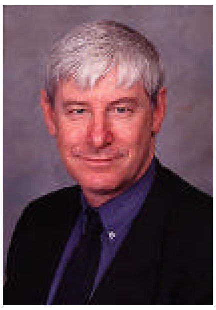

OBJECTIVE MEASUREMENTS – MORE THAN PRETTY NUMBERS

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WORKING WITH WOOL SEMINAR
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Objective measurement is now an integral part of the preparation, marketing and processing of wool produced in Australia, New Zealand and South Africa. Following the recent establishment of a modern independent commercial laboratory in Argentina objective measurement is beginning to assume a similar importance South America.

The wool industry now has a number of objective measurements defining a wide range of characteristics of raw and processed wool, which are supported by internationally recognised Standard Test Methods. These include

- Yield and Vegetable Matter
- Diameter and Coefficient of Variation in Diameter
- Staple Length, Strength and Position of Break
- Clean Colour
- Hauteur

Objective measurements are indeed more than pretty numbers. They are progressively supplanting subjective assessment of raw wool characteristics, subjective determination of raw wool value and subjective prediction of raw wool processing performance. Most of the measurements now utilised have been available for many years. However much still remains to be done to ensure that the quantitative information they provide is effectively utilised to reduce costs and improve quality at all stages in the production, marketing and processing of wool fibre. Understanding of the measurements, and of their limitations, by all players in the industry, is essential if this is to occur. Furthermore, opportunities still remain for existing measurement systems to be improved and new measurement systems to be developed. Over the last 15 years new technologies have emerged, providing new improved ways for measuring some characteristics of wool fibres. At the same time in some cases these technologies offer further exciting possibilities for quantifying characteristics which are still subjectively assessed.

The down side of all this activity is alternative instruments, based on very different physical principles now exist for measuring ostensibly the same characteristics of wool fibre. Fibre fineness and fibre curvature are two examples of where this has occurred. Differences in the values provided by these instruments are being observed. Reconciling these differences, without undermining commercial confidence, presents a new challenge for the industry.

The intention of this paper is to describe where the real value of objective measurements to the wool industry may be (or in some cases, has been) discovered. It also aims to provide a framework for better understanding the basis of objective measurement and thereby a framework for reconciling conflicts when they occur. Two case studies are presented to illustrate the points that are made. The first example involves the measurement of fibre fineness. The second example involves the measurement of fibre curvature.

Defining Quality – the Real Value of Measurement

It is essential that raw materials, products and services meet the requirements of those who use them. This **fitness for use** defines the quality of the raw materials, products or services. There are two general aspects of quality: **quality of design** and **quality of conformance**.

Goods and services are generally produced in various grades or levels of quality. These variations are often intentional, and consequently the appropriate technical term in such instances is quality of design. For example, wool suits serve the same basic function, but they are available in a range of designs, fabrics and prices, aimed at specific market segments.

On the other hand, quality of conformance is how well the product conforms to the specifications and tolerances required by the design. Quality of conformance is influenced by a number of factors. In the case of wool suits these may include the following:

- Variability of the raw wool,
- Choice of the manufacturing processes,
- Operation of these processes,
- Training and supervision of the work force,
- Type of quality-assurance system (process controls, tests, inspection activities etc),
- Extent to which these quality assurance systems are followed, and
- Motivation of the workforce to achieve quality.

Every product, including wool, possesses a number of elements that jointly describe its fitness for use. These elements are often called **quality characteristics**. Quality characteristics may be of several types, for example:

1. **Physical:** length, weight, fineness, and yarn evenness.
2. **Sensory:** handle, feel, appearance, and colour.
3. **Time Orientation:** reliability, durability, and serviceability.

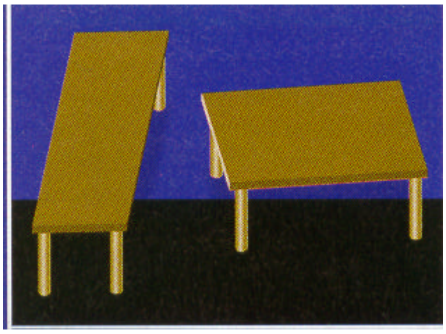

Figure 1: Fooling the eye. Subjective judgements are prone to error. One table seems more elongated than the other - but their dimensions are in fact identical!

Most organisations find it difficult (and expensive) to provide the customer with products that have flawless quality characteristics. A major reason for this difficulty is **variability**. There is a certain amount of variability in any product and consequently two products can never be identical. Wool is an extremely variable product, more so than most. It varies along the fibre, between fibres, between staples, between animals, between mobs, between bloodlines and between regions. However, if the wool industry wishes to improve quality and reduce overall cost it must find ways of restricting or controlling the impact of this inherent variability of the fibre on the quality of finished textile products.

Quality characteristics can be estimated subjectively, or they can be assigned a numerical value using objective measurements. **With few exceptions, objective measurements will always be more precise than subjective estimates**. Figure 1 illustrates how easily subjective visual judgements can be confused by errors in perception[1]. Subjective assessment of the quality characteristics of wool is equally error prone.

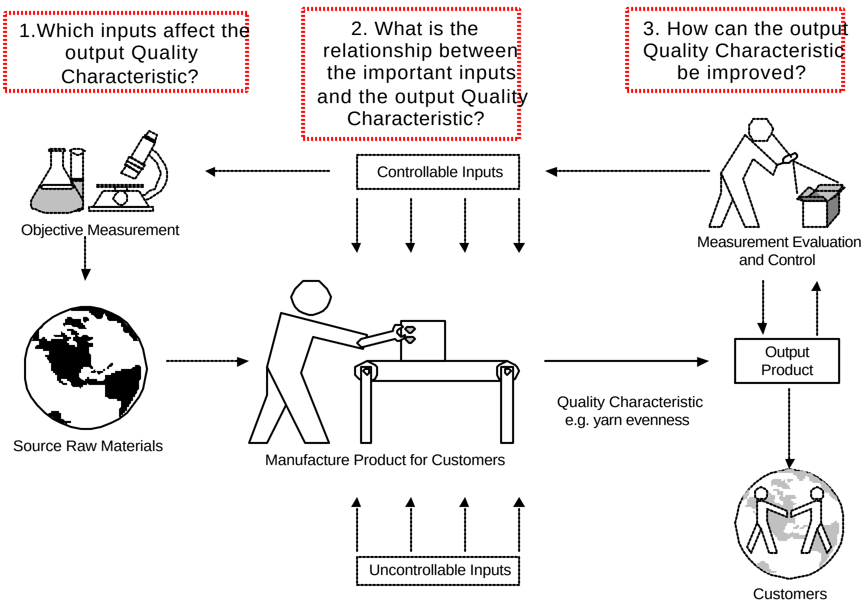

Figure 2: Schematic representation of the value of measurement in improving process quality. In this illustration, measurement is seen as a part of a continuous cycle of process improvement.

[1] Bob Holmes, *Irresistible Illusions*, New Scientist, No. 2150, 37, 5th September, 1998

It is now well accepted that there is also a direct link between quality improvement and productivity through reduction of waste and rework. Objective measurement of quality characteristics of raw and processed wool provides the only reliable mechanism for minimising variation, for monitoring quality improvement, and thereby improving productivity and reducing costs.

The cycle this involves is illustrated in Figure 2. One of the problems faced by the wool industry is that the predominant application of raw wool measurements has been in a trading context, not in a processing context. While this is necessary, it is not sufficient in itself, as is illustrated in Figure 2, for the industry to derive the maximum benefit from the measurements.

