The Micrometer Caliper for Measuring the Thickness of Wool Fibers

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*As of March 18, 1935.
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‡In cooperation with U. S. Department of Agriculture.
The Micrometer Caliper for Measuring the Thickness of Wool Fibers

By Robert H. Burns

HISTORY

The physical attributes of the wool fiber were neglected in earlier years, because the product was matured throughout its length and ready for use from the time it emerged from the follicle. Many attempts were made to relate various measurements of fineness to the commercial grades of wool at the time when fine wool brought a premium (1800-1850), but little definite progress was made in formulating definite standards for any one dimensional characteristic of the fiber. Many other different characters of the fiber besides the dimensional measurements were considered by the grader in classifying the wool into the different commercial grades. However, in later years the general consensus of opinion has been that fineness or thickness of fiber is the most important dimensional characteristic of the wool fiber to be considered in wool grading.

Wool measurement, as well as any studies of structure in the fiber, did not develop until after the discovery of the microscope. Daubenton (1777), a French experimentalist, was the first one to mention wool fineness and to attempt to measure it with the microscope and associate these measurements with standards applicable to wool grading in the trade. Then a long series of experiments began with the object of formulating standards of thickness, measured by various methods and instruments, which could be used as guides in the commercial classification of wool. It is interesting to note that as early as 1825, at a time of extreme controversial attitudes, various authors wrote that one must not be too hasty in applying wool thickness measurement to all classes and types of material. Its primary usefulness was to set up standards of comparison in commercial grades and point out non-uniformity of fiber thickness in breeding flocks. The last point was not emphasized much at that time, but became of increasing importance through the years, until today it is considered the primary purpose of wool measurement.
MICROSCOPIC METHODS FOR MEASURING THE FINENESS OF WOOL

Daubenton (1777) was the first experimentalist to use the microscope for measuring wool fibers. He measured their thickness by comparing them with a fine scale he had drawn on a piece of quartz and placed under the microscope.

Parry (1806) criticized Daubenton’s methods and was among the first to measure the image of the fiber as shown by the microscope.

Rohde (1857) was the first to use a microscope equipped with an eyepiece micrometer for the measurement of wool. He stated that the accuracy and speed of this method could not be duplicated when using other methods.

The Dollond Eriometer enjoyed considerable popularity, and for some time it was considered the basis of comparison, and the Dollond units were standard units of measurement. McMurtrie (1886) and also Probst (1926) describe the Dollond Eriometer fully and state that it was quick, accurate, and easy to use. The word “eriometer” was coined from two Greek words meaning wool measurer.

Pilgram (1826) devised an eriometer which was widely used and was described by Pabst, as well as McMurtrie. This instrument consisted of a polished slide ruled to thousandths of a Paris line, which was slipped under the microscope. The fiber was superimposed on this scale and measured.

Nathusius (1886) and Bohm (1873) also used the microscope as a wool measuring device. All of the methods mentioned up to this point have used single fibers as a unit for measurement.

Voigtländer (1815) and Winckler (1821) measured ten fibers simultaneously by microscopic methods, using a special technique in which the fibers were mounted parallel to each other on a frame. The frame was placed under the microscope, and the thickness of the “ribbon” of fibers was measured.

In recent years a number of methods have been developed for measuring images projected by the microscope. Kronacher and Lodemann (1930: 56) used the Leitz projection apparatus as de-
signed by Edinger. Henseler (1926: 520) and Doehner (1926) have developed what they designate the lanometer (wool meter), which is an adaptation of horizontal projection of the image. The Wool Industries Research Association (Barker: 1931: 111) has also designed a projection apparatus which is called the wool fiber comparator. This instrument has a double optical system, giving two images, side by side, of a test sample as well as a standard sample for comparison. Von Bergen (1932) has recently developed a new adaptation for reading measurements of projected images by means of graduated wedges. He uses a projection apparatus manufactured by Bausch and Lomb.

Duerden (1929: A: 346) uses a Zeiss-Hegener micro-camera to obtain a projection used for measuring the thickness of fibers and prepares the sample by cutting it into short lengths and thoroughly mixing the clippings before they are selected for measurement.

The various investigators using microscopic methods for measuring thickness take direct readings through eyepiece micrometers or by calibrated projection scales of different forms. They use in their measurement entire fibers, small sections of fibers, and cross-sections of fibers.

The fiber rotating devices, which have been used for examining different sides of the fibers under the microscope, should be mentioned.

Nathusius, cited from Kronacher and Lodemann (1930: 53), made one of the first rotators, which consisted of two corks mounted on a base. The fiber to be examined was drawn through the corks, and the corks were rotated upon their axes. Bohm, cited by Froelich, Spoettel, and Taenzer (1929: 120), designed a rotator which clips on the substage of the microscope. This is the instrument which was later modified by Taenzer and known as the Polikeit apparatus after its manufacturer (Barker, 1931: 59 and Kronacher and Lodemann, 1930: 56). The Capillary Rotator designed by Zeiss has been used considerably in recent years (Froelich, Spoettel, and Taenzer, 1929: 121, and Kronacher and Lodemann, 1930: 54). The Cambridge and Wira Fiber Rotator (Barker, 1931: 113) is a device of recent design, which
is quite useful and has been used considerably. It measures the angle of rotation of the single fiber at any particular point of observation.

Two new methods have been developed for making cross-sections of fibers. Barker (1931: 114) describes a method developed at the laboratories of the Wool Industries Research Association in England in which a bundle of fibers is saturated with collodion and later imbedded in wax, which gives a very rigid bundle from which satisfactory cross-sections may be cut. Hardy (1933: A) describes a new quick method of making cross-sections where no mounting medium is needed, as the washed fibers are cut while held in the slot of a special instrument, which can be carried in the pocket.

NON-MICROSCOPIC METHODS FOR MEASURING THE THICKNESS OF WOOL FIBERS

1. Measurement between the jaws of screw thread micrometers. Grawert (1831) was probably the first one to attempt the direct measurement of wool fibers by mechanical means. He was a jeweler and thus was well acquainted with precision instruments. His instrument was the forerunner of the machinist’s micrometer caliper of today, and consisted of a pair of jointed tongs opened and closed by a screw so threaded that one revolution of the screw opened or closed the jaws by one unit. The unit of measurement with this instrument was 0.255 of a micron. Hofmann (1831), general overseer of shepherds in Sweden, purchased a Grawert apparatus and made thousands of measurements with it. It is interesting to note that this instrument merits the only citation in literature in which a series of measurements coincide with the practical results of grading. Koerte (1831), a well-known writer of that time on sheep and wool, speaks of it as a very interesting development in wool science and praises its ease of manipulation and high degree of accuracy. Thaer (1831), probably the leading exponent of wool research in that period, who held a government position as overseer of sheep breeding, praises the Grawert caliper as a discovery which marks the beginning of a progressive era in wool production.
The Skiadan instrument is described by Probst (1926: 197) and by Barker (1931: 51). Skiadan was an English inventor, and his micrometer was similar to the Grawert apparatus except that one of the jaws was attached to a long pointer moving in an arc over a scale graduated to show variations of 0.00001 of an inch or 0.000254 mm. In 1847 Thaer and Kleinert brought out a modified instrument of the Grawert type, which is described by McMurtrie (1886: 48). According to McMurtrie, this instrument had several refinements, but in general it offered no marked improvement over the earlier Grawert instrument. All of these instruments were slightly different from the micrometer caliper of today. They had a set of clamps to hold the fiber by its end, while it swung free between the other pair of jaws below. The jaws were adjusted so that they fitted snugly against the fiber and stopped its pendulum-like motion, and the distance between the jaws was recorded by the pointer. The Wyoming wool laboratory has found that, when using micrometer measurement any unit smaller than .0001 inch is of doubtful accuracy, and it is quite questionable whether readings finer than this are obtainable except by the use of very delicate instruments with electrical contacts.

