APPENDICES

MATURITY, FINENESS & MICRONAIRE
Definitions, Measurement and Relationships

S. Allan Heap, Cotton Technology International, Stockport, UK

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MATURITY

DEFINITION

Maturity is the degree of fibre wall development. It may be expressed as either relative wall area or relative wall thickness.

Relative wall area is the cross-sectional area of the fibre (excluding lumen) divided by the area of a circle having the same perimeter as the fibre. It is given the symbol θ (theta) and may be calculated from the following formula.

$$\theta = 4\pi A_w / P^2$$

Where A_w is the area of the cell wall cross section and P is the perimeter.

Relative wall thickness is twice the average wall thickness divided by the diameter of a circle having the same perimeter as the fibre. It may be calculated from the following formulae.

$$Rwt = 2e / D$$
$$Rwt = (D - d) / D$$

Where e is the average wall thickness, D is the diameter of a circle having the same perimeter as the fibre, and d is the diameter of a circle having the same perimeter as the lumen.

Maturity is a ratio and has no units.

MEASUREMENT

Fundamental (Reference) Method

Perimeter, wall thickness and cell wall area can be measured directly by preparing magnified images of an adequate selection of transverse fibre sections. The microscope images are magnified by projection or by photography. Normally the fibres are selected from several of the length groups of a fibre array, ignoring those length groups that are less than half the upper quartile length. At least five hundred fibres are required from each of two replications. Sections are cut from the middles of the fibres.

The method is extremely slow and is subject to difficulties and errors in preparing the sections, tracing the images and measuring the tracings. It has not been standardised and its precision is not known.

Practical Methods

Two indirect, practical methods for measuring maturity have been standardised, BS 3085 and ASTM D 1442. Both depend on classifying the appearance of (the middle portions of) longitudinal views of fibres swollen in 18% sodium hydroxide solution. The international standard ISO 4912 describes both procedures and relates one to the other.

Maturity Ratio (M)

British Standard BS 3085: 1981 describes a method in which the swollen fibres are classified as “normal”, “dead”, or “thin-walled”.

- Normal fibres are those that appear as solid rods and show no continuous lumen nor have well-defined convolutions.
- Dead fibres are those that have a continuous lumen and the wall thickness is not more than one fifth of the ribbon width (measured at the widest portion of the fibre in the field of view). They may show frequent convolutions or may appear as flat unconvoluted ribbons.
- Thin-walled fibres are those that are not classed as Normal or Dead.

The test is made on a group of five mounted microscope slides, each with about 100 fibres. The fibres are selected from the length groups above half the upper quartile length. Three traverses of the slide are required: one to count the total number of fibres, one to count the normal fibres and one to count the dead fibres. Two to four replicates are measured depending on the accuracy required. Maturity Ratio is calculated from the following formula.

$$M = (N - D) / 200 + 0.70$$

Where N is the average percentage of normal fibres and D is the average percentage of dead fibres.

Percent Mature Fibres (Pm)

ASTM Standard D 1442 – 93 describes a method in which the swollen fibres are classified as either “mature” or “immature”.

- Mature fibres are those that have a rod-like shape, without convolutions and the wall width is equal to or greater than half the lumen width.
- Immature fibres may be highly convoluted or completely flat, and the wall width is less than half the lumen width.

Only two traverses of the slide are required: one to count the total number of fibres and one to count the number of mature fibres. The average number of mature fibres is expressed as a percentage of the total. Two to four replicates are measured depending on the accuracy required.

FINENESS

DEFINITION

Fineness may be defined in two ways: gravimetric fineness or biological fineness.

Gravimetric fineness is synonymous with linear density or mass per unit length. It is given the symbol H (hair weight) and normally has the units of millitex.

Biological fineness expresses the intrinsic thickness of the fibre, independent of the mass, in terms of its perimeter (or the diameter of the equivalent circle). Units are usually micrometres.

MEASUREMENT

Gravimetric Fineness (H)

Two direct methods for measuring gravimetric fineness have been standardised; BS 2016: 1973 (now replaced by ISO 1973: 1996) and ASTM 1769 (now discontinued). Both methods rely on weighing a known number of fibres from various length groups of the fibre array, but they differ in their detail.

In the British method, the length groups are taken from fibres longer than half the upper quartile length. The bundles are straightened and lightly tensioned and a segment of known length (1 cm) is cut from the middles of the fibres. The fibre segments are counted and weighed.

In the American method the length groups are taken from fibres longer than about 5 mm. All of the fibres in a length group are assumed to have the mean length of the length group. They are weighed whole and counted. Weights and lengths of the different length groups are combined appropriately to arrive at an overall average.

In either case, at least 500 fibres or fibre segments should be weighed and at least two replications performed.

Biological Fineness

The fibre perimeter (P) is determined from direct measurements made on transverse sections – the same method as for the fundamental measure of maturity. The equivalent diameter (D) is calculated from the perimeter.

MICRONAIRE

DEFINITION

There is no engineering definition of Micronaire because it is an arbitrary unit, which does not correspond directly to any single fibre property. It is an indication of the resistance to airflow through a plug of cotton, measured on an arbitrary scale developed and maintained by USDA. From theory, it is expected that the airflow resistance of a given cotton should be strongly related to the inverse square of the average fibre specific surface (surface area per unit volume), S_v, and this has been confirmed by experiment.

$$Mic = f(1 / S_v^2)$$

The fibre surface area per unit volume is given by the perimeter of the transverse section divided by the total area of the section (including the lumen).

$$S_v = P / A_t$$

The units of specific surface are usually micrometres^{-1}.

MEASUREMENT

Micronaire is measured by forcing air through a specimen of cotton with a defined mass contained in a chamber of fixed dimensions. Most Micronaire instruments measure the rate of airflow when the pressure drop is held constant, but some measure the pressure drop at a constant rate of airflow. In either case, the result is converted to a Micronaire reading, either by means of a calibrated scale on the instrument or by a suitable conversion formula, or by integrated software.

The method has been standardised by ASTM as D 1448-90, by BSI as BS 3181 Part 1 1987, and by ISO as ISO 2403.

RELATIONSHIPS

Standard Fineness (H_s) is defined as the gravimetric fineness at unit Maturity Ratio.

$$H_s = H / M$$

Empirical relationships have been established as follows.

$$\theta = 0.577 M$$

$$M = 1.76 - (2.44 - 0.021 Pm)^{0.5}$$

$$M.H = 3.32 Mic^2 + 23.21 Mic$$

In addition, the following geometric relationships can be derived - where ρ is the average density of the cell wall material (generally taken to be 1.52) and v is the average whole-fibre specific volume (generally taken to be 0.75).

$$A_w = H / \rho$$

$$\theta = 4 \pi H / \rho P^2$$

$$D^2 = 4 H / (\pi \rho \theta)$$
$$= 0.838 H / \theta$$
$$= 1.452 H / M$$

$$d^2 = 4 H (1/\theta - 1) / (\pi \rho)$$
$$= 0.838 H (1/\theta - 1)$$
$$= 1.452 H / M - 0.838 H$$

$$P = 3.785 H_s^{0.5}$$

$$1 / S_v^2 = \theta H . \rho v^2 / 4 \pi$$
$$= M.H / 25.472$$

It has been suggested that A_w calculated from H / ρ may be a more reliable estimate than that measured directly on transverse sections.

THE MEANING OF MICRONAIRE

S. Allan Heap, Cotton Technology International, Stockport, UK

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INTRODUCTION

Micronaire is the archetypal cotton fibre characteristic, for at least four reasons.

1. It was the first objective, instrumental measure to be included in the classification system for cotton.

2. It represents an arbitrary scale of relative values, and does not directly evaluate any single physical fibre property.

3. The integrity of the scale (i.e. the calibration level) is maintained by a sophisticated empirical operation involving
   - selection of (a limited number of) cotton bales to be designated as calibration standards,
   - testing of samples from these bales for Micronaire reading by (a small number of) designated laboratories,
   - assigning the mean and standard deviation of the results to the whole bale, for each standard,
   - making small samples of the bales available to the cotton testing community, world-wide, so that each laboratory may adjust the level (calibration) of its own instrument to that of the reference laboratories,
   - organising regular international check-test exercises, in which the results of Micronaire measurements, made on samples of the same cotton by a large number of laboratories, are collected and analysed – so that each laboratory can see how it compares to the others.

4. In spite of the arbitrary nature of the measurement itself, and the empirical, circular, self-referencing nature of the calibration maintenance system, the Micronaire reading has proved to be an extremely practical and effective parameter over a long period.

It could be argued that, together with the fibre length, Micronaire is the most important and useful cotton fibre characteristic, for cotton classers and spinners. The Micronaire reading is taken as an indication of fineness (linear density) and maturity (degree of cell-wall development). For a given cotton type, a relatively low Micronaire reading is a predictor for problems in processing, generation of neps, and inefficient dyeing. Therefore, a great deal of trouble is taken, when blending cottons, to try to obtain a constant average Micronaire between laydowns, and uniformity of Micronaire within laydowns.

INTERPRETATION OF AIRFLOW MEASUREMENTS

Micronaire is an indication of the air permeability, or resistance to airflow of a cotton sample. It is measured by forcing air through a specimen of defined weight confined in a chamber of fixed dimensions [1]. Most Micronaire instruments measure the rate of airflow when the pressure drop is held constant, but a few - e.g. the IIC-Shirley Fineness and Maturity Tester (FMT) [2] - measure the pressure drop at a constant rate of airflow. In either case, the result is converted to a Micronaire reading, either by means of a calibrated scale on the instrument or by a suitable conversion formula, or by integrated software.

Originally, the Micronaire scale was arrived at, and subsequently adjusted [3], to correlate with the average fibre linear density (in μg/inch) determined by the ASTM array method [4]. However, it was subsequently found that the correlation with fibre fineness was not very satisfactory and the unit μg/inch was dropped [5]. ***Figures 1 to 3*** show examples of the relationship between Micronaire and fibre fineness. The data in ***Figure 1*** are taken from a USDA research publication [6], where fineness was determined by the ASTM reference array method. The data of *Figure 2* are taken from Lord [7], where fineness was measured by the British method [8] and has been converted to μg/inch. The data of ***Figure 3*** are taken from the Bremen Round Test results since 1978 [9], where fineness was estimated with the FMT and has been converted to μg/inch. Although the correlations are good to very good, the slopes and offsets are unacceptable and the actual deviation from the trend line of many of the samples is too great. Nevertheless, the terminology has persisted in many areas and one still can find references to Micronaire units of μg/inch.

Pioneers in the interpretation of airflow measurements on textile fibre plugs were Hertel [10] and Lord [11]. Hertel, in connection with the development of the Arealometer instrument, and Lord, in a thorough review of airflow through fibre plugs, showed that the relationship arrived at by Kozeny [12] and by Fair and Hatch [13] can be suitably modified to provide an accurate description of airflow through cotton fibres.

One formulation of this relationship is the following.

$$Q / \delta P = K.I \;.\; 1 / So^2 \;.\; \varepsilon^3 / (1 - \varepsilon)^2 \qquad (1)$$

where,

- Q is the rate of airflow.
- δP is the pressure drop across the sample.
- K is a constant, for a given experimental set-up, mainly determined by specimen orientation and fibre type (average shape of cross section).
- I is an instrument constant containing the dimensions of the chamber and the viscosity of the air.
- So is the average fibre specific surface, i.e. the perimeter of the fibre cross section divided by the area of the whole fibre cross section, including lumen.
- ε is the specimen porosity, i.e. the proportion of the chamber volume occupied by the fibres.

The specimen porosity, ε, is given by the weight of the specimen multiplied by the average specific volume of the fibres divided by the volume of the chamber. If we can assume, for the time being, that the average specific volume of cotton fibres is approximately the same for all growths, and that the weight of the specimen is held constant, then the last term can be included into an instrument / environment constant, and

$$Q / \delta P = C / So^2 \qquad (2)$$

where,

$C = K \,.\, I \,.\, \varepsilon^3 / (1 - \varepsilon)^2$

Thus, to a first approximation,

- measurements of the rate of flow, Q, should be directly related to the inverse square of the Specific Surface, $1/So^2$, and
- measurements of the pressure drop, δP should be directly related to the square of the Specific Surface, So^2.

Hertel and Lord both showed that airflow instruments in general closely follow this relationship although, of course, any given instrument has to be calibrated to take account of the specific experimental conditions embodied in *C*. In particular, Lord confirmed the expected strong correlations between airflow and pressure drop, and between airflow and $1/So^2$. More recently, Heap [14] has shown that the IIC-Shirley FMT instrument also obeys the same general rules to a high degree of precision.

SPECIFIC SURFACE, FINENESS AND MATURITY

Specific surface is the perimeter of the fibre cross section divided by the area of the whole fibre cross section, including lumen. If we set P = fibre perimeter and At = the total area of the whole fibre cross section, then

$$1 / So^2 = (At / P)^2 \qquad (3)$$

Thus, Q, the airflow at constant pressure drop – and hence the Micronaire Reading - should be directly proportional to the square of fibre cross sectional area and inversely proportional to the square of fibre perimeter.

By making a few simple assumptions, we can easily see how the original supposition arose, that Micronaire was directly related to fibre fineness.

- *An individual, pure strain, cotton variety shows a rather small variation in average fibre perimeter between samples. It is not a very large departure from the truth to assume that cottons of closely similar types (e.g. Upland cottons grown in the 1950s and 1960s) have very similar average perimeters, one to another.*

- *For the same group of Upland cottons, the average proportion of the fibre cross section occupied by the lumen is, presumably, more or less the same. In any case, the average area of the lumen is a relatively minor proportion of the area of the whole section. Fibre fineness is simply the area of the fibre cell wall (i.e. cross-sectional area minus lumen area) multiplied by the average cell wall density.*

- *For the same group of Upland cottons, if the average cell wall density is about the same, then* At *is proportional to fibre fineness.*

Thus, for an individual, pure strain cotton variety, and hence (approximately) for a group of closely related cottons, with more or less constant perimeter, the inverse square of specific surface is directly proportional to the square of fibre fineness.

Figure 4 shows two subsets of the Bremen Round Test data, in which the fibre perimeters were calculated to be between 48 and 50, or 52 and 54 micrometres, respectively.

If practical experience is gained with processing a particular type of cotton, so that the optimal value for its Micronaire reading is well known, then a sample of that type, which presents a relatively low Micronaire reading can be assumed to have a relatively low linear density. Since the fibre perimeter probably has not altered by much, this can also be taken as a relatively low level of maturity. This is the basis for the enormous practical value of the Micronaire reading for trade and industry. In effect, a relatively low Micronaire value is signalling a low maturity.

In general, however, the Micronaire Reading will not correspond to the actual fineness in μg / inch unless the particular variety being measured has a fibre perimeter, which corresponds to the average of those that were used in the construction of the Micronaire scale.

It was only when cottons with a much greater genetic diversity, and hence a greater range in fibre perimeter were examined that the apparent link between Micronaire and fibre fineness was broken.

MICRONAIRE, FINENESS AND MATURITY

It can easily be shown that, for an individual fibre, the inverse square of fibre specific surface is directly proportional to the product of fineness and maturity.

If we define maturity as the degree of secondary wall thickening, θ, [2, 8, 17, 19], then

$$\theta = 4 \pi Aw / P^2 \qquad (4)$$

or

$$P^2 = 4 \pi Aw / \theta \qquad (5)$$

where,

Aw is the cell-wall area (cross-sectional area minus lumen area).

If we then set ν = whole fibre specific volume, ρ = cell wall density, and H = fibre fineness, in mtex, then

$$At = H \nu \qquad (6)$$

and

$$Aw = H / \rho \qquad (7)$$

Substitution of (6) and (7) into (5) and (3), leads to

$$1 / So^2 = \theta H . \rho \nu^2 . 4 \pi \qquad (8)$$

By convention, the Maturity Ratio, M, is taken as unity when θ = 0.577. Reasonable values for the average fibre specific volume and the average cell wall density are 0.75 and 1.52, respectively. Substitution of these values into (8) yields

$$1 / So^2 = MH / 25.472 \qquad (9)$$

Thus, Q, the airflow at constant pressure drop, should be directly proportional to the product of Fineness and Maturity, MH.

Since the Micronaire reading is a transformation of the airflow at constant pressure drop, for a fixed set of experimental conditions, then there should be a direct relationship between Micronaire and the product MH, which encompasses the instrument constants, the experimental conditions, and the arbitrary transformation built into the Micronaire scale.

If this is can be substantiated experimentally, then it is very important, for (at least) two reasons.

1. It provides a way of linking Micronaire readings directly with particular fibre properties.
2. It holds forth the possibility of providing an objective calibration for the Micronaire instrument, traceable to direct measurements of the Specific Surface.

Therefore, some attention will be paid to substantiating this general relationship.

In a detailed evaluation of the Micronaire instrument, Lord confirmed that, for a set of 100 cottons, the relationship between *MH* and Micronaire (*Mic*) could be described by the following formulation [7].

$$MH = 3.86\, Mic^2 + 18.16\, Mic + 13.0 \qquad (10)$$

with a correlation of R^2 = 0.9809.

Using a limited range of cottons - the International Calibration Cotton Standards (ICCS) - Heap has shown [2] that a similar relationship exists for the corresponding parameters estimated with the IIC-Shirley FMT instrument.

$$Mat.Fin = 2.07\ Meq^2 + 32.09\ Meq - 12.68 \quad (11)$$

with a correlation of $R^2 = 0.998$.

Lord's and (a sub-set of) Heap's original data have been re-examined and it was found that (10) and (11) can be slightly simplified, with negligible loss in the correlations, by forcing the curves to pass through the origin.

$$MH = 3.32\ Mic^2 + 23.67\ Mic \quad (12)$$

with a correlation of $R^2 = 0.9808$ (***Figure 5***), and

$$Mat.Fin = 2.55\ Meq^2 + 26.90\ Meq \quad (13)$$

with a correlation of $R^2 = 0.9997$.

Very high correlations between *Mat.Fin* and *Meq* are to be expected from the FMT, of course, because of the way that these parameters are all calculated from the two pressure-drop measurements. Furthermore, these particular Mat, Fin, and *Meq* values are the averages from five separate FMT instruments, and the range of cottons is a very special one – the calibration standards. When Heap's data were examined using Micronaire instead of FMT *Meq*, then the following relationship was found.

$$Mat.Fin = 2.76\ Mic^2 + 25.56\ Mic \quad (14)$$

with a correlation of $R^2 = 0.9985$ (***Figure 6***).

Thus, the expected good correlations between *Mic* and *MH,* or *Mat.Fin* appear to have been substantiated, and to a high level of precision. However, Lord's measurements were made more than four decades ago, and Heap's data are of a limited and very special nature. Therefore, it is worthwhile to see if additional confirmation can be found from the more recent literature.

There are two additional literature sources, which can provide a useful check on the relationships between *Mic* and *MH* or *Mat.Fin*.

Mitchell [15] has reported both *MH* and *Mat.Fin* data for a range of 30 cottons. Analysis of his data results in the following relationships.

$$MH = 3.23\ Mic^2 + 23.21\ Mic \quad (15)$$

with a correlation of $R^2 = 0.9876$ (***Figure 7***), and

$$Mat.Fin = 2.69\ Mic^2 + 26.09\ Mic \quad (16)$$

with a correlation of $R^2 = 0.9968$ (***Figure 8***).

The close agreement between equations (12) and (15) not only substantiates Lord's original analysis but also suggests that the Micronaire instrument calibration had remained substantially constant over the intervening period. However, it should be pointed out that a certain number of Mitchell's cottons were taken from the same source as Lord's (the Shirley Institute cotton library).

A more independent set of data is provided by the results of the Bremen Round Tests [9]. The Bremen Fibre Institute has carried out round tests for several decades, in which many laboratories test samples of the same cottons. Micronaire has been included in these round tests from the beginning and the FMT instrument has been included since the middle 1970's. Because the mean of all laboratories is statistically secure, and because it represents the actual situation in the field – with many different types of laboratories (and different types of Micronaire instruments) - these data are particularly valuable.

