ASME B89.1.5-1998

MEASUREMENT OF PLAIN EXTERNAL DIAMETERS FOR USE AS MASTER DISCS OR CYLINDRICAL PLUG GAGES

AN AMERICAN NATIONAL STANDARD

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The American Society of
Mechanical Engineers

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The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

FOREWORD

(This Foreword is not part of ASME B89.1.5-1998.)

It was beyond our imagination that a standard was not yet in place when we, Working Group 1.5 of the ASME B89 Standards Committee, were formed. Today we are humbled by the complexity and work necessary to complete the task. We consider this a start to an ongoing need to improve our techniques in outside diameter measurement. With this Standard we hope to improve correlation in measurement across the country and the world. Revisions to come will only improve the state of the art.

This Standard is dedicated to Dr. Richard Zipin, Eli Whitney Laboratory, Dayton, Ohio. It was approved by the American National Standards Institute on March 4, 1998.

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Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
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MEASUREMENT OF PLAIN EXTERNAL DIAMETERS FOR USE AS MASTER DISCS OR CYLINDRICAL PLUG GAGES

1 SCOPE

This Standard is intended to establish uniform practices for the measurement of master discs or cylindrical plug gages to a given tolerance using vertical or horizontal comparators and laser instruments. The Standard includes requirements for geometric qualities of master discs or cylindrical plugs, the important characteristics of the comparison equipment, environmental conditions, and the means to assure that measurements are made with an acceptable level of accuracy. This Standard does not address thread or gear measuring wires.

2 DEFINITIONS

circularity (roundness): a condition of a surface of revolution where:

(a) for a cylinder or cone, all points of the surface intersected by any plane perpendicular to a common axis are equidistant from that axis;

(b) for a sphere, all points of the surface intersected by any plane passing through a common center are equidistant from that center.

cosine error: the measurement error in the measurement direction caused by angular misalignment between a measuring system and the gage or part being measured.

cylindricity: a condition of a surface of revolution in which all points of the surface are equidistant from a common axis.

diameter: the length of a straight line through the center of a circular cross section of an object. In the case of a cylinder, the line is considered to be perpendicular to the axis.

dimensional stability: ability of an object (e.g., measuring instrument or workpiece) to maintain its metrological characteristics with time.

NOTES:

(1) Where stability with respect to a quantity other than time is considered, this should be stated explicitly.

(2) Stability may be quantified in several ways, for example:

(a) in terms of the time in which a metrological characteristic changes by a stated amount; or

(b) in terms of the change in a characteristic over a stated time.

discrimination (threshold): largest change in a stimulus that produces no detectable change in the response of a measuring instrument, the change in the stimulus taking place slowly and monotonically.

elastic deformation: the nonpermanent (reversible) change in the size or geometry of a part due to an applied force.

gage block: a length standard with rectangular, round, or square cross section, having flat, parallel opposing gaging faces.

NOTE: The surface finish of the gaging faces should be such as to allow gages to be wrung together.

index of refraction: for a given wavelength, the ratio of the velocity of light in a vacuum to the velocity of light in a refractive material.

NOTE: As used in this Standard, the material is air.

line contact: the zone of contact between a flat surface and a cylinder.

lobing: systematic variations in the radius around a part (measured in the cross section perpendicular to the axis).

master cylinder: a known-size cylinder used for setup for comparison to the gage being measured.

master disc: a cylinder of known size, with insulating grips, used to set or verify another gage. The tolerance is typically bilateral.

measurand: particular quantity subjected to measurement.

EXAMPLE: Diameter of a cylindrical gage at 20°C.

measurement force: the amount of force exerted upon the object being measured by a measuring instrument during the act of measurement. Measurement force is an important factor used in the calculations of elastic deformation.

microinch: one millionth of an inch, i.e., 0.000001 in., or 25.4 nm.

micrometer: one millionth of a meter, i.e., 0.000001 m, or approximately 39.37 μin.

modulus of elasticity: the ratio of unit stress to unit deformation for a particular material, within the limit of proportionality, i.e., $E = \sigma/\epsilon$.

NOTE: The modulus of elasticity is sometimes known as Young's modulus.

nominal coefficient of thermal expansion: approximate value (ISO VIM:1993 Section 5.3) for the coefficient of thermal expansion over a range from a temperature T to 20°C and denoted α_n for the part and α_{ns} for the reference standard. Estimated values for α_n and α_{ns} may be obtained from experiments on like objects, or from published data.

out-of-roundness: term used to describe a deviation from being round; its value is defined as the minimum radial separation between two concentric circles within which all points on the circular cross section lie.

out-of-straightness: the deviation of the straightness of a line is the minimum distance between two parallel lines that contain the line profile.

plug gage: a cylindrical outside diameter gage typically used to check holes for size or fit and function. GO and NOGO are typically used for high and low limit checks. Refer to ASME/ANSI B47.1 for designs.

point contact: the single point of contact when using a sphere or section of a sphere in a measurement.

NOTE: The idealized point becomes an area of contact under the measurement force.

Poisson's ratio: the ratio of the transverse unit deformation of a body to the unit deformation in length, within the limit of proportionality.

resolution (of a displaying device): smallest difference between indications of a displaying device that can be meaningfully distinguished.

NOTES:
(1) For a digital displaying device, this is the change in the indication when the least significant digit changes one step.
(2) This concept also applies to a recording device.

roundness: see *circularity*

straightness: the minimum distance between two parallel lines that contain the line profile.

surface texture: repetitive or random deviations from the nominal surface which form the pattern of the surface. Surface texture includes roughness, waviness, lay, and flaws.

taper: for the purposes of this Standard, taper is defined as the gradual increase or decrease in diameter over the full length of the gage.

thermal gradients: the rate of change of temperature as a function of another parameter.

NOTES:
(1) Temporal thermal gradient is the variation of temperature as a function of time, denoted by $\Delta T/\Delta t$, °C/h (or °F/hr).
(2) Spatial thermal gradient is the variation in temperature as a function of length, denoted by $\Delta T/\Delta L$, °C/m (or °F/in.).

uncertainty of measurement: parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES:
(1) The parameter may be, for example, a standard deviation (or a given multiple of it), or the half width of an interval having a stated level of confidence.
(2) See NIST Technical Note 1297 for additional information.