Hill (1921) reported on the use of the micrometer to help students in the discrimination of fineness of wool.

Burns and W. B. Koehler (1925) give a comparison of measurements of wool fibers by the micrometer caliper and by the microscope which has been widely cited (Froelich, Spoettel, and Taenzer, 1929: 157, and Barker, 1931: 17).

2. Measurement of the Cross-sectional Area of a Bundle of Fibers. Koehler in 1823 brought out an instrument for measuring wool fineness which was entirely different from the others presented up to that time. Koehler was a wool handler and was noted for his excellent knowledge of wool and also owned a woolen mill. His instrument has been described by Probst, Froelich, Spoettel and Taenzer, and McMurtrie. This instrument was developed through a period of ten years, during which time Koehler worked in close conjunction with Hofmann, a mechanic of Leipzig. His idea was to count out 100 fibers and measure the space
they occupied in cross-section, while under pressure by a constant weight. His method was adopted by both breeders and research workers and to a limited extent in the trade, which shows that by this time all phases of the wool industry were interested in the classification of wool by means of standards based on the measurement of fiber thickness. The writer had the opportunity of seeing one of the Koehler wool measurers at the Institute of Animal Breeding at the University of Leipzig in 1931.

Kuesebauch (1931) developed a modification of the Koehler wool measurer and named his product the Rapid Lanometer. It has been put on the market by L. Schopper of Leipzig, a noted manufacturer of textile testing apparatus. The Rapid Lanometer is designed to overcome the objections to the Koehler wool measurer, namely, that the determinations made by it are not affected by the crimp and curl of the fibers being measured. The Rapid Lanometer has a system of wedge-shaped interfitting parts, which tend to overcome the effects caused by the crimp and curl of the fibers. One hundred fibers are used, and these are counted out in different lengths, using a triangular-shaped series of combs for separating the fibers. A classification system for commercial wools has been worked out and was presented before the International Wool Conference at Liege in 1931. Hardy (1933: B) describes a new device for determining wool fineness which consists of a slot of predetermined size cut into the edge of a piece of brass. The slot is filled with cleaned fibers, and the number of fibers which fill the slot is counted. This number is compared with a standard of classification, which has been worked out with rayon fibers, which are uniform in size. This device has been developed primarily for sheep breeders and wool handlers who want a quick check on the fineness of wool samples.

3. Measurement of Crimp as an Indicator of Fineness. Crimp was one of the first characters of wool to be determined and classified in relationship to the commercial grades. Block (1820), Pabst (1836), Hartmann (1848), and Bohm (1873) all constructed crimp measurers, which consisted of sections, each with a distinctive number of projections or teeth per unit length, which were used to compare with the sample being tested. In recent years
Duerden (1929: B) has done a large amount of work on the relationship between crimp and fineness and has formulated standards for the classification of fine-wooled fleeces in South Africa. His work shows considerable agreement, but his total range of fineness was small when dealing only with Merinos. The crimp is not of necessity closely associated with fineness in all classes of wool, and for this reason practically all of the crimp measurers were discarded after a brief period of testing. The variability of the number of crimps per unit length in relation to fineness is shown by results reported by various workers. Hultz (1927: 110), working with Rambouillets, found a correlation of 0.321±0.081, while Davenport and Ritzman (1926: 53), working with Rambouillets, obtained a figure of 0.216±0.094, neither of which is a particularly high correlation.

4. Measurement of Gauge of Fiber as an Indicator of Fineness. Winckler (1821) devised a graduated cylinder of designated diameter, which he divided into fourteen divisions. The fibers are wound around the cylinder, and the space covered on the cylinder gives a reading of fineness. The fact that this instrument was seldom mentioned gives testimony that it received little attention.

Schandl (1925) devised a new apparatus for measuring wool fineness in which wool fibers were compared with six platinum threads of known thickness. This method has received some attention in Europe in recent years.

5. Measurement by Means of Light Diffraction Bands. Young (1824) was the first to adapt the phenomenon of light diffraction to the measurement of fiber thickness. In this method a group of fibers were measured at the same time. Ewles (1928) made an instrument based on this principle, which consisted of a portable tube, but gave no experimental and comparative data on the measurements obtained with it. Burns (1930: 117) reported a few measurements with the Ewles apparatus as compared with the micrometer caliper, in which the micrometer measurements were on the average about two ten-thousandths of an inch finer than the measurements taken with the Ewles apparatus. Duerden (1921: A: 348) reported experiments with a laboratory diffrac-
tion apparatus, which he designed in conjunction with the physics department of Rhodes University College, South Africa. He made a large number of comparative measurements, using the microscopic and diffraction methods, and found a very close agreement. In fact, all wools fell into the same respective grades when classified by measurement, regardless of whether they were measured by light diffraction or by means of the microscope. McNicholas and Curtis (1931) surveyed the history of diffraction apparatus and described an improved device perfected at the Bureau of Standards, which they call the eriometer (wool measurer), and thus revived a name used by the instrument makers in the early nineteenth century. They made a critical study of the accuracy and adaptability of the eriometer in averaging a wide range of thicknesses, as distributed in a group of fibers. They found the average fineness obtained by the eriometer in close agreement with comparable data obtained with the microscope, and concluded that, "the diffraction method offers considerable opportunity for the further development of instruments to include additional features which are desirable in the study of wool and other textile fibers." Matthew (1932) reports favorably on the diffraction method for the measurement of thickness in fibers and yarns. He states that the long, straight fibers are the easiest to measure, and that one must be careful to prepare the wool sample so that the fibers are parallel, doing away with the fuzziness of the bands so prevalent when the fibers are crossed over one another, a common condition in strands of wool.

6. Measurement of Fineness by the Ratio of Length per Unit Weight. The main advantage of this method is that every portion of the fiber contributes equally to the measurement of fineness, which is not the case with other methods. Krauter (1929) states that the weight per unit length was first used as a measurement of fineness in 1826. Barker and King (1926) used a microbalance for finding the weight of single fibers, and Wilkinson (1915) and Krauter (1926) used a method of determining the fineness of wool tops in which a large number of clippings cut to a definite length were weighed. Roberts (1927) and again in 1930 has applied this method of weight per unit length to the
determination of fineness of raw wool. In the latter paper Roberts gives a fine summary of the advantages and disadvantages of the different methods of measuring fineness, but unfortunately he does not give any definite comparison based on experimental data. He emphasizes the importance of sample preparation, zoning or quartering, to obtain an accurate composite sample before measuring begins.

