NBSIR 73-136

Measurements of Cylindrical Standards

Ralph C. Veale

Institute for Basic Standards
National Bureau of Standards
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U. S. DEPARTMENT OF COMMERCE
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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Introduction

Cylindrical standards may be sent to the Bureau for calibration listed as cylinders, rolls, plugs, plug gages, wires, thread wires, plain setting plugs or possibly other names. Regardless of what they are called, they can generally be put in one of two categories: (1) thread measuring wires and (2) other cylinders.

It is necessary to establish which they are because the reported value of most thread wires is not the true diameter but a deformed diameter to approximate the deformation that will occur when the wire is used to measure a thread. A separate manual has been prepared on how to measure thread wires, NBS Report No. 10 987. In almost all cases they will be compared to two sets of NBS master wires.

The second category can be further divided into two groups: the first being those cylinders for which we have master cylinders and the second, those for which we do not. At the present time, we have only one set of calibrated master cylinders consisting of 16 cylinders from 1/16 inch to 1 inch in increments of 1/16 inch. We also have another set which has never been calibrated consisting of decimal inch sizes. They go from 0.05 inch to 0.3 inch in increments of 0.05 inch and from 0.3 inch to 1 inch in 0.1 inch increments. This set will be calibrated in the near future.

In both cases the measurement technique is essentially the same, i.e. we compare the unknown (or unknowns) to two masters, one master serving as the restraint and the other as a check. In all cases a gage block combination will serve as the restraint and the check will be either a gage block combination or an NBS master cylinder. The latter is felt to be more desirable in that it is certainly faster and it allows us to maintain a history of our cylindrical standards. A set of cylindrical check standards enables us to detect systematic errors that could be missed using two gage block combinations. The disadvantage of the system is that until we build up a history of the cylinders, we know the length of the gage block more accurately than we know the diameter of the cylinder.

This is not to say that the preceding method is the only way cylinders can be measured. There are interferometric techniques using the thread wire interferometer or ball interferometer and a polychromatic viewer. Work has been done showing that the Zeiss Optimeter and a fringe counter can be used. Cylinders can be and often are calibrated with a gage block comparator. Commercial instruments can be bought specifically for cylinder measurement which employ a variety of both optical and mechanical techniques. In principle, all of them work but the instruments must be properly constructed, considerable care must be taken in making the measurements and all the proper corrections must be made. A common error is to use a comparator with ball contacts to measure a cylinder by comparing it to a gage block and not apply a deformation correction. The difference between ball to plane and ball to cylinder deformation is not always trivial, especially where the probe diameter is nearly the same size or larger than the cylinder. As an example, 2.2 microinches must be added to the value of a 1/8 inch steel cylinder which has been measured in this manner under a one pound force assuming the comparator is of the single probe type having a diamond contact with a radius of curvature of 0.0625 inch.[1]

It is our belief that the method described below is the best method currently available at the Bureau. It is obviously impossible to maintain a set of masters for every conveivable size that might come in, so our measuring process will be described assuming the cylinder is an odd size.

Measurement Procedure

The cylinder is first examined by taking Talyrond* traces. One may find the out-of-roundness so bad that an accurate measurement makes little sense. In this case, one stops and consults

*Certain commerical equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

with the customer on the best course to take. No strict rules can be given other than it must be remembered that the uncertainty of the measurement cannot be smaller than the model ambiguity (see appendix V). The model ambiguity can usually be reduced, however, by defining the diameter to be measured.

Assuming the quality of the cylinders is reasonably good, three traces should be made on each cylinder -- at the center and about 1/16 inch from the ends. Here again, there may be exceptions such as the NBS Pressure Section will often specify exactly how many and where they want traces made. The next step is to measure the variation in diameter along the cylinder. This is done using the same machine that will be used to make the diameter measurement -- a modified Pratt and Whitney measuring machine. The ways of the modified Pratt and Whitney have been carefully scraped so that the headstock can be moved without appreciably altering the parallelism of the jaws. One inch of travel can be obtained with the screw without moving the headstock.

The regular tailstock has been replaced by one having flexure springs which give very nearly linear motion over a short range. The measuring force is set by a dead weight placed on the pan under the machine rather than the more common but less accurate coil spring. When setting the machine force, the transducer is adjusted with no weight on the pan until the dial reads zero.