3 REFERENCES

This Standard has been coordinated as much as possible with the following standards and specifications. Unless otherwise stated, the latest issue is implied.

ASME B46.1-1995, Surface Texture (Surface Roughness, Waviness, and Lay)
ASME/ANSI B47.1, Gage Blanks
ANSI B89.3.1, Measurement of Out-of-Roundness
ANSI B89.6.2, Temperature and Humidity Environment for Dimensional Measurement
ASME Y14.5M-1994, Dimensioning and Tolerancing

ISO 1, Standard Reference Temperature

NIST Technical Note 1297, 1994 Edition, Guidelines for Evaluation and Expressing the Uncertainty of NIST Measurement Results

M. J. Puttock and E. G. Thwaite, "Elastic Compression of Spheres and Cylinders at Point and Line Contact," National Standards Laboratory Technical Paper No. 25, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, 1969

4 REQUIREMENTS OF MASTER DISCS AND CYLINDRICAL PLUG GAGES

4.1 General

The capability of measuring equipment and techniques to achieve a high order of precision in the calibration of master discs or cylindrical plug gages is limited by relevant features and conditions of the gage to be measured. These are discussed in paras. 4.2 through 4.8.

4.2 Design

The design and proportion specifications for gage blanks are given in ASME/ANSI B47.1.

4.3 Material

The material, including coatings or wear inserts, of master discs or cylindrical plug gage blanks shall be free from inclusions or other imperfections that would affect surface texture. The material shall respond to applicable hardening and stabilizing processes to permit finishing to the essential surface texture and to assure dimensional stability. Finished surfaces shall have a minimum hardness equivalent to 60 on the Rockwell C Scale. Master gages shall not be subjected to any quick aging or shock treatment as a check of stability.

4.4 Surface Texture

The surface texture shall be consistent with the class tolerance of the gage. Table 1 lists maximum roughness values expressed in arithmetic average (R_a) roughness values. ASME B46.1 shall be consulted for reference information.

4.5 Geometric Requirements

4.5.1 General. The diameter will be measured per para. 6 of this Standard. Typical acceptance criteria for geometric requirements are diameter measurements spaced approximately 90 deg apart in each of three planes: the midsection, and each end, located 1.6 mm ($^1/_{16}$ in.) from inside the ends of corner radii or chamfers.

Two-point diameter measurements will not detect the effect that odd-numbered or irregular lobing has on size. Diameter measurements taken at multiple locations may not fully detect ovality, even-numbered lobing, or straightness deviation.

If the gage is measured with nonstandard techniques, such as multiple-point methods or unusually wide plane anvils, the values in Table 3 may not be appropriate. The purchaser and the manufacturer should consult on acceptable limits in these cases.

The practical application of Table 3 would be to compare the measured size of a gage to the prescribed size plus (for GO) or minus (for NOGO) the tabulated tolerance (for bilateral gages, plus and minus one-half the tabulated tolerance). The measured size should fall within the size range thus specified. The practical application of Table 2 would be to compare all the measurements taken on a gage and find the difference between the largest and smallest measurements. The difference should not exceed the tabulated value.

NOTE: ASME Y14.5M RULE #1 (para. 2.7.1) DOES NOT APPLY DUE TO THE LIMITATIONS OF PRECISION MEASURING EQUIPMENT AND THE INABILITY TO CORRELATE COMPOSITE FORM DEVIATIONS WITH ABSOLUTE SIZE. (Perfect form at maximum material condition is not required.)

4.5.2 Roundness. Deviations in roundness can be determined at three planes (see para. 4.5.1) perpendicular to the axis of the gage, using a chart type precision spindle instrument. The out-of-round condition shall not exceed the value shown in Table 2. ANSI B89.3.1 shall be consulted for measurement information. Plug gages used other than as diameter masters, such as limit gages, shall be evaluated by criteria applicable to the intended use.

4.5.3 Straightness and Taper. Deviations from surface element straightness can be determined by making axial tracings approximately 90 deg apart using a profile type instrument. The determined value shall not exceed the tolerances listed in Table 2. Taper is measured as the gradual increase or decrease in diameter over the full length of the gage.

4.6 Face Perpendicularity of Master Discs

The faces of master discs are not required to be ground square to the gaging surface. However, proper measurement techniques must be followed (see para. 6).

4.7 Face Perpendicularity of Plug Gages

Plug gage ends are not required to be perpendicular (square) or controlled. Remove sharp edges to prevent damage to the product being measured and to provide for the user's safety. If depth steps are required, ends shall be ground. See Appendix C.

4.8 Tolerance Classes

Master discs and cylindrical plug gages are graded into classes identified by XXX, XX, X, Y, Z, and ZZ

TABLE 1 SURFACE ROUGHNESS LIMITS FOR MASTER DISCS AND PLUG GAGES

Diameter, in.		Tolerance Class, μin. (R_a)					
Above	To and Including	XXX	XX	X	Y	Z	ZZ
0.010	0.825	2	2	4	4	8	10
0.825	1.510	2	2	4	8	12	14
1.510	2.510	4	4	8	12	16	16
2.510	4.510	4	4	8	12	16	16
4.510	6.510	6	6	12	16	16	16
6.510	9.010	8	8	16	16	16	16
9.010	12.010	8	8	16	16	16	16
12.010	21.010	16	16	16	16	16	16
Diameter, mm		**Tolerance Class, μm (R_a)**					
Above	**To and Including**	**XXX**	**XX**	**X**	**Y**	**Z**	**ZZ**
0.254	20.96	0.05	0.05	0.10	0.10	0.20	0.25
20.96	38.35	0.05	0.05	0.10	0.20	0.30	0.36
38.35	63.75	0.10	0.10	0.20	0.30	0.41	0.41
63.75	114.55	0.10	0.10	0.20	0.30	0.41	0.41
114.55	165.35	0.15	0.15	0.30	0.41	0.41	0.41
165.35	228.85	0.20	0.20	0.41	0.41	0.41	0.41
228.85	305.05	0.20	0.20	0.41	0.41	0.41	0.41
305.05	533.65	0.41	0.41	0.41	0.41	0.41	0.41

which determine the total applicable tolerance for a given size. Master discs are to have the total tolerance applied bilaterally (i.e., nominal size with one-half the tolerance applied plus and one-half the tolerance applied minus). Unless otherwise specified, cylindrical plug gages are to have the tolerance all plus on the GO gage and all minus on the NOGO. Gages marked with class identification shall conform to these tolerances, as well as to the other requirements in para. 4.5. Table 3 lists class tolerances.