Smith (1928) found that the weight of a definite length of wool fiber is closely related to its diameter measured with the micrometer caliper. He concludes, however, that measurement of diameter by means of weight cannot replace methods of direct measurement.

THE MICROMETER CALIPER VS. THE MICROSCOPE

Burns and Koehler (1925) reported on comparative measurements of 27 samples in which not only the average thickness of the entire sample was compared, but also the thickness of each caliper unit was compared with its corresponding value obtained with the microscope. Their conclusions are as follows: "The di-
ameter as measured by the caliper plus one ten-thousandth of an inch equals the diameter by the microscope.”

Unpublished data by J. G. Hutton of the University of Wyoming (1927) with methods similar to those used by Burns and Koehler give very interesting results with different kinds of fibers. He measured five fibers with the micrometer and then measured each clipping (fiber clipped close to the jaws of the micrometer) at three places, both ends and the middle.

The results of this experiment as shown in Table I verify in every way the results obtained earlier by Burns and Koehler.

This experiment was designed to give information on the crushing effect of the micrometer jaws in so far as shown by a comparison of the differences in the measurements of soft and hard fibers. The Lincoln and mohair samples would class as hard fibers, while the Merino, fine camel hair, fine cashmere, and alpaca would class as soft fibers. The differences between micrometer and microscopic measurements seemed to remain the same, re-

<table>
<thead>
<tr>
<th>Sample</th>
<th>Micrometer mean ( \frac{\text{ten-thousandths}}{\text{an inch}} )</th>
<th>Corrected micrometer mean ( \frac{\text{ten-thousandths}}{\text{an inch}} )</th>
<th>Per cent of micrometer mean shown by microscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>South African Merino</td>
<td>7.6</td>
<td>7.5</td>
<td>117.0</td>
</tr>
<tr>
<td>Delaine Merino</td>
<td>5.2</td>
<td>5.2</td>
<td>123.8</td>
</tr>
<tr>
<td>Australian Merino</td>
<td>6.1</td>
<td>6.0</td>
<td>122.0</td>
</tr>
<tr>
<td>Rambouillet</td>
<td>6.6</td>
<td>6.5</td>
<td>120.0</td>
</tr>
<tr>
<td>Hampshire</td>
<td>10.0</td>
<td>9.8</td>
<td>113.8</td>
</tr>
<tr>
<td>Southdown</td>
<td>10.0</td>
<td>10.2</td>
<td>113.0</td>
</tr>
<tr>
<td>Corriedale</td>
<td>10.0</td>
<td>9.0</td>
<td>115.0</td>
</tr>
<tr>
<td>Oxford</td>
<td>12.6</td>
<td>12.6</td>
<td>108.6</td>
</tr>
<tr>
<td>Shropshire</td>
<td>13.2</td>
<td>13.2</td>
<td>109.0</td>
</tr>
<tr>
<td>Lincoln</td>
<td>19.1</td>
<td>19.1</td>
<td>105.5</td>
</tr>
<tr>
<td>Texas mohair</td>
<td>11.6</td>
<td>11.6</td>
<td>109.4</td>
</tr>
<tr>
<td>Cape mohair</td>
<td>15.4</td>
<td>15.4</td>
<td>106.9</td>
</tr>
<tr>
<td>Alpaca</td>
<td>15.3</td>
<td>15.3</td>
<td>107.7</td>
</tr>
<tr>
<td>Fine cashmere</td>
<td>5.8</td>
<td>5.5</td>
<td>128.9</td>
</tr>
<tr>
<td>Coarse cashmere</td>
<td>20.6</td>
<td>20.9</td>
<td>105.3</td>
</tr>
<tr>
<td>Coarse camel hair</td>
<td>19.0</td>
<td>19.0</td>
<td>105.6</td>
</tr>
<tr>
<td>Fine camel hair</td>
<td>6.5</td>
<td>6.5</td>
<td>118.9</td>
</tr>
<tr>
<td>Mean</td>
<td>11.42± .8</td>
<td>11.30± .8</td>
<td>113.7± 1.1</td>
</tr>
</tbody>
</table>

The reults of this experiment as shown in Table I verify in every way the results obtained earlier by Burns and Koehler.

This experiment was designed to give information on the crushing effect of the micrometer jaws in so far as shown by a comparison of the differences in the measurements of soft and hard fibers. The Lincoln and mohair samples would class as hard fibers, while the Merino, fine camel hair, fine cashmere, and alpaca would class as soft fibers. The differences between micrometer and microscopic measurements seemed to remain the same, re-
Regardless of the sample which was measured, although these differences were slightly magnified in the smaller fibers when a percentage figure was calculated. These results would tend to indicate that there is a fundamental basis for the difference in measurement, which is probably due to the contour of the fiber rather than to any definite crushing action of the caliper jaws. The ratchet adjustment is so delicate and the operator becomes so conscious of the proper touch and tension to apply to the ratchet spindle, in order to make the micrometer readings check at zero, that the same tension is used in measuring the thickness of the fiber, and little or no crushing takes place. This observation is also supported by what is known of the structure of the wool fiber, which is composed of a series of unyielding, firm cortical cells which give the fiber great resistance to lateral pressure.

The finer fibers, such as the Merino, alpaca, and fine camel hair and cashmere, have a more oval shape of cross-section and give a greater difference in micrometer and microscopic measurements than the coarser fibers such as Lincoln, mohair, Corriedale, etc., which have a cross-section which is more circular in shape. From these results it would seem quite probable that the difference between micrometer and microscopic measurements is largely due to differences in contour (shape of cross-section) or ovalness rather than to any crushing action of the micrometer jaws. The microscopic measurements obtain the largest axis of the fiber, while the micrometer takes the thickness of the smallest axis. This last point was conclusively proved by watching a fiber through a magnifying glass while the micrometer jaws were closing up against it. The fiber twisted itself until its smallest axis was presented to the jaws of the micrometer.

To further test the crushing effect of the micrometer caliper on wool fibers and to obtain theoretically more accurate results, a special wide-disk micrometer was constructed to order. This micrometer had disks 12 mm. in diameter as compared with 6.5 mm. for the regular micrometer. This would theoretically eliminate a considerable part of the crushing action, and at the same time give a measurement representing twice the length of fiber covered by the ordinary micrometer. Nine samples were measured. One
hundred fibers were measured from each sample, measuring the same portion of the fiber with both the regular and wide-disk micrometer.