Analysis of the Micronaire and *Mat.Fin* data from the round tests has been carried out for the period 1978 – 1999 (72 cottons), with the following result.

$$Mat.Fin \ = \ 2.53 \ Mic^2 \ + \ 26.86 \ Mic \qquad (17)$$

with a correlation of $R^2 = 0.990$ (***Figure 9*****).**

Equations (14), (16), and (17) are almost indistinguishable over the range of interest (***Figure 10***) and, when given equal weight, produce the following relationship.

$$Mat.Fin \ = \ 2.66 \ Mic^2 \ + \ 26.17 \ Mic \qquad (18)$$

It seems safe to assume that the Micronaire reading is a pretty accurate reflection of the whole fibre specific surface, and hence the product of fibre linear density and Maturity Ratio. Unfortunately, the relationship is an empirical one, forced by the (more or less) arbitrary transformation of the measured airflow into the Micronaire scale and the choice of a constant value for all cottons of the average fibre specific volume. Small differences in the various regression equations (if, indeed, they are at all significant) may be to do with the particular set of cottons that is included and may indicate that the fibre specific volume is not quite constant for all cottons. In fact, Neelakantan has argued for such differences [16], and Lord has noted [2] that some cottons consistently return anomalous results, when measured on the FMT, indicating that other fibre properties besides fineness and maturity can play a significant role in the interpretation of airflow measurements.

CALIBRATION OF AIRFLOW INSTRUMENTS

Until very recently, it was unthinkable that the Micronaire instrument (or the FMT) should be calibrated properly, using direct measurements of fibre specific surface, or fibre linear density and maturity. Although linear density may be estimated quite accurately, in a reasonable time (for research purposes), by one or other of the reference gravimetric methods, the direct measurement of specific surface or maturity – by cutting and measuring fibre cross sections – was prohibitively expensive and subject to considerable operator error. However, developments in the techniques for making fibre cross sections, and for measuring these using image analysis have been impressive in the last few years [17, 18, 20].

With image analysis systems the fibre perimeter and the area of the whole fibre cross section can be measured relatively easily and accurately. The specific surface, *So*, is given by the ratio of perimeter to whole fibre area so, in principle, it is now possible to calibrate airflow instruments directly, so that they can deliver an estimate of specific surface that should be relatively accurate and traceable to a direct reference method.

Image analysis also allows the measurement of the area of the fibre cell wall and hence, by assuming a value for the average density of the cell wall, an estimate for fibre linear density. It should be noted that, although the value for fineness so derived refers to nominally random fibre sections, with the current specimen preparation techniques the longer fibres are probably over-represented. This is different from either the ASTM array method or the British method, but might be quite similar to an airflow measurement, in which the longer fibres are probably also over-represented.

Maturity also can be calculated from the cell-wall area and the perimeter. For this purpose, maturity must be defined in fundamental terms, as the degree of secondary wall thickening, θ.

The Maturity Ratio, if required, is calculated from the (arbitrary) convention, originally proposed by Pierce & Lord [2, 8], that Maturity Ratio is taken as unity when $\theta = 0.577$.

It can be argued that a proper calibration of the Micronaire instrument is unnecessary and even counter-productive, because of the apparent stability of the Micronaire calibration over several decades and the wide familiarity of the cotton marketing and processing industries with the *practical* interpretation of the Micronaire scale of values.

Nevertheless, there seems little doubt that direct measurements of fibre cross sections, using image analysis, will be required for calibrating airflow (and other) instruments which measure maturity [2, 20]. Therefore, the additional effort needed to provide a direct calibration for Micronaire instruments will be trivial and could provide significant benefits. Ideally, direct calibration should be made against the whole-fibre specific surface and we can perhaps assess the potential for such calibrations by checking whether image analysis measurements of specific surface, fineness and maturity conform to the expected relationships with Micronaire reading.

Unfortunately, measurements of the whole fibre cross section area are not usually made by image analysis because, until now, the objective of such work has been to estimate fineness and maturity. Therefore, the only relationship that can be examined, at present, is that between Micronaire and the product of fineness and maturity, as determined by image analysis. Thibodeaux has made one such comparison [18], and concludes that his image analysis estimates of fineness and maturity are at least consistent with the relationship of equation (10).

Thibodeaux has kindly made available further data (published at this conference), which include Micronaire readings as well as image analysis measurements of cell wall area and fibre perimeter. When these new data are combined with those of the earlier publication, the following relationship emerges, where *Imat* and *Ifin* are the maturity and fineness derived from image analysis of fibre cross sections.

$$Imat.Ifin = 1.89\,Mic^2 + 32.97\,Mic \qquad (19)$$

with a correlation of $R^2 = 0.917$ (***Figure 11***).

The three equations, (12), (18), and (19) yield very similar results, as can be seen from ***Figure 12***. To the (rather doubtful) extent that the curves may be significantly different, one may perhaps speculate that the relationships derived from Mat.Fin and Imat.Ifin data seem to be almost parallel, over the range of interest. They might be made to coincide by a suitable choice of fibre density for the image analysis calculation of fineness. Lord's equation straddles the other two and might reflect the fact that the British method for fibre fineness determination is (almost) not length-biased and involves only the central portions of the fibres, whereas both image analysis and FMT measurements may be somewhat length-biased and involve the whole fibres. Note, however, that the original calibration for FMT Fin was in terms of the British method for measuring fibre fineness [2].

Taken as a whole, these results suggest that it should be possible to provide a more or less precise, direct calibration of airflow instruments, such as Micronaire or FMT, in terms of a single fibre property, namely the specific surface. Specific surface, the ratio of fibre cross section perimeter to whole-fibre cross section area, can be rather easily measured by image analysis. For individual cottons, the actual average fibre specific volume can be established by comparing image analysis measurements of whole fibre cross sections to direct, gravimetric measurements of average fibre linear density.

Once a direct calibration has been provided, in terms of specific surface and specific volume, the relationship between airflow and the product of fineness and maturity, can be scrutinised with greater rigour than has been possible up to now. Such scrutiny could prove to be extremely valuable for researchers and instrument manufacturers, who are striving to produce better, more rapid methods for measuring fineness and maturity. In addition, it should be possible to deduce, once and for all time, what is the “true” relationship between fibre specific surface and Micronaire value, and hence to provide a “hard” calibration for Micronaire.

For this purpose, reliable estimates of the true whole-fibre density and the cell-wall density may be required. In addition, it may be advisable to specify a constant geometry for airflow instruments – otherwise every type of instrument has to be separately calibrated, because of differences in the instrument / environment constant, *C*, in equation (2).

Finally, it may be important to establish whether the relatively greater scatter in image analysis estimates of the product fineness.maturity, compared to FMT estimates, is random or systematic. A greater level of random scatter is perhaps to be expected at this stage in the development of the image analysis procedure. The available data have been collected during a period when great improvements were being made to the procedures, and improvements are still being made. Systematic scatter could be introduced, for example, by the assumption of a constant cell-wall density for all cottons, when calculating fineness from cell-wall area.

If the extent of any systematic scatter can be quantified, and allocated to its proper source, then this will provide the baseline for the ultimate accuracy of image analysis measurements of fineness and, by extension, the fundamental limitations to the accuracy of airflow devices, however calibrated. For this purpose, the image analysis procedure will have to be calibrated against an appropriate reference gravimetric fineness procedure.

CONCLUSIONS

The Micronaire scale is essentially a more or less arbitrary transformation of an air permeability measurement.

For an individual, pure strain cotton variety and, to a lesser degree, within a group of cottons of closely related varieties, the Micronaire Reading is directly related to fibre fineness, and hence to fibre maturity, but it does not indicate the actual fineness in μg */ inch*.

In general, for the whole range of commercial cottons, the Micronaire reading can not be taken as a measure of either fibre fineness or fibre maturity alone.

From the basic theory, Micronaire is expected to be directly related to the inverse square of the average fibre specific surface, moderated by the (arbitrary) transformation, which converts airflow (or pressure drop) to Micronaire reading, and the experimental conditions of the particular airflow instrument used.

The inverse square of the fibre specific surface is directly related to the product of fineness and maturity, moderated by the whole-fibre density.

Therefore, Micronaire should be directly related to the product of fineness and maturity. The extent of the effect of differences in whole-fibre density between cottons of different growths is not known, but it seems to be rather small.

Examination of several data sets, where both fineness and maturity have been estimated by different methods, has confirmed that the expected relationship between Micronaire and the product of fineness and maturity is obeyed rather faithfully. This includes estimates of fineness and maturity obtained by image analysis.

Image analysis should be capable of providing direct calibrations for airflow instruments, in terms of the average fibre specific surface. Several benefits can be envisaged to flow from such a “proper” calibration, not only for Micronaire measurement, but also for the determination of fibre fineness and maturity.

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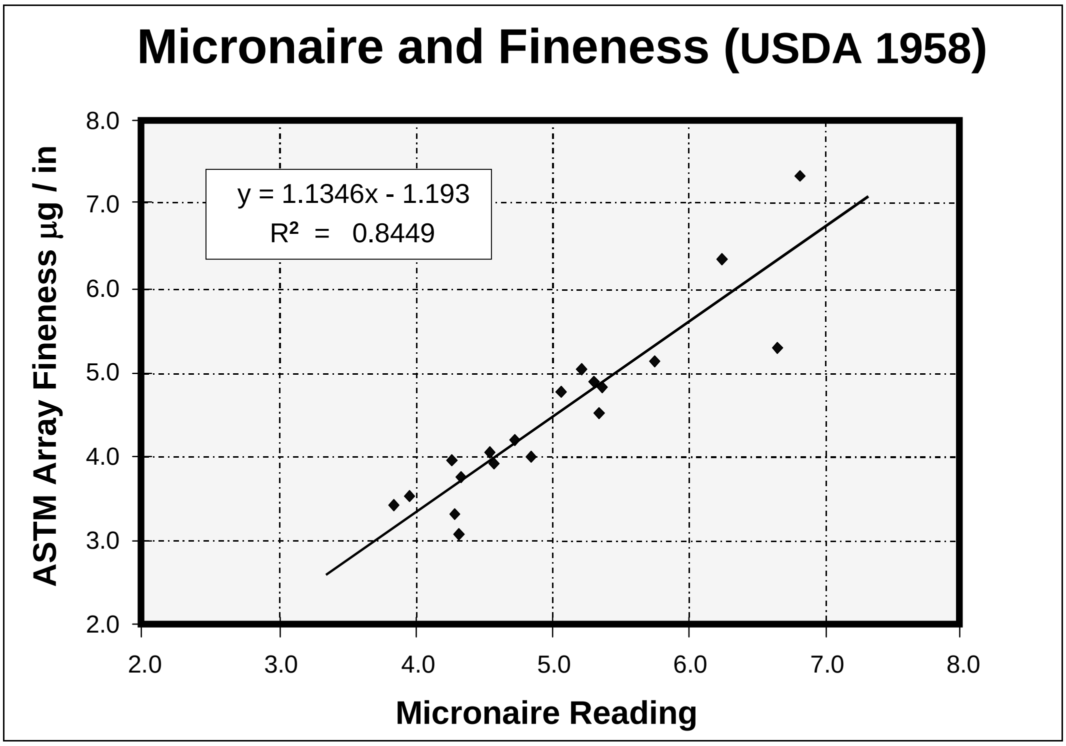
Figure 1



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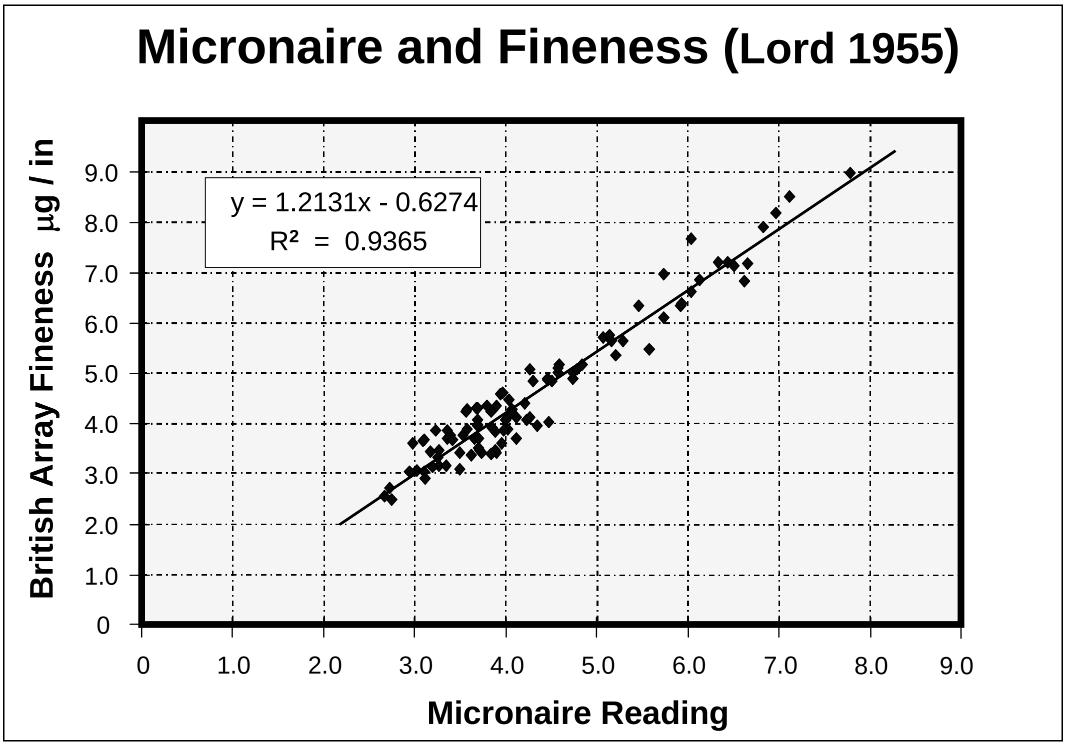


Figure 3

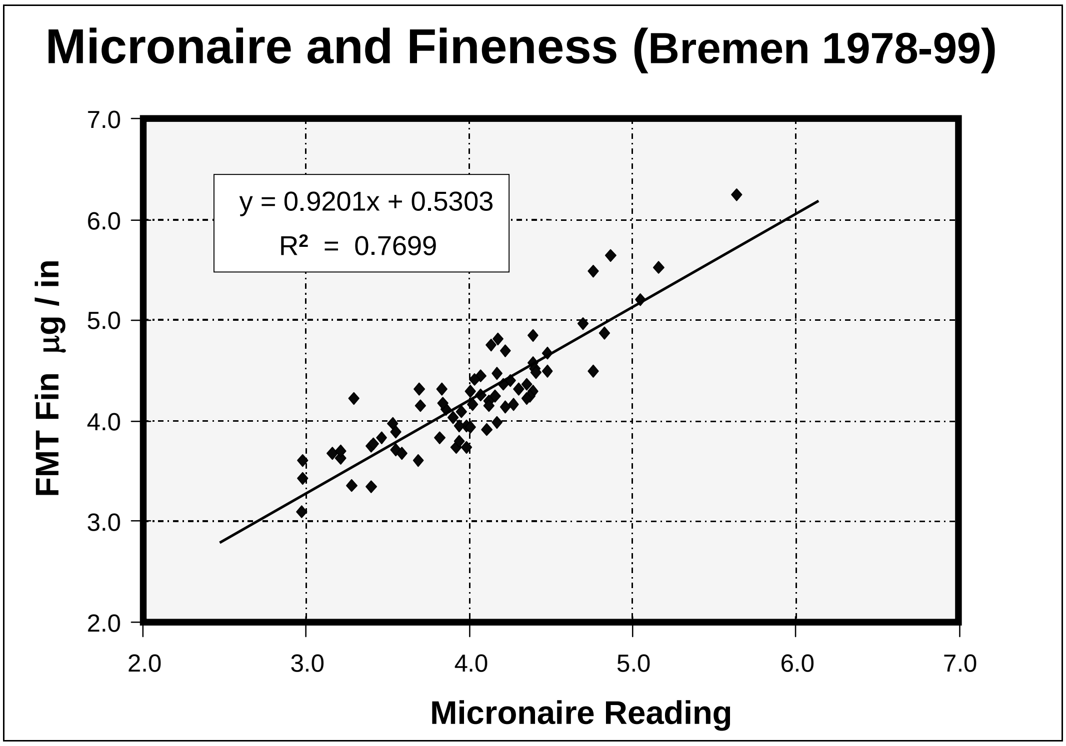
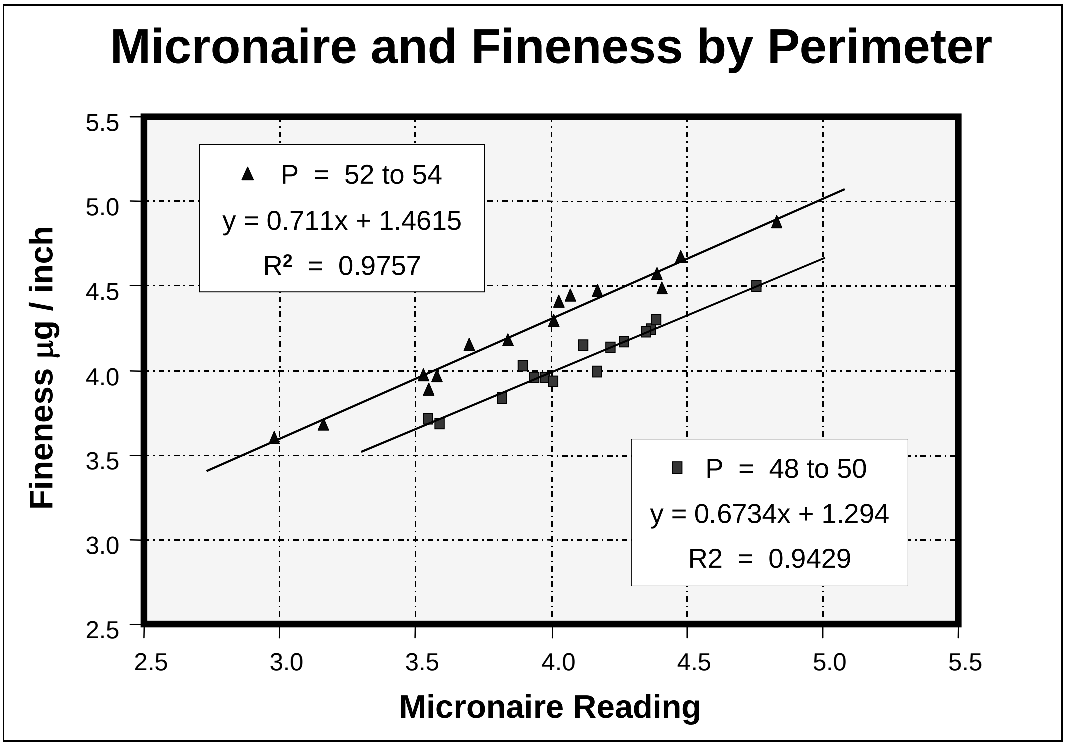