Essential Elements of Measurement Systems

The primary requirement of any measurement system is that the parameter to be measured is clearly defined. The converse of this is that frequently the measurement system itself defines the parameter being measured. This is not a contradiction. We do not live in a perfect world and frequently compromise is necessary. Unfortunately, the latter instance lends itself to circumstances where different measurement systems can be developed (and frequently are) which purport to measure the same quality characteristic, but provide quite different “pretty numbers”. Usually this is not a problem of measurement – it is a problem of definition of the property being measured.

A good illustration of this is provided by the water industry. An important quality characteristic for water supplies is turbidity. Turbidity is defined as the opacity of a column of water. It is a consequence of suspended mineral or organic material scattering light as it passes through the fluid. Before the advent of electronics it was measured using a candle turbidimeter, as illustrated in Figure 3.

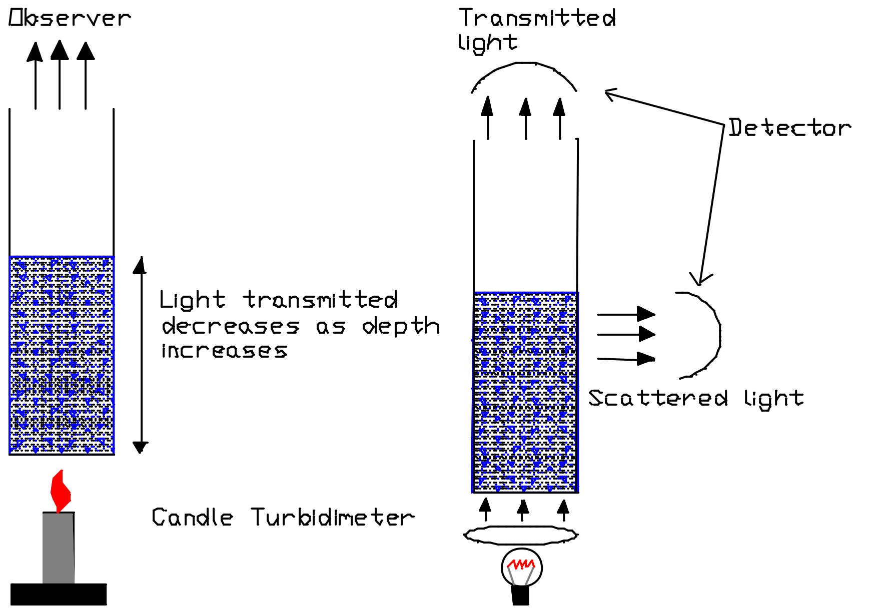

Figure 3: The measurement of turbidity in water was originally defined by the candle turbidimeter, illustrated on the left. With the development of electronics new instruments emerged, based on either the transmission of light through a column of water, or the amount of light scattered at an angle of 90 degrees. The diagram on the right illustrates this.

The candle turbidimeter operates on a very simple principle. A candle, with constant luminescence is placed underneath a tall cylinder, and a sample of water is poured into the cylinder until the light from the candle is just extinguished. The height of the column of water is then measured. The instrument is calibrated using suspensions of clay (“fuller’s earth”), where the density of the clay suspension (milligrams/litre) is known. The water industry is primarily interested in very low levels of turbidity. One aim of water treatment is to remove suspended solids. Understandably then, the candle turbidimeter is a somewhat clumsy instrument, the water cylinder needing to be quite high to achieve the sensitivity required.

Electronic instruments are now available using electric light sources and optical detectors to replace the candle and the human eye. These come in two variants – the first detects the light transmitted though the sample and the other detects the light scattered at 90 degrees[2]. The depth of the liquid (or the path length of the light) is maintained constant. These machines can also be calibrated using fuller's earth, but technology being what it is, the practice now is to use an organic polymer, which produces highly reproducible colloidal dispersions, as calibration standards.

It should not be surprising that measurements on the same sample are not the same for these instruments, even when the same calibrating system is used. **The reason for the difference is the simple fact that each of these instruments defines turbidity in a different way**. Even the candle turbidimeter and the electronic instrument measuring the transmitted light are different, although on first sight it seems reasonable to assume they would be very similar. The reason why the water industry can cope with these differences is very simple. The water industry is interested in very low units of turbidity (<5) and below this level the instruments are reasonably close. However, as the turbidity increases the divergence also rapidly increases. Again, for routine monitoring, or for regulatory (or trading) purposes such divergences are also not a problem, providing the instrumentation and calibration systems employed are clearly nominated. It is for this reason that all industries develop Standard Test Methods for measuring quality characteristics of their products and raw materials. Without Standard Test Methods there can be no certainty in the numbers produced, particularly where the measurements are conducted and compared between different facilities or over a period of time.

A further point needs to be fully understood. Science defines systems that measure a particular characteristic by direct reference to primary reference standards such as length or weight, as **primary systems**. Systems that measure the same characteristic, but require calibration by reference to a primary system are **secondary systems**. These distinctions are important because instruments based on primary systems should be expected to give the same answers, whereas instruments based on secondary systems may not, particularly if they define the quality characteristic in a different way.

An additional and essential requirement for any measurement system is that its **accuracy** and **precision** can also be defined. These terms are frequently confused. Accuracy refers to the closeness of the measurements to the "true" value. **Accuracy must always be determined by reference to a primary system**. Precision refers to the reproducibility of the measurements. However, precision does not need to be determined by reference to a primary system. One function of Standard Test Methods is to ensure that the precision and accuracy of the method are clearly defined so that comparisons between measurements can be made with predictable certainty irrespective of where or when the measurements are made.

Ideally, the accuracy and the precision of any measurement system will be identical, but frequently they are not. It is quite possible to have a very precise secondary measurement system (the answers are highly reproducible), which differs consistently from the "true" value. This does not limit its usefulness, **provided it is used in all instances where comparisons must be made**. However, without a primary system against which a secondary system can be calibrated, there is always a risk that the values provided by a secondary system will not be consistent when determined by different facilities or over a period of time.

When measurement systems are developed, two competing factors must also be reconciled. The measurement system must have an acceptable accuracy and precision (fit for use), but also deliver measurements at an acceptable cost. Increasing accuracy and precision invariably implies increasing the cost.

The suite of objective measurements currently available for wool is quite large. The International Wool Textile Organisation has developed 42 different Standard Test Specifications and has 13 Draft Specifications under development. These provide objective measurements for a range of quality characteristics for greasy wool, scoured wool, wool top, and wool yarn. In addition to this the Textile Industry as a whole has a large number of methods for evaluating different quality characteristics of finished fabrics. Quite clearly, for the wool industry, objective measurements provide much more than simply pretty numbers.

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[2] These were not the only variants. Other instruments were developed for in-process continuous measurement, but for simplicity these will not be discussed here.

CASE 1 – WOOL FIBRE FINENESS

The fineness[3] of wool fibres is of fundamental importance to spinners and weavers. The finer the fibres, and the fewer the number of fibres present in a cross section of yarn produced from the fibres, the more flexible the yarn. These factors are the major determinants of the quality of wool fabrics. It is desirable therefore, that the different instruments now available to measure wool fibre fineness provide equivalent answers. Nevertheless differences exist between these instruments. From the preceding discussion it can be appreciated that there are fundamental reasons why these differences exist and why it is most unlikely that in every instance they will ever be totally resolved. At the same time, once the measurement is understood, the small differences that do exist in no way in themselves limit the usefulness of these instruments or reduce the validity of the measurements they produce.

Defining Wool Fibre Fineness

Fibre fineness is a relative term, and therefore somewhat subjective. Numerically quantifying fibre fineness requires the measurement of a particular geometrical dimension of the fibre. In the case of wool fibres this is not as simple as it may at first seem.