The mean thickness obtained with the two micrometers is compared in Table II.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean thickness of 100 fibers in ten-thousandths of an inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Regular micrometer</strong></td>
</tr>
<tr>
<td>1</td>
<td>6.96</td>
</tr>
<tr>
<td>2</td>
<td>8.91</td>
</tr>
<tr>
<td>3</td>
<td>8.96</td>
</tr>
<tr>
<td>4</td>
<td>7.86</td>
</tr>
<tr>
<td>5</td>
<td>8.56</td>
</tr>
<tr>
<td>6</td>
<td>8.75</td>
</tr>
<tr>
<td>7</td>
<td>9.36</td>
</tr>
<tr>
<td>8</td>
<td>8.61</td>
</tr>
<tr>
<td>9</td>
<td>8.57</td>
</tr>
<tr>
<td>Average of 9 samples</td>
<td>8.507</td>
</tr>
</tbody>
</table>

Contrary to expectations, the wide-disk micrometer measurements were not larger but smaller than those obtained with the regular micrometer. This difference was fairly constant in all of the samples, showing that the relationship was quite marked and that the regular micrometer gave measurements of about one-half of one ten-thousandth of an inch larger than the special-disk micrometer. However, there is reason to believe that the differences were largely due to mechanical defects, as the manufacturers had great difficulty in grinding down the faces of the plates of the micrometer jaws, so that they were accurate.

**THE PERSONAL AND MECHANICAL ERRORS IN MICROMETER MEASUREMENT**

There are two major sources of variability in micrometer measurements which are independent of the variations of thickness in the fibers being measured. The personal error may be measured by comparing measurements made on the same fiber with the same micrometer by different operators. The mechanical error is measured by comparing measurements of the same fiber by the same operator on different micrometers. Koehler (1924) gives the results of three tests of the personal error, as shown in Table III.
TABLE III.

<table>
<thead>
<tr>
<th></th>
<th>Operator No. 1</th>
<th>Operator No. 2</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No. 1</td>
<td>5.39 ± .090</td>
<td>5.42 ± .092</td>
<td>.03</td>
</tr>
<tr>
<td>Test No. 2</td>
<td>6.56 ± .090</td>
<td>6.68 ± .098</td>
<td>.12</td>
</tr>
<tr>
<td>Test No. 3</td>
<td>6.09 ± .068</td>
<td>6.12 ± .069</td>
<td>.03</td>
</tr>
</tbody>
</table>

These results show a very close correspondence in the tension applied with the micrometer by these two operators. Their results show that these two operators could measure fibers on the same micrometer without any appreciable difference in the resulting measurements.

D. C. Hutton (1930) made a special study of the personal and mechanical errors of micrometer measurement.

Two operators working independently of each other measured twenty samples of wool taken from the shoulder area of show sheep at the Chicago International Livestock Exposition. The results of this experiment are shown in Table IV.

TABLE IV.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mean thickness of 100 fibers in ten-thousandths of an inch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operator No. 1</td>
</tr>
<tr>
<td>1</td>
<td>5.72 ± 0.070</td>
</tr>
<tr>
<td>2</td>
<td>5.27 ± 0.100</td>
</tr>
<tr>
<td>3</td>
<td>5.01 ± 0.107</td>
</tr>
<tr>
<td>4</td>
<td>5.36 ± 0.081</td>
</tr>
<tr>
<td>5</td>
<td>6.33 ± 0.079</td>
</tr>
<tr>
<td>6</td>
<td>6.62 ± 0.126</td>
</tr>
<tr>
<td>7</td>
<td>5.09 ± 0.083</td>
</tr>
<tr>
<td>8</td>
<td>4.97 ± 0.076</td>
</tr>
<tr>
<td>9</td>
<td>5.83 ± 0.085</td>
</tr>
<tr>
<td>10</td>
<td>6.14 ± 0.081</td>
</tr>
<tr>
<td>11</td>
<td>4.97 ± 0.100</td>
</tr>
<tr>
<td>12</td>
<td>4.51 ± 0.084</td>
</tr>
<tr>
<td>13</td>
<td>4.88 ± 0.083</td>
</tr>
<tr>
<td>14</td>
<td>4.23 ± 0.072</td>
</tr>
<tr>
<td>15</td>
<td>7.43 ± 0.099</td>
</tr>
<tr>
<td>16</td>
<td>7.47 ± 0.153</td>
</tr>
<tr>
<td>17</td>
<td>6.31 ± 0.151</td>
</tr>
<tr>
<td>18</td>
<td>7.06 ± 0.186</td>
</tr>
<tr>
<td>19</td>
<td>5.77 ± 0.086</td>
</tr>
<tr>
<td>20</td>
<td>7.56 ± 0.098</td>
</tr>
</tbody>
</table>
The difference in measurement between the two operators includes the variation of the tension applied in operating the micrometers as well as an error in selecting the fibers for measurement. The fact that operator No. 2 consistently measured coarser than operator No. 1 shows that there are definite personal tendencies in the technique of measurement. It is quite probable that operator No. 2 had a greater tendency to pull fibers from near the tip of the sample and thus obtained a coarser measurement. Neither of these operators "quartered" or zoned their samples, which would have decreased the variability of their measurements.

Koehler (1924) gives the result of one test to compare different micrometers when the operator measures the same 100 fibers on different machines.

Mean fineness of 100 fibers (.0001 inch)

<table>
<thead>
<tr>
<th>Micrometer No. 1</th>
<th>Micrometer No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.36±0.086</td>
<td>7.39±0.096</td>
</tr>
</tbody>
</table>

These results show a very close correspondence in measurement between these two micrometers.

D. C. Hutton (1930) placed four micrometers in a line and measured each of 100 fibers with each of the micrometers in turn. The fibers were taken from a sample commercially graded as one-half blood wool. The results are shown in Table V.

<table>
<thead>
<tr>
<th>TABLE V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size in .0001 inch</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>Mean size</td>
</tr>
<tr>
<td>Mean size measured by all four micrometers</td>
</tr>
<tr>
<td>Variation from mean size (4 micrometers)</td>
</tr>
</tbody>
</table>
These data give some interesting information concerning the crushing effect of the micrometer jaw. Micrometer No. 4, which was the last to measure each of the 100 fibers, gave a value higher than the others, showing that there is no appreciable crushing of the fiber. The micrometers were checked for their zero points after each ten fibers had been measured, and they remained in perfect adjustment throughout the experiment. Micrometer No. 3 gave the largest variation from the mean (.000035 inch), which was equal to 4.5 per cent. The variation of the individual fibers when measured on each of the four micrometers was as follows: 5 fibers out of the hundred varied by 3 units, with two micrometers giving the same measurement; 30 fibers varied 2 units; 50 fibers varied by 1 unit; and 15 fibers measured the same on all four micrometers.

Gorman (1931) attempted to trace the relationships of different methods of measuring the fineness of wool in respect to the commercial grades and the different breeds of sheep. He found that the various methods differed considerably and further that the grades differed when measured by various methods. He made up a set of commercial grade samples which measured from 5.2 ten-thousandths of an inch for the 80s to 16.30 for the 36s. He was unable to formulate definite standards for breed wools in respect to the fineness of fiber.