Figure 4



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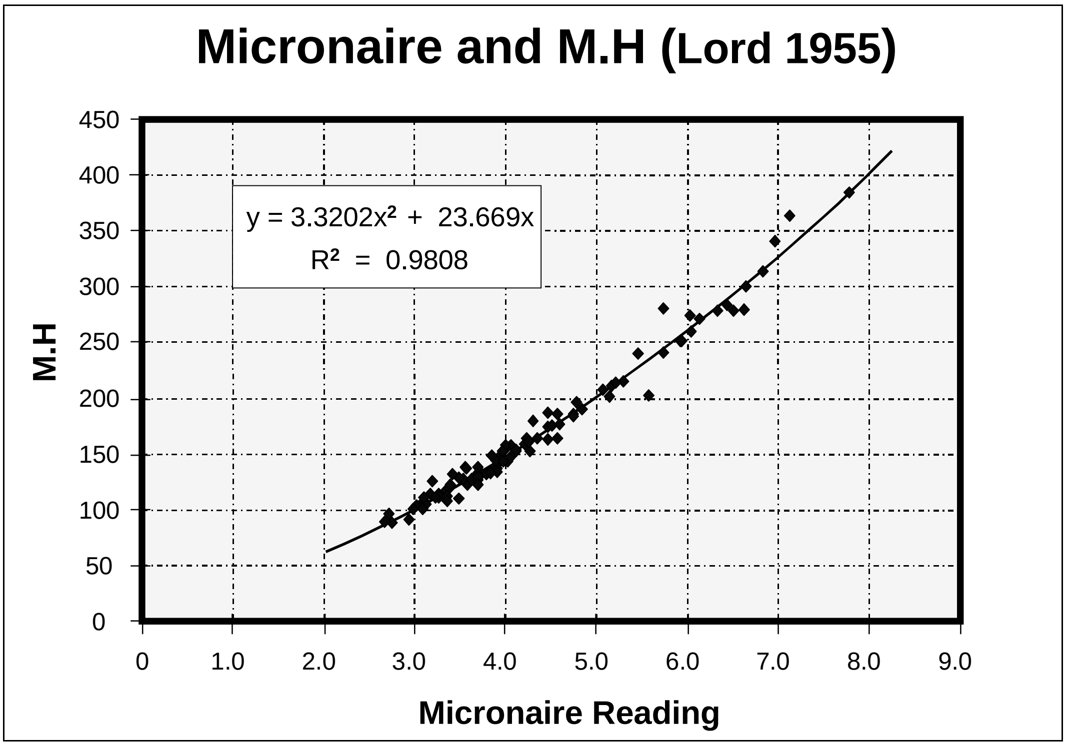

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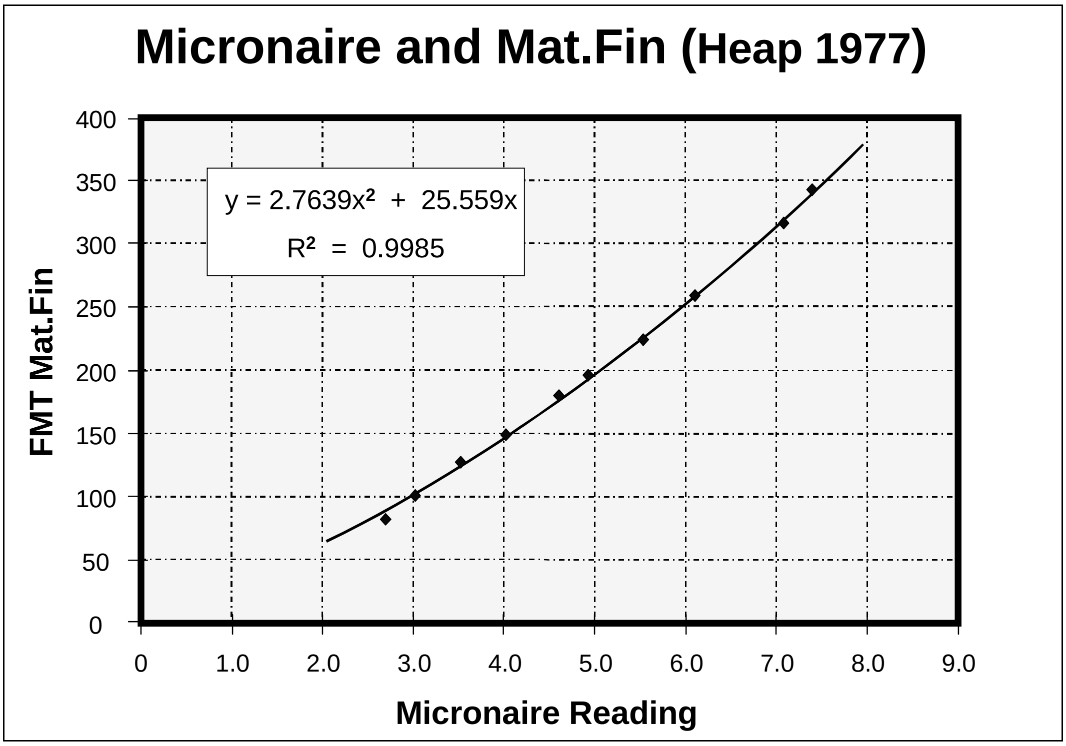

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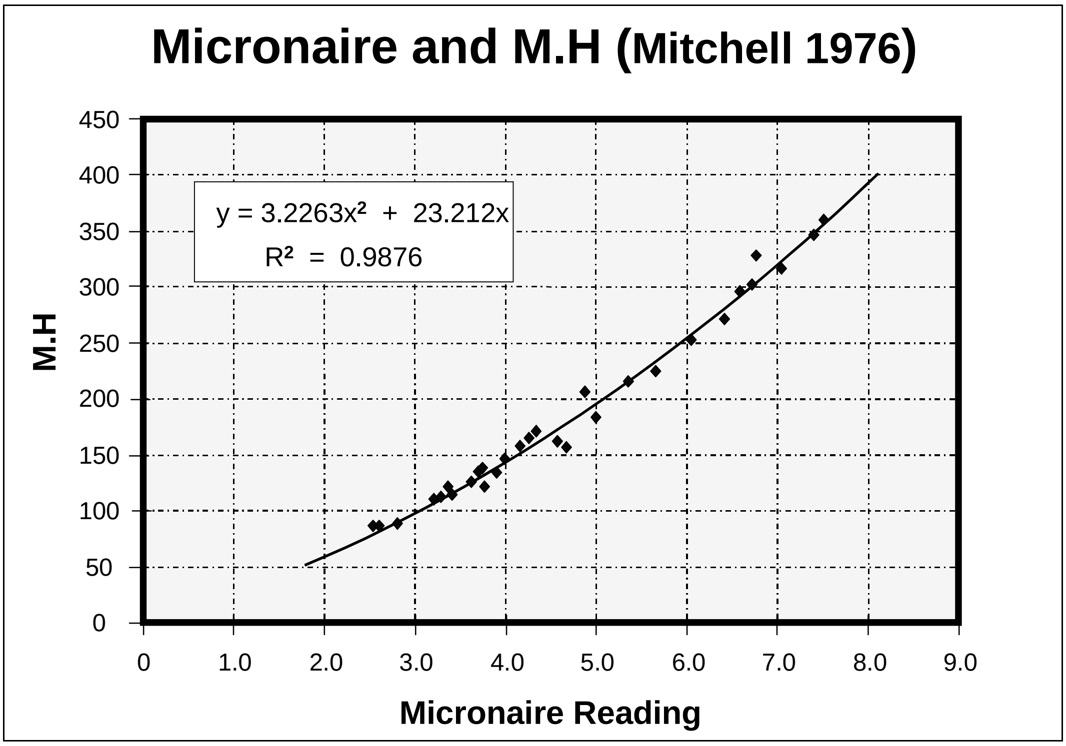

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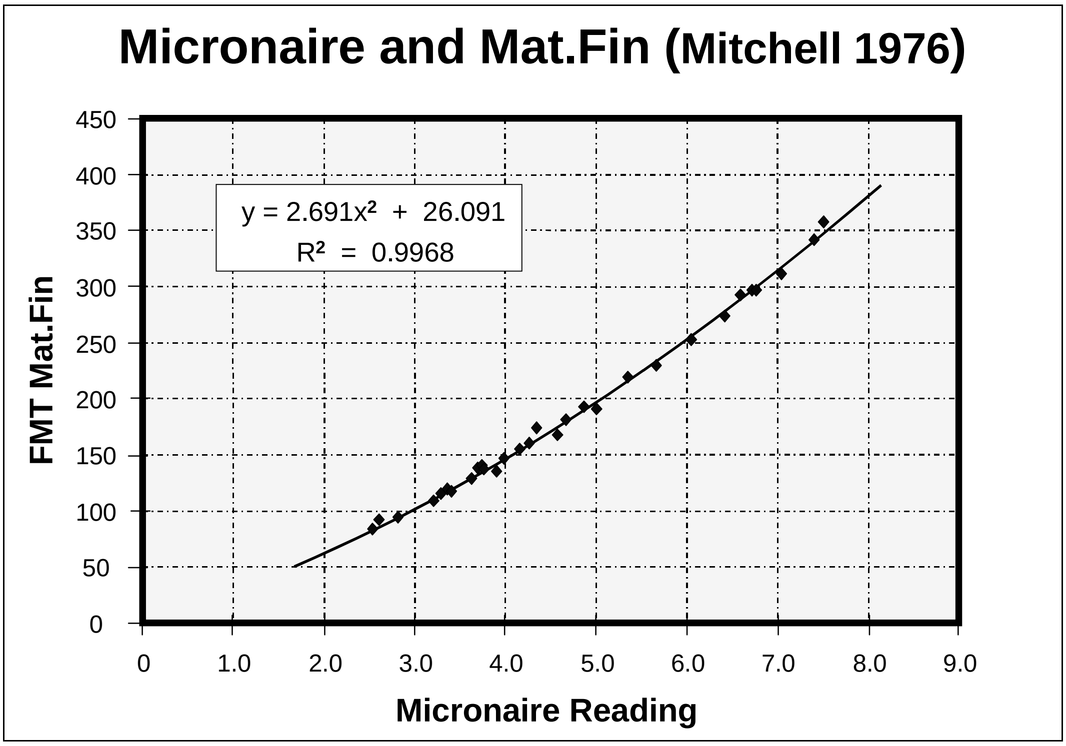

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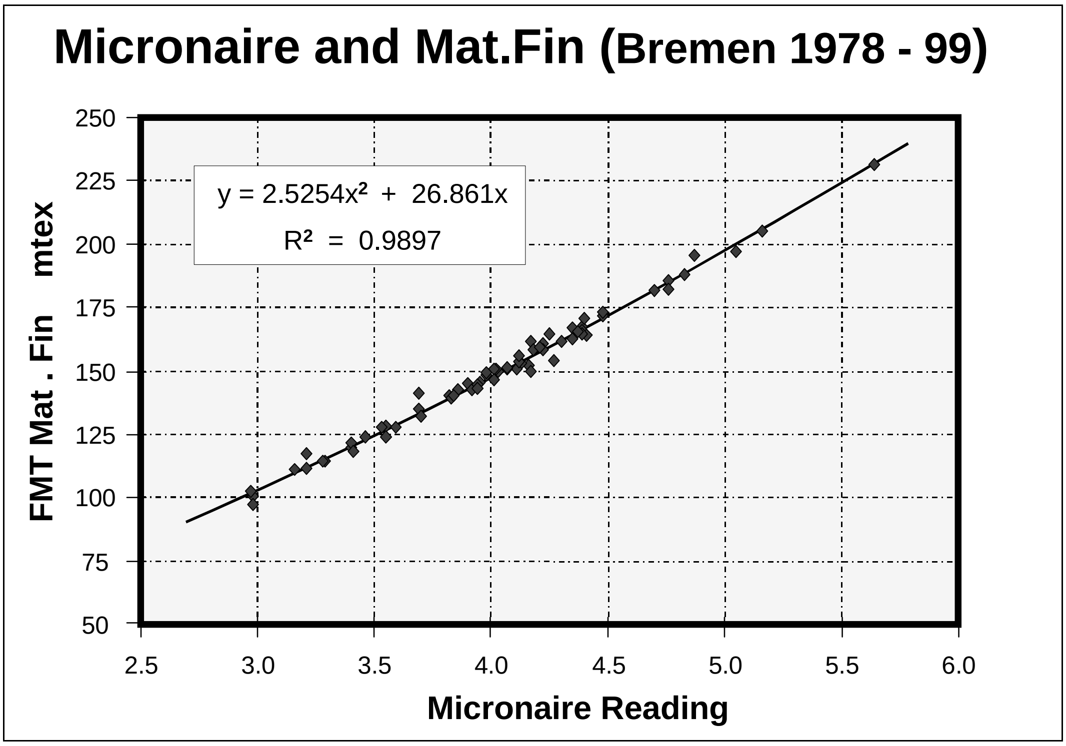

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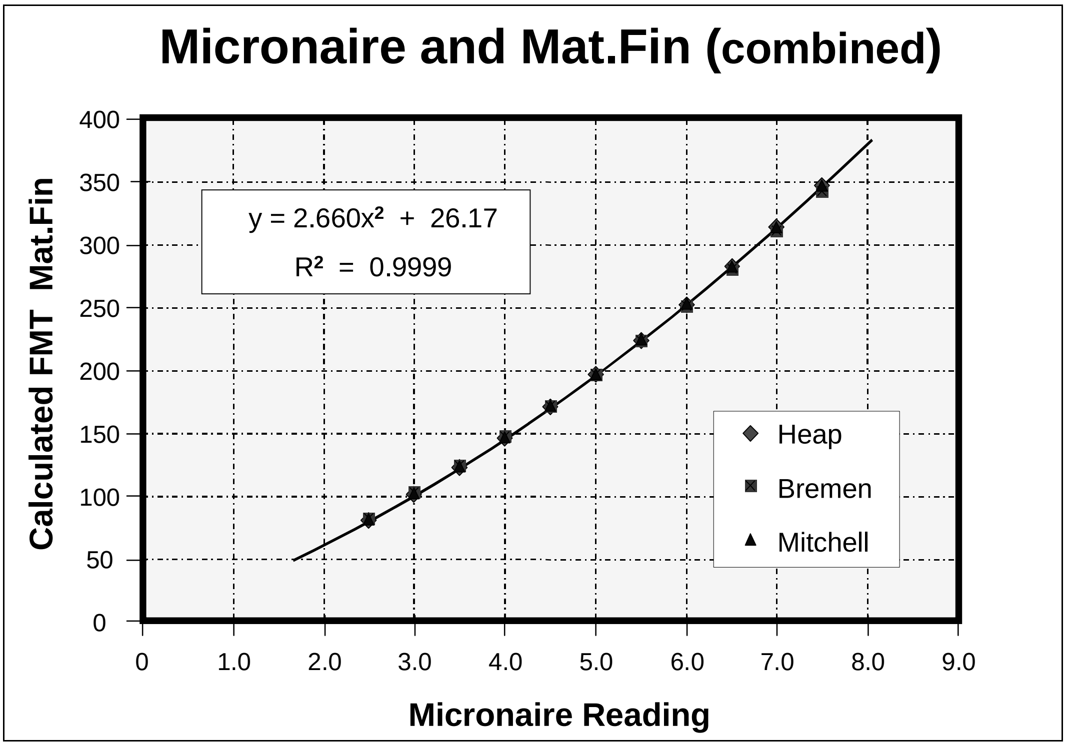

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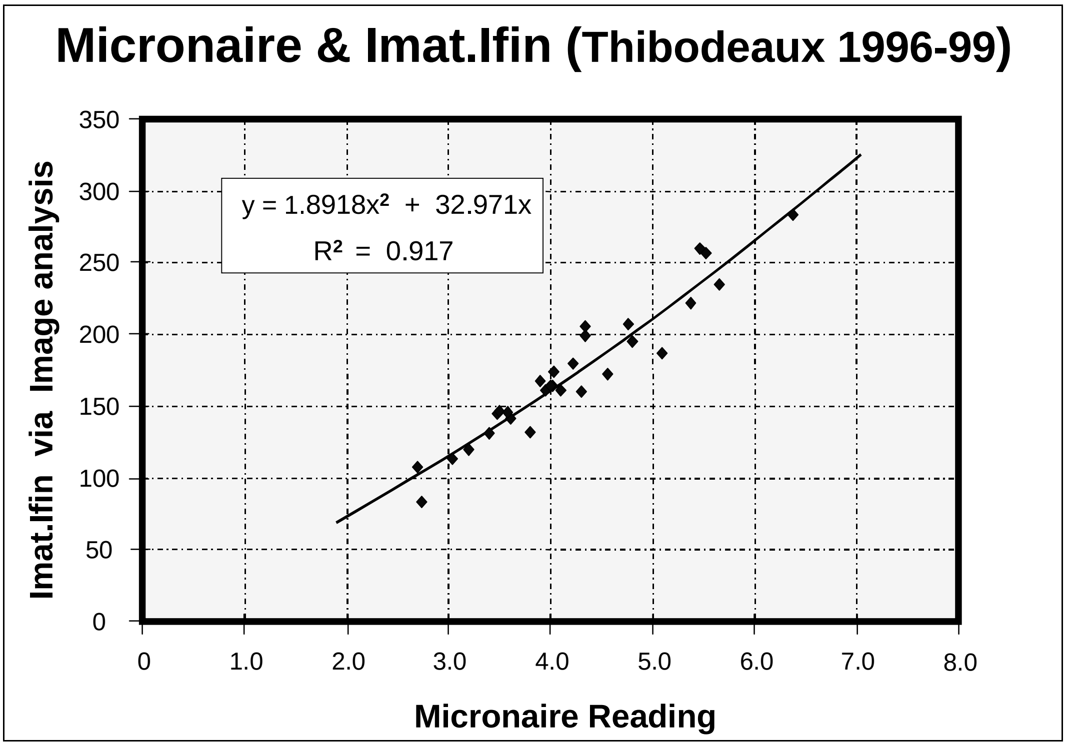

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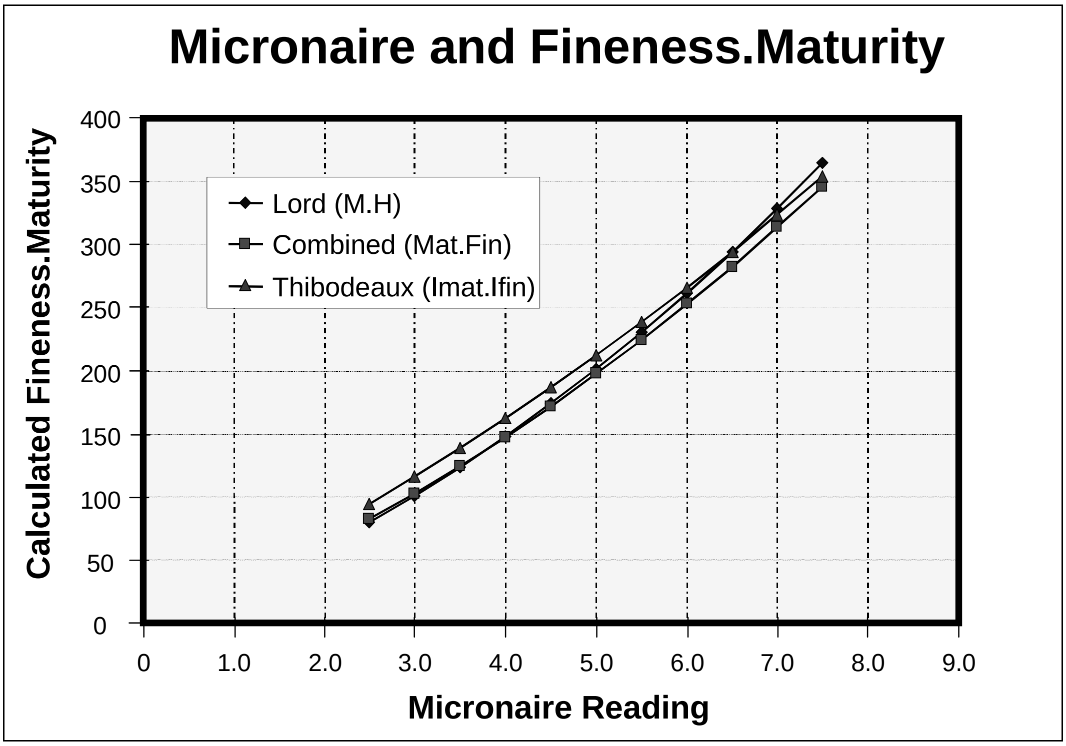


MOISTURE CONTENT CORRECTION

S. Allan Heap, Cotton Technology International, Stockport, UK

INTRODUCTION

The weight of a fabric containing a hygroscopic fibre such as cotton is affected by its moisture content, which depends on the Relative Humidity of the atmosphere that is used for conditioning. It is always recommended that test specimens should be conditioned in an atmosphere of 65% RH at a temperature of 20 Celsius, but some manufacturers can not justify the expense of a conditioned laboratory. For many purposes, and in many locations, when test specimens are allowed to condition in the ambient atmosphere, the variation introduced by day to day changes in temperature and relative humidity will not be of much practical significance. However, sometimes it is necessary to have improved accuracy in weight measurements.