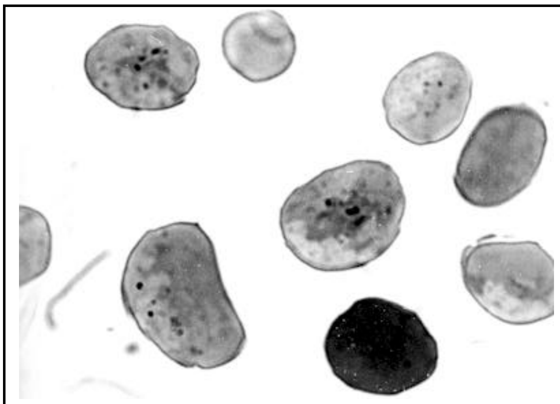

Figure 4: Magnified images of the cross sections of a number of wool fibres from a 19 micron top [4].

Most of us have an intuitive understanding of the meaning of "mean diameter" in referring to a length of pipe, because we imagine that a pipe is circular. Indeed if each fibre of wool had an exactly circular transverse cross section, and the diameter of this circular cross section was exactly the same along the length of the fibre, then this uniform geometry would make the definition of the fineness of wool exceedingly simple. But wool fibres are neither circular in cross section, nor of uniform thickness along their length.

Figure 4 clearly illustrates this point. It shows the magnified transverse cross sections of a number of wool fibres from a 19-micron wool top. While some fibre cross sections are approximately circular, most of them are not.

Consider these fibre cross sections, and the range of shapes exhibited. How then do we determine the Mean Fibre Diameter? Clearly, if we use a ruler to measure the "diameter" of these images, the "diameter" we obtain for each image will depend where we place the ruler. We could of course use our ruler to measure a very large number of transects across each fibre cross section, and then calculate the average of all these transects, but that would be unbelievably tiresome. And in doing so, we would not have taken account of any variation in the dimensions of the cross section along the length of each fibre. We could only do this by taking a very large number of cross sections and making a large number of measurements – an even more tedious exercise.

Alternatively, we could define the fibre fineness in terms of the area of the cross section. This could be measured using a primary system such as planimetry or a related technique. Once again, the measurement would be slow and tedious because many cross sections would have to be measured to obtain a reasonable estimate of the "area" or fineness of each fibre, and thus the average fineness of the sample.

If fibre fineness is to be objectively measured any definition of fibre fineness must ultimately be related to some geometrical dimension of the fibre. There are effectively only four geometrical dimensions that are suitable. These are:

- the area of the cross section;
- the width of a 2-dimensional projected image;
- the area of the surface; or
- the area of a 2-dimensional projected image.

[3] The term "Mean Fibre Diameter" in the context of wool fibres is a little misleading, since it implies that wool fibres have a circular cross section. In describing the thickness or thinness of wool fibres it is more accurate to use the term "fibre fineness" rather than "fibre diameter". The word "fineness" does not imply any particular geometry for the shape of the cross section.
[4] Photograph provided by Peter Turner, CSIRO Division of Wool Technology, Belmont, Victoria, Australia

Due to the non-uniform geometry of wool fibres a meaningful estimate of fibre fineness requires a large number of measurements of any one of these geometrical features.

Measuring Wool Fibre Fineness

Over the past 175 years a number of different techniques have been explored, with varying degrees of success, in order to provide an objective numerical description of the fineness of wool fibres. The International Wool Textile Organisation (IWTO) has developed Specifications for only 4 of these techniques.

- Projection Microscope
- Airflow
- Sirolan LASERSCAN
- OFDA (Optical Fibre Diameter Analyser)

Only the Projection Microscope is traceable to primary reference standards. In simple terms this means that the Projection Microscope is calibrated by reference to units of length, not by reference to "standard wools". On the other hand, Airflow, LASERSCAN and OFDA **must** be calibrated using "standard wools", where the "standard values" for these "standard wools" have initially been determined by Projection Microscope. In this sense the Projection Microscope is the primary system, and the others are secondary systems.

All these instruments provide a measurement of Mean Fibre Diameter (MFD) or "fineness". With the exception of the Airflow, they also provide information about the distribution of fibre fineness, from which we can derive the Standard Deviation (SD) and the Coefficient of Variation in Diameter (CVD).

The advantage of the calibrated systems is that the variability between instruments is considerably less than the variability between operators of the Projection Microscope. Therefore they can actually provide more precise measurements at a lower cost.

Comparison of the Instruments

Most us are aware that duplicate measurements of fibre fineness on the same sample will probably be different, irrespective of the instrument used. The difference arises predominantly from the variability of the fibre, but is confounded by other sources of variation in the measurement system. The objective of IWTO Specifications is to contain these sources of variation within an acceptable and predictable range, while at the same time providing the measurement at an acceptable cost.

Table 1: Precision of the Instruments used for determining the Fineness of Wool Fibres.

Instrument	Precision (95% Confidence Level)	
	20 µm	35 µm
Projection Microscope	± 0.87 µm	± 1.07 µm
Airflow	± 0.45 µm	± 0.80 µm
OFDA	± 0.36 µm	± 0.67 µm
LASERSCAN	± 0.32 µm	± 0.70 µm

The precision limits of the IWTO Specifications for determination of MFD of raw wool by Projection Microscope[5], Airflow[6], OFDA[7] and LASERSCAN[8] are summarised in Table 1. The Projection Microscope is the least precise, while the OFDA and the LASERSCAN are the most precise. These precision limits can be substantially reduced, at a cost, by measuring more than one sample. For example, testing duplicate samples will improve the precision by 29%, and testing triplicate samples will improve the precision by 42%. The question of how much precision is enough is fundamentally an economic rather than a technical decision. The development of the IWTO Specifications has primarily been aimed at improving prediction of processing performance, and thereby facilitating the purchasing and trading of wool. Given that most processing consignments consist of a number of individual farm lots, the precision of the average MFD for such consignments is substantially better than indicated by the limits in Table 1.

[5] IWTO-8-89, *Method for Determining Fibre Diameter and Percentage of Medullated Fibres in Wool and other Animal Fibres by the Projection Microscope*
[6] IWTO-28-93, *Determination by the Airflow Method of the Mean Fibre Diameter of Core Samples of Raw Wool*
[7] IWTO-47-95, *Measurement of the Mean and Distribution of Fibre Diameter of Wool using an Optical Fibre Diameter Analyser*

Our major concern should be whether or not there are systematic differences or biases between the instruments. Here we must consider both tops and raw wool.

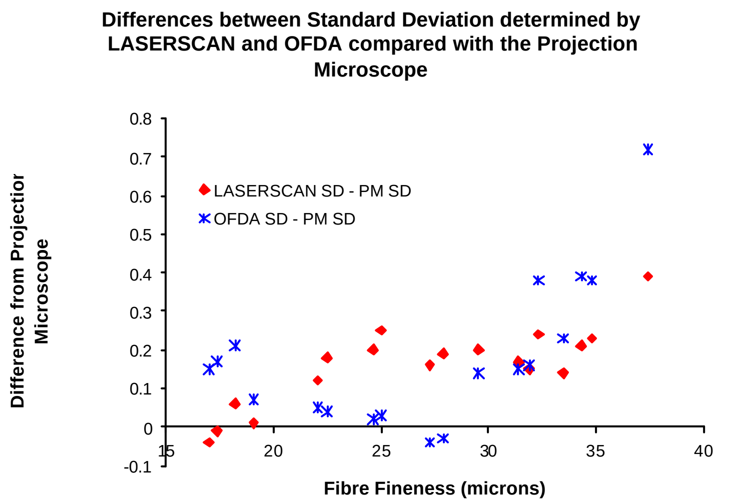

Figure 5: The Standard Deviation measured by OFDA and LASERSCAN differs systematically from the values determined by Projection Microscope. However, as shown in the above diagram they do not vary in the same way.