**Necessary Number of Fibers to Measure in Determining Fiber Thickness.**

In order to test the effect of measuring more than one set of 100 fibers for the determination of the average thickness of fiber, the writer measured four different samples of wool, keeping records of each set of 100 fibers, until a total of 500 fibers had been measured from each sample. The results are shown in Table VI.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Sample No. 1</th>
<th>Sample No. 2</th>
<th>Sample No. 3</th>
<th>Sample No. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size in ten-thousandths of an inch</td>
<td>Frequency</td>
<td>Size in ten-thousandths of an inch</td>
<td>Frequency</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>1st 100</td>
<td>7</td>
<td>15</td>
<td>31</td>
<td>25</td>
</tr>
<tr>
<td>2nd 100</td>
<td>6</td>
<td>30</td>
<td>38</td>
<td>14</td>
</tr>
<tr>
<td>3rd 100</td>
<td>7</td>
<td>30</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>4th 100</td>
<td>12</td>
<td>22</td>
<td>35</td>
<td>18</td>
</tr>
<tr>
<td>5th 100</td>
<td>11</td>
<td>34</td>
<td>31</td>
<td>16</td>
</tr>
<tr>
<td>All 500</td>
<td>43</td>
<td>131</td>
<td>170</td>
<td>88</td>
</tr>
<tr>
<td>1st 100</td>
<td>8</td>
<td>26</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>2nd 100</td>
<td>9</td>
<td>36</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>3rd 100</td>
<td>8</td>
<td>29</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td>4th 100</td>
<td>10</td>
<td>32</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>5th 100</td>
<td>13</td>
<td>25</td>
<td>37</td>
<td>16</td>
</tr>
<tr>
<td>All 500</td>
<td>1</td>
<td>48</td>
<td>148</td>
<td>172</td>
</tr>
<tr>
<td>1st 100</td>
<td>12</td>
<td>28</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>2nd 100</td>
<td>17</td>
<td>27</td>
<td>32</td>
<td>13</td>
</tr>
<tr>
<td>3rd 100</td>
<td>13</td>
<td>30</td>
<td>29</td>
<td>14</td>
</tr>
<tr>
<td>4th 100</td>
<td>20</td>
<td>32</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>5th 100</td>
<td>5</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>All 500</td>
<td>6</td>
<td>87</td>
<td>143</td>
<td>147</td>
</tr>
<tr>
<td>1st 100</td>
<td>1</td>
<td>6</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>2nd 100</td>
<td>10</td>
<td>19</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>3rd 100</td>
<td>1</td>
<td>7</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>4th 100</td>
<td>1</td>
<td>12</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>5th 100</td>
<td>8</td>
<td>18</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>All 500</td>
<td>11</td>
<td>53</td>
<td>109</td>
<td>128</td>
</tr>
</tbody>
</table>

**CUMULATIVE MEANS OF FINENESS**

<table>
<thead>
<tr>
<th>No. of fibers measured</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No. 1</td>
<td>5.57</td>
<td>5.30</td>
<td>5.19</td>
<td>5.16</td>
<td>5.08</td>
</tr>
<tr>
<td>Sample No. 2</td>
<td>5.10</td>
<td>4.96</td>
<td>4.99</td>
<td>4.95</td>
<td>4.94</td>
</tr>
<tr>
<td>Sample No. 3</td>
<td>4.96</td>
<td>4.87</td>
<td>4.82</td>
<td>4.79</td>
<td>4.72</td>
</tr>
<tr>
<td>Sample No. 4</td>
<td>6.60</td>
<td>6.50</td>
<td>6.49</td>
<td>6.35</td>
<td>6.21</td>
</tr>
</tbody>
</table>

In all cases the measurement of 500 fibers gave a smaller mean thickness than when only 100 fibers were measured. The differences for the four samples were .49, .16, .24, and .39. When 500 fibers were measured instead of only 100, the probable error of the mean was reduced by half. This difference is largely due to the method of calculating the probable error which is reduced in
the ratio of the square root of the number of fibers measured. The fact that as more fibers are measured the mean thickness becomes smaller, as is strikingly shown by the cumulative means of fineness, would indicate that even though all of the fibers were drawn in order from the same side of the sample, the tendency was still present to pick out the coarser fibers first. Roberts (1930: T146) used a formula, \( n = \left( \frac{c}{s_1} \right)^2 \), to calculate the number of fibers to be measured in order to come within a prescribed limit of error. In this formula,

- \( n \) is the necessary number of fibers to be measured
- \( c \) is the coefficient of variability or \( \frac{100\sigma}{M} \)
- \( s_1 \) is the per cent standard error.

The usual accuracy desired in the measurement of wool thickness is a ten per cent difference exceeded by chance once in 250 times. The constant figure for \( s_1 \) for this selected limit of accuracy is 2.457 (See Roberts 1930: T132). The application of this formula for the data of the four samples just considered gives the results shown in Table VII.

**TABLE VII**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1st 100</th>
<th>2nd 100</th>
<th>3rd 100</th>
<th>4th 100</th>
<th>5th 100</th>
<th>All 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No. 1...</td>
<td>125</td>
<td>100</td>
<td>90</td>
<td>115</td>
<td>110</td>
<td>115</td>
</tr>
<tr>
<td>Sample No. 2...</td>
<td>115</td>
<td>110</td>
<td>115</td>
<td>110</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Sample No. 3...</td>
<td>115</td>
<td>125</td>
<td>120</td>
<td>135</td>
<td>190</td>
<td>140</td>
</tr>
<tr>
<td>Sample No. 4...</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>80</td>
<td>140</td>
<td>100</td>
</tr>
</tbody>
</table>

Average figure for all four samples 135.

This same formula was applied also to samples of wool which were measured for use in a study of wool inheritance (Burns: 1933). Those samples of each purebred and crossbred generation showing the greatest and least variability (largest and smallest figures for \( c \)) were selected and used for the calculations, the results of which are given in Table VIII.
<table>
<thead>
<tr>
<th>Breed and Sex</th>
<th>Number of samples</th>
<th>Maximum necessary number</th>
<th>Minimum necessary number</th>
<th>Mean necessary number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rambouillet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ewes</td>
<td>6</td>
<td>185</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Rams</td>
<td>1</td>
<td>100</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Hampshire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ewes</td>
<td>2</td>
<td>125</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Rams</td>
<td>1</td>
<td>115</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>F&lt;sub&gt;1&lt;/sub&gt; Generation</td>
<td>Rams</td>
<td>3</td>
<td>135</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Ewes</td>
<td>20</td>
<td>220</td>
<td>20</td>
</tr>
<tr>
<td>F&lt;sub&gt;2&lt;/sub&gt; Generation</td>
<td>Ewes</td>
<td>13</td>
<td>215</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Rams</td>
<td>5</td>
<td>225</td>
<td>25</td>
</tr>
<tr>
<td>All fifty samples</td>
<td></td>
<td>225</td>
<td>20</td>
<td>80</td>
</tr>
</tbody>
</table>

The use of the standard error formula for calculating the number of fibers to measure in order to fall within the limits of a certain prescribed error confirmed the results obtained by the probable error treatment, both of which are derived from the statistical treatment of the standard deviation formula. The necessary number of fibers to be measured in all cases where mean figures were used was well below the 100-fiber standard, which has been used in the Wyoming wool laboratory in the measurement of wool fibers.