This procedure allows the weight of a cotton or cotton/polyester blend specimen to be corrected to 65% Relative Humidity (RH) when it has been conditioned and measured at some other RH (X%) after conditioning from the dry side (e.g. after tumble drying).

As presented here, the procedure is valid only for RH values between X = 35 and 85%, because the equation for calculating moisture regain as a function of RH should not be extrapolated outside this range. Obviously a more complex equation could be developed to cover the whole range of RH but the range covered here is considered to be adequate for practical purposes.

ASSUMPTIONS

- The relative humidity of the atmosphere in which the specimen was conditioned and weighed is continuously monitored and is noted at the time of weighing.
- Between X = 35 and 85% Relative Humidity, the moisture regain (Mr) of 100% cotton fabrics is given by the following expression, derived from detailed data published in the Shirley Institute Memoirs.

$$Mr = 2.2\, e^{\,0.0183\, X} \qquad (1)$$

- The cotton blend was made at a relative humidity of 50% (in the spinning mill). Thus, the nominal blend ratio is correct at 50% RH.
- The moisture regain of polyester is zero at any RH. Actually, it is about 0.3% at 65% RH. Therefore, in a 50:50 blend, the corresponding error must be less than about 0.05% of the specimen weight.
- The effect of temperature is neglected.

Of course, the actual conditions will not be exactly these but the errors produced by these assumptions will be negligible. For a specific set of conditions, the real figures can be determined but this will hardly be worthwhile.

Note that the largest correction that will be calculated using this procedure is about 3%. It applies to 100% cotton weighed at either 35 or 85% RH. Between 45 and 80% RH, the correction is not more than about 2%. Between 55 and 75% RH, it is not more than about 1%. Thus, the correction is required only when such levels of accuracy are necessary.

If a scientific calculator or spreadsheet program is not available for evaluating the exponential in equation (1), then a linear proportioning approximation can be used.

Thus:

$$Mr(lin) = 7.228 * X / 65 \qquad (2)$$

The constant 7.228 is the regain calculated by equation (1) for a RH of 65%. The loss of accuracy due to the linear proportioning model is very small when conditioning is in an atmosphere on the dry side of 65%, but quickly becomes larger on the wet side. Nevertheless, within X = 35 to 85% RH, the error is never greater than about 1% of the specimen weight. For example, starting from equation (1) the correction factor for 100% cotton weighed at 85% RH works out to be 0.971. Starting from the linear approximation, the corresponding correction factor is 0.980.

DEFINITIONS

X The relative humidity that was noted at the time the specimen was weighed.

Mr Moisture regain of 100% cotton at the given RH.

F_X *1 + Mr / 100* when *Mr* is the equilibrium regain for *X*% RH

Cn Nominal cotton content in the original blend. For a 50:50 blend, *Cn* = 0.5.

Cd Bone dry weight of cotton per gram of the original blend.

Cc Cotton content of the specimen after conditioning to *X*% RH

Pd Bone dry weight of polyester per gram of the original blend, given by (*1 – Cn*)

Pc Polyester content of the conditioned specimen, given by (*1 – Cc*)

WF_X Specimen weight correction factor – the result of this procedure.

CALCULATION STEPS

1. Calculate the moisture regain and a moisture correction factor for 100% cotton conditioned in an atmosphere with the RH that was noted at the time of weighing. The regain for a given RH is calculated using either equation (1) or equation (2). The corresponding moisture correction factor (F_X) is given by the following expression.

$$F_X = 1 + Mr / 100$$

Some values of *Mr* and F_X calculated using equation (1) are given in ***Table 1***.

2. If the specimen is 100% cotton, go to Step 5.

3. Given the proportion of cotton, *Cn*, in the original blend (at 50% RH) calculate the bone-dry weight of cotton (zero moisture content) per gram of the original blend. This is achieved simply by applying the moisture correction factor for a RH of 50% to the nominal blend ratio.

$$Cd = Cn / F_{50}$$

According to ***Table 1***, the appropriate correction factor is F_{50} = 1.0549. Some calculations are shown in ***Table 2***, where the dry weight of the polyester component, *Pd* = (*1 – Cn*) is also shown.

4. Starting from the bone-dry weight of ***Table 2***, adjust the weight of the cotton portion according to the relative humidity in which the specimen was weighed and then calculate the weight of cotton per gram of the conditioned specimen.

The weight of the cotton portion is the bone-dry weight multiplied by the moisture correction factor for the appropriate relative humidity. The weight of the polyester portion does not change. Thus, the conditioned weight of the cotton is $Cd * F_X$, the conditioned weight of the polyester is *Pd*, and the weight of conditioned cotton per gram of conditioned specimen, is calculated as follows.

$$Cc = (Cd * F_X) / (Cd * F_X + Pd)$$

Table 3 shows the result of these calculations. The weight of polyester per gram of conditioned specimen is *Pc = (1 – Cc).*

5. Starting from the conditioned weight of ***Table 3***, adjust the moisture content of the cotton portion to correspond to 65% RH and add on the weight of polyester. This yields the weight that one gram of specimen would have at a relative humidity of 65%. It represents a specimen weight correction factor, WF_X, for a specimen that was conditioned and weighed at *X*% RH.

$$WF_X = Cc * (F_{65} / F_X) + Pc$$

Results of these calculations are given in ***Table 4*** and plotted in ***Figure 1***. ***Figure 1*** also shows the correction factors that would be calculated if *Mr* were estimated by the linear proportioning approximation of equation (2) rather than by the exponential equation (1).

6. The weight of a specimen, measured at *X*% RH is multiplied by the appropriate WF_X extracted from ***Table 4*** or ***Figure 1*** to arrive at the weight that would have been measured if the specimen had been conditioned in the standard atmosphere for testing.

EXAMPLE 1

A specimen of 100% cotton fabric weighs 0.500 gram after conditioning in an atmosphere of 46% relative humidity.

1. *Mr* at 46% RH is found by direct calculation using equation (1), or by interpolation from ***Table 1***. The interpolated rate of change for *Mr* between 45 and 50% RH is $(5.493 - 5.013) / 5 = 0.096$.

Therefore *Mr* for 46% RH is $5.013 + 0.096 = 5.109$.

The corresponding moisture correction factor F_{46} is $1 + 5.109 / 100 = 1.0511$.

2. Go to Step 5

5. The Weight Correction Factor for 100% cotton at 46% RH is found by calculation or by interpolation from ***Table 4*** or ***Figure 1***. From ***Table 4***, the interpolated rate of change for WF_X between 45 and 50% RH is $(1.016 - 1.021) / 5 = -0.001$.

Therefore WF_{46} is $1.021 - 0.001 = 1.020$.

6. The corrected weight is $0.500 * 1.020 = 0.510$ *gram*.

EXAMPLE 2

A specimen of 50:50 cotton/polyester fabric weighs 0.500 gram after conditioning in an atmosphere of 46% relative humidity.

1. Same as Step 1 in Example 1.

2. Continue.

3. The proportion of cotton in the bone-dry fabric is $Cd = 0.5 / F_{50} = 0.474$ (***Table 2***).

4. Adjusting the cotton portion from bone dry to 46% RH gives a cotton weight of

$(Cd * F_{46}) = 0.474 * 1.0511 = 0.4982$.

The weight of polyester is 0.5, so the proportion of cotton in the conditioned specimen is

$Cc = 0.4982 / (0.4982 + 0.5) = 0.4991$.

5. The Weight Correction Factor for 50% cotton at 46% RH is found by calculation or by interpolation from ***Table 4*** or ***Figure 1***. From ***Table 4*** the interpolated rate of change for WF_X between 45 and 50% RH is $(1.008 - 1.011) / 5 = -0.0006$.

Therefore WF_{46} *is* $1.011 - 0.0006 = 1.0104$.

6. The corrected weight is $0.500 * 1.0104 = 0.5052$ *gram*.

Table 1

Moisture regain and moisture correction factor at different relative humidities

RH	Mr	F_X
35	4.174	1.0417
40	4.574	1.0457
45	5.013	1.0501
50	5.493	1.0549
55	6.019	1.0602
60	6.596	1.0660
65	7.228	1.0723
70	7.921	1.0792
75	8.679	1.0868
80	9.511	1.0951
85	10.422	1.1042

Table 2

Bone dry weights of cotton and polyester per gram of the original blend

Nominal cotton content Cn	Bone dry	
	cotton Cd	polyester Pd
0.50	0.474	0.500
0.55	0.521	0.450
0.60	0.569	0.400
0.65	0.616	0.350
0.70	0.664	0.300
0.75	0.711	0.250
0.80	0.758	0.200
0.85	0.806	0.150
0.90	0.853	0.100
0.95	0.853	0.050
1.00	0.948	0.000

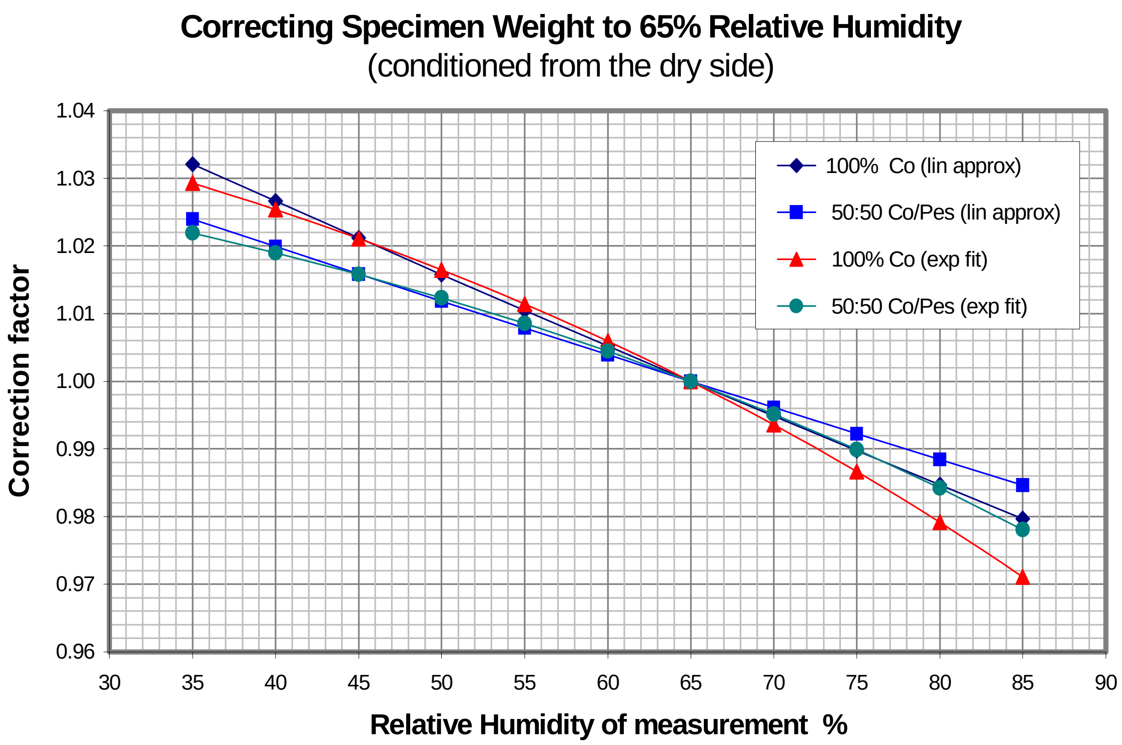
Table 3

Cn	Weight of cotton per gram of blend at the given RH										
	35	40	45	50	55	60	65	70	75	80	85
0.50	0.4969	0.4978	0.4989	0.5000	0.5012	0.5026	0.5041	0.5057	0.5074	0.5093	0.5114
0.55	0.5469	0.5478	0.5489	0.5500	0.5512	0.5526	0.5540	0.5556	0.5574	0.5592	0.5613
0.60	0.5970	0.5979	0.5989	0.6000	0.6012	0.6025	0.6039	0.6054	0.6071	0.6089	0.6109
0.65	0.6471	0.6480	0.6490	0.6500	0.6511	0.6524	0.6537	0.6552	0.6567	0.6585	0.6603
0.70	0.6974	0.6982	0.6990	0.7000	0.7010	0.7022	0.7034	0.7048	0.7062	0.7078	0.7095
0.75	0.7476	0.7484	0.7491	0.7500	0.7509	0.7519	0.7530	0.7542	0.7555	0.7569	0.7585
0.80	0.7980	0.7986	0.7993	0.8000	0.8008	0.8017	0.8026	0.8036	0.8047	0.8059	0.8072
0.85	0.8484	0.8489	0.8494	0.8500	0.8506	0.8513	0.8521	0.8529	0.8538	0.8547	0.8557
0.90	0.8989	0.8992	0.8996	0.9000	0.9004	0.9009	0.9015	0.9020	0.9026	0.9033	0.9040
0.95	0.9494	0.9496	0.9498	0.9500	0.9502	0.9505	0.9508	0.9511	0.9514	0.9517	0.9521
1.00	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4

Cn	Corrected weight per gram, when measured at the given RH										
	35	40	45	50	55	60	65	70	75	80	85
0.50	1.015	1.013	1.011	1.008	1.006	1.003	1.000	0.997	0.993	0.989	0.985
0.55	1.016	1.014	1.012	1.009	1.006	1.003	1.000	0.996	0.993	0.988	0.984
0.60	1.017	1.015	1.013	1.010	1.007	1.004	1.000	0.996	0.992	0.987	0.982
0.65	1.019	1.016	1.014	1.011	1.007	1.004	1.000	0.996	0.991	0.986	0.981
0.70	1.020	1.018	1.015	1.012	1.008	1.004	1.000	0.995	0.991	0.985	0.979
0.75	1.022	1.019	1.016	1.012	1.009	1.004	1.000	0.995	0.990	0.984	0.978
0.80	1.023	1.020	1.017	1.013	1.009	1.005	1.000	0.995	0.989	0.983	0.977
0.85	1.025	1.022	1.018	1.014	1.010	1.005	1.000	0.995	0.989	0.982	0.975
0.90	1.026	1.023	1.019	1.015	1.010	1.005	1.000	0.994	0.988	0.981	0.974
0.95	1.028	1.024	1.020	1.016	1.011	1.006	1.000	0.994	0.987	0.980	0.972
1.00	1.029	1.025	1.021	1.016	1.011	1.006	1.000	0.994	0.987	0.979	0.971

Figure 1



GENERAL PRINCIPLES OF QUALITY ASSURANCE

BACKGROUND

We start from the following assumptions:

a. In the developed consumer markets of Western Europe, Japan, and the USA, there is a large demand for cotton knitted goods together with a strong desire for wider choice and higher quality.

b. The demand for wider choice means that frequent changes in styles and colours have to be made. It is no longer the case that a single range will suffice for a whole season.

c. This means that new products have to be continually evolved at a much faster rate than before and consumer response to poor quality will be felt more rapidly.

d. The consequence is that reputable high street retailers in advanced consumer markets are becoming more interested in suppliers who can deliver new products very quickly and who can guarantee to have the quality right first time at reasonable cost.

e. There will always be a market for low cost, low quality suppliers but they will suffer from low profit margins and stiff competition from producers in less well-developed economies.

The STARFISH Workshop is designed to address only one aspect, though an important one, of these problems. It is how to set about developing new circular knitted cotton products more rapidly, more reliably, and with guaranteed performance in terms of the major technical specifications of weight, width, and shrinkage.

However, in this introductory paper, we will deal with some of the more general aspects of quality assurance, which are applicable across the whole field.

BASIC CONCEPTS

The modern idea of Quality Assurance supersedes the old idea of quality control, which is now relegated to a subsection of a total quality system. The old-fashioned concept of quality control is that goods are inspected at various stages in production to determine if they conform to given quality standards so that remedial action (such as mending or reprocessing) can be taken if they do not. Great emphasis is placed on final inspection with sub-standard products possibly being assigned to "second grade" and being sold at lower prices.

This approach was acceptable for simple production systems where long runs of a single product could be guaranteed, where markets were dominated by domestic suppliers who were all competing on a more-or-less equal cost basis, and where the range and quality of products on sale in various markets were determined by what the manufacturers were prepared to supply.

Quality Assurance is designed as a response to much more sophisticated and complicated, capital intensive manufacturing technology and much more stringent and *internationally* competitive markets where the dominant force is consumer choice. It depends not on the detection and correction of poor quality (however that may be defined within a particular company) but on the positive guidance and control of the product design and production environment so that poor quality is never made. It also stems from the recognition that, in today's production and market conditions, poor quality has a very high cost. Even though quality assurance systems can be expensive, if they are properly applied, they will save money in direct costs and they will generate or preserve sales due to enhanced reputation and customer confidence.

The technology of quality assurance has made great progress in the last few decades and much of it has been codified into a series of standards. The most basic and important of these is ISO 9000.

These (and other related) standards will repay very careful study before any attempt is made to try to introduce new quality assurance schemes into a factory. However, it should be remembered that the standards represent a rather full statement of complete and very sophisticated quality assurance systems. Usually it will not be either possible or desirable to attempt to introduce such a complex system wholesale into an operation which may be accustomed to working with traditional routine quality control procedures, and which may have no familiarity with quality assurance concepts.

It must also be remembered that the standards concentrate on *systems and mechanisms*, they say little about the changes in *culture and philosophy* which are required if a true company-wide quality assurance effort is to be successful. It is very much more important to develop an appropriate attitude and approach to Quality Assurance than to implement complicated theoretical systems.

OBJECTIVES OF QUALITY ASSURANCE

A quality assurance system has two sides to its major objectives. One side is related to the direct benefits, which are expected for the company itself; the other side relates to the needs and expectations of the customer. From the point of view of the company, these can be thought of as internal objectives and external objectives.

The internal objectives of the company are: -

- To eliminate the internal costs associated with sub-standard quality, such as waste, reprocessing, loss of production, and "second grade" selling prices.
- To generate the information and the knowledge which allows proper control of machinery and processes in the most economical way, consistent with the required quality.
- To generate the information and knowledge that allows proper prediction of the performance of a given product and, hence, facilitates new product development at minimum cost.
- To generate the knowledge of the critical product parameters and process conditions which allows the quality assurance system itself to deliver the ability to continuously reduce the total cost of quality, whilst maintaining the performance of the product at a level which will satisfy the customer.

The external objectives of the company are: -

- To avoid the direct and indirect costs of sub-standard quality in terms of returned goods, lost sales, and marketing claims.
- to build confidence in the customers and reputation in the market, which will assure the retention of customers in difficult times and adequate profits in good times
- To develop a system of feedback from customers which allows advance information about market requirements and ensures that products are made available which actually satisfy a known need.
- To develop a communication system with suppliers so that materials which will critically affect the cost and quality of the company's product are delivered consistently to the required quality specification at the optimum cost.

COMPONENTS OF A QUALITY ASSURANCE SYSTEM

An overall quality assurance system basically comprises three main elements. These are the Quality Policy, the Quality Targets, and the Quality System. All three are embraced by the Company-wide Quality Culture.

Quality Policy must be set at the highest level of management. It is a statement of what the general attitude of the company is towards the level of quality and the means and resources for obtaining it.

Quality Targets are specific values and tolerances for quality standards to be achieved (e.g. waste below w%, reworking below r%, yarn count tolerances within plus or minus y%, shrinkage values below s%)

The **Quality System** is the organisational structure that will be used to implement the policy and achieve the targets (personnel, responsibilities, procedures, resources).

All of the above three elements embody two main perspectives:

- The average level of quality. This defines the position of the company in the market (e.g. Rolls Royce vs. Ford).
- The general approach towards quality improvement. This defines the attitude or the culture of a company.

Most of the additional work and the cost of Quality Assurance are concentrated in the System and so it tends, quite rightly, to get the greatest concentration of effort. However, if the Policy and the Targets are not consistent and realistic, and if they are not adequately supported by the whole workforce, then even the best-organised System will fail to meet its objectives.