Movement of the left anvil moves the transducer pickup. The signal is amplified and displayed on the meter of the amplifier. On the low scale each division is two microinches with an 80 microinch range and each division on the high scale is 1/2 microinch with a 20 microinch range. Using the appropriate scale of the meter, the jaws are brought to the correct separation either by turning the screw or moving the headstock.

Measurements are then made at several places along the cylinder to determine the variation in diameter from the midpoint. In some cases, we will report all of these values and in others it is sufficient just to give a maximum value. If we know how the cylinder being measured will be used, we can usually make this decision with no difficulty. As an example, suppose the cylinder being calibrated will be used only to calibrate other cylinders. Then it is apparent that one can define a gage point to be used, which will usually be at the center. If there is an out-of-roundness problem, the plane of measurement can also be defined. In this case, the diameter at the end is of no importance as long as they are used only for transfer standards. On the other hand, if the cylinder is to be used as a go or no go plug gage then the end value would be very significant. The rule that we follow is to give the customer as much information about the cylinder as is economically feasible. We try to avoid doing work that is not needed but we don't withhold information that has been gathered. If we are uncertain as to what the customer wants or how they are to be used, a phone call is made to the person who will be using our report.

Having decided that we want to measure the cylinder to the best reasonably obtainable accuracy, we first get a value accurate to about 50 microinches by measuring it in a standard measuring machine. A combination from a grade 2 set of gage blocks is then wrung to the nearest 0.0001 inch of that size and we again measure the cylinder by comparing it to the combination using the modified Pratt and Whitney. Some of the blocks may deviate appreciably from nominal so we use the corrections listed in the calibration report. This measurement which is not taken with any great amount of care will give a value for the cylinder which is accurate to about 15 or 20 microinches.

From our grade 1 sets, we then wring two more combinations such that they are within 25 microinches or less of what we expect the cylinder to be. Of course if we are measuring class XXX gages, we can safely assume that the actual size will be very close to the nominal size and we can skip the first two steps. We also maintain a fractional gage block set so fewer blocks are required to be wrung together in measuring fractional size cylinders.

It is very difficult to wring blocks whose thickness is less than 0.1 inch and the wringing of such sizes should be avoided if possible. One way to avoid combinations made with thin blocks is to include another block as part of the test item. Suppose we had a 0.038 wire to measure, we could then choose a 0.140 as our nominal and compare a 0.102 block and the wire to the 0.140 block. There are of course other combinations that would work equally well. The diameter of the wire in this case would be the measured value minus the actual value of the 0.102 block. The term "block combinations" is used here to mean one or more blocks.

Measuring a one inch cylinder does not require wringing several blocks together; one simply selects two 1 inch blocks. If more than one block is used in our combination and if we are still trying to get the best reasonably obtainable value, the combination should then be measured rather than using the sum of the individual blocks. This work is currently being done at the Bureau by the Mass, Length and Volume Section. In a combination involving several blocks, it is necessary to check the parallelism as they are wrung together to insure that the complete stack will be parallel. Two blocks that are not parallel can often be made so by changing their relative positions. For small combinations up to about 0.5 inch, we can do this on the Acme viewer which is a Fizeau type interferometer. For the larger sizes, we ask the gage block group to both wring and measure the combination.

While the combinations are being measured, the measuring machine is checked. The amplifier is not solid state and can change with time, therefore, it is calibrated often, usually before starting any new job. This is done by using special brass fixtures which are kept with the machine. They are pressed over the anvils of the measuring machine and rotated slightly until they feel firm. One fixture has three balls attached to the end and the other fixture has one. This contact system is better for calibrating the amplifier than wringing in that it is more accurate and much faster. Two gage blocks are chosen such that their difference is slightly less than full scale reading. The low scale is usually used as its resolution is adequate and the range on the high scale is often too small. Past experience has shown that the scale is linear. The difference between the blocks is then measured and the magnification factor, K, is the actual difference between the blocks divided by the measured difference.

Next, after removing the ball fixtures, the anvils are stoned to remove any burrs. A special stone (a gage block stone whose faces are parallel) is used. Both the stone and anvil are cleaned and the stone is brought on scale as if we were going to measure it. The stone is then moved in a circular path parallel to the jaws until it seems to wring. Occasionally a burr will appear on the jaws that cannot be removed with the stone but requires a diamond lap. This is done only by someone familiar with lapping techniques.