5 REQUIREMENTS FOR USING REFERENCE GAGE BLOCKS

5.1 Length

To achieve optimum accuracy, the calibrated deviation of each gage block in the stack shall be summed, then used in the measurement process. Good temperature control becomes increasingly important as the gage diameter increases (see para. 7.4).

5.2 Material

It is recommended that the gage block(s) be made of the same material as the gage to minimize variations due to differences in contact deformation and the nominal coefficient of thermal expansion.

6 CALIBRATION OF AN IDENTIFIED DIAMETER

Cylinders shall be measured in a manner consistent with sound metrological principles. An associated measurement uncertainty must accompany each measurement. Some acceptable methods are described in this paragraph.

6.1 Measurements Using a Mechanical Comparator

Cylindrical gages are usually measured by comparing them to a reference cylinder or, more often, to a gage block or combination of gage blocks. The method of measuring the difference in diameter between the

TABLE 2 LIMITS FOR ROUNDNESS, TAPER, OR STRAIGHTNESS FOR MASTER DISCS AND PLUG GAGES

Diameter, in.		Tolerance Class, µin.					
Above	To and Including	XXX	XX	X	Y	Z	ZZ
0.010	0.825	5	10	20	35	50	100
0.825	1.510	8	15	30	45	60	120
1.510	2.510	10	20	40	60	80	160
2.510	4.510	13	25	50	75	100	200
4.510	6.510	16	33	65	95	125	250
6.510	9.010	20	40	80	120	160	320
9.010	12.010	25	50	100	150	200	400
12.010	15.010	38	75	150	225	300	600
15.010	18.010	50	100	200	300	400	800
18.010	21.010	63	125	250	375	500	1000

Diameter, mm		Tolerance Class, µm					
Above	To and Including	XXX	XX	X	Y	Z	ZZ
0.254	20.96	0.13	0.25	0.51	0.89	1.27	2.54
20.96	38.35	0.20	0.38	0.76	1.14	1.52	3.05
38.35	63.75	0.25	0.51	1.02	1.52	2.03	4.06
63.75	114.55	0.33	0.64	1.27	1.91	2.54	5.08
114.55	165.35	0.41	0.84	1.65	2.41	3.18	6.35
165.35	228.85	0.51	1.02	2.03	3.05	4.06	8.13
228.85	305.05	0.64	1.27	2.54	3.81	5.08	10.16
305.05	381.25	0.97	1.91	3.81	5.72	7.62	15.24
381.25	457.45	1.27	2.54	5.08	7.62	10.16	20.32
457.45	533.65	1.60	3.18	6.35	9.53	12.70	25.40

GENERAL NOTE:
Any single geometric error, such as those outlined in this Table (roundness, taper, or straightness), shall not exceed the listed values. The tabulated values are one-half of the total diameter tolerance applicable for the class of gage.

reference gage block and the test cylinder consists of measuring the displacement of one or both of the contacts that touch the gage. The various types of contact geometries are flat-to-flat, flat-to-sphere, sphere-to-sphere, and flat-to-cylinder. Each configuration has both advantages and disadvantages. Diagrams of the setups are in Fig. 1. Each method will be discussed individually.

6.1.1 Flat-to-Flat [Fig. 1, Illustration (a)]. The flat-to-flat method is the most common technique. A standard measuring machine is used as the comparator. The difference between the reference gage block and the test cylinder is obtained through a lead screw, laser, line scale, or other appropriate method used to measure the linear displacement of the moving contact.

Errors in the lead screw or scale can be minimized by choosing a reference gage block of the same nominal value as the test cylinder. Some flatness errors and lack of parallelism always exist in the contacts of any measuring machine. The lack of flatness and parallelism of the contacts is a limitation of this method. Figure 2 shows some of the possible geometric conditions that can cause errors when comparing a gage block to a cylinder.

When measurements are made with a comparator having two flat, parallel anvils, the cylinder may be supported with its axis in either a horizontal or vertical position. When a large cylinder is measured with its axis in the horizontal position, care shall be taken to insure that the friction of the cylinder on the holding fixture does not introduce an error. If a large cylinder is measured in a vertical orientation, it shall be supported on a roll to insure that the cylinder's axis is parallel to the contacts. The reason for the roll is because the

TABLE 3 DIAMETER TOLERANCES FOR CLASSES AND SIZES FOR MASTER DISCS AND PLUG GAGES

Diameter, in.		Tolerance Class, μin.					
Above	To and Including	XXX	XX	X	Y	Z	ZZ
0.010	0.825	10	20	40	70	100	200
0.825	1.510	15	30	60	90	120	240
1.510	2.510	20	40	80	120	160	320
2.510	4.510	25	50	100	150	200	400
4.510	6.510	33	65	130	190	250	500
6.510	9.010	40	80	160	240	320	640
9.010	12.010	50	100	200	300	400	800
12.010	15.010	75	150	300	450	600	1200
15.010	18.010	100	200	400	600	800	1600
18.010	21.010	125	250	500	750	1000	2000
Diameter, mm		**Tolerance Class, μm**					
Above	**To and Including**	**XXX**	**XX**	**X**	**Y**	**Z**	**ZZ**
0.254	20.96	0.25	0.51	1.02	1.78	2.54	5.08
20.96	38.35	0.38	0.76	1.52	2.29	3.05	6.10
38.35	63.75	0.51	1.02	2.03	3.05	4.06	8.13
63.75	114.55	0.64	1.27	2.54	3.81	5.08	10.16
114.55	165.35	0.84	1.65	3.30	4.83	6.35	12.70
165.35	228.85	1.02	2.03	4.06	6.10	8.13	16.26
228.85	305.05	1.27	2.54	5.08	7.62	10.16	20.32
305.05	381.25	1.90	3.81	7.62	11.43	15.24	30.48
381.25	457.45	2.54	5.08	10.16	15.24	20.32	40.64
457.45	533.65	3.18	6.35	12.70	19.05	25.40	50.80

base of the cylinder is not necessarily perpendicular to its axis. If the cylinder is small, no special care is required.