The single most important principle of quality assurance is that conditions of manufacturing should be organised so that poor quality is never made. A system, which merely emphasises detection and correction of poor quality, will be expensive and ineffective in terms of the internal and external objectives given above.

There are three basic tenets that will serve to guide any quality assurance system in the right direction.

1. It is always cheaper to do the job right first time.
2. The only performance indicator is the cost of quality.
3. The only performance standard is zero defects.

SOME SPECIFIC ASPECTS

DEFINITIONS OF QUALITY

At least three different perspectives can be distinguished, namely Consumer Quality, Market Quality and Manufacturing Quality.

Consumer Quality

So far as the ultimate consumer of products is concerned, Quality simply means performance per unit of price. The problem arises in defining the meaning of performance. There are at least three aspects to performance. These are Objective performance, Subjective perceptions, and Service.

- **Objective performance** includes tangible physical properties such as colour, weight, handle, shrinkage, durability, garment design, size and goodness of fit, neatness of seams and hems. Some of these properties can be evaluated by the consumer at the point of sale; some manifest themselves only after more or less extended periods of use.
- **Subjective perceptions** are those intangible aspects, which influence the consumer to value a given product more or less highly, regardless of its objective performance. Included are image, lifestyle, fashion, and promotion. It has often been said that a $50 tee shirt is a $10 tee shirt with a $40 logo attached. Whilst this view is perhaps over-cynical, it does illustrate that consumers are influenced by intangible aspects of quality.

- **Service** relates mainly to the environment in which the product is purchased, combined with previous experience of the product or the environment. A high-class boutique can sell the same objective performance at a higher price than a market stall. Because many of the objective aspects of performance can not be evaluated at the point of sale (e.g. shrinkage, wash fastness), a consumer will be influenced by previous experience of buying a given product brand, or the general reputation of a given retail store, and its policy in handling complaints.

Consumer Quality is measured in terms of satisfaction. The only reliable indicator of satisfaction is repeat purchases at the asking price.

Market Quality

Market Quality has two faces. One face is directed towards the Consumers, the other is directed towards the Manufacturing Operation.

- On the one hand, Market Quality is the general performance level that a manufacturer or retailer sets for his products, in order to target a particular sector of consumers.
- On the other hand, it is a collection of design and manufacturing targets and tolerances that will be used by the manufacturing operation to develop and deliver specific products.

The manufacturer has to decide what sector of the market he is targeting and, consequently, what levels of Objective, Subjective, and Service performance he will be obliged to provide, and at what price. Once the general performance levels have been decided, they have to be converted into specific product designs, marketing strategies, and objective performance requirements. The objective performance requirements have to be translated into design, engineering, and manufacturing specifications, with appropriate tolerances, for each specific product.

Market Quality is measured in terms of product demand compared to the estimated total demand in the targeted sector.

Manufacturing Quality

So far as the manufacturing operation is concerned, the definition of quality is very simple. It is Conformance to the Objective Specification. More complicated definitions are a distraction from the business of manufacturing.

Manufacturing Quality is measured in terms of the cost of quality as a whole and the cost of non-conformance in particular.

COMPANY-WIDE CULTURE

The traditional systems of quality control depend on inspection of the products for defects, followed by corrective action or grading into first- and second-class quality. Under such systems, the cost of quality is large and is represented by waste, reprocessing, lost production, lost sales, and lost market opportunity. In general, individual operatives have little or no control over quality; their main emphasis is on production. Managers spend the majority of their time sorting out problems both inside the factory and with customers and suppliers. This kind of system can be thought of as the product of an "**Inspection-driven**" culture.

The Inspection culture is basically out of control. The underlying driving force is production. There are frequent disputes between the production, inspection, quality control, and marketing departments. Unless their domestic markets are heavily protected, such companies will eventually fail under modern international competitive pressures.

A company which has realised that the cost of quality can be reduced by closer control of supplies and processing progresses to a better degree of control. This is achieved by the installation of rigid systems for specifying and checking supplies, more highly automated machinery and the imposition of strict discipline in the operation of machinery and control systems. Some form of Statistical Process Control may be introduced, along with Quality Manuals and Standardised Quality Procedures (ISO 9000). Operator training may be improved, and there may be some move away from a reward system based purely on productivity bonuses. This kind of system allows for the stabilisation of quality levels and for much improved customer satisfaction, but it does not necessarily reduce the cost of quality by very much, since the new control systems are expensive to operate. This is a "**Control-driven**" culture. Managers spend a lot of time supervising the system.

The Control culture always attempts to maintain the status quo. There are seven basic activities in a Control-driven system.

- Choosing objectives for control.
- Selecting the control methods.
- Deciding standards of performance.
- Installing measuring equipment.
- Measuring performance.
- Comparing performance with the standard.
- Acting on the difference.

The underlying driving force is measurement. The objective is to maintain existing practices and standards. The system has large advantages over the Inspection culture because its result is a greater uniformity and reliability. However, it can become inflexible and can not easily develop better or more cost-effective ways of operating.

The final step in quality and cost control can be taken only when the system is driven by quantitative evaluations of the effect of working methods and production systems upon the quality-related cost of each individual process within the whole chain, from raw materials supply to marketing and customer service. This is a "**Continuous evolution-driven**" culture. It recognises that:

- The raw material with the cheapest price is not always that which provides the minimum overall cost. The quality culture in a supplier's factory is of vital importance.
- "Quality and cost improvements can not be dictated by management; they have to be earned through the hard process of data collection, analysis, and problem solving."
- "The control of quality can only be exercised at the point of production, i.e. by individual operatives."
- Each process is "owned" by a responsible operative or team. To be a responsible owner, the team has to have:
  - ⇒ full understanding of what needs to be done,
  - ⇒ the means to know what is actually being done, and the cost,
  - ⇒ the ability to evaluate and regulate their performance.

The Continuous evolution culture is always looking for a way to achieve a breakthrough to a different way of operating at a lower cost at the same or better quality. The sequence of activities required for a breakthrough takes place in eight stages.

- Choosing objectives for breakthrough.
- Convincing colleagues that a breakthrough is needed.
- Identifying the vital few projects.

- Organising for a breakthrough.
- Creation of a project team, and a champion to steer the effort.
- Diagnosis.
- Breakthrough in cultural pattern of working.
- Transition to a new level.

The underlying driving force is the cost of quality. The result is a continuous evolution towards higher standards and new practices.

PRODUCT DESIGN AND SPECIFICATION

The most important source of new product design information is the customer and he is ultimately the most important person to satisfy. No product will succeed in the long term unless it has been designed to satisfy a specific customer need. However, remember that most customers are still working under the Inspection-driven culture.

The following are points to watch.

1. The customer often has very short-term horizons; be sure that his immediate requests are consistent with long term company policy.
2. The customer often is not technically trained; be sure that the specified performance is actually achievable and, if not, establish as quickly as possible what is the best compromise.
3. The customer often is very hazy about realistic target values and tolerances; be sure that he understands the advantages of fixing required quality standards but that there is bound to be some range in performance. Acceptance levels for performance should be defined in terms of specific test methods, which are reliable and are used by both parties in the same way.

In summary it is a fundamental aspect of quality assurance policy that time should be spent with key customers and prospective customers finding out what are their real needs and objectives. Quality assurance policy objectives should be led by market requirements as much as by company capabilities.

SUPPLIERS

One of the most important influences on the quality of a company's product is the quality of the supplies that go into it. In the case of the knitter, a good example is the yarn that he buys. In the case of the finisher it is the grey fabric with which he is supplied. A Company must spend time with its suppliers in explaining its needs and limitations as well as its expectations. An explicit system of quality assurance should be set up between the company and its suppliers to guarantee the quality of their deliveries. Long term, stable relationships with trusted and reliable suppliers are invaluable.

More than half of all sales revenue is spent on purchasing raw materials, services, and supplies. It has been estimated that 50% of a company's problems are caused by purchases that did not meet the required specification and that at least 70% of the blame for this lies with the purchaser.

All of the above is relevant for transactions between sections of a vertical company.

PROCESS CONTROL

There are certain key machines and processes that have a drastic effect on quality if they are not properly understood and controlled. The quality assurance system must have at least two objectives in process control.

Firstly, it must ensure that the key operating conditions of particular machines and processes are maintained at the proper levels to guarantee the required quality. The most obvious examples are the control of course length in knitting and the control of fabric length and width in finishing.

Secondly, the system must be designed to develop the information that is needed to understand the influence of variation in machine and process conditions upon the final quality and cost of the product. This is required for three reasons: -

- To be able to predict what machine or process settings are required to achieve a particular desired result.
- To identify the most important control parameters, which have to be included as quality control targets, and to eliminate the cost of monitoring redundant parameters.
- To quantify the major quality-related cost elements of the process so that pressure may be brought to bear to reduce these costs.

SPECIFIC QUALITY TARGETS

Market requirements and production performance have to be translated into specific quality targets e.g. weight, width, shrinkage, and tolerances. These targets should be as few as possible in order to satisfy the requirements of process control and product performance.

For example, if a knitter has proper control over his course length and the correct yarn has been supplied, and if the correct number of machine revolutions (courses) has been knitted then it is not necessary to make any further dimensional measurements on the grey fabric, since the correct piece weight and the ultimate fabric weight, width and shrinkages must follow. Other measurements may be made for other reasons (for example yarn friction to assure good knitting efficiency) but strict control of these three will guarantee the correct dimensions - so far as it is in the power of the knitter to do so.

Additional measurements and control systems represent additional cost without commensurate benefit. Furthermore, the advantage of yarn count and course length as control parameters is that they are fixed before the cloth is made and therefore, they fulfil the requirement that poor quality has to be prevented, rather than corrected later.

Targets and tolerances must be unambiguously defined, in terms that are easily understood by the workforce, and they must actually be attainable by the installed production regime and measurement system. Individual operators must be properly trained in how to achieve and maintain the targets and should have the means to control their performance. Their remuneration should be influenced strongly by the degree to which they are able to achieve the targets and reduce the overall quality related costs.

When setting targets, it is important to distinguish between average values and maximum or minimum values as the key parameter. A good example is in the setting of shrinkage targets. Many customers will demand that shrinkage must not exceed a certain maximum level. This implies that the target average level must be lower by about two standard deviations in order to guarantee that 95% of deliveries will have shrinkages below the required maximum. This means that close control over the sources of variation in production will be needed, so that the standard deviation stays under control.

There is no point in specifying a level of 5% shrinkage if the basic product design will not allow such a low level at the required weight, or if the finishing equipment is not capable of delivering the required length relaxation.

Likewise, there is no point in specifying course length tolerances of plus or minus 0.5% when the knitting machines are not fitted with properly maintained positive feed units and the quality control staff do not have access to properly calibrated electronic yarn length measuring devices.

Appropriate product design changes, machinery investments, and working practices have to be investigated and implemented before improved performance is specified. Targets are not to be seen as either a carrot for the customer or a stick for the workforce, but as a way of achieving control over what is actually possible.

In summary, quality targets must be evaluated from the following points of view.

a) Is it something that is important to the customer - will the customer want to see quality records for this parameter?

b) Is it going to function as a guarantee of good quality, or merely a detector of poor quality?

c) Will it help in monitoring the capability or the long-term performance of a key production stage?

d) Does it help to understand the technology of the process in the sense that it can be used as a prediction parameter?

e) Is it something that can actually be achieved and, if not, what has to be done in order that a desired target can be achieved in the future?

RESOURCES

It is important to remember that: -

- quality target parameters have to be measured in a reliable, consistent and reproducible way,
- good records have to be kept which are accessible to management in an appropriate form, and
- the data have to be used constructively not only in monitoring performance in the short term but in generating the kind of knowledge which leads to improvements in quality, or reductions in cost in the long term.

It is therefore necessary to have the appropriate measuring equipment, the appropriate sampling and measuring systems, regular standardisation and calibration of test methods and instrumentation, and well-trained staff.

The people who take the samples and make the measurements may have to be independent from those who are responsible for setting the targets or running the process. They should be trained in statistical assessment techniques and should be capable of preparing objective digestible reports for the decision-makers. They should have sufficient confidence in their function that they are under no pressure to "bend" the data. Unreliable data and inadequate evaluation do not help anybody and may lead to a harmful interpretation of the manufacturing operation.

Responsibility for making quality-related decisions on the factory floor has to be well defined, well known to the whole workforce, and supported by an appreciation of the importance of quality as a whole to the future well being of the company.

QUALITY RELATED COSTS

One of the most important functions of the quality assurance system is to measure the cost of quality. It has been estimated that around 25% of total manufacturing costs can be ascribed to poor quality.

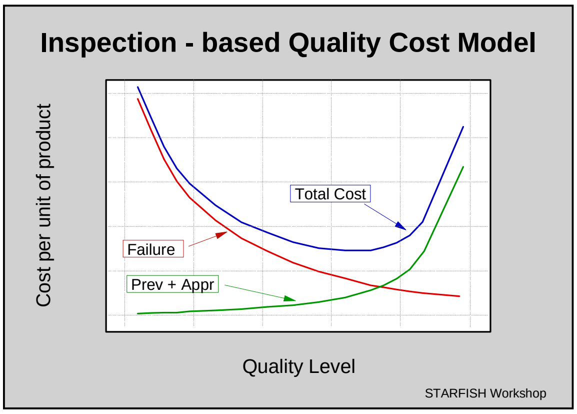
Quality related costs can be conveniently divided into three parts.

- ***Failure costs***
  These are costs attributed to scrap, reworking, lost sales, low sales prices, lost production, etc. They represent the cost of non-conformance and are the prime indicator of manufacturing quality.

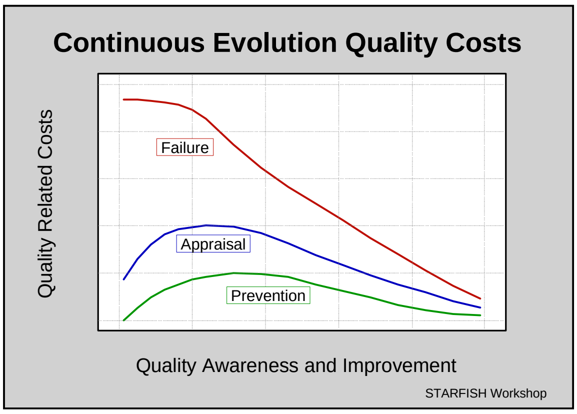
- ***Appraisal costs***
  The cost of inspection, measurement, testing, and control.

- ***Prevention costs***.
  The costs of supplementary actions taken to investigate, prevent or reduce the risk of non-conformance or defects.

The following two illustrations are based on the ideas presented in BS 6143: Part 1, 1992 and BS 6143: Part 2, 1990, on Quality Costing.



The implication of the first diagram is that there is an economic balance in the cost of quality. When quality levels are low there is a large Failure cost but very low Appraisal and Prevention costs. Investment in prevention and appraisal brings quick rewards in quality level and reduced failure costs but there is a limit to this investment, beyond which the total cost rises. It seems that this model is based in the ideas of a Control-driven culture.



The second diagram, on the other hand, recognises that (in a Continuously-evolving culture) the cost of appraisal and prevention should eventually begin to reduce as a result of improved working practices and a better understanding of quality related costs. After an initial period of rising costs for appraisal and prevention, progress is made towards a zero-defect target with all quality related costs reducing as overall reliability and predictability improve.

BS 6143: Part 1, 1992 and BS 6143: Part 2 1990 give alternate models for analysing the cost of quality and other recommendations can be found in the extensive literature on Quality Assurance. The various models are not mutually exclusive and may be adapted to local circumstances.

Also, it should be emphasised that there is no need for very detailed attempts to identify every single penny spent on Prevention and Appraisal, or every dollar lost in Failure costs. Approximate figures will serve, especially in the early stages of a quality costing exercise. In any event a continuous effort must be made to evaluate the cost of quality, since it will generally be found that any action which significantly reduces quality related costs will have a large impact on the reliability of the product and the profitability of the enterprise.

THE ROLE OF SHRINKAGE AND EXTENSIBILITY IN THE COMFORT AND FIT OF KNITTED COTTON GARMENTS

S. Allan Heap and Jill C. Stevens, International Institute for Cotton, Manchester, UK

Presentation to the Textile Institute Fibre Science Group, September 1990

INTRODUCTION

Cotton is by far the world's most important textile fibre with an annual consumption of more than 18 million tonnes - about 48% of all textile fibres. In spite of fierce competition from man-made fibres, cotton consumption continues to grow steadily so that the present level of utilisation is more than 30% greater than that of only 10 years ago (Figure 1). The correspondingly large growth in production of raw cotton fibre has been achieved without any increase in the area of farm land, which has been virtually constant since the 1950's due to increases in the productivity of cotton farming (Figure 2). A detailed analysis of projected population growth and agricultural resources undertaken some years ago revealed that there is no reason to doubt that cotton producers can continue to supply the appropriate quantities of cotton well into the next century without straining the food production capacity of the world agricultural system.

Within this global trend of rising cotton consumption, the key market areas of Western Europe and Japan, where the International Institute for Cotton (IIC) has been most active, have seen the most dramatic shifts in demand during the 1980's. For example, according to the United Nations Food and Agriculture Organisation (FAO), between 1981 and 1987 the amount of cotton available for final consumption in the IIC programme area of Western Europe and Japan rose by some 1.22 million tonnes, or by 51.2 %, while cotton's market share grew from less than 36% to more than 43% (Figure 3). In Japan the performance of cotton in the supply of textiles for domestic consumption has been very impressive over the last few years compared to the synthetic substitutes (Figure 4).

The explanation for cotton's outstanding performance in the market over the last decade is not very difficult to understand. In the first place it remains as true as ever that people prefer cotton - it is simply the most pleasant and comfortable fibre to wear. After a relatively brief period of rapid growth in synthetic substitutes - due to their novelty, their good easy-care performance, and the strong technical and market support supplied by the chemical companies - consumers are returning to a more relaxed lifestyle where comfort and cotton are natural partners.

In the second place, cotton interests have not been idle in meeting the challenge of synthetic fibres. Great efforts have been expended in providing improved market support for cotton with the result that it now has a modern fashion image. The results of closely targeted technical research and development are also coming through to market so that cotton fabrics are increasingly better able to compete in terms of performance requirements.

The question of technical performance is a very important one because one clear result of the intrusion of man-made fibres into the market has been their demonstration that the performance of many textile products could be improved substantially. The result is that, although the modern consumer is demanding the comfort of cotton textiles, she is also demanding better performance from them.

An important growth area for cotton is knitted garments for casual leisure wear where comfort is a key aspect of performance. There are many factors which affect the comfort of a garment, but one of the most important aspects is the fit - i.e. the relationship between the size of the garment and the body size of the wearer - and the way that the fit changes over the lifetime of the garment. This paper will outline some of the research and development work which is aimed at improving the performance of knitted cotton garments in respect of fit and fit retention, particularly for close fitting garments such as T-shirts, polo shirts, sports shirts, and ladies tops.

BASIC CONCEPTS

The comfort of a close-fitting garment depends to a large extent on how tightly it hugs the body. These garments are designed to be close fitting but not tight. Therefore, the size of a given item has to be large enough to fit comfortably around the largest body expected in a given size range, but small enough so that the smallest member of that size range also has a close-fitting garment. Because garments are normally produced in only a limited number of size ranges, this usually means that they will have to be able to stretch somewhat when worn over a body which is relatively large for the given size range.

Workers at the Swedish Textile Research Institute (TEFO) have shown that a close-fitting garment becomes uncomfortable when it exerts more than a certain level of pressure on the body. The precise comfort threshold obviously varies with different individuals (and fashions) but, after a large series of practical test measurements, TEFO found that a garment will normally be felt to be comfortable when the tension developed in the fabric is not greater than about 0.25 Newtons per centimetre of garment length, when the garment is stretched over the body. This value therefore sets one constraint upon the amount of stretching which can be allowed in the width of a garment when it is being worn by an individual with the largest body in the given size range.