**THE WEIGHT-LENGTH RATIO COMPARED WITH THE MICROMETER FOR MEASURING FIBER THICKNESS**

Wool research has had a steady growth in all of its phases, since the time, 1800-1850, when superfine wool brought a premium. When fineness was so important in commercial wool, it was natural that more interest was initiated in wool research, particularly in stimulating the invention of instruments for measuring the fineness. First, the physical and chemical properties of the wool fiber were studied, and later the biological and histological phases of its development have received considerable attention.
In the determination of fineness, one must make measurements which accurately represent the entire population of fibers within the sample. Several important factors must be considered in attaining this result. First, the instrument used must accurately measure the dimensional characteristic sought. Second, the measurement of a single fiber must be representative of the entire extent of that particular fiber. Third, the series of fibers chosen to represent the sample must be an accurate index of the entire sample. Therefore, after the mechanical considerations of the measuring instrument are taken care of, one must consider the following phases of wool fiber measurement keeping in mind the peculiar nature of the available material and the object of the experiment which one is undertaking. These factors will determine to what extent one will follow the detailed steps of obtaining accurate average measurements of fibers as outlined in the following tabulation:

1. The relationship of individual measurements of a fiber to a large number of measurements of the same fiber.

2. The relationship of the average measurement of an individual fiber to the measurements of a number of fibers representative of a single area of skin.

3. The relationship of the average measurement of a number of fibers representative of a single skin area to the much larger population of a body area.

4. The relationship of the average measurement of a number of fibers from a number of different body areas to the entire fleece of an individual sheep.

5. The relationship of average measurements of a number of fibers from different sheep as compared with the remainder of the sheep in the flock.

6. The relationship of the average measurements of a number of fibers from sheep in different flocks as compared with other flocks of the same breed, and different breeds and crossbreeds.
The system of sampling and measurement adopted for any particular experiment would depend on the nature of the fleeces of the sheep under study and the objects of the experiment.

When one studies these questions, the fact is apparent that sampling and preparation of the samples is a paramount consideration in obtaining data which give an accurate analysis of individual sheep and entire flocks. It is unfortunate that the sampling and preparation phases of fleece measurements have been neglected to a considerable extent. It is quite probable that the serious errors of measurement ascribed to various instruments were in large part due to differences in sampling and preparation of samples and the technique of measuring, rather than to any inherent difference in the measuring instruments being tested.

Theoretically, the length-weight ratio, as a measure of fiber substance or fineness, is the most accurate index, for in it every portion of each of the fibers measured contributes equally to the value obtained for fineness. In the other systems of measurement, each portion of the fiber does not contribute equally, for in these the data are dependent upon the selective factor, unless the fiber is measured along its entire length, which would multiply the measurements to such an extent as to make such a procedure impracticable.

Inasmuch as the length-weight ratio is generally considered as the most definite measure of fineness, it was selected as the basis of comparison in the following test, the purpose of which was to determine the accuracy of the micrometer caliper for measuring the thickness of wool fibers.

**Sampling Technique**

In connection with a project on fleece analysis and one on the accuracy of the Wyedesa* fleece caliper for obtaining wool samples from unit areas of skin, 186 samples were available for this study. These samples were taken from the following sheep:

---

*This fleece caliper was developed to separate the wool growing on a definite area of skin, and is fully described by Burns and Miller (Jour. Textile Institute XXII: T547—T564 Dec. 1931).*
Fleece Analysis Project:
- Border Leicester ewe No. K953 19 samples
- Cheviot ewe No. 117 19 samples
- Southdown ewe No. 58807 14 samples
- Rambouillet ewe No. 704 14 samples

Wyedesa Fleece Caliper Project:
- Lincoln ewe No. 049 8 samples
- Lincoln ewe No. 804 8 samples
- Lincoln ewe No. 942 8 samples
- Corriedale ewe No. 701 8 samples
- Corriedale ewe No. 811 8 samples
- Corriedale ewe No. 918 8 samples
- Hampshire ewe No. 016 8 samples
- Hampshire ewe No. 708 8 samples
- Hampshire ewe No. 801 8 samples
- Southdown ewe No. 034 8 samples
- Southdown ewe No. 039 8 samples
- Southdown ewe No. 964 8 samples
- Rambouillet ewe No. 007 8 samples
- Rambouillet ewe No. 746 8 samples
- Rambouillet ewe No. 809 8 samples

Total of 186 samples.

The samples taken for the fleece analysis project were taken from 14 different body areas, while those taken for the Wyedesa fleece caliper project were taken from the side area. So the 186 samples represent all portions of the body of seven different breeds, which represent the major types of sheep producing a true wool fiber. This gives an opportunity to compare all of the types of fiber found in true wool.

The samples in the fleece analysis project were taken from a skin area measuring from one to two and a half centimeters on a side.

The samples in the Wyedesa fleece caliper project were taken from a skin area measuring from one to two centimeters on a side. Four of the samples were from a square area measuring one centimeter on a side, while the other four were from a triangular area measuring two centimeters on a side.
Preparation of Samples

The samples were washed and dried and then were repeatedly split, until sixteen portions had been formed. They were split from the middle each way rather than from the base or tip in order to avoid as much as possible any tearing action due to excessive "binding" fibers. This process of repeated splitting is called "quartering" or "zoning," and insures a thorough representation of the original sample in the final composite sample composed of small wisps of fibers from each of the sixteen portions divided out by the splitting process.

Measurement of Thickness and Stretched Length of Fiber

One hundred fibers were measured for thickness and stretched length of fiber, taking 50 fibers from each side of the composite sample. The fibers were grasped at their middle portion, so as to avoid selective action due to different length of fibers. The fibers were first measured with the micrometer caliper for thickness, using the method illustrated in Figure No. 2.

Fig. 2. Measuring a Wool Fiber with the Micrometer Caliper.
The thickness of each fiber was measured at three places along its middle third of length, and the average of the three readings was recorded. The statistical effect of taking three measurements along the fiber is to increase the number of measurements from one hundred to three hundred. However, when the measurements were taken, only the average of the three readings was recorded, so that the means of the samples are calculated from the average thicknesses of one hundred individual fibers.

The measurement of stretched fiber length was carried out with a simple method devised by the writer. The equipment used in this method consists of a black chenille rug swatch (12 x 18 inches in size), with a deep pile (one inch), a pair of special cross-arm forceps, and a steel rule 30 centimeters long, graduated in millimeters. The forceps are the regular cross-arm tissue forceps in the six-inch size as used by physicians. These forceps have been fitted with lead blocks in the following manner. The tips, which are fitted with sharp prongs, are smoothed with emery cloth, and after an acid bath are ready to be soldered. A small block of solder is built up on each tip until the block reaches a thickness of about 5 millimeters. The depth needs to be about 8 millimeters, and the blocks should extend 3 millimeters below the bottom of the forcep, so as to leave room to solder in a metal pointer. A three-fourths inch nail, cut off and flattened, is suitable to use for this pointer. It should be placed so that it will be even with the point of contact between the two blocks. The pointer will accurately indicate the end of the fiber, which is caught by the blocks at the point where they come into contact with each other.