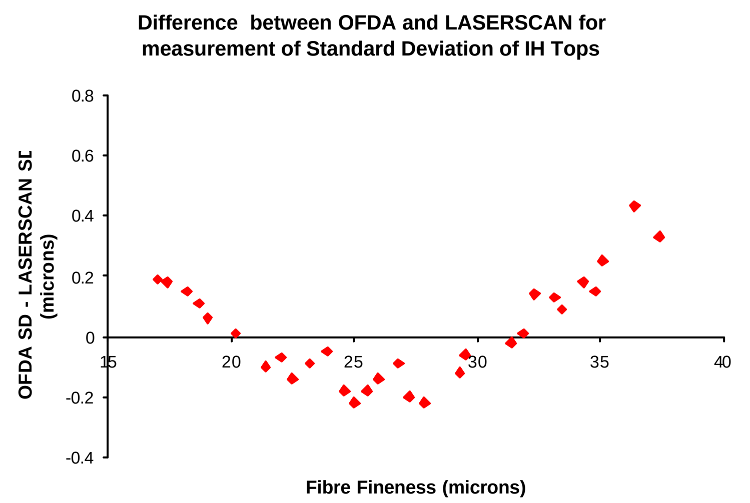

Figure 6: The difference between Standard Deviation measured by OFDA and LASERSCAN is non-linear but systematic. The above diagram demonstrates this difference for tops, but a very similar pattern is observed for raw wool.

Measurement of Tops

When measuring MFD of Interwoollabs standard tops Airflow, LASERSCAN and OFDA are generally in close agreement with the assigned values of the tops (as determined by Projection Microscope)[9]. Given that Airflow, OFDA and LASERSCAN are calibrated using the Interwoollabs tops this is hardly surprising, and were it not so it would be cause for great concern. The observed variation between the instruments for these tops is generally within the precision limits of the particular IWTO Specification involved. As expected, the variation is greatest for coarser wools (above 28 microns). Analysis of more recent round trials has confirmed these observations[10].

However, when measuring SD of the same tops both OFDA and LASERSCAN exhibit systematic fineness dependent differences from the assigned Projection Microscope values (see Figure 5). In the case of LASERSCAN, the measured SD tends to be higher than the assigned SD and the difference increases with increasing coarseness. In the case of OFDA the behaviour is more complex. Values from OFDA measurements tend to be higher for both coarser and finer wools, and approach the Projection Microscope values for the medium wools.

These differences become even more apparent when the OFDA and LASERSCAN values for SD are compared directly. In Figure 6 this comparison is expressed in terms of the difference between the two instruments.

Measurement of Raw Wool

There are inherent difficulties in obtaining accurate estimates of diameter and distribution characteristics of raw wool using the Projection Microscope. As a result there is little information available to compare the Projection Microscope with Airflow, LASERSCAN and OFDA in this instance. There is however a large body of information comparing Airflow, LASERSCAN and OFDA for the measurement of MFD on such wools.

[8] IWTO-12-95, *Measurement of the Mean and Distribution of Fibre Diameter using the Sirolan-LASERSCAN Fibre Diameter Analyser*

[9] H. Harig, *Report of the 1995 IWTO Round Trial, Part II: Wool Tops*, IWTO Technology & Standards Committee, Report No. 16, Harrogate, 1995

[10] J. W. Marler & H. Harig, *A Comparison of Diameter Measurement Technologies fom Interwoollabs International Round Trials for Wool Tops*, IWTO Technology & Standards Committee, Report No. 10, Dresden, 1998

Some early trials provided some evidence that there are small systematic biases between the Airflow and both OFDA and LASERSCAN[11,12]. Stronger evidence of these differences has been recently published for a trial involving 2500 farm lots in New Zealand[13]. This information shows that the LASERSCAN, at least on these wools, provides a higher value for MFD than the Airflow. The comparison with OFDA is more complex. However, in either case about 70% of the observed variation is attributable to medullation. A smaller proportion is attributable to CVD. Despite this, significant unexplained differences remain.

It has also been shown that the SD differences between OFDA and LASERSCAN, illustrated so graphically in Figure 6, also occur for raw wool[11,14].

Measurement of Superfine and Ultra-fine Wool

While the quantities of superfine and ultra-fine wool are not large they are commercially and technically very important. Quite large differences in MFD between Airflow, OFDA and LASERSCAN have been reported for these wools in Australia[15]. The observed differences are shown in Figure 7. Above 15.5 microns, both LASERSCAN (using the calibration prior to 1997) and OFDA are broader than Airflow, with the difference decreasing as the fineness decreases. Below 15.5 microns, OFDA becomes increasingly finer than Airflow, with LASERCAN remaining broader. The increasing difference between LASERSCAN and OFDA as the fineness decreases is due to the OFDA reporting a larger number of very fine fibres (<10-12 microns) than the LASERSCAN.

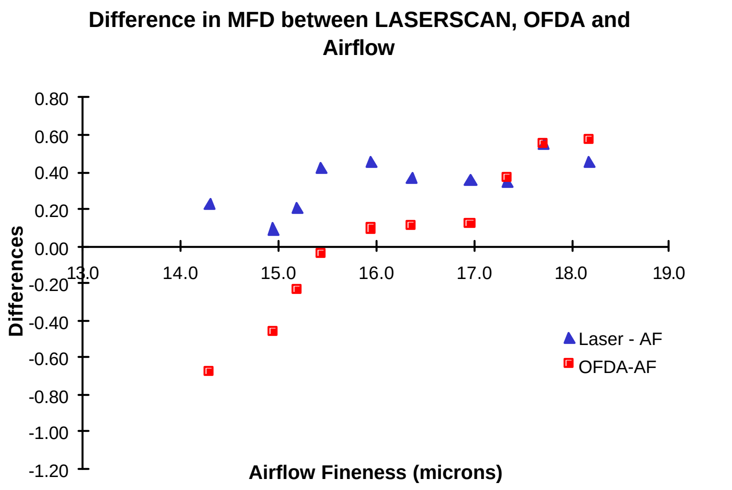

Figure 7: Comparison of LASERSCAN and OFDA with Airflow for Australian superfine wool. The illustration shows the differences between the instruments, using the Airflow as the reference point.

A new calibration function for the LASERSCAN was introduced in 1997[16]. This has little effect above 17 microns, but reduces the difference between LASERSCAN and Airflow for finer wools. Recent work on New Zealand superfine wools[17] has indicated that between 15.5 and 17.0 microns there is now no difference between LASERSCAN and Airflow. However, some very recent measurements on Australian superfine wool[18], using the new calibration, have shown that the trends illustrated in Figure 4 still exist, although the LASERSCAN is now finer than Airflow below 15.5 microns (see Figure 8). It is now closer to, but still coarser than OFDA, for these superfine wools.

Significant differences in SD between LASERSCAN and OFDA are also observed for superfine wools. Invariably OFDA gives a higher SD. The differences between the two instruments increase with decreasing fineness. The new calibration function for the LASERSCAN has reduced these differences for wools finer than 16.0 microns.