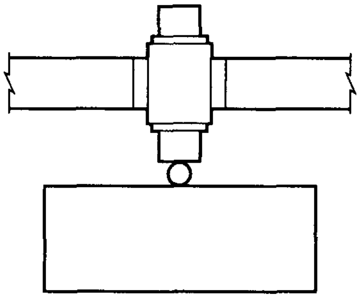
The most common displacement sensor is a linear variable displacement transducer (LVDT). Systems that use displacement sensors with limited range (e.g., LVDTs) have the disadvantage that the reference gage block must be nearly the same size as the cylinder. This requires the use of gage blocks wrung together. Since the uncertainty of the value for an individual gage block is less than that for a stack, systems that have longer ranges (e.g., lasers) have some advantages. A machine equipped with a displacement laser interferometer can measure cylinders without requiring a separate gage block or reference cylinder as a comparison standard for every cylinder size measured. Instruments using laser interferometers are sometimes called *absolute* measuring systems.

If a displacement interferometer system is used, corrections must be made for the index of refraction of the air and the deviation of the test cylinder from the standard reference temperature of 20°C. Another limitation of the absolute system is the difficulty in achieving a zero setting. Because of the presence of dirt, it is almost impossible to get a reliable zero by bringing the two flat contacts together. A small gage block is usually used to get the initial reading.

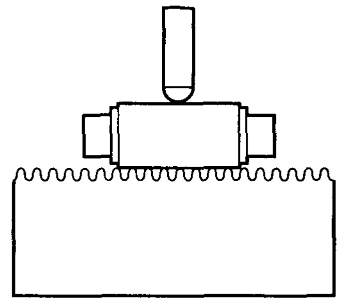
Although small, elastic deformation of a cylinder between two flat, parallel contacts is not negligible. A contact force between 1 and 4 N (Newtons) is recommended. In measuring cylinders more than 100 mm in diameter, increasing the force to 10 N may be desirable. Equations are available to calculate the elastic deformation of a cylinder between flat, parallel contacts.

Table 4 shows, in nanometers, the total deformation for a steel cylinder between flat, parallel, 9.5 mm carbide contacts for a few selected sizes and forces. If a cylinder is used as a reference, no correction is needed. The values were computed using the equation in Puttock and Thwaite's CSIRO Technical Paper No. 25.

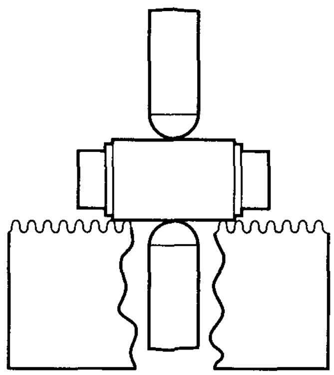
6.1.2 Flat-to-Sphere [Fig. 1, Illustration (b)]. The flat-to-sphere technique is another common method for measuring reference cylinders. In most situations,



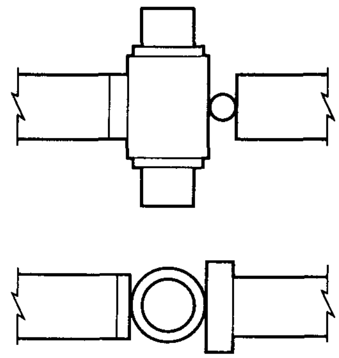
(a) Flat-to-Flat



(b) Flat-to-Sphere



(c) Sphere-to-Sphere



(d) Flat-to-Cylinder

FIG. 1 FOUR COMMON METHODS OF MEASUREMENT

TABLE 4 DEFORMATION OF A STEEL CYLINDER BETWEEN FLAT CARBIDE CONTACTS (Deformation Values in Nanometers)

Cylinder Size, mm	Measuring Force, N					
	0.5	1	2	4	8	10
1	4	8	16	31	59	73
10	4	7	14	27	52	64
25	4	7	14	26	49	61

GENERAL NOTE: 1 N (Newton) is approximately 4 oz and 25.4 nm (nanometers) equals 1 μin.

it provides for a more accurate measurement than the flat-to-flat technique. This method is also popular because it uses a gage block comparator that is common in most gage labs. The bottom flat consists of a serrated anvil that allows dirt to escape into the grooves. The serration is not an absolute necessity if care is taken to maintain a clean working area. Care must also be taken to maintain the flatness of the anvil. The movable probe on some gage block comparators consists of a sensor with a limited range of not more than a few micrometers; therefore, a gage block combination nearly the same size as the cylinder shall be used.

If a gage block stack is made to the exact nominal size of the cylinder, it introduces the cumulative errors of several gage blocks. If a single gage block close to the nominal size is used, the nonlinearity of the sensor may introduce errors.

Some skill is required to make this measurement because the maximum indicated reading must be recorded. Any other reading would represent the length of a chord rather than the diameter. A probe with a radius between 1 and 3 mm is recommended. The measuring force shall be approximately 1 N. This method does not work well for small cylinders, approximately 3 mm or less, due to the difficulty of finding the largest reading.

