presence is detected. Hence the length of each fibre can be recorded. Computer software analyses the data and provides numerical and mass-biased length distributions, short fibre content, upper quartile length, 5.0% length and coefficients of variation.

Cui *et al*. [33] compare measurements of length by AFIS with those by Spinlab HVI and Suter-Webb array (Table 4.3). Values of mean length are reasonably consistent, but there are appreciable differences in short fibre content. Accuracy of prediction may be affected by natural fibre length variation in sampling, number of fibres in each test, number of repeats and accuracy of the length measurement. A major factor is the length calibration level for short fibres. A shift of 0.01 inch (0.25 mm) would change the short fibre content percentage by about 0.4%. There is high variability in the short fibre contents, so that sample non-uniformity is another source of differences. There is reasonable correlation between the different methods, so that users of a given method can assess the relative incidence of short fibres in different consignments of cotton.

4.11.2 Digital imaging

The application of digital imaging, which is the technology of the 21st century, to length testing is a severe challenge. Whereas snippets can be used for diameter measurement, whole fibres must be presented for length measurements.

The OFDA 4000 [34] prepares wool on a moving needle bed to form an end-aligned beard of fibres, like that in Fig. 4.16. A moving gripper transports the beard along a guide past a digital video-microscope in 5 mm steps. At each step, a digital image across the beard is recorded and the sequence is continued until the longest fibre has been scanned. The images are processed to count the number of fibres in the cross-section and their diameters are saved on the computer. A minimum number of fibres, typically 4000, are included in the count. The OFDA software analyses the data to provide distributions of fibre length and compute values of hauteur and barbe.

Table 4.3 Fibre length measurements for 45 cottons by three methods. From Cui *et al.* [33]

	Mean length (inches*)			Short fibre content (%)		
	Array	AFIS	HVI	array	AFIS	HVI
Average	0.92	0.96	0.89	11.41	7.41	9.56
Minimum	0.66	0.73	0.72	6.48	3.50	5.50
Maximum	1.13	1.19	1.13	26.13	17.40	23.20

* 1 inch = 25.4 mm.

As described in Section 3.7.1, the data are also processed for diameter and curvature. A draft test method for diameter and length measurements by OFDA4000 has been reported by Caroll [35].

4.12 References

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