Obviously, in order to calculate the maximum allowable stretch, we need to know something about the stress-strain characteristics of the fabric. TEFO have developed test equipment and procedures for evaluating fabrics and garments for the tension developed when they are stretched to a given body size.

Another constraint on garment size is provided by width shrinkage in the fabric as a result of home laundering procedures. If the fabric shrinks to a significant degree then, during the lifetime of the garment, its width will be reduced and hence the amount of extension which is imposed by placing the garment over its owner's body will increase. This would be expected to result in a higher level of pressure being generated by the garment on the body. The greater the shrinkage, the greater the increase in pressure of the washed garment compared to the new one.

Shrinkage in the length direction can also not be neglected in terms of comfort. In the first place, excessive length shrinkage will cause the garment hem to rise towards the waist line which (if not intended as a deliberate fashion feature) can be inconvenient, possibly uncomfortable. In the second place, stretching a garment in its width direction will usually cause some contraction in the length. Thus, a further consequence of excessive width shrinkage in a close-fitting garment can be additional shrinkage in the length, over and above that which may have been measured by quality control laboratories at the fabric or garment production stage.

Spirality in plain jersey fabrics, caused by twist liveliness in the yarn, can also be a problem if it causes the garment to twist to such an extent that the side seams are displaced by a significant amount.

A final, though less obvious constraint is the weight per unit area of the fabric demanded by the customer (e.g. the retailer) at the time the fabric or garments are first commissioned. Surprisingly enough in our modern technological age, it is not always appreciated by customers that, for a given knitting quality (i.e. for a given yarn knitted to a given tightness on a given machine and processed through a given finishing sequence), there is a strict relationship between the weight and width which is specified by the customer and the shrinkages which will be developed in the fabric after washing. Often a customer will demand improvements in the level of shrinkage without allowing any change in the weight per unit area or the width. Since this is an impossible demand when the quality is maintained unchanged, it follows that the manufacturer has to undertake a new fabric development programme to discover what changes have to be made at the knitting stage in order to accommodate the demand for improved shrinkages in the garment.

This is already difficult enough but, in fact, changes in the knitting conditions will also change the extensibility and the spirality of the fabric. Therefore, if the further constraint of maintaining the proper comfort and fit of the garment through its lifetime is added to the problem of improving the shrinkages, then a further level of complication is imposed.

The engineering of knitted fabric constructions to yield a predictable array of performance characteristics is a very imperfect science in the knitting industry today. In most cases, development of new or improved qualities proceeds largely on an empirical trial and error basis. In the majority of companies there will be a separate fabric development department which, depending on the size of the company, may comprise several senior staff members who have access to their own pilot scale processing equipment or who consume a significant proportion of the operating time of the standard production machinery.

It is a well-known fact that the demands of customers are often based largely upon wishful thinking rather than solid experience, or careful engineering design of the product that they have in mind. Often a product will be commissioned on the basis of a trial sample because it looks and feels good with much less regard for the technical performance, on the assumption that this can be put right later. This kind of situation is almost inevitable under present conditions and has to be accepted as a fact of life - part of the process of product evolution and improvement in response to market opportunities.

However, it was this situation which led us at IIC to the conclusion some time ago that what the industry needs is a predictive system for fabric development. If we could predict in advance of manufacture what would be the dimensions, the extensibility and the shrinkage of any fabric quality then a great deal of time and effort could be saved. Not only would costs be saved in developing new or improved products but also it would be possible to arrive at a firm idea of whether a particular set of customer demands could actually be met in practice and, more importantly, where compromises would have to be made.

DEVELOPMENT OF A PREDICTIVE SYSTEM

Bringing all of these (and other) considerations together, it turns out that the following information is needed in order to construct a product development system for knitted cotton fabrics and garments which will allow a rational choice of manufacturing conditions in order to guarantee good performance in terms of reasonable levels of shrinkage together with proper comfort and fit of knitted cotton garments throughout their lifetime.

i) A standard relaxation procedure which will deliver the fabric into its fully relaxed state i.e. the state in which essentially no further shrinkage is possible. This fully relaxed state is one which a manufacturer or retailer very seldom sees, because he does not have time to indulge in multiple laundering trials, but the consumer always experiences sooner or later. This will be our reference state in which all of our empirical measurements will be made and upon which our predictive equations will be based.

ii) A comprehensive data base comprising large numbers of measurements made on a wide range of qualities of fabrics, all in their reference state of relaxation. The measurements will include the major manufacturing parameters such as yarn count and knitted stitch length (which will be our inputs) and the fabric dimensional properties of interest such as stitch density, weight per unit area, spirality and extensibility (which will be our outputs).

iii) A set of equations**,** developed from the data base, which link the manufacturing parameters to the desired output properties. A major feature of these equations is that they must contain only those variables which a manufacturer is likely to know, or can obtain quickly and easily in advance of manufacture. Parameters which are too difficult or too tedious to measure using current technology are of little value since they will not actually be known.

iv) A computer programme which is capable of manipulating the equations in such a way as to allow a technologist to simulate the production and processing of the fabrics modelled in the data base and to deliver the expected performance attributes of the simulated fabrics.

For the past twelve years or so, IIC has been collecting such a data base and constructing such a computer programme. We have proceeded so far to the stage where fabric dimensions and shrinkages can be modelled pretty accurately for a wide range of plain jersey, interlock, and lx1 rib fabrics. Data in the pipeline will soon allow the simulation of certain single jersey crosstuck fabrics. However, progress in data collection and modelling of the spirality and extensibility of these fabrics has been slower so that, although a good deal of data are available, the final analysis has not been completed and the computer software has not yet been constructed which would allow predictions for garment sizing to be made. It is hoped to complete this part of the model over the next few years.

EXAMPLES

A few examples can be given of the kind of data which have resulted from this research and the kind of relationships which have emerged.

Figure 5 shows the effect of the knitted yarn count and stitch length upon the number of courses and wales per unit length of a dyed and finished plain jersey fabric in its reference state. These effects are modelled by equations of the form

$$Y = a/S + f(Tex) \qquad [1]$$

Where Y is the course or wale density,
S is the reference stitch length,
a is a coefficient which depends mainly on the fabric type,
f(Tex) is a function which depends on the basic yarn properties and the way that these are modified by the wet processing route.

The evaluation of these functions requires very large volumes of data. In small data sets it can appear that there is no system to the coefficients. It is only when large data sets are available that patterns begin to emerge of the way that the coefficients vary systematically across yarn types, fabric types, and wet process routes.

Once the density of courses and wales in the reference state of relaxation are available from equation [1], then the other major dimensional properties can all be simply found, since:-

- ⇒ Width is given by the number of wales per cm and the number of needles in the knitting machine,
- ⇒ Weight per unit area is given by the product of yarn count, stitch length, courses per unit length, and wales per unit width,
- ⇒ Shrinkages are given by the differences in courses and wales in the as delivered fabric and the reference state.

Figures 6 and 7 show that the type of yarn has an influence on final fabric dimensions. The use of twofold yarns, or OE rotor yarns in place of ring yarns makes a significant difference to the end result.

Figure 8 shows that the level of twist in a yarn also affects the dimensional properties. This is due to twist liveliness in the yarn causing bending and twisting of the loops out of the plane of the fabric. These effects are not directly modelled in the current computer programme; partly because we need more data and partly because all of our existing data have not yet been analysed. In fact, this is not a serious limitation because only a rather narrow range of twist factors is actually used in the trade for a given yarn count. Thus, the action of twist can be absorbed into the yarn tex function for the time being.

Figure 9 shows the effect of different wet processing treatments. We have data for a rather large number of wet processing types and it turns out (so far) that the relative effects of a given finishing procedure are rather consistent across fabric types.

Figures 10 and 11 show the effect of yarn count and stitch length on the extensibility of 14g 1x1 rib fabrics at applied loads of 0.15 and 0.30 N/cm respectively i.e. at loads which straddle the average comfort threshold. The measurements were made at TEFO using a test rig which simulates the stretching of a garment over a body. For a given load, these data can be adequately modelled by expressions of the type

$$E = a + b . S^2/Tex \qquad [2]$$

Where E is the percent extension at the given load,
S is the stitch length,
a and b are coefficients whose generalised application (across yarn types, fabric types, and wet processes) has yet to be elucidated.

Since the square root of tex divided by the stitch length is known as the Tightness Factor, K, equation [2] reduces to

$$Ext\% = a + b/K^2 \qquad [3]$$

Figure 12 shows a plot of the extensibility at a load of 0.3 N/cm as a function of the Tightness Factor which confirms the strong influence of this parameter and also shows that the fully shrunk fabric does not extend as far as the unwashed material at a given load. Similar curve forms are found for other levels of loading, for other fabric types, and for fabrics which have had other wet finishing treatments.

If such data are transposed so that extensibility is expressed in terms of relative width, Wr, (i.e. the extended width divided by the fully relaxed reference width), and all of the data for different fabric constructions and loading levels are included in the analysis, then expressions of the following form are found to model the data pretty well (Fig 13).

$$Wr = 1 + L^a . \exp(-bK) \qquad [4]$$

Where K is the tightness factor
L is the load in N/cm
a and b are coefficients whose values depend mainly on the fabric type and the degree of relaxation.

Figure 14 shows the relationship between width extension and length contraction under a load of 0.3 N/cm for a range of lx1 rib fabrics. Results are given for the unwashed fabrics and for the fully relaxed, reference state materials. In the latter case, two curves are shown. In the upper curve, the width extensions and length contractions are expressed on the basis of the original, unwashed dimensions. Thus, in this case the contractions in length include both those due to shrinkage and those due to the extension in the width. The average shrinkages in the fabrics were about 10% in both length and width directions (although there was considerable variation over the range). In the lower curve, the extensions and contractions are based on the relaxed dimensions. Thus, in this case the contraction in length is caused only by extension in width.

In each of these data sets, it is quite remarkable how closely the data follow a single trend line, which appears to be a simple exponential function, even though a wide range of constructions and (in the case of the unwashed series) shrinkage levels are present.

Figure 15 shows the relationship between the length and width of a series of single jersey T-shirts when they were stretched over a rectangular frame according to a test procedure developed by Marks and Spencer (based on the TEFO static garment test equipment). In this graph, both length and width are expressed as a percentage of the Reference, fully relaxed dimensions. The data for the washed garments are averages from several sets of specimens which had been subjected to different methods of laundering. With T-shirts, it is not uncommon for the washed garment to be called upon to stretch by 15 to 20% in order to fit over a relatively large body in a given size range. For the garments in this data set, the consequence would be an additional length shrinkage of two to four percent.

Figure 16 shows the angle of spirality, A, measured in the reference fully relaxed state on a series of dyed and finished plain jersey fabrics made from Ne16 to Ne 40 yarns, all with similar twist factors (3.6 to 3.8), plotted as a function of the tightness factor.

These data can be modelled approximately by a simple exponential function of the form

$$A = a \,.\, \exp(-bK) - c \qquad [5]$$

where a and b depend mainly on the twist liveliness of the yarn and the way that this is modified by the wet processing treatment.

Twist liveliness in ring yarns is directly related to the number of turns per metre in singles yarn or the difference between singles and folding twist in two-fold yarns. Twist liveliness in singles yarn is invariably reduced by wet processing but, in twofold yarns it can be significantly increased.

Although equation [5] is an adequate model for practical purposes, the data can actually be represented more satisfactorily by using more complex equations which take explicit account of the twist level, and which acknowledge the probable boundary conditions of spirality.

Figure 17 shows spirality plotted against the stitch length for three of the seven yarns. The model which is being investigated for such data has the following form

$$A = a \,.\, (1 - \exp[-bL^{c} \,.\, (1 - L)^{-d}]) \qquad [6]$$

where

A	is the spiral angle,
a	is a simple function of the yarn twist whose coefficients depend on the yarn type and the wet process route
b	is a coefficient which appears to be a simple function of the yarn tex
c and d	are probably constants.

The relationship between spirality and the amount of twisting or seam displacement (SD) which can develop in a garment after laundering is a simple geometrical one which can be derived from the spiral angle (B) in the new garment, the spiral angle (A) in the laundered garment, and the length (Lf) of that part of the garment which is free to twist.

It is given approximately by

$$SD = Lf\,(\tan A - \tan B) \qquad [7]$$

For most garments, the free length is significantly less than the total garment length. For T-shirts it seems to correspond roughly to the distance from the hem to the underside of the arm.

For practical purposes, equation [7] can be simplified further since, for the small angles which are normally encountered in fabric spirality, (tan A - tan B) is given approximately by

$$(\tan A / A) \,.\, (A - B)$$

and (tanA / A) is approximately equal to 0.0176

Thus, the following equation can be used with negligible loss of accuracy to predict the seam displacement in laundered garments.

$$SD = 0.0176\ Lf \cdot (A - B) \qquad [8]$$

Figure 18 shows the results of some measurements of seam displacement made on a series of plain jersey T-shirts compared to those predicted by equation [8].

CONCLUSIONS

From the data which have been gathered so far, it seems quite clear that the required dimensional and stress-strain relationships can be modelled with an acceptable level of precision using only those production parameters which are readily available to the manufacturer. Therefore, a practical predictive design engineering system can be constructed for knitted cotton fabrics and garments.

A user-friendly computer programme has already been developed which allows the prediction of dimensional properties and shrinkages. It is called STARFISH, which is short for "Start as you mean to finish", and is currently (1990) in use by more than thirty companies and institutes all around the world.

In addition, a good start has been made with the collection and analysis of corresponding data on extensibility and spirality so that the computer programme-should be capable of being extended into predictions of optimum garment size, and hence to garment comfort and fit, in the medium-term future.

ACKNOWLEDGEMENT

The extensibility data reported here were collected in the course of a collaborative research programme between IIC and TEFO some years ago. Particular thanks are due to Bernt Johansen and Zdenek Dusek for their supervision of the extensibility measurements which were made on specially designed apparatus at TEFO.

International Institute for Cotton
Technical Research Division
Manchester M20 8RX

August 1990

Figure 1

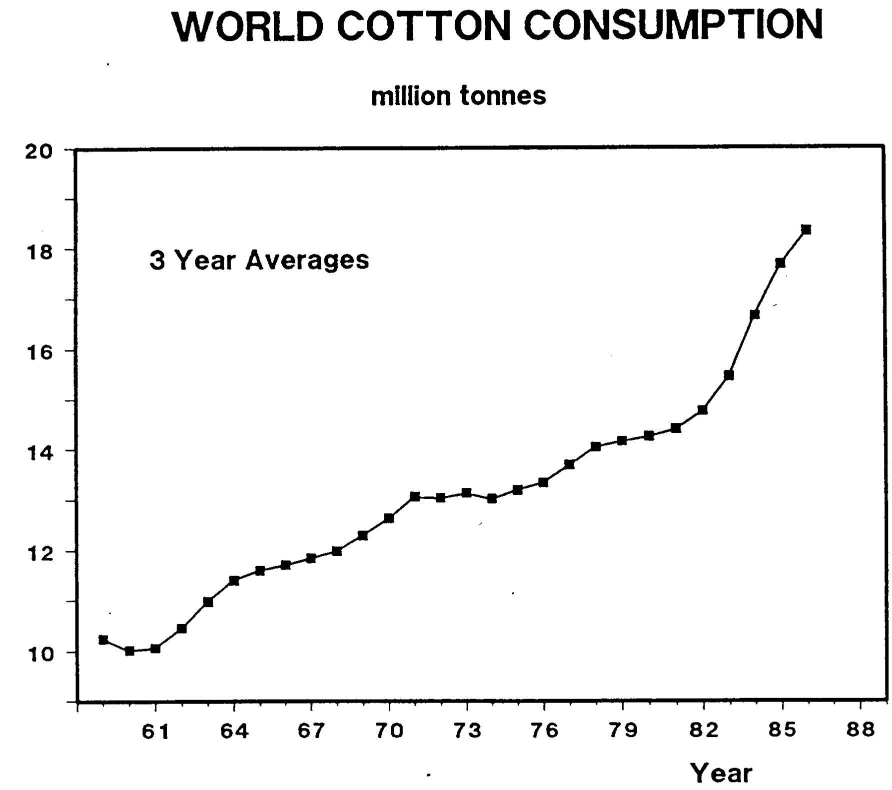


Figure 2

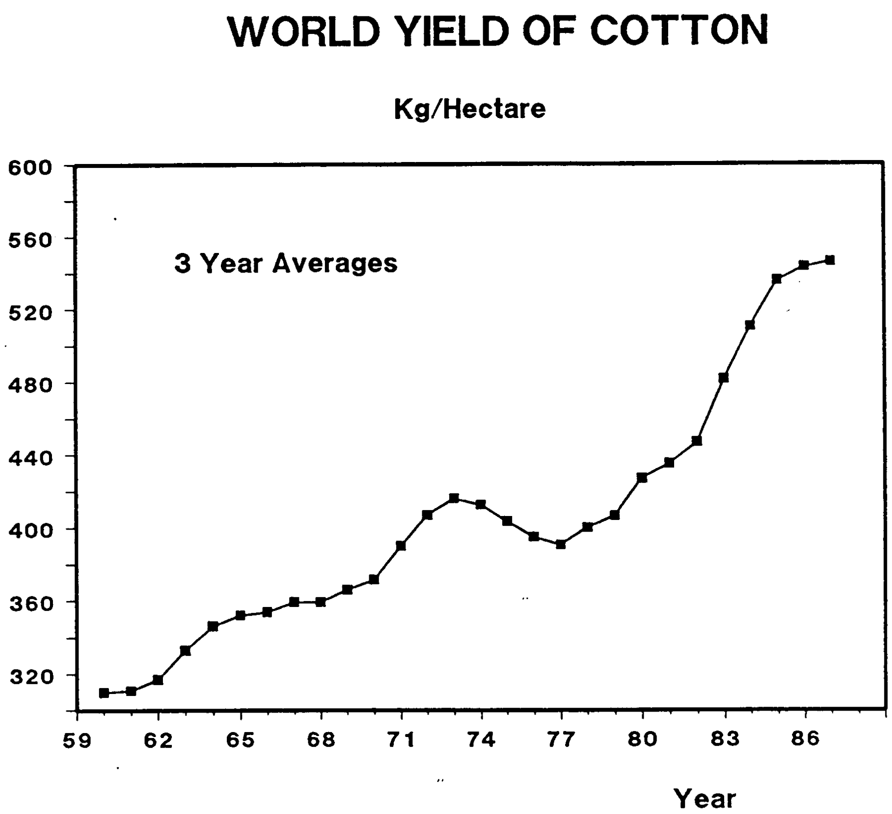
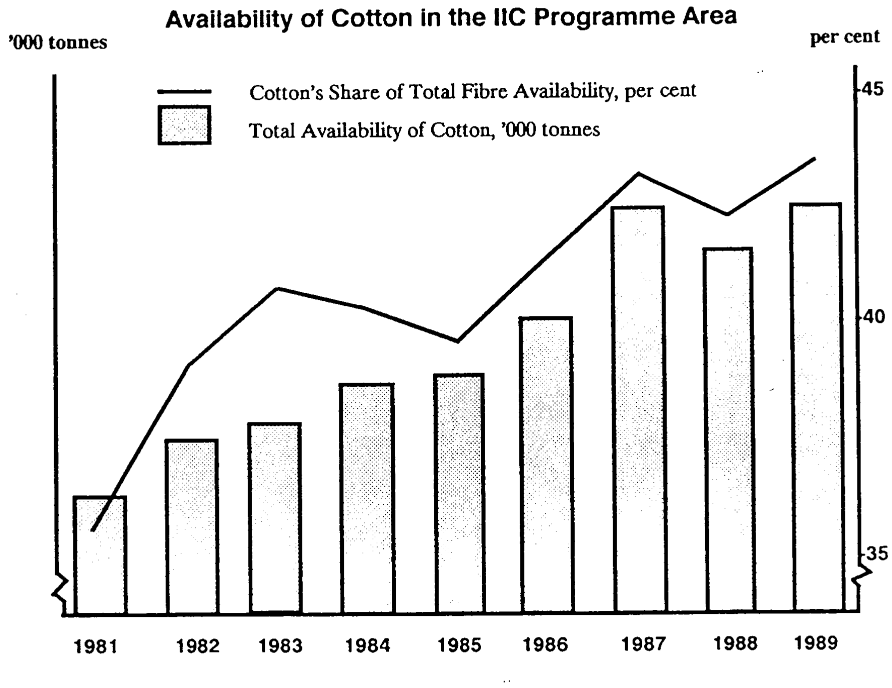


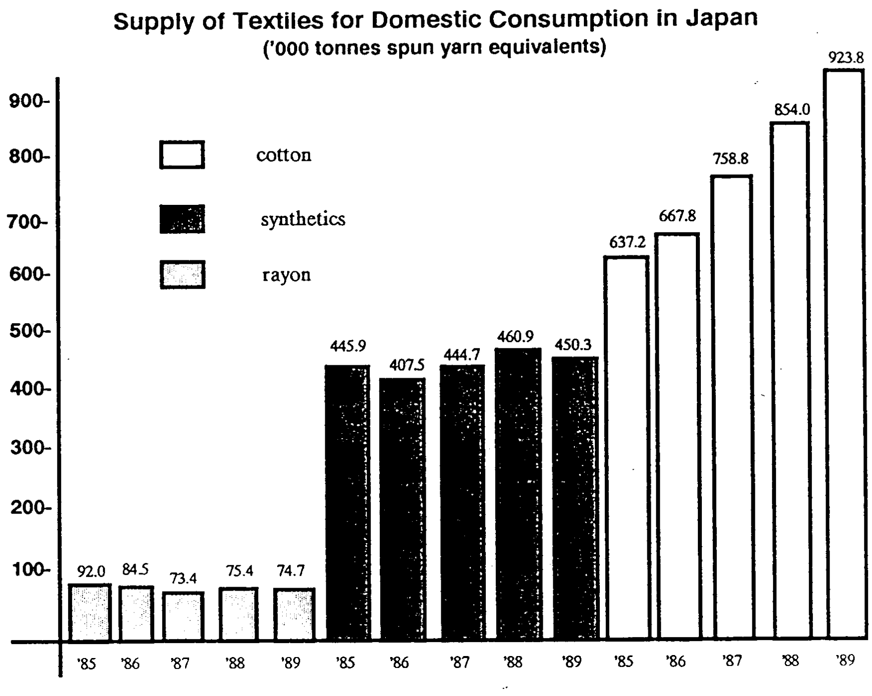
Figure 3



Sources:

World Apparel Fibre Consumption Survey (various years),
Food and Agriculture Organisation of the United Nations;
IIC Estimates .