The difference in deformation between a ball and a cylinder, and between a ball and a gage block (or reference flat), must be calculated if the highest accuracy

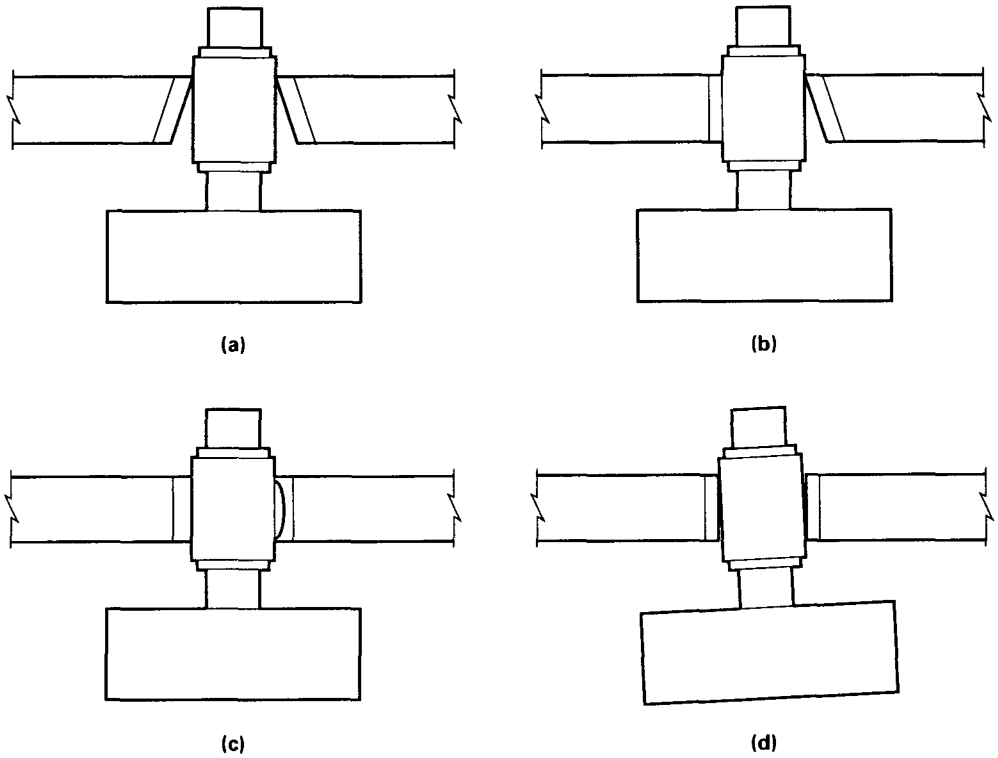


FIG. 2 POSSIBLE ERROR CONDITIONS OF FLAT-TO-FLAT CONTACTS

is desired. The deformation correction can often be ignored because it is small. In most cases the correction is less than 25 nm (nanometers) if similar materials are used. (See Table 5 for some representative values which were calculated from equations in Puttock and Thwaite's CSIRO Technical Paper No. 25.) If the gage block and cylinder are of dissimilar materials, it may not be safe to ignore the correction. The correction would be 70 nm for a steel cylinder compared to a chrome carbide gage block when using a 1 N force on a comparator having a diamond probe with a 1 mm radius.

A problem with computing elastic deformation exists when using a gage block comparator. When a spherical probe is used, a flat tends to wear on the bottom of the sphere. This means that accurate deformation corrections cannot be made. On the other hand, it makes the difference in deformation between the sphere-to-cylinder value and the sphere-to-flat smaller. Since the differences in deformation are small for similar materials, the flattening of the probe makes a small correction even smaller.

TABLE 5 DIFFERENCE IN DEFORMATION OF 2 mm DIAMETER DIAMOND BALL TO STEEL CYLINDER AND 2 mm DIAMETER DIAMOND BALL TO CHROME CARBIDE FLAT (Values in Nanometers)

Cylinder Size, mm	Measuring Force, N			
	0.25	0.5	1	2
3	30	48	76	121
12	24	38	60	96
25	23	36	57	90

GENERAL NOTE: 1 N (Newton) is approximately 4 oz and 25.4 nm (nanometers) equals 1 μin.

For this method, it is safe, in all but the most exacting measurements, to ignore the elastic deformation corrections. However, this is true only when the gage block and the cylinder are of the same material. When the reference gage block is not of the same material as the test cylinder, one shall either use a new probe, know that the probe is not worn, or compute the deformation by measuring it at different forces. Usually, when a low uncertainty is required (less than 0.1 μm), the only safe thing to do is to use a reference of the same material. Corrections can be computed using equations from Puttock and Thwaite's CSIRO Technical Paper No. 25.

Note that the flat-to-sphere method gives the diameter of the cylinder at a point on one side relative to a plane on the opposing surface. If the gage has imperfect geometry, one may get a different value than if, e.g., a point-to-point method were used. Figure 3 illustrates some of the problems imperfect geometry introduces when using this technique (see Appendix A).

As in the flat-to-flat method, it is possible to purchase instruments where the upper probe has a range of 100 or 200 mm. With this instrument, it is possible to get a zero setting without a gage block because the contaminant problem is less acute with a point-to-flat contact than with a flat-to-flat contact.

On some instruments of this type, if an attempt is made to move the cylinder under the probe to obtain a maximum reading, bending of the probe spindle will introduce errors into the measurement. The same precautions must be taken to correct for deformation as when using a standard gage block comparator.

If a laser interferometer is used as the measuring scale, one must correct for the temperature of the cylinder and for the index of refraction of the air if they deviate from standard metrological conditions.

6.1.3 Sphere-to-Sphere [Fig. 1, Illustration (c)]. If a gage block-style comparator with opposing contacts is available, measurements at a specified location can be made without concern for the geometric errors discussed in the single probe method. In this case, corrections for the difference in elastic deformation, although small, will be larger than in the flat-to-sphere contact because point contact will exist at both the top and bottom probes.

As in the flat-to-sphere contact, if the reference gage block and test cylinder are not of the same material, the deformation corrections will be much larger. The sphere-to-sphere technique also has the same potential for cumulative errors in a gage block stack and/or the transducer scale errors as in other methods.

Again, similar to the single ball contact, the danger exists that a flat spot will have worn on the ball contact if it has been used extensively. A flat contact means that accurate deformation corrections cannot be made. If the condition of the probe is unknown, one must use a gage block of the same material as the cylinder. Since this makes a small correction even smaller, it will be safe, in all but the most exacting measurements, to ignore the elastic deformation corrections. The probe geometry must be known, or experiments must be made to determine the deformation, if a reference of different material is used. Equations to compute elastic deformation are available in Puttock and Thwaite's CSIRO Technical Paper No. 25.