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[11] H. Harig, *Report of the 1995 IWTO Round Trial, Part I: Raw Wool*, IWTO Technology & Standards Committee, Report No. 15, Harrogate, 1995

[12] K. Baird, R.G Barry & J. W. Marler, *Comparison of Mean Fibre Diameter Measurements by Airflow and LASERSCAN for a Wide Range of Wool Types*, IWTO Technology & Standards Committee, Report No. 7, Nice,1994,

[13] D. G. Knowles, P. R. Greatorex and G. V. Barker, *Comparison of IWTO Test Methods for Fibre Diameter Measurement of the New Zealand Wool Clip – Part 1: Mean Fibre Diameter*, IWTO Technology & Standards Committee, Report No. 12, Dresden, 1998

[14] D. G. Knowles, P. R. Greatorex and G. V. Barker, *Comparison of IWTO Test Methods for Fibre Diameter Measurement of the New Zealand Wool Clip – Part 2: Fibre Diameter Variability*, IWTO Technology & Standards Committee, Report No. 13, Dresden, 1998

[15] P. J. Sommerville, *Measurement of the Fineness of Superfine Wool: A Comparison of Airflow, LASERSCAN and OFDA*, IWTO Technology & Standards Committee, Report No.15, Boston, 1997

[16] P. A. Irvine & R. G. Barry, *An Improved Calibration Model for the Sirolan LASERSCAN*, IWTO Technology & Standards Committee, Report No. 16, Nice 1997.

[17] D. G. Knowles, *Investigation into Mean Diameter Instrument Differences in the Measurement of New Zealand Superfine Wool*, IWTO Technology & Standards Committee, Dresden, 1998.

[18] P J Sommerville, Unpublished data, June 1998

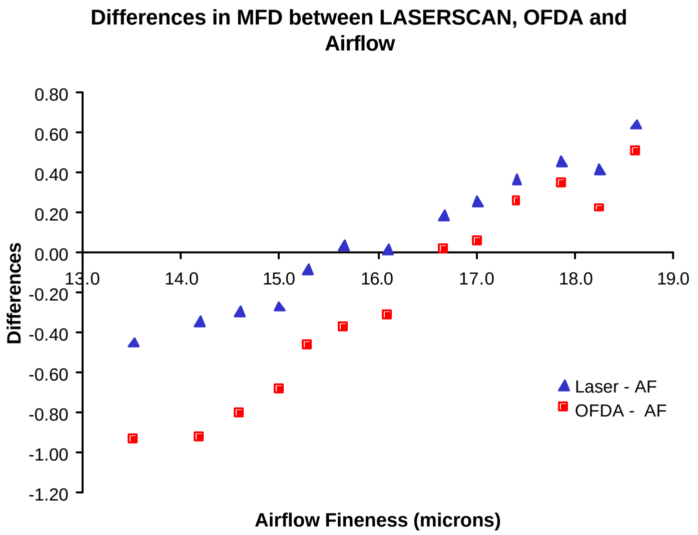

Figure 8: Comparison of LASERSCAN and OFDA with Airflow for Australian superfine wool, using the new calibration function for LASERSCAN introduced in 1997. As in Figure 7 the Airflow is used as the reference point.

Reconciling the Differences

Each of these instruments uses different geometric definitions of fibre fineness. This is a fundamental difference, which must result in differences being observed for certain wools, particularly where the characteristics of the wools differ in some way from the calibration wools[19] and/or the fibre fineness is outside the range of the calibration wools.

The Projection Microscope measures the average width of the two-dimensional projected image. The OFDA attempts to emulate this by using a television camera to replace the human eye, and a computer program to replace the human hand and the human brain. Nevertheless, the **OFDA is not an exact replica of the projection Microscope**. There are fundamental differences in the measurement techniques employed, and the assumptions made. On the other hand the Airflow responds to the surface area of a bulk sample of fibres, while the LASERSCAN responds to the projected area of a segment of each fibre.

One may well ask which instrument provides the “true” result? Given that the Projection Microscope is the industry accepted primary measurement system for determining the fineness of wool fibres, the extent to which a particular instrument emulates the Projection Microscope must be the criterion that is used to determine whether or not a particular instrument provides the “true” answer. To do otherwise would require the wool industry to change the definition of fibre fineness that has been in place for over 50 years. The reality is that none of the calibrated instruments exactly emulate the Projection Microscope in all instances, but for a wide range of wool types the correspondence is very close.

For more than 25 years the Airflow, rather than the Projection Microscope, has been the industry’s accepted baseline for commercial and technical evaluation of wool fibre fineness. This has been in the full knowledge that the Airflow does not closely emulate the Projection Microscope in all instances[17]. This clearly demonstrates that for the wool industry the “true” answer is not the primary criterion for establishing the usefulness of a specification for fibre fineness. The cost, the precision and the predictability of processing performance, coupled with an understanding of the discrepancies that may occur in particular circumstances, are far more important.

If this is the case, then with respect to precision, there is no particular technical reason to favour Airflow, LASERSCAN or OFDA for the specification of MFD for most commercial consignments of wool. What is more important is that the same specification is used to determine fibre fineness for any individual consignment at all points in the production, marketing and processing pipeline. If this is not done then the industry must be prepared to make judgements about any differences that are observed in the light of knowledge about the differences that may occur.

This approach is also entirely appropriate for Wool Growers who chose to use objective information to assist them in improving the productivity of their flocks. For this particular application all the calibrated instruments are sufficiently precise to provide the necessary information about the fibre fineness. It is also an appropriate approach for those Growers who chose to use objective measurements of fleece samples to assist them to class their wool. However in the latter case, the grower should not expect to accurately predict the sale lot MFD if the fleece measurements are based on a technology other than the technology used to determine the MFD of the sale lot.

[19] In the case of the Airflow instrument it is well known that changes in the effective density of the fibre, which occurs in medullated wools, can cause significant errors. It is also known that differences in CVD of the sample from the CVD of the calibration top will also cause small errors in measurement of MFD by this instrument.

IWTO has decided that for the moment, Airflow will remain the basis for determining MFD for the purpose of trading consignments of wool fibre. LASERSCAN and OFDA results can be provided as well, to enable the users of the information to establish new core/comb comparisons based on the new instrumentation. This decision is reviewed annually. Again this is a sensible and practical approach.

However in the longer term it is over simplistic to assume that precision is the only significant issue to be considered. All the formulae used to predict processing performance are based on assumptions about accuracy. The major attraction of the new technologies of LASERSCAN and OFDA is the potential to improve the prediction of processing performance, through the provision of information about fineness distribution as well as mean fineness, and they do offer some potential for further improvement in precision at an acceptable cost. If there are inherent inaccuracies in the measurement of MFD by these instruments, these inaccuracies are likely to affect the predictive capability of the measurements. This is why it is important to minimise any differences, or at least to identify the reasons why they occur or the particular wools for which they occur. However, these circumstances are no different from those that have applied to the Airflow for the past 25 years. The IWTO Specification for the Airflow carries quite explicit notes warning that for wool types such as lambs wool and medullated wool inaccuracies may occur. It is entirely feasible that future versions of the specifications for OFDA and LASERSCAN will carry similar notes for appropriate situations as and when they are identified. Indeed the specification for OFDA already includes a note concerning the difference in SD that has been mentioned previously.

The significance of the differences between OFDA and LASERSCAN in determining SD also needs to be put in context. The most immediate observation is that OFDA is likely to produce lower estimates of comfort factor than LASERSCAN, for the coarse and fine wools, and for some this might seem to be a significant issue. For medium wools there will be little difference. However, when making such comparisons some attention should also be paid to the precision of this particular measurement. Estimates of comfort factor are not very precise.

In terms of processing predictions, the effect of the differences in SD and hence CVD on prediction of top fineness is very small, and generally too small to be of any real technical importance.