The steel rule is laid on the rug swatch, and then the fiber is laid in front of the rule, after the fiber tip has been caught in the blocks of the forceps. The cross-action feature of the forceps is remarkably valuable in avoiding fatigue in measurement, a very important consideration. The index finger nail of the left hand is placed over the fiber at a point even with the zero point of the rule. Thus, when the fiber is drawn taut, it pulls along under the finger nail, but only very gradually, as it is gently held by the deep pile of the rug in which it is imbedded. The forceps are held in the right hand in a position similar to that assumed by a pencil in writ-
ing, with the pointer extending out over the edge of the rule. When the unattached end of the fiber comes out from under the finger nail, there is no tendency for it to jump, because it is held by the pile of the rug. A reading of stretched length is easily and quickly obtained by means of the pointer. This method of measuring stretched fiber length is shown in Figure No. 3.

The absolute or bone-dry weights are obtained by computations based on the proportional loss of moisture in three sub-samples dried to a constant weight at a temperature of 100 degrees Centigrade, from which the absolute or bone-dry weight of the fourth sub-sample or test sample is computed. This test sample which has not been dried out is used to compute the absolute or bone-dry weights of the 100 fiber bundles, as it reflects the moisture conditions of the air during the time when the weights are being taken.

Length per unit weight is inversely proportional to the square of the diameter, and hence the figures to be directly comparable would have to read micrometer units as against the square root of the length per unit weight or weight-length ratio.

There was a close correspondence between the two systems of measurement, which was confirmed by the high correlation coefficient. There were 46 reversals out of the 186 samples, and most of these were of small magnitude. Although there was a high correlation, there was no definite ratio or conversion factor between units, for the units of determination were far too dissimilar to expect such a definite conversion factor. However, the general relationship was found definitely to exist, and one can, therefore,
Graph No. 1. Comparison of Micrometer Means of Fineness with Root of Weight-Length Ratio. 186 Samples: 3 Lincoln, 1 Border Leicester, 1 Cheviot, 3 Corriedales, 3 Hampshires, 4 Southdowns, and 4 Rambouillets. Arranged by Fineness of Micrometer Mean by Samples from the Coarsest to the Finest.

Micrometer Mean Fineness .0001 Inch
Root of Weight Length Ratio Cms. Per Mg.
Coefficient of Correlation 0.875 ± 0.0008
proceed with micrometer measurements with assurance that the mean fineness obtained will be in direct relationship, though not necessarily corresponding to a figure obtained when the weight-length ratio is used. According to Table 16 in Wallace and Snedecor (1931) the minimum values which can be considered significant and highly significant when using the values of this problem are .159 and .208, which cover 150 cases, a smaller number of cases than in this problem. So this correlation figure can be regarded as highly significant.

There are some variations in each of the breed wools which are interesting and not what would be expected, for one would expect larger variations between the systems of measurement in the coarser wools, while the actual result was a larger difference in the fine wools.

The correlation figures for each kind of wool are given in Table X.

<table>
<thead>
<tr>
<th>Breed</th>
<th>Actual</th>
<th>Minimum required to be:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Significant</td>
</tr>
<tr>
<td>3 Lincolns</td>
<td>$-0.958 \pm 0.0023$</td>
<td>.388</td>
</tr>
<tr>
<td>1 Border Leicester</td>
<td>$-0.953 \pm 0.0033$</td>
<td>.388</td>
</tr>
<tr>
<td>1 Cheviot</td>
<td>$-0.979 \pm 0.0015$</td>
<td>.388</td>
</tr>
<tr>
<td>3 Corriedales</td>
<td>$-0.949 \pm 0.0028$</td>
<td>.388</td>
</tr>
<tr>
<td>3 Hampshires</td>
<td>$-0.963 \pm 0.0020$</td>
<td>.388</td>
</tr>
<tr>
<td>4 Southdowns</td>
<td>$-0.596 \pm 0.0114$</td>
<td>.325</td>
</tr>
<tr>
<td>1 Southdown</td>
<td>$-0.759 \pm 0.0201$</td>
<td>.497</td>
</tr>
<tr>
<td>3 Southdowns</td>
<td>$-0.906 \pm 0.0050$</td>
<td>.388</td>
</tr>
<tr>
<td>4 Rambouillets</td>
<td>$-0.435 \pm 0.0144$</td>
<td>.325</td>
</tr>
<tr>
<td>1 Rambouillet</td>
<td>$-0.574 \pm 0.0323$</td>
<td>.497</td>
</tr>
<tr>
<td>3 Rambouillets</td>
<td>$-0.406 \pm 0.0240$</td>
<td>.388</td>
</tr>
<tr>
<td>All breeds</td>
<td>$-0.875 \pm 0.0008$</td>
<td>.159</td>
</tr>
</tbody>
</table>

All samples with the single exception of the Rambouillets give a correlation figure highly significant, according to the table of significant values of $r$ (Table 16, Wallace and Snedecor: 1931). All figures without exception show a significant relationship between micrometer fineness and weight-length ratio.

The coarser wools without exception gave a closer relationship between the two systems of measurement, while the Southdown and Rambouillet, two much finer wools, gave a less distinct relationship.
The comparison of the weight-length ratio and the micrometer thickness of wool fibers should give very high correlation factors for these methods both give different expressions of the physical dimensions of the same material, the wool fiber shaft. However, the relationship in wool fibers is not perfect for wool fibers are not flawless in their formation. If iron rods of uniform density and thickness were measured by these methods, the results should give a perfect correlation. In the coarse and medium wools the relationship is quite close, but in fine wool the relationship is less marked, and more work needs to be done in a specific study of fine wools to clear up this relationship.

When the relationship between the two systems of measurement is not in agreement, as in fine wools, it may be due to the following causes:

1. A difference in density (specific gravity) of the fibers.
2. A difference in softness or pliability of the fibers.
3. A difference in the contour or cross-sectional shape of the fibers.
4. A variation in thickness along the length of the fiber such as constrictions and protruberances.

CONCLUSIONS

One can take micrometer measurements of coarse and medium wools with the assurance that the fineness obtained will be in direct relationship to a number obtained when the weight-length ratio is used.

Micrometer measurements give a picture of the variability of fiber size using entire fibers as units, while cross-sectional methods alter the identity of the individual fibers.

Micrometer measurements with careful technique as to the fibers measured and the places measured on each fiber, give as representative results as any other method, and the place measured at a single reading is five times the microscopic field at a magnification of 185 times (low power).

There is little, if any, crushing action in micrometer measurement, as proved by a series of measurements on four different micrometers, when the last measurement was even slightly larger than the first.
The micrometer measurements are about one ten-thousandth of an inch smaller than the microscopic measurements of the same fibers. This difference is due to differences in fiber contour, as reflected in the two systems of measurement rather than to any crushing effect of the micrometer jaws.