A set of optical parallels is then used to verify that the faces are flat and parallel. Any value for either flatness or parallelism error greater than 2 microinches is considered excessive. As a final check, a gage block should easily wring to either of the jaws. The magnification factor, the date and any changes made to the machine are recorded in a log book.

How accurately we measure the temperature while making the measurements depends on the size and composition of the test cylinder. The linear coefficient of thermal expansion is about 11.5 parts per million per degree Celsius for steel and varies from near zero for some of the ceramic materials such as Cervit to around 30 parts per million for some metal alloys. If we are measuring a 0.1 inch or less steel cylinder, we can safely ignore temperature when working in our temperature controlled rooms. If we are measuring a two inch carbide piston using steel gage blocks, we not only must measure the temperature of each individual piece accurately, but we also need to know the coefficient of expansion for each of the materials.[1]

Most cases will lie between these two extremes and a mercury thermometer and "soak plate" are adequate. The gage blocks, cylinders

1. Appendix IV lists the coefficient of most of our blocks.

and thermometer are left on the "soak plate" to equalize. They should be covered with a clean towel to minimize the effect of uneven radiant heating. The transducer is a source of heat, so the soak plate should be placed away from the tailstock. Equations are available to determine the time to achieve temperature equalibrium, but the time is a function of so many variables that it is impractical to compute it in each case. When measuring pieces of dissimilar metals, allow 10 to 20 minutes for the smaller sizes and about two or three hours for a one inch cylinder. Less time is required if all the items are of the same metal and more if the test item has a low thermal conductivity such as glass.

Data Analysis

There are many ways that the data can be taken, but our statistical group feels that the best system when we have from one to three test items is a permutation shown in the following diagram where #1 is the master block, #2 is the check standard and #3 is the test cylinder and R is the reading of the measuring machine.

R1 #1	R2 #2	R3 #3
R4 #2	R5 #3	R6 #1
R7 #3	R8 #1	R9 #2

If there are two test cylinders, the reading would be a 4 x 4 matrix and a 5 x 5 matrix for three test items. Each set must be completed without interruption using approximately the same length of time for each reading.

Tongs should be used to handle the blocks and cylinders while making the measurements. A bit of practice is necessary to develop the technique of picking up a gage block combination with tongs and inserting it between the jaws in a manner such that the block wrings to each jaw. It is best to first put just the edge of the block between the jaws then move it to the center with the same motion used to wring a gage block to a platen. When the measuring force is one pound or under, increasing the force with another pair of tongs by pushing the left anvil against the block while centering it seems to give a tighter wring. It is customary to use a one pound force for all the measurements except where there is some logical reason not to such as a small copper wire where the force might permanently deform the wire. The cam release which moves the left anvil to the open position must be opened and closed at least once before making the first measurement. Also after moving the right anvil with the screw, it should be pushed hard to the right to remove the oil film between the thread flanks. If this is not done, the measurements will show a large drift with time.

The standard deviation of an individual reading will be between 1 1/2 to 2 microinches depending on the size of the piston and the skill of the operator; therefore, the number of sets of readings one must take will vary. It may be necessary to take as many as ten sets (3 x 3 matrix) to keep the random component of the transfer under 1 microinch which is what we usually aim for.

A computer program is used to analyze the data. The program requires a temperature value for each set of readings. Also, it requires the measuring force, magnification factor, master and check standard values and the type of material and coefficient of expansion for both the blocks and the piston.

If a computer is not available, the values of the diameters can still be determined using a slide rule or desk calculator. The readings are first multiplied by K to get what the reading would have been if there were no error in the amplifier. The product of the size, coefficient of thermal expansion and deviation from nominal 20° Celsius is subtracted from each value to get what the reading would have been if all the pieces were at exactly 20°. Next, the amount of deformation is added to each reading on a cylinder to get the undeformed diameter. The deformation equation that we are now using is the empirically derived Bochmann equation although many feel its values are subject to question, especially for very small diameter cylinders. This problem is being investigated and we will probably soon be converting to a theoretical equation. Because line contact is involved, the deformation in most cases is small and an error of 20 to 30 percent is negligible. The Bochmann equation is:

$$M = C \bullet \frac{P}{L} \sqrt[3]{\frac{1}{D}} \qquad C \cdot \frac{P}{L} \left(\frac{1}{D} \right)^{1/3}$$

where M is the total deformation, C is a constant depending on the material, P is the force in pounds, L is the length of contact and D is the diameter in inches. The value for C that we use is $.22. \times 10^{-6}$ for a steel cylinder and $.170 \times 10^{-6}$ for a carbide cylinder.