It may be considered desirable that only one instrument is used throughout the wool industry. However, this is a totally unrealistic expectation. In any event it is a situation that has never existed. There are still combing mills that measure MFD in the top using Projection Microscope rather than Airflow. The industry participants will decide on commercial and technical grounds which if any measurement system predominates in the future. The availability of the new technology provides an opportunity for choice that has not existed previously. It is a situation that other industries have long since learned to handle.

The truth is that a sample of wool remains the same, irrespective of the exact value of fineness assigned to it by any one of these instruments. Once it is accepted that these technologies measure different definitions of fibre fineness, work can begin to work out procedures and mechanisms to enable production, purchasing and processing to proceed on an equitable commercial and technical basis.

The value of the measurements provided by all these instruments is that they are supported by Standard Test Specifications that define their accuracy and precision. These specifications are themselves supported by extensive research and extensive metrology studies. Any of the instruments can be used with confidence, provided the documented limitations are understood.

CASE 2 – FIBRE CURVATURE

The crimp of wool fibres has an impact on processing efficiency in top making[20,21,22,23,24,25], spinning efficiency and yarn properties[26,27,28,29,30,31,32,33,34,35] and the structural and tactile properties of fabrics[20,27,33,34,36,37,38,39,40]. This characteristic is of considerably less direct importance in processing and product performance than fibre fineness or fibre length. However, if its impact can be reliably predicted, this may well provide opportunity for improving the quality of yarns and fabrics and for reducing production costs. Fibre curvature may be related to crimp[41] and therefore measurement of fibre curvature of raw wool may provide an alternative to measuring fibre crimp[42].

Defining Fibre Curvature

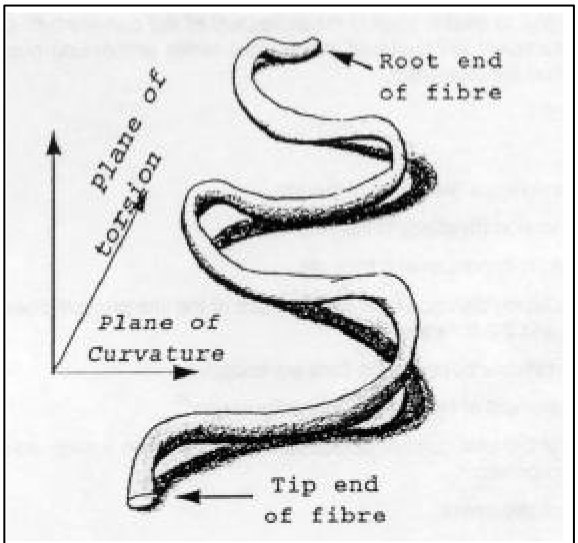

Figure 9: Generalised form of Merino Wool Fibres showing planes of curvature (bending) and torsion (twisting)[40].

Defining fibre curvature is even more complex than defining fibre fineness. This is because curvature exists in 3 dimensions. Fibre fineness must also be considered in 3 dimensions but, as has been discussed previously, the Wool Industry has simplified the problem in that instance by creating a one-dimensional definition of fibre fineness, based on the mean transverse dimension of the fibre

Figure 9 provides a generalised view of the curvature of a merino wool fibre[41]. The fibre bends (curves) and twists (torsion) along its length. In general, the curvature of wool fibres is predominantly in one plane. There are exceptions, which appear to be related to the density of the wool staple. The studies that are available are not extensive, but nevertheless they tend to support the view that the measurement of fibre curvature in the predominant plane will provide a reasonable quantitative

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estimate of this particular characteristic. Provided a sufficiently short length of fibre is measured, the definition of fibre curvature is effectively reduced to a two-dimensional problem. Defining fibre curvature in terms of the arc of a two-dimensional projected image of a short snippet provides scope for the use of conventional microscope assessments of curvature. Certainly there are practical difficulties in doing this, and these are very similar to microscope assessments of fibre fineness. The measurement is very tedious (indeed tiresome), and to obtain a reasonable estimate a large number of individual measurements are required.

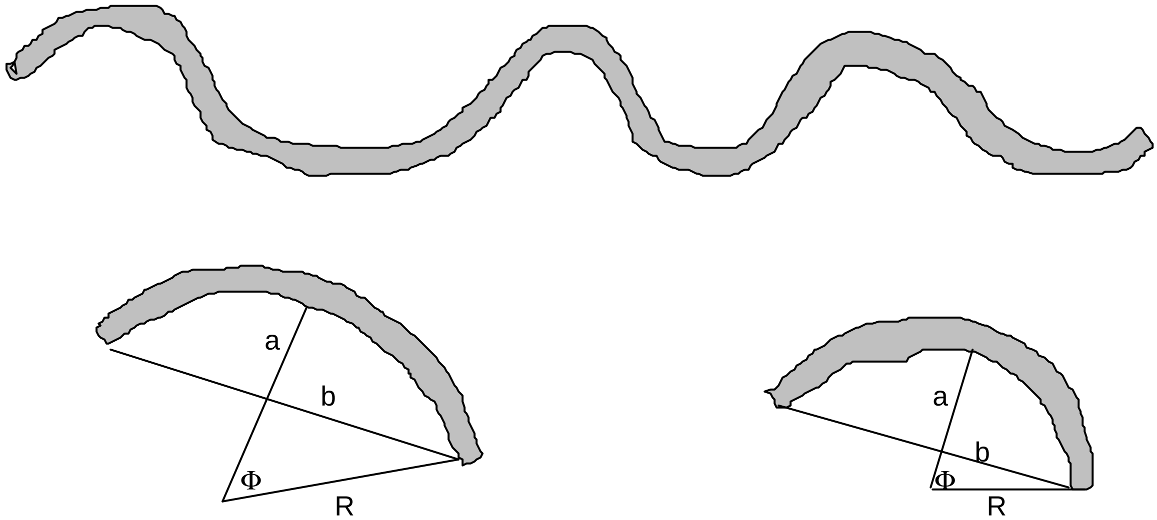

Figure 10: Fibre curvature is not uniform along the length of the fibre and there is variation between fibres as well. The measurement methodology needs to take account of this variation. The most practical way to do this is to examine individual segments of the fibres and determine the curvature on each segment. Repeated measurements will build up a distribution of curvature from which the average can be calculated. Measurement of small segments allows the measurement to be reduced to two-dimensions. This simplification will introduce an error in the curvature measurement but this is quite small - < 10%. The radius of curvature can then be defined as the radius of the arc represented by the two dimensional projection of the fibre snippet. This is indicated in the above diagram by R and it can be shown, using simple geometry, that $R = 2a/\left(a^2 + b^2\right)$, where R is the radius of the arc of the fibre, and a is the height of the arc and b is half the breadth of the arc. However, R decreases as the curvature increases, so for convenience the curvature is defined as $C = 1/R$. The effect of this transformation is to create an index of curvature, which decreases as the arc approaches a straight line. The unit of this measure is mm^{-1}.

Because it is a more complex geometrical property of wool fibres than fineness, the range of options for defining curvature is considerably less, and indeed by reducing the definition to the radius of a two dimensional arc, as shown in Figure 10, a compromise is being made.

Measurement of Fibre Curvature

Standard Methods for determining fibre curvature have not yet been developed. However the definition described above lends itself to measurement using a microscope, image analysis or other optical techniques.

In his original work on fibre curvature Swan[32] used an optical microscope and also an image analysis system consisting of a monochrome CCD camera mounted on a light microscope, with the image analysis operations being performed on a 768x512 pixel image. Image analysis systems are inherently faster than manual measurements through an optical microscope.