It cannot be assumed that the axes of the two probes are collinear. In fact, it is almost a certainty they will not be in line at all positions. Because of this lack of collinearity, the test cylinder must be aligned parallel to the plane that contains the axes of the two contacts. This orientation can be found by searching for the largest reading with the cylinder in various orientations. This orientation can then be marked. It is not necessary to make the search each time a measurement is made. A measurement made at any other orientation would represent the length of a chord rather than the diameter.

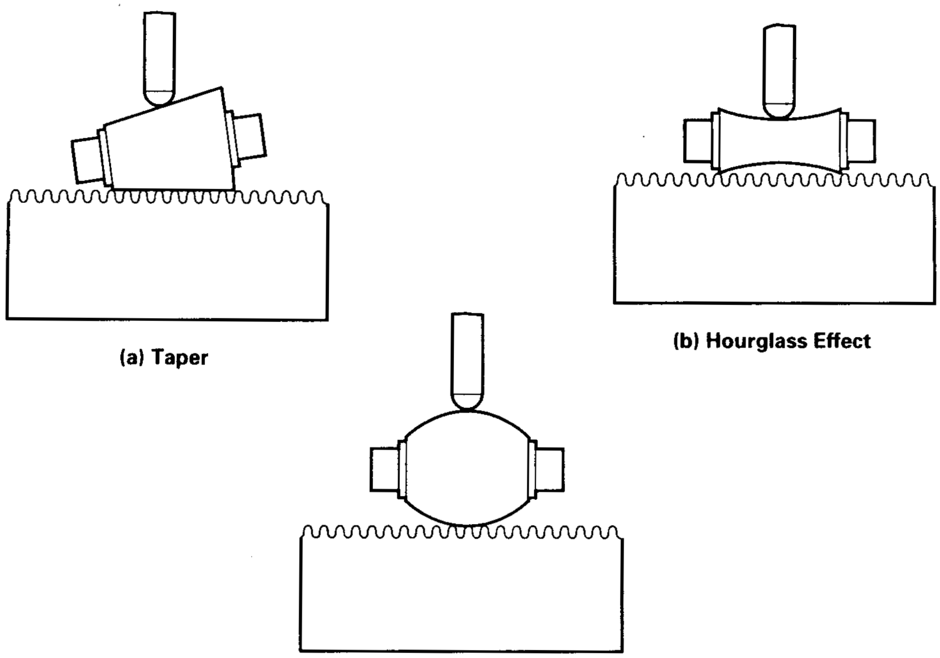
The sphere-to-sphere technique does not work well with small cylinders. It is very difficult to find the maximum diameter when the cylinder is less than 3 mm in diameter.

Dual contact gage block comparators that use a laser as the measurement sensor exist. If a displacement laser interferometer is used, then one must correct for the temperature of the cylinder and for the index of refraction of the air.

6.1.4 Flat-to-Cylinder [Fig. 1, Illustration (d)]. An instrument using the flat-to-cylinder technique, if equipped with a high accuracy transducer, offers the highest accuracy of any of the methods. One advantage of using this method is that it is relatively easy to establish full contact between a flat surface and a cylinder.

Although problems with contaminants getting between the two contacts can exist, flat-to-cylinder contacts are much less troublesome than flat-to-flat contacts. The flat-to-cylinder contact instrument is normally designed to be used as an absolute measuring instrument using a laser or precision line scale as the reference metric.

Unlike the other methods, the elastic deformation corrections using this method can never be ignored. The deformation between the line contact of a cylinder and a flat is small, but the deformation between two crossed cylinders is large. For example, the elastic deformation of a 3 mm steel cylinder measured between a 12 mm steel roll and a steel flat is approximately 240 nm. (See Puttock and Thwaite's CSIRO Technical Paper No. 25.)



(a) Taper

(b) Hourglass Effect

(c) Barrel Shape

FIG. 3 VARIOUS ERROR CONDITIONS WITH IMPERFECT GEOMETRY

A disadvantage of this method is that the elastic constants (Young's modulus and Poisson's ratio) of the material of the cylinder being measured must be known. For most materials, these constants are readily available in engineering handbooks. Instruments of this type, which allow the measuring force to be changed, enable the calculation of the elastic constants by measuring at different forces in situations where the constants are unavailable.

A flat-to-cylinder type of instrument can be used as a comparator to compare a reference cylinder to a test cylinder. In this case, no deformation corrections need to be made if the reference and test piece are identical materials.

If the instrument is equipped with a displacement laser interferometer, then one must correct for the temperature of the cylinder and for the index of refraction of the air if the temperature and index deviate from standard metrological conditions.

6.1.5 General Note. The out-of-roundness cannot always be found by taking diameter measurements around the cylinder. Where a cylinder has an odd number of lobes, it is possible to get constant diameter measurements even when the cylinder has large radial variations. (See Appendix A.)

6.1.6 Analog Scale. Depending on the method used, flat-to-flat, flat-to-sphere, sphere-to-sphere, or flat-to-cylinder, caution must be exercised when reading an analog scale. When graduations are widely spaced, measurements of one-half or one-fourth of an increment can be successfully estimated. If graduations are close together, splitting an increment becomes unrealistic. Good judgment must be used in either case.

6.1.7 Recalibration of 0.0025/0.005 mm (0.0001/0.0002 in.) Pins or Pin Sets. Due to typical usage and economics, recalibration of 0.0025/0.005 mm (0.0001/0.0002 in.) tolerance pins or pin sets requires only two measurements, 6.35 mm ($^1/_4$ in.) from each end, unless otherwise specified.

6.2 Laser Scanning Measurement

A method related to optical projection is laser scanning. A simple system might use a rotating mirror to send a laser beam through the focal point of the projection lens system. As the mirror rotates, the beam changes direction, staying through the focal point. The result is a laser beam that leaves the transmitter and scans down with the beam direction fixed. This produces an apparent plane of light. The light then goes to a receiver, which could be another lens that focuses the parallel plane of light onto a photodiode. A cylinder is placed in the plane of light, interrupting the scanning beam.