Because of the stiffness of the flexure springs, the actual measuring force is the same as the pan weight only when the reading is zero. The total low scale is 0.75 ounce. What this means is that if the machine is set for one pound and the reading on a cylinder is + 20 microinches, the actual force is one pound plus 20/80 x .75 ounces or about 16.2 ounces. The computer program takes this into account; however, because it is such a small correction, it can be safely ignored when doing the calculations by hand.

The last step in calculating the piston diameter is to average all the values. The difference between the test and the master is subtracted from the best value of the master to get the cylinder diameter. The same is done for the test standard. If the test standard is not within 3 microinches of its best value, the measurement set should be considered out of control and not used.

Computing a standard deviation for an individual reading involves a considerable amount of work so it is easier to do several sets and compute a standard deviation of each set which can be done from the familiar equation.

$$S = \sqrt{\frac{\Sigma(X_i - \bar{X})^2}{N - 1}}$$

If the standard deviation is greater than two microinches, it means that not enough care is being taken in making the measurements. At least six sets of readings (five degrees of freedom) must be taken for the standard deviation to be meaningful. In doing a 5 x 5 matrix, we might take a lesser number of sets and perhaps just make an estimate of the standard deviation from the range.

The accuracy statement in the test report should list the total uncertainty as the sum of the three standard deviation random component of error of the measuring process and the additional systematic errors involved. The random component is computed from the data but estimating the systematic errors involves a combination of science, art and guesswork. The block combinations used in our laboratory carry an estimated uncertainty of 1 microinch. When added to the random component of error, this yields an uncertainty of about two microinches.

There is some uncertainty in every correction that we have used. The values for the amplifier magnification factor, temperature, coefficient of expansion, machine force and Hertzian correction are certainly not exact and contribute some error. The contributing factor of all these is a function of the size of the piece to be measured. A complete error analysis study could be made but this has not been done, therefore, we add an estimated half microinch to the uncertainty to account for these factors.

Another error is introduced by the lack of parallelism of the machine jaws; this error is independent of cylinder size. About one microinch is a reasonable guess for this, thus making the total uncertainty around 3 1/2 microinches.

Although there is no fixed format on exactly how a calibration report should be written, it should follow somewhat the example given in Appendix III. Appendixes I and II are examples showing one data set taken for a piston and the calculations used to arrive at its best value based on the one set of measurements.

References

[1] Hertz, H., Miscellaneous Papers (translated by Jones, D. E., and Schott, G. A.). Macmillan and Co., Ltd., London, 1896 pp. 146-183. Contains English translations of the papers from Journal Reine und angewandte Mathematik (Crelle). Vol. 92, 1881, pp. 156-171, and Verhand Vereins Beforder Gewerbefleisses, Nov. 1882.

APPENDIX I

Cylinder Measurement Data Sheet

0.99995 Carbide

Set Number 1 L 78 X 4

#1 Master: 0.99995 set 5617 .10005, .1009, .149, .65

#2 Check: 0.999975 set 4620 .100075, .1009, .149, .65

K Factor: 1.075

Temp: 19.73

Force: 16 oz

-17 (1)	12 (2)	1 (3)
16 (2)	3 (3)	-13 (1)
2 (3)	-11 (1)	19 (2)

	Best Value	Coefficient of Thermal Expansion	Deformation Constant
#1	0.999948^{0}	11.7×10^{-6}	—
#2	0.999979^{8}	11.7×10^{-6}	—
#3	—	5×10^{-6}	$.170 \times 10^{-6}$