The OFDA instrument is an improved image analysis system, primarily developed for fineness measurement, but now also capable of curvature measurement (see Figure 11). While making the measurements the instrument assumes that the fibre snippets are lying in a two-dimensional plane. Clearly some of them are not, but the approximation appears to be close. As discussed previously, in determining fibre fineness the OFDA must be calibrated. The extent to which this calibration interacts with the measurement of curvature has not been determined. In principle the instrument could base its estimates of a and b (see Figure 10) on knowledge of the physical structure of the detector in the camera, but such an assumption lends itself to the possibility of significant differences between instruments. The OFDA makes its estimates of curvature on a subset of the fibre snippets used for estimating diameter because it needs to select snippets, which are unimpeded by other snippets.

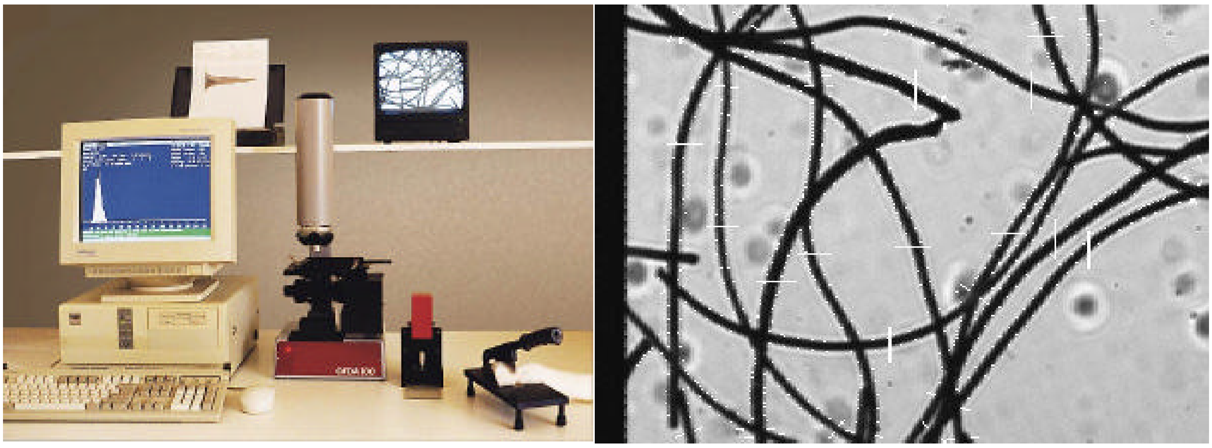

Figure 11: The OFDA (Optical Fibre Diameter Analyser) is illustrated on the left. It consists of a video camera mounted on an optical microscope that captures "snapshots" of fibre snippets spread on a slide. A typical "snapshot" is shown on the right. The "snapshot" is analysed by a computer program to measure the fineness of the fibres and also the curvature of sections of fibres.

The instrument measures a large number of snippets and from this information the mean curvature is calculated. The curvature is expressed in degrees mm^{-1} of arc rather than as mm^{-1}, and the data is accumulated into class intervals of 8 degrees mm^{-1}. It is known that the distribution of curvature is extremely skewed. This "*lack of symmetry in the distribution prevents meaningful estimation of the standard deviation of the distribution*"[32]. Nevertheless the OFDA software generates a distribution histogram and calculates its standard deviation. (see Figure 12)

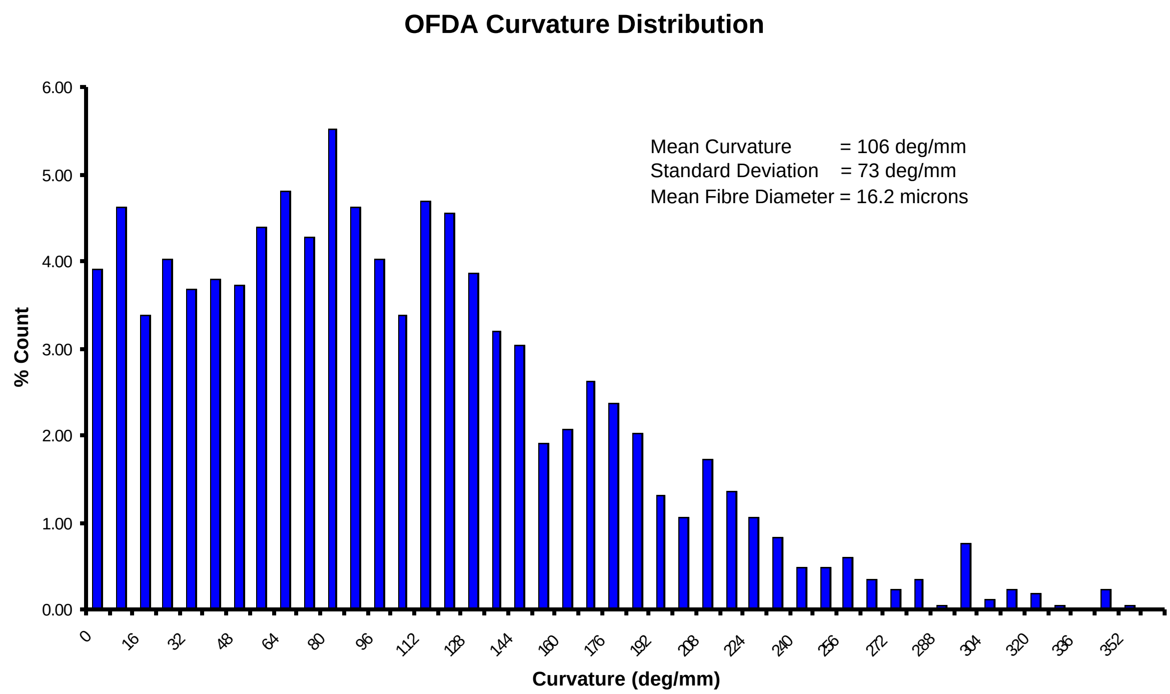

Figure 12: Example of an OFDA Curvature Distribution

One of the features of the OFDA is that it frequently records curvature values greater than 360 degrees/mm for a small number of individual snippets. The software does not report these on the printed histogram.

Clearly, considering the definition of curvature, these data represent some idiosyncracy of the image analysis software, as such values suggest the arc of curvature is greater than a complete circle. This is impossible. In the above example the histogram also shows significant numbers of measurements in excess of 180 degrees/mm – which is quite remarkable. This is one aspect of this measurement system that requires further investigation.

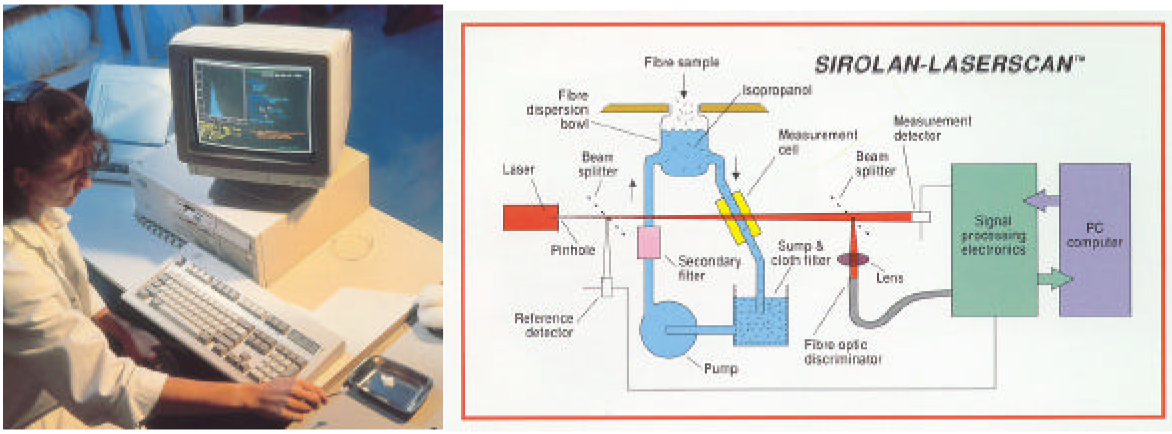

Figure 13: The LASERSCAN instrument is illustrated on the left and the principle of the instrument is illustrated in the schematic on the right. It consists of a laser beam and an optical detector and associated electronics. The fibre snippets are transported individually through the beam by an organic solvent, and the change in the signal from the detector is used to measure the fineness of the fibres and also their curvature.