As the light scans the receiver, it has light except where the beam hits the cylinder. A threshold level is chosen to represent when the light is interrupted by the cylinder. The time between these threshold crossings represents a measure of the cylinder diameter.

The scanning systems and the interval measurement between threshold crossings are mature technologies. The scan rate is very high, allowing averages of a large number of measurements to be made in less than a second. The precision of the system depends on the averaging time and is typically sub-micrometer.

Because of diffraction and other edge effects, the system is generally not used as an absolute instrument. One or more cylinders of known diameter are used to set the measurement scale.

6.2.1 Range. The resolution of the system is set by the scanning spot size, the quality of the optics and scanning system, and the averaging time used. None of the major factors affecting the resolution are size dependent. Therefore, the instrument resolution does not depend on the cylinder size except for very small wires where diffraction effects may dominate. Figure 4 illustrates the standard method of measurement. Since the system is a comparator, there are a number of alternative setups which allow measurement of large cylinders and gaps. The manufacturer shall be contacted for application notes.

6.2.2 Error Sources. The cylinder shall be perpendicular to the measurement beam or the measurement will contain a cosine error.

This is a noncontact measurement; therefore, the cleanliness of the part is important. The laser beam will not displace any dust, dirt, or oil films.

The laser beam diameter is usually between 100 μm and 5 mm, depending on the application and range of the system. The beam also may not be perfectly circular. The cylinder shall be uniform over the size of the beam. If the surface irregularities are large, the measured size depends on the threshold in a complicated manner. It is difficult to correlate the measurements to the diameter measured with contact instruments such as micrometers.

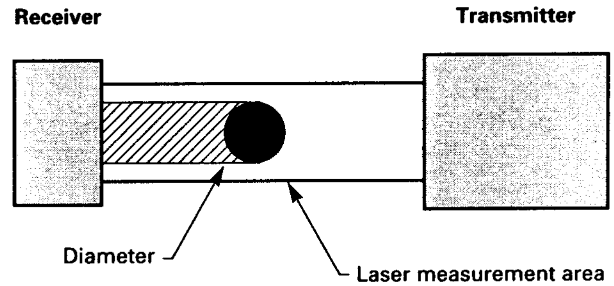


FIG. 4 LASER STANDARD MEASUREMENT

In some circumstances, the ambient light may affect the measurement. The manufacturer's recommended lighting requirements shall be followed.

For highest accuracy measurements, the reference master cylinder shall approximately bracket the size of the measured cylinder. The measurements of the master and test cylinder shall be made in the same portion of the beam. This will minimize any error due to nonlinearities in the beam scan.

7 ENVIRONMENT

7.1 General

All environmental factors shall be controlled to achieve repeatability and accuracy as required in the measurement of master discs and cylindrical plug gages. The factors are:

(a) cleanliness
(b) vibration
(c) temperature
(d) humidity
(e) electrical interference
(f) illumination

This section contains only essentials for a metrology laboratory concerned with calibration of master discs and cylindrical plug gages. More complete coverage of essentials recommended for metrology laboratories is included in ANSI B89.6.2.

7.2 Cleanliness

Areas where calibration is performed shall be shielded from smoke, dust, mist, and other contaminants typical of some production areas. During calibration, the instrument, master, and cylinder shall be clean.

7.3 Vibration

Excessive vibration has serious detrimental effects on the accuracy attainable in precise measurements. Objectionable vibrations take two different forms and may be constant, periodic, or random in occurrence. These two forms are tactile and audible. Tactile vibrations (feel) are objectionable because they may cause inconsistent and unstable contact at the point of measurement and instability in the readout of the amplifier. Audible vibrations (noise) are objectionable if they adversely affect the performance of the operator. Following are the most common methods to bring vibration levels to acceptable values.

(a) When locating the metrology laboratory, avoid areas adjacent to, or affected by, heavy machinery, internal, or external traffic.

(b) Insulate the areas from known potential sources of vibration and use insulating mountings when installing sensitive apparatus.

(c) Create an acceptable, low operational noise level and require strict observance of it at all times.

7.4 Temperature

The standard reference temperature for industrial length measurements is fixed at 20°C (68°F). See ISO 1. The ambient temperature of the measurement area must be controlled close to the reference temperature if accurate measurements are required.

While it is never possible to control the ambient temperature to exactly 20°C, the degree of control shall be consistent with the required accuracy of the measurements. If the master and the test parts are of the same material, a larger deviation from the nominal temperature can be tolerated than if the master and test parts are of different materials. Even when the master and test parts are of the same material, care must be taken to insure that the two parts are at nearly the same temperature. If a part is brought from a 23°C shop environment into a 20°C metrology laboratory, adequate time must be allowed for the part to reach temperature equilibrium. The use of soaking plates and thermal shielding can help equalize the temperature between the two parts.

Even when care is taken to insure the parts are at nearly the same temperature and corrections are made to correct the parts to the reference temperature of 20°C, errors will result if the ambient temperature is far from the nominal 20°C. The errors will result from uncertainties in the coefficient of linear expansion. The change in length ΔL of a part with length L is

$$\Delta L = \alpha L(t - 20)$$

where α is the nominal coefficient of linear expansion and t is the temperature of the part. The value of the coefficient of linear expansion is not known any better than about 1.5 parts in 10^{-6}. In a measurement area maintained at 23°C, an error of 0.23 μm (9 μin.) could result, solely from the uncertainty in the value of the coefficient, if a 25.4 mm (1 in.) cylinder is measured by comparing it to a gage block of the same material.

Further refinement can be achieved by determining the temperature of each pertinent component and applying the necessary corrections. For optimum accuracy, a thermometer can measure the parts and corrections made to compensate for the difference in temperature from master to test piece. A detailed discussion of the effects of making measurements at temperatures other than at 20°C is given in ANSI B89.6.2-1973.