Figure 4



Source: Ministry of International Trade and Industry, Japan

Figure 5

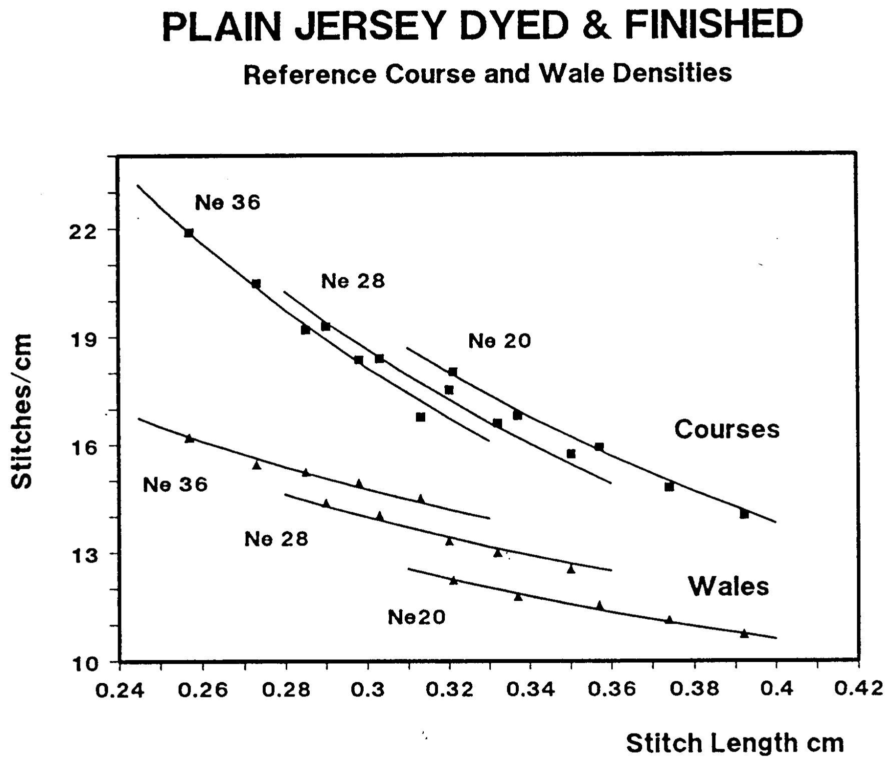


Figure 6

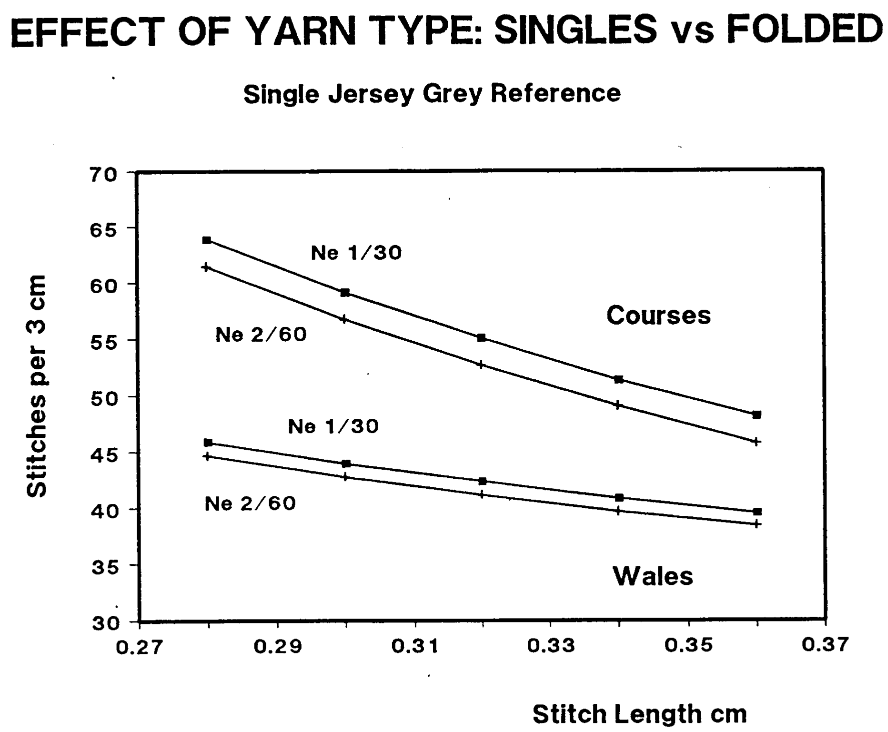


Figure 7

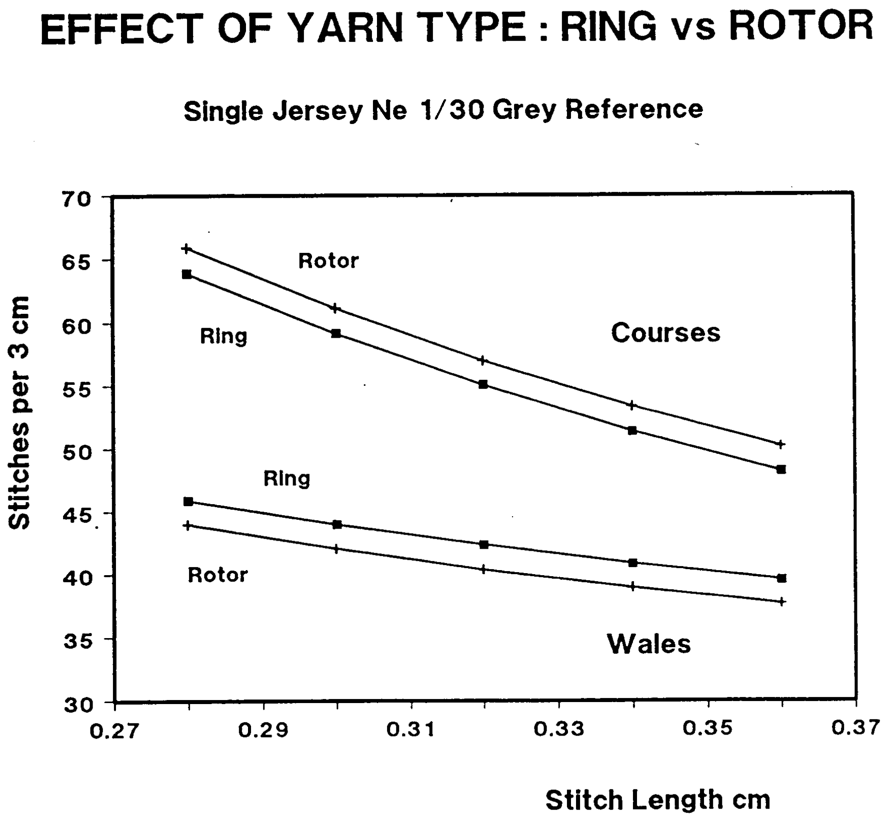
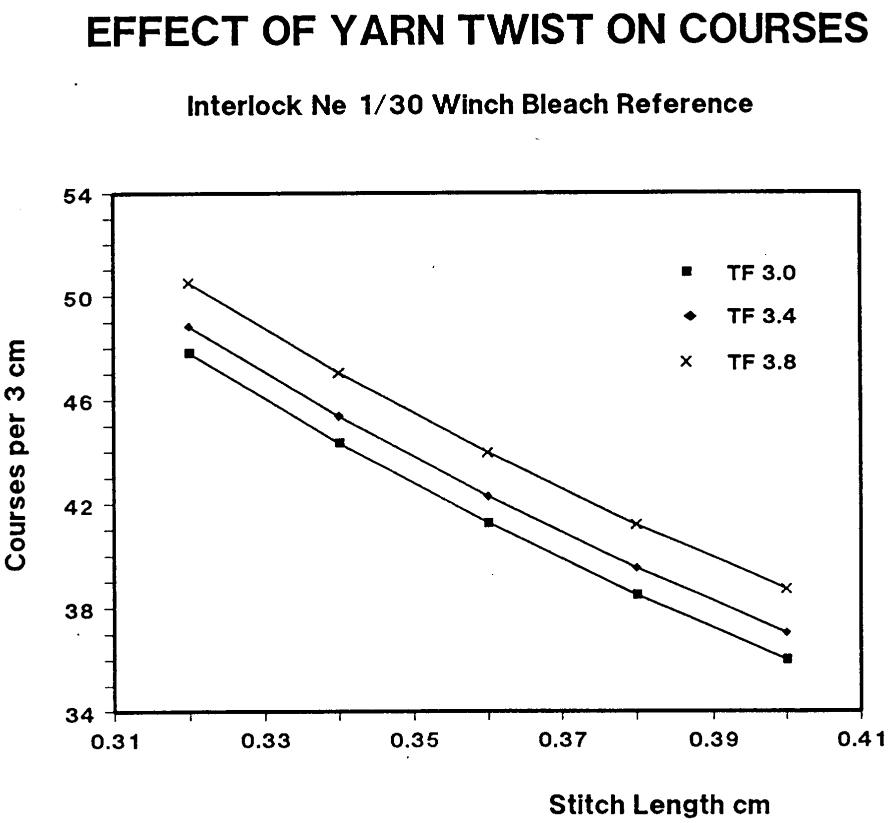


Figure 8



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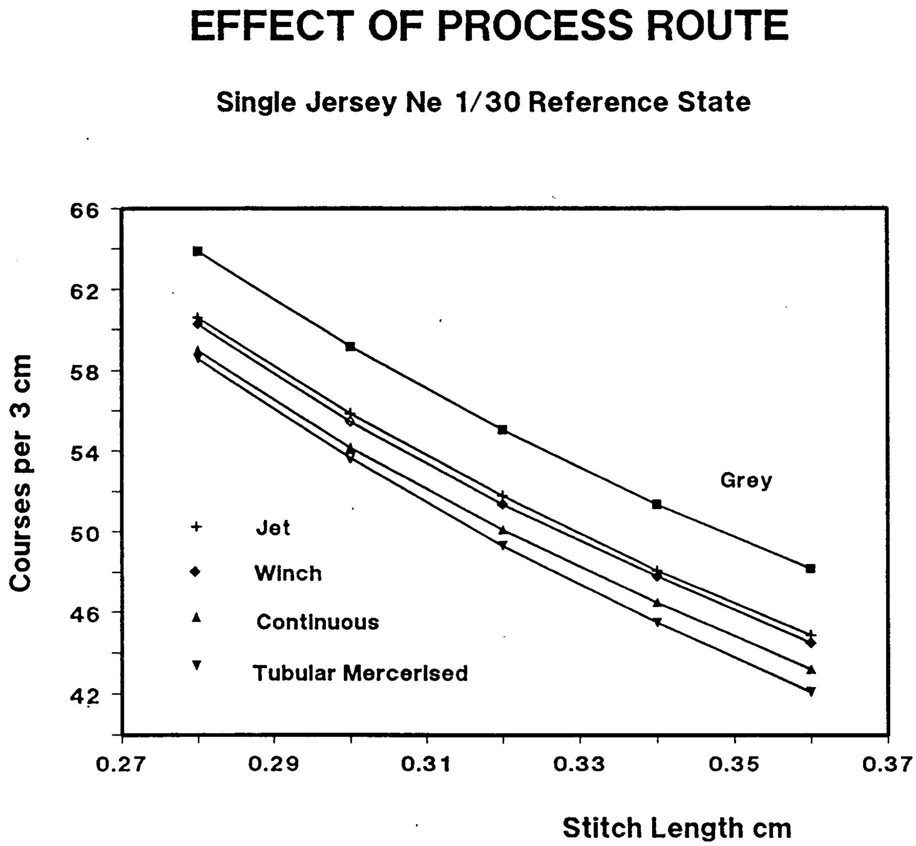
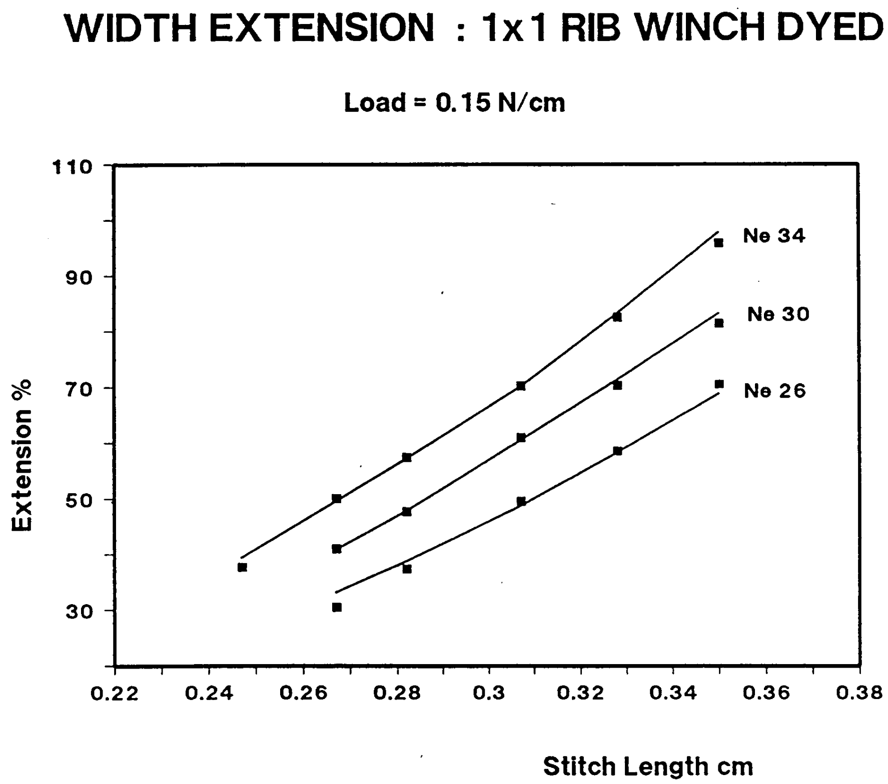


Figure 10



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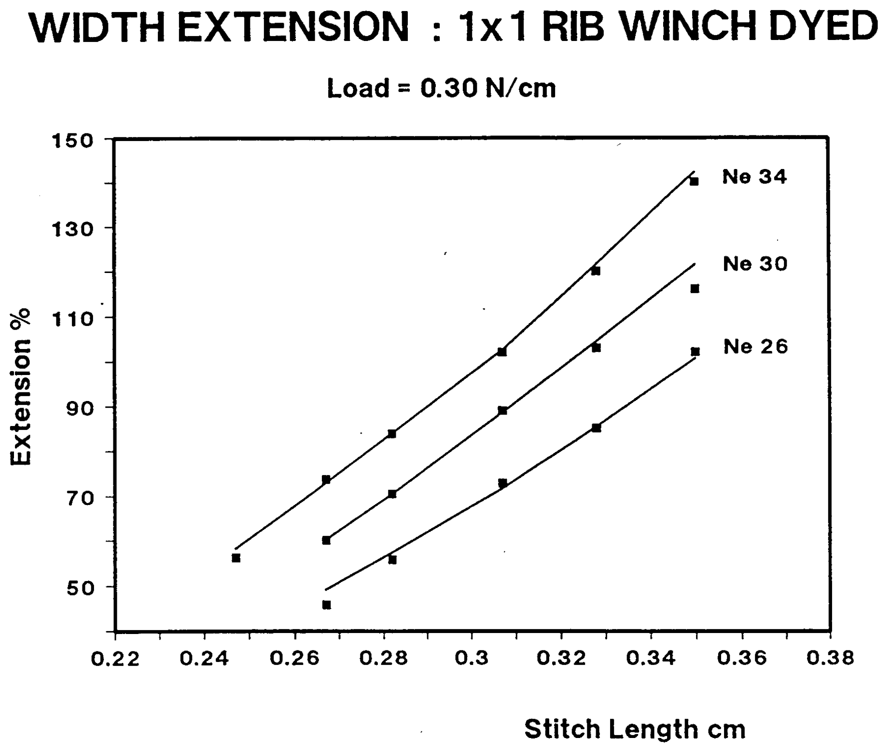

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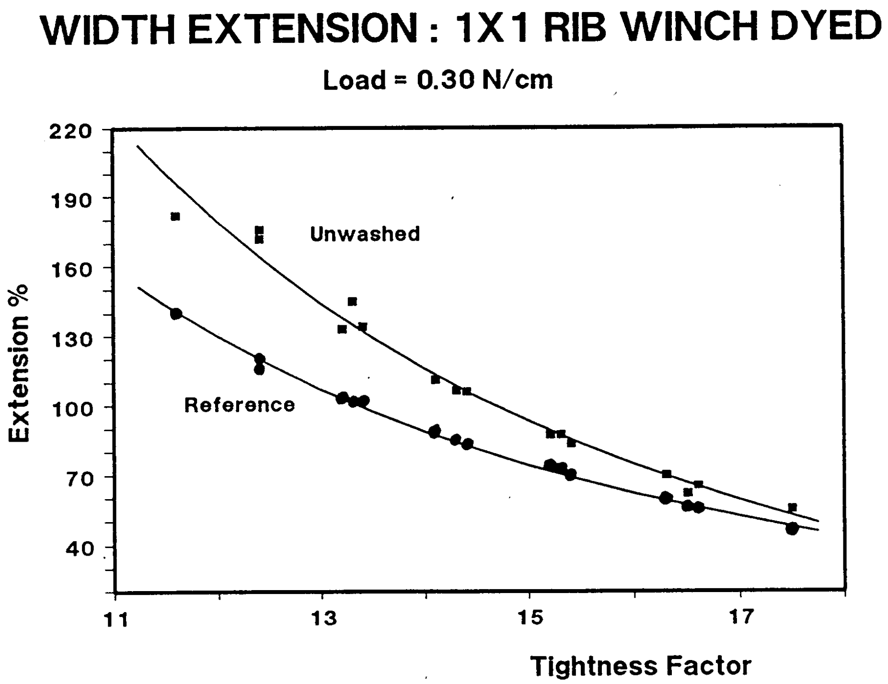