The physical structure of the optical discriminator used in the LASERSCAN also allows this instrument to provide an estimate of curvature. The instrument assumes that the fibre snippets pass through the laser beam such that the plane of curvature is roughly perpendicular to the beam. Since the fibres are suspended in a liquid medium, it is likely that this is indeed an approximation, and the orientation of the plane of curvature in the beam is one aspect of the metrology that requires further investigation.

As discussed previously, in determining fibre fineness the LASERSCAN must be calibrated. The extent to which this calibration interacts with the measurement of curvature has not been determined. In measuring curvature LASERSCAN relies completely on the geometric arrangement of the optical discriminator (see Figure 14). Because the prime function of the discriminator is to select fibres that will be measured for fineness, the LASERSCAN is able to estimate the curvature more than 90% of the fibre snippets it measures for diameter.

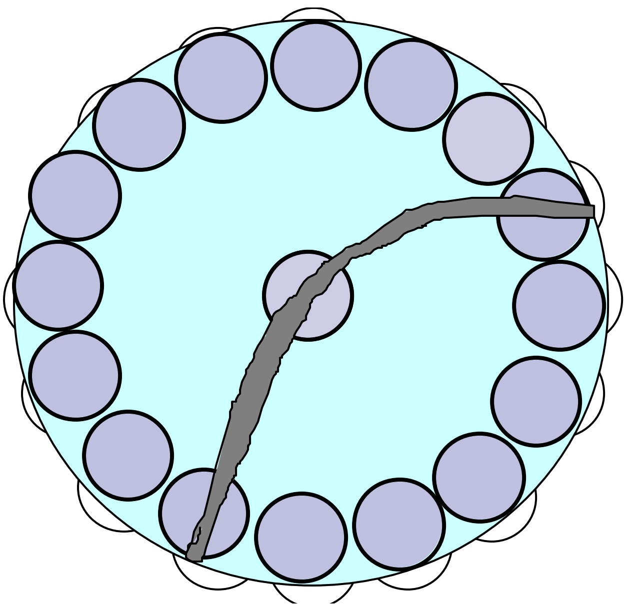

Figure 14: The LASERSCAN's optical discriminator is fundamentally designed for selecting snippets for the determination of fibre fineness. It consists of a central detector surrounded by 16 smaller detectors. The instrument will only accept a snippet for measurement if the snippet intersects the central detector and two of the surrounding detectors. Because the physical dimensions of the detector array is precisely known, the instrument can differentiate the curvature of the individual fibre snippets, depending upon which pair of the surrounding detectors is intersected by the fibre. The value of a and b (see Figure 10) for each corresponding pair may be inferred from the physical dimensions of the discriminator.

The limitation of this approach is that fibres can only be classified into one of eight class intervals, whereas the OFDA can classify fibres into any one of forty-five class intervals. In reality the total number of class intervals actually used in both instruments will be less than the total number available simply because the fibre geometry for the higher intervals is such that the fibres would have to be bent rather than curved.

The larger number of class intervals available to the OFDA suggests that the sensitivity of this instrument to differences in curvature between individual fibres will be greater than LASERSCAN. It does not follow that the sensitivity of the instrument to differences in mean curvature between samples will be greater.

Comparison of the Instruments

Despite the considerable difference between the measurement systems employed by OFDA and LASERSCAN there is a considerable degree of correlation between the mean values produced by both instruments. This is illustrated in Figure 15.

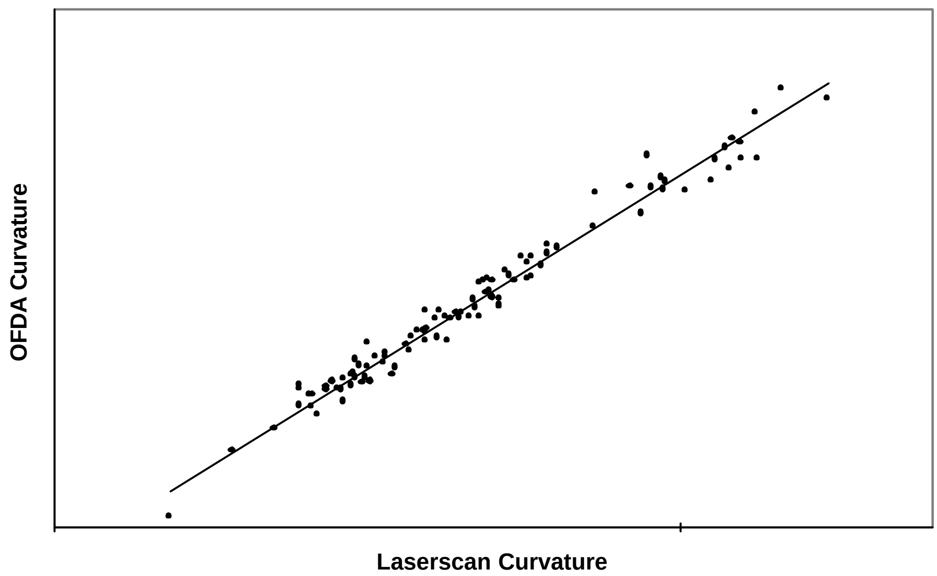

Figure 15: Relationship between mean curvature estimates by OFDA and LASERSCAN

Despite this strong association, the numbers produced by the instruments are not the same.

The curvature measurements provided by these instruments are not supported by Standard Test Specifications that define their accuracy and precision. The research and metrology studies required to support these specifications have barely begun. Until this basic work is completed, the measurements must be used with some caution.

SUMMARY

Objective measurements are much more than just pretty numbers. Measurement provides the only effective means to minimise variation and improve quality.

Understanding measurement systems requires a clear understanding of the definition of the parameter being measured. Frequently, different measurement systems employ different definitions of the parameter. This has been illustrated using fibre fineness and fibre curvature as examples. In such instances it is highly likely that the numbers provided by such methods will not be the same in all instances. This does not limit the usefulness of such systems provided the same system is always used when comparisons are made.

The most important issue with any measurement, or measurement technology, is to achieve a predictable consistency of the results. Consistency can only be obtained after standardisation of sampling and testing processes, and to do this, data must be collected on:

- sampling and sample preparation variation;

- calibration techniques for test instruments;
- between-instrument comparisons;
- repeatability of measurements on the same wools; and
- between-laboratory effects.

With this data, a Test Method can be established, the precision of the test calculated and, if required by industry, a Standard Test Method issued.

This does not imply that every measurement technology needs to be progressed to Test Method status before it can be used. There are numerous measurement systems used by scientists and engineers that never develop into Standard Test Methods. Waiting for every measurement system to be developed into a standard will inhibit the very research required to develop the method, and stunt any exploration of its potential. However, in commercial situations, where the measurement adds value to the raw material or product, predictable consistency of results is critical in developing commercial confidence. This can only be provided by Standard Test Methods.