Micrometer measurements are particularly well adapted for instructional purposes, for they alone give the student through actual measurement a coordinated training in the senses of sight and feeling, which must be mutually adjusted in the classification of wool.

Micrometer measurements do not require a complicated and tedious system of mounting, and the equipment is compact and easily transported.

The different systems of measuring wool fineness all have their advantages and disadvantages, and it might be desirable to consider the particular adaptations of each method.

The microscopic measuring method is particularly useful in obtaining a definite picture of the fiber at any point or series of points along the shaft of the fiber. It gives a precise picture of a small portion of the fiber which is shown in the microscopic field at one time. These pictures can be multiplied by the operator, but entail a great amount of time and are thus not so suitable for the analysis of a large number of samples. This method is particularly adapted to the study of histological and physiological changes of fiber structure in a relatively small population of fibers.

The micrometer measuring method gives a quick, average figure of fiber thickness which represents a considerable part of the-fiber shaft in one measurement. It also obtains a variability between the thicknesses of the different fibers within the sample. Its value lies in the fact that a fairly accurate index of fiber thickness can be obtained for a great amount of material with a minimum expenditure of time and labor. It is particularly adapted to the analysis of large numbers of samples where an index of the variability of fiber thickness is desired as well as an average value.

The weight-length ratio is particularly adapted to the analysis of a large number of samples where an average figure is desired and where the variability between samples is considered of more importance than the variability between fibers within each sample.
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LITERATURE CITED

Barker, S. G., 1931.
Wool Quality.

A Comparison of Diameters of Wool Fibres with the Micro-balance and the Projecting Microscope with Applications to the Determination of Density and Medulla (Kemp) Composition.
Jour. Textile Institute, 17: T68-T74.

Measurements of Fibre Widths by the Wedge Method.

Block, 1820.
Cited from Barker: 1931, page 47.

Bohm, J.
Froelich, Spoettel and Taenzer: 1929, page 254.

Burns, R. H., 1930.
Wool Measurement Technic.

Burns, R. H., 1933.
Wool Inheritance in Hampshire-Rambouillet Crossbreds.

Burns, R. H., and Koehler, W. B., 1925.
The Micrometer Caliper as an Instrument for Measuring the Diameter of Wool Fibers.

Daubenton, 1777.
Davenport, C. B., and Ritzman, E. G., 1926.
Some Wool Characters and their Inheritance.

Dollond, 1811.
Cited from McMurtrie, 1886, page 46.
Probst, 1926, pages 183, 184.

Doehner, H., 1926.
Eine neue Methode zur Feinheitsbestimmung von einzel-
en Wollhaaren und zur Sortimentsbestimmung von
Wollproben.
Zuechtungskunde, 1: pages 282-295.

Duerden, J. E., 1929: A.
Wool Research in South Africa.
Union of South Africa, Department of Agriculture,
Pan-African Agricultural and Veterinary Confer-
ce. Papers: Agricultural Section, pages 344-360.

Duerden, J. E., 1929: B.
Standards of Thickness and Crimps in Merino Grease
Wools.
British Research Assn. for Woolen and Worsted

Ewles, E., 1928.
Wool Fibre Measurement.

The Measurement of the Diameter of Wool Fibers. A
historical study of methods and results.

Grawert, 1831.
Cited from McMurtrie: 1886, page 47.
Probst: 1926, page 196.

Hardy, J. I., 1933: A.
Determination of Fibre Fineness. A Rapid Method Us-
ing a New Cross-sectioning Device.
Textile Research, III: 8: pages 381-387.

Hardy, J. I., 1933: B.
A New Device for Determining Wool Fineness.

Hartmann, 1848.
Cited from Barker: 1931, page 54.
Kronacher and Lodemann: 1930, page 22.
Heyne: 1924, page 535.
Mentzel: 1892, page 40.
Henseler, E., 1926.
Wool Standardization.

Heyne, Johannes, 1924.
Leipzig: Reichenbach's che Verlagsbuchhandlung. S. 638.

Hill, J. A., 1921.
Micrometer Calipers for Teaching the Discrimination of Fineness of Wool.

Hofmann, 1831.

Hultz, F. S., 1927.
Wool Studies with Rambouillet Sheep.

Hutton, D. C., 1930.
The Personal and Mechanical Errors in the Measurement of Wool Fibers with the Micrometer Caliper.

Hutton, J. G., 1927.
Unpublished Data in the Wool Department Files.

Koehler, 1823.
Cited from Froelich, Spoettel, and Taenzer: 1929, page 156.

Koehler, W. B., 1924.
Comparison of the Micrometer Caliper and the Microscopic Measurements of Wool Fibers.

Koerte, 1831.

Krauter, G., 1929.
Ueber die Feinheitsmessung.
Kronacher, C., und Lodemann, G., 1930. 
Technik de Haar-und Wolleuntersuchung. 
Berlin und Wien: Urban & Schwarzenberg.

Kuesebauch, Karl, 1931. 
Neue Methode zur Wollfeinheits-bzw. Wolldickenbestimmung, sowie zur Guetebeurteilung nach Faserlaenge und Dicke. 
Melliand Textilberichte, XII Band, Lieferung 1, S. 21-23. Lieferung 2, S. 97-100.

Measurement of Fibre and Yarn Diameters by the Diffraction Method. 
Jour. Text. Inst. 23: T55-T70.

McMurtrie, William, 1886. 
Report upon an Examination of Wools and other Animal Fibers. 

Measurement of Fiber Diameters by the Diffraction Method. 

Mentzel, O., 1892. 
Mentzel's Schafzucht. Dritte neubearbeitete Auflage. 
Berlin: Verlag von Paul Parey, S. 246.

Nathusius, W. v. —Koenigsborn. 1866. 
Das Wollhaar des Schafes in histologischer und technischer Beziehung mit vergleichender Beruecksichtigung anderer Haare und der Haut. 

Parry, C. H., 1806. 
Cited from Barker: 1921, page 42.

Pilgram, 1826. 
Cited from McMurtrie: 1886, page 47. 
Probst: 1926, page 194. 
Probst, E., 1926.
Die Feinheitsbestimmung des Wollhaares.
VI: 3: 403-488.

Roberts, J. A. F., 1927.
A New Method for the Determination of the Fineness of Wool and of the Fleece.

Roberts, J. A. F., 1930.
Fleece Analysis for Biological and Agricultural Purposes.
I. The Average Fineness of a Sample of Wool.

Rohde, O., 1856-1857.

Schmedel, J., 1925.
Cited from Barker: 1931, page 75.

Skiadan, 1831.

Smith, L. S.
The Determination of Fineness of Wool by Weight.

Thaer, 1831.

Thaer und Kleinert, 1847.


Voigtlaender, 1815.

Correlation and Machine Calculation. Revised by G. W. Snedecor.

Treatise Respecting Wool and the Construction of Worsted Fabrics—to Find the Average Diameter of Fibre.
Cited from Roberts: 1930, page T129.

Winckler, 1821.
Cited from Probst: 1926, page 188.

Young, 1824.