Figure 13

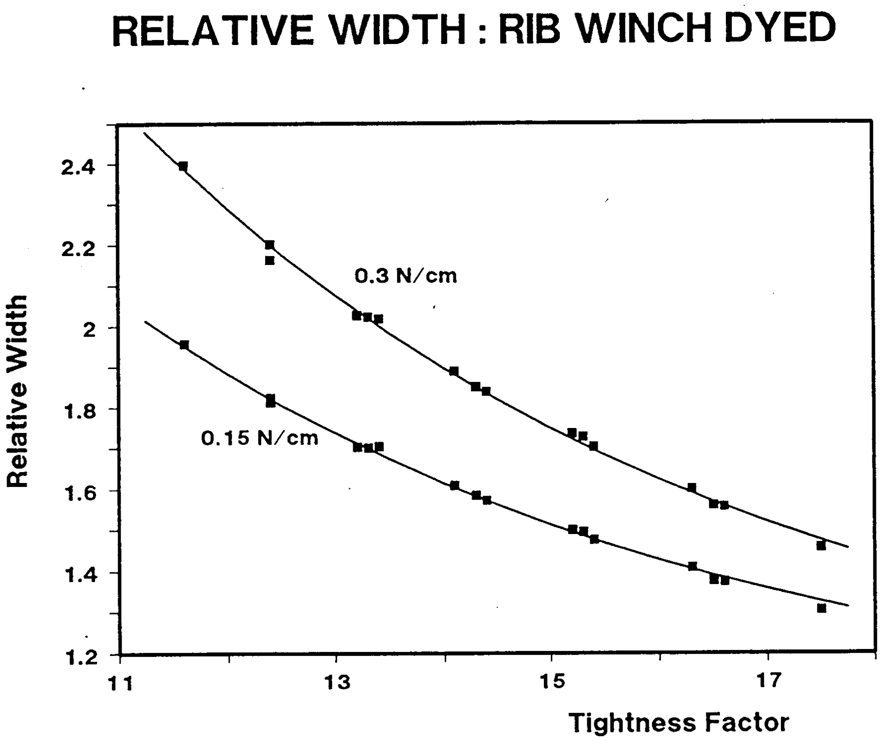


Figure 14

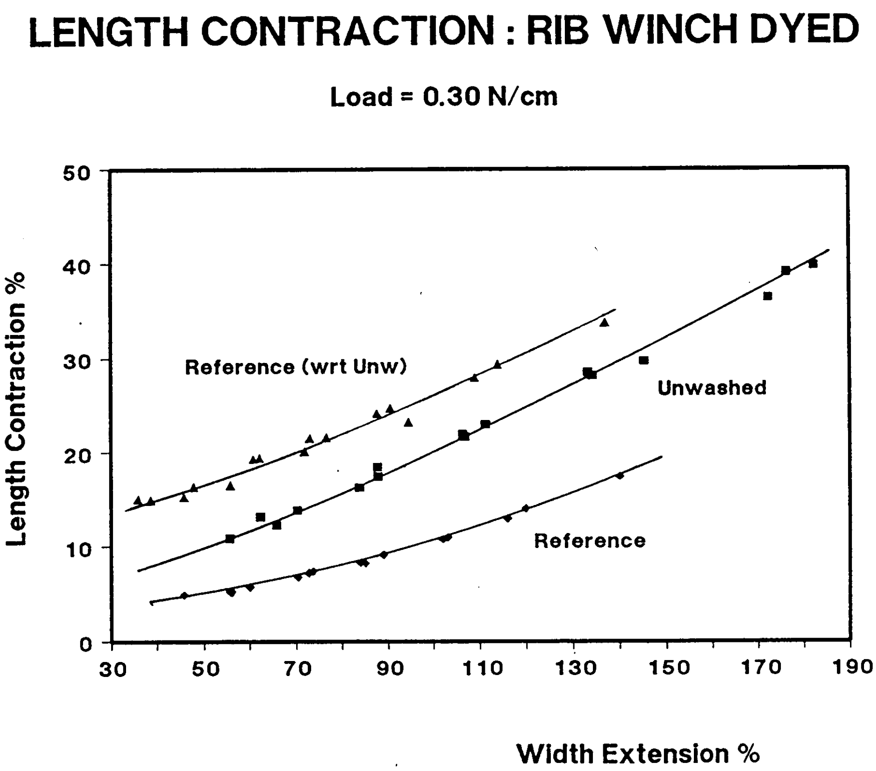


Figure 15

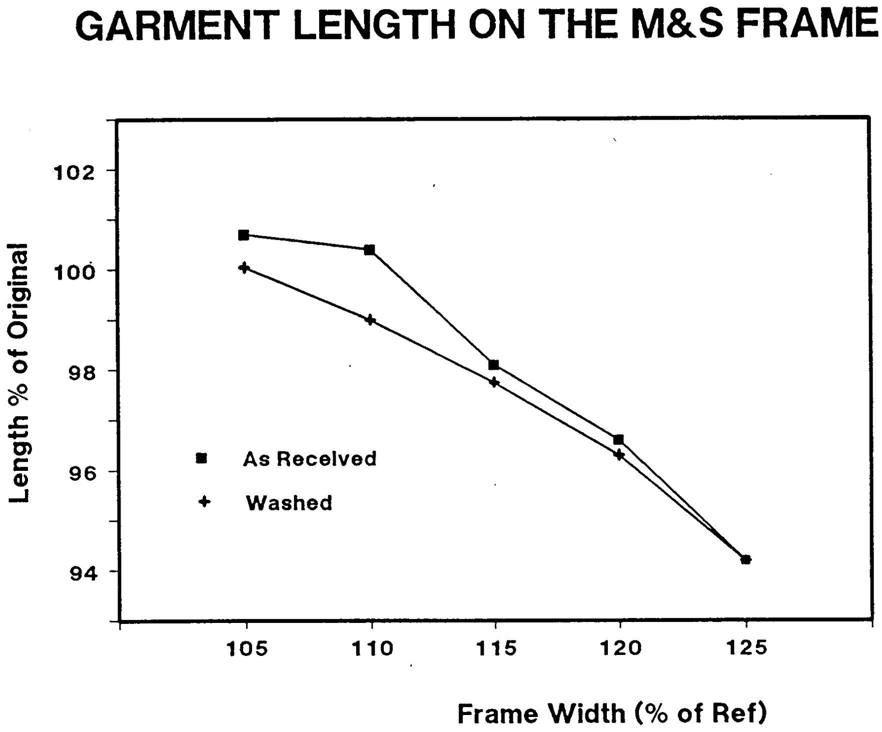


Figure 16

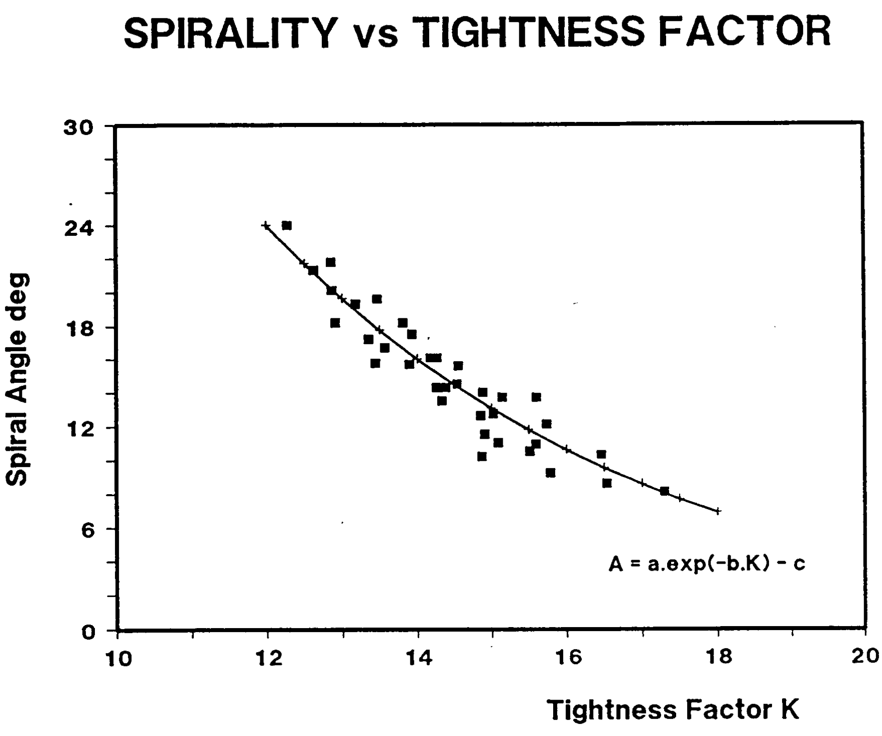


Figure 17

SPIRALITY : PLAIN JERSEY JET DYED

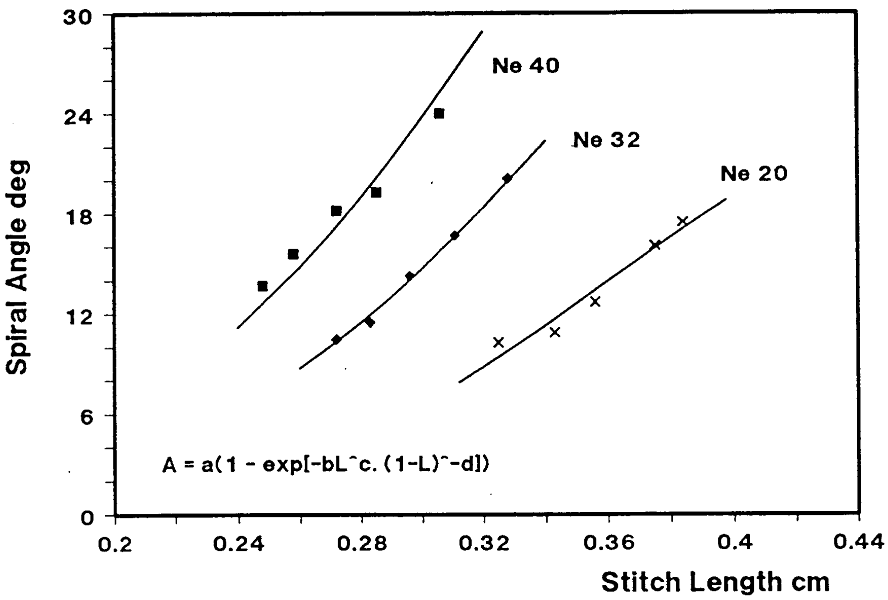
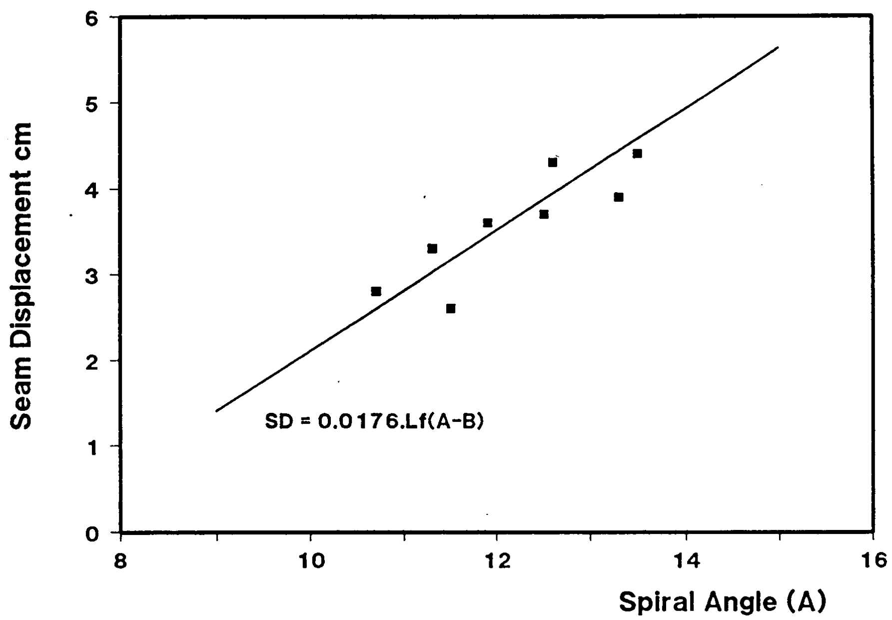


Figure 18

SEAM DISPLACEMENT vs SPIRALITY



Using STARFISH to Calculate for Broad Rib Constructions

Rib fabrics can be seen a mixture of plain jersey and 1x1 rib. In order to make (approximate) predictions for broad ribs, it is first necessary to determine the proportions of plain and rib stitches in the construction, and then to make a weighted average of the appropriate plain jersey and 1x1 rib fabrics.

Several STARFISH users have found that successful predictions for 2 by 2 rib can be made, by assuming that this construction is a 50 / 50 mix of plain jersey and 1x1 rib, with an appropriate adjustment for the number of needles actually active. The following is an attempt to generalise that finding for broad ribs. Note that it is an entirely theoretical construct, which has not been properly tested against real fabrics.

The general rule is:
Whenever knitting changes from cylinder to dial, or from dial to cylinder, there is one rib stitch and one plain stitch, requiring two needles - one on the cylinder and one on the dial (each of these two needles can be visualised as knitting half plain and half rib). The remaining stitches are all plain, each requiring only one needle, either on the cylinder or on the dial. Therefore, in an N by M pattern repeat, there are always two rib stitches and N + M - 2 plain stitches.

For example, consider an 8 by 4 rib. If you draw the construction on paper, you will see that it consists of:

(8 + 4 - 2) = 10 plain stitches, plus 2 rib stitches.

Thus the proportion of plain fabric is 10 / 12 and the proportion of rib is 2 / 12.

Generally, for an N by M rib,

the proportion of plain fabric will always be (N + M - 2) / (N + M),

the proportion of rib fabric will always be 2 / (N + M).

Presumably, this reasoning can be extrapolated to analyse more complicated rib patterns.

Having decided on the proportions, we can then make separate STARFISH predictions for the plain and the 1x1 rib fabrics, using the same stitch lengths, then combine the results according to the calculated proportions. Once again, we have to remember that the answer will be only approximate.

Here is the calculation for an 8 by 4 rib, using Ne30 combed ring yarn on an 18g, 30" machine with 1692 needles, at a stitch length of 2.778. The STARFISH predictions are made for a shrinkage of 6 x 6%, when the wet process route is jet dye (mid tension) to a medium shade.

	Courses /cm	Wales /cm	Width cm tub	Weight gsm
Plain Jersey	19.08	14.45	58.5	144.8
1x1 Rib	17.65	10.97	77.1	203.4
Proportional mix	18.60	13.29	64.7	164.3

There is one potentially serious problem with this calculation, which needs to be mentioned. This is the fact that the plain portions of fabric do not lie flat - they tend to bow out of the fabric.

Face ribs will bow in the opposite direction to back ribs. This enhances the ribbed effect of the fabric and is considered an advantage from the aesthetic point of view.

On the other hand, the STARFISH prediction refers to a perfectly flat fabric. The practical consequence of this effect is that, after relaxation (and maybe especially after laundering), the fabric width will actually be significantly less than when the fabric is pressed flat. It may well be found that the width of the fabric relaxes quite a bit between the finishing plant and the laying-up table. We have no way of knowing in advance what will be the size of this effect, because it depends on several factors - including the count and twist of the yarn, and the tightness factor of the fabric, as well as the width of the ribs.

The effect will, of course, affect the weight of the fabric after relaxation: it will be heavier than expected.

Another potential problem is the course density. For a 2 by 2 rib, it seems reasonable to assume that the course density will be midway between those of the plain and 1x1 rib structures. For a broad rib, however, it is easy to imagine that the course density will be more strongly affected by the plain structure, than is given by a simple proportional mix.

This effect would cause a slight increase in the course density and the weight. However, if such an effect exists, it is not expected to be very large.

Using STARFISH to develop Needle-out Interlock Constructions

Needle-out interlock fabrics are made by taking a certain number of needles out of action, either on the cylinder or the dial, at regular intervals. One side of the fabric looks like plain interlock, but the other side has vertical stripes at regular intervals. In the simplest case, there are X needles knitting normally on both cylinder and dial, alternating with Y needles inactive on one or other side, and the pattern repeat is over X+Y needles.

The effect of taking needles out, either on the cylinder or the dial, is to alter the average loop length for a given course length. The dimensions of the fabric are determined by the length of yarn *in each loop*. The miss stitches do not affect the fabric dimensions but they do contribute to the total length of yarn in a course. Therefore, the solution to the design problem is to be able to estimate the proportion of the total course length that is provided only by miss stitches.

The following line of reasoning has proved useful for a simple X + Y pattern. More complicated patterns can be simulated by appropriate modification of the same reasoning. Solutions will be approximate, and final decisions should be taken only after appropriate confirmation trials.

Let X be the number of wales that are knitted plain
Let Y be the number of wales in the needle-out zone
Then W = X + Y, the total number of Wales per repeat.

Let K be the number of Knit stitches per repeat.
Let M be the number of Miss stitches per repeat.
Then S = K + M, the total number of Stitches per repeat.

Note that K, M, and S can be divided by a common factor, to reduce the size of the numbers whilst preserving the proportions. Also, for a simple pattern, the repeat is over two courses, and S = 2 x W.

Let Lk be the length of the knitted loops.
Let Lm be the length of the miss stitches.
Let L be the average stitch length (course length / No of needles).

If you draw one repeat of the construction (two courses for a simple pattern) on paper you will see that, in every W wales, there are (2X + Y) knit stitches and Y miss stitches. For example, in a 10 by 5 pattern, there will be 25 loops and 5 misses over the two courses. Thus K = 25, M = 5, and S = 30. This can be reduced to K = 5, M = 1 and S = 6.

In order to calculate the average length of the knit loops, we need to know the length of yarn taken by a miss.

The length of yarn in a miss stitch must be approximately the same as the width of a wale, in the Reference State. The width of a wale is the inverse of the number of wales per cm.

We can calculate the approximate number of wales per cm using STARFISH, by using the average (uncorrected) stitch length. The average stitch length is the course length divided by the number of needles. All cylinder needles are included in this calculation, including the inactive ones, if any. For example, a course length of 640 cm, on an 1872 needle machine yields an average stitch length of L = 3.419 mm. If the yarn is Ne 30 single combed ring and the wet process is winch-jet medium tension (pastel), then STARFISH predicts 15.9 wales per cm. Therefore, the width of each wale is 1/15.9 = 0.0629 cm, or 0.629 mm.

We can now set up the following equation, based on the fact that the course length is equal to the sum of the lengths of the knit loops and the lengths of the miss loops.

$$(K \times Lk) + (M \times Lm) = S \times L$$

i.e. Lk = [(S x L) - (M x Lm)] / K

or (5 x Lk) + (1 x 0.629) = 6 x 3.419

i.e. Lk = [(6 x 3.419) - (1 x 0.629) / 5

The solution to this equation is Lk = 3.977.

Therefore, we use a stitch length of 3.977 mm in STARFISH to find the finishing targets when the actual average stitch length knitted is 3.419 mm.

The result will not be quite correct, because of the approximation that we used to estimate the length of a miss. A closer approximation can be obtained by using the width of a wale calculated by STARFISH for a stitch length of 3.977 mm. We then go through the same calculation again to get a slightly better approximation for Lk. However, the difference is very small so it may not be worth the effort.

In general.

Once we know the ratio Lk/L for a given needle-out pattern, then we can use STARFISH in the normal way to make predictions for plain interlock. When a satisfactory stitch length has been found, then we simply divide it by Lk/L to find the average stitch length that should be knitted for the needle-out pattern. Multiplication by the number of needles gives the corresponding course length for controlling production.