APPENDIX II

		Reading	Corrected for Amplifier	Corrected for Temperature	Corrected for Deformation
R_1	1	−17	−18.3	−15.1	−15.1
R_2	2	12	12.9	16.1	16.1
R_3	3	1	1.1	2.4	2.8
R_4	2	16	17.2	20.4	20.4
R_5	3	3	3.2	4.5	4.9
R_6	1	−13	−14.0	−10.8	−10.8
R_7	3	2	2.2	3.5	3.9
R_8	1	−11	−11.8	−8.6	−8.6
R_9	2	19	20.4	23.7	23.7

$$-.27 \times .9999 \times 11.7 = -3.2$$

$$-.27 \times .9999 \times 5.0 = -1.3$$

$$M = .170 \times 10^{-6} \times \frac{1}{.375} \sqrt[3]{\frac{1}{.9999}} = .453 \times 10^{-6} \cong .4\mu''$$

	Average	Difference
#1	−11.5	
#2	20.1	+31.6
#3	3.9	+15.4

$$\begin{array}{r} 0.999948^{0} \\ +\ 31^{6} \\ \hline 0.999979^{6} \end{array} \qquad \begin{array}{r} 0.999948^{0} \\ +\ 15^{4} \\ \hline 0.999963^{4} \end{array}$$

	Measured Value	Accepted Value
Check Standard	0.9999796	0.9999798
Test	0.9999634	

APPENDIX III

Report of Calibration L----

For: One Carbide Piston

Submitted by: The Super Accurate Gage Co.
P. O. Box 777
Fort Gary, Montana

The diameter of the piston was measured midway between ends in the plane passing through the scribed index marking. Variations from the midpoint diameter at either end in the same plane were also measured. The values at 20° Celsius are as follows:

Midpoint Diameter inches	Deviation from Midpoint Diameter microinches	
	1/16" from marked end	1/16" from unmarked end
0.9999634	+1.4	-0.8

The measurement was made by comparing it to two gage block combinations of known length using one as the restraint and the other as the check. The three standard deviation for random error was 0.9 microinch. Additional sources of error are believed not to exceed 3 microinches giving a total uncertainty of 3.9 microinches.

Talyrond traces are enclosed showing the profile of the piston at the measured positions.

Measurements made by ______________________________

For the Director,

Chief
Section
Division, Institute

P. O. No.
Test No.
Date:

APPENDIX IV

Manufacturer or Trade Name	Material	Coefficient of Linear Thermal Expansion (Parts per Million Per Degree Celsius)*
	Quartz	0.4
Brown & Sharp, C.E.J.	Steel	11.2
Ellstrom	Chromium plated on Steel	11.5
DoAll	Steel	11.7
DoAll	Stainless	10.3
Fonda	Chrome Carbide	8.1
Fonda	Steel	11.5
Fonda	Tungsten Carbide	6.5
Fonda	Tantalum carbide and tungsten carbide	4.6
Hommel	Steel	11.7
Jansson	Steel	11.5
C.E.Johansson	Steel	11.5
Matrix	Steel	10.7
Pratt & Whitney	Chrome Carbide	8.1
Pratt & Whitney	Steel	11.5
Pratt & Whitney	Tungsten carbide	4.8
Van Keuren	Steel	11.5
Webber	Chrome Carbide (new)	8.4
Webber	Steel	11.7
Webber	Tungsten Carbide	6.5
Webber	Chrome Carbide (old)	7.2
Zeiss	Steel	11.5

* Used in the NBS Optical Physics Division.

APPENDIX V

Investigated Object:	The material thing which is the subject of the measurement process.
Concept:	The parameters, length, mass, volume, etc., which appear in the equations of theoretical physics.
Unit:	The arbitrary scale on which the magnitude of the parameter is expressed.
Unit Error:	The difference between the scale on which the magnitude of the parameter is expressed and the scale on which it (arbitrarily) should be expressed.
Model:	The theory which relates a material property of the investigated object to the concept the object is presumed to embody and predicts the signal produced by the object.
Signal:	That physical property or influence by which the measuring algorithm detects and measures the embodiment of the concept of interest in the investigated object.
Model Ambiguity:	The difference between the <u>embodiment of the concept in the investigated object to that embodiment presumed in the Model</u>; i.e. the difference between the signal observed and the signal predicted.

Measurement Algorithm: The prescription by which the magnitude of desired property is extracted from the object. It includes the instrument, all relevant procedures, environmental factors and calculations, etc., involved.

Algorithm Error: The difference between the assumed response of the measurement algorithm to the signal from the object and its response during the measurement.

Measurement Station: An independent location, apparatus or environment where a measurement algorithm is implemented.

Prototype: An investigated object that is its own Model.