7.5 Humidity

It is recommended that relative humidity in the measuring environment not exceed 45%. Humidity significantly beyond that value may cause problems with corrosion of iron or steel surfaces. Also, caution shall be used when establishing the low limit due to static electricity.

7.6 Electrical Interference

When installing electrical utilities in a metrology laboratory, be sure the utilities leave the environment relatively free from stray electrical fields.

7.7 Illumination

The four factors of vision are brightness, size, contrast, and time. Variations in one factor may affect one or all of the others. Increasing brightness lets the eyes see small objects. However, this brightness may lessen the contrast and make it difficult or impractical to read fine scale graduations.

Essential illumination provisions for specific tasks shall be provided. From a practical viewpoint, an illumination of 50 footcandles at working height may be the starting point for general work unless the manufacturer suggests otherwise. For example, interferometry is usually done in low lighting.

8 WRITTEN PROCEDURES

Any measurement facility or laboratory shall have written procedures for the particular application (e.g., aerospace, automotive, or commercial). Laboratories shall adhere to each specific method for consistency in measurement and periodically use an outside source for measurement correlation.

9 PACKAGING, SHIPPING, AND STORAGE

Master discs and plug gages shall always be packaged and stored in a preservative to prevent damage or corrosion while not in use. Proper packaging shall be used to prevent damage during shipment.

APPENDIX A
THE EFFECTS OF FORM AND FORM ERRORS ON SIZE (Geometry)

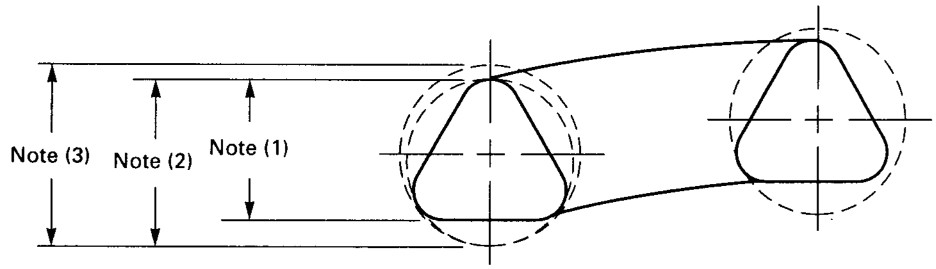
(This Appendix is not part of ASME B89.1.5-1998, and is included for information purposes only.)

In this Appendix we discuss a number of typical geometry errors in cylinders and how they affect the measured diameter for different measurement methods. An understanding of these interactions between form errors and measurement methods is important in choosing the most appropriate method.

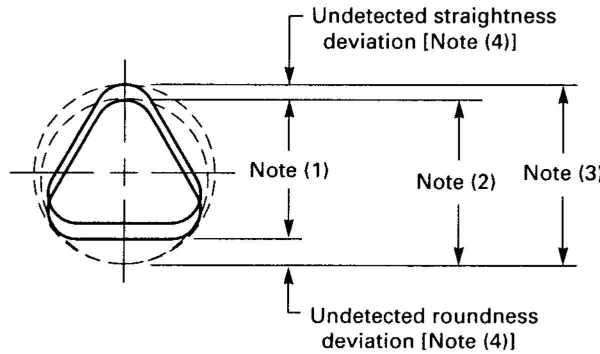
For example, if a cylinder is manufactured by centerless grinding, the typical form has three lobes. A two-point diameter measurement, using a typical micrometer, would show the part as round and give a diameter that is smaller than the diameter of the circumscribed circle diameter. Thus the part would not fit in a hole slightly larger than the measured two-point diameter. A three-point method or measurement using a precision rotary spindle, which detects three-lobe errors, would be the appropriate measurement method.

Figures A1, A2, and A3 present a number of examples of how form errors affect the measured size. Table A1 presents the appropriate measurement method for some common form errors.

Tables A2, A3, and A4 discuss how the examples in Figs. A2 and A3 affect the measured size. Table A5 shows the relation of machining practices to the number of lobes typically found in the part form.



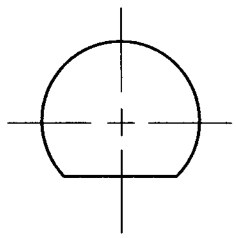
(a)



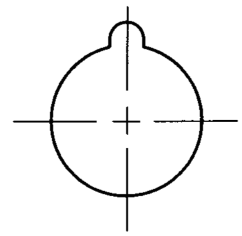
(b) End View

NOTES:
(1) Actual local size (one-dimensional distance), as measured with a micrometer or other two-point measuring device at any measuring plane.
(2) Local mating diameter (two-dimensional circle); minimum circumscribed circle at any measuring plane (this is the size of a hole that the plug gage could enter).
(3) Actual mating size (three-dimensional envelope); minimum circumscribed cylinder encompassing entire part (this is the size of a hole that the full length of the plug gage could pass through).
(4) Conventional two-point size (distance) measurement will not recognize certain form imperfections that will influence actual mating size.

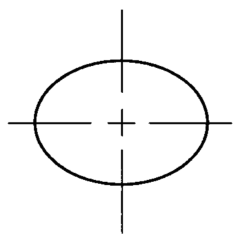
FIG. A1 ANALYSIS OF A TRILOBED AND CAMBERED PLUG GAGE



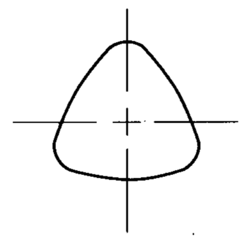
(a) Single Flat [Note (1)]



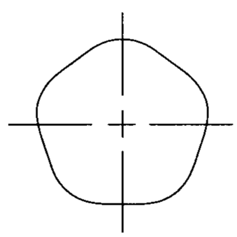
(b) Single Hump [Note (1)]



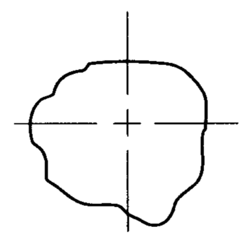
(c) Uniform Oval or Regular Even-Numbered Lobing [Note (2)]



(d) Uniform Trilobe [Note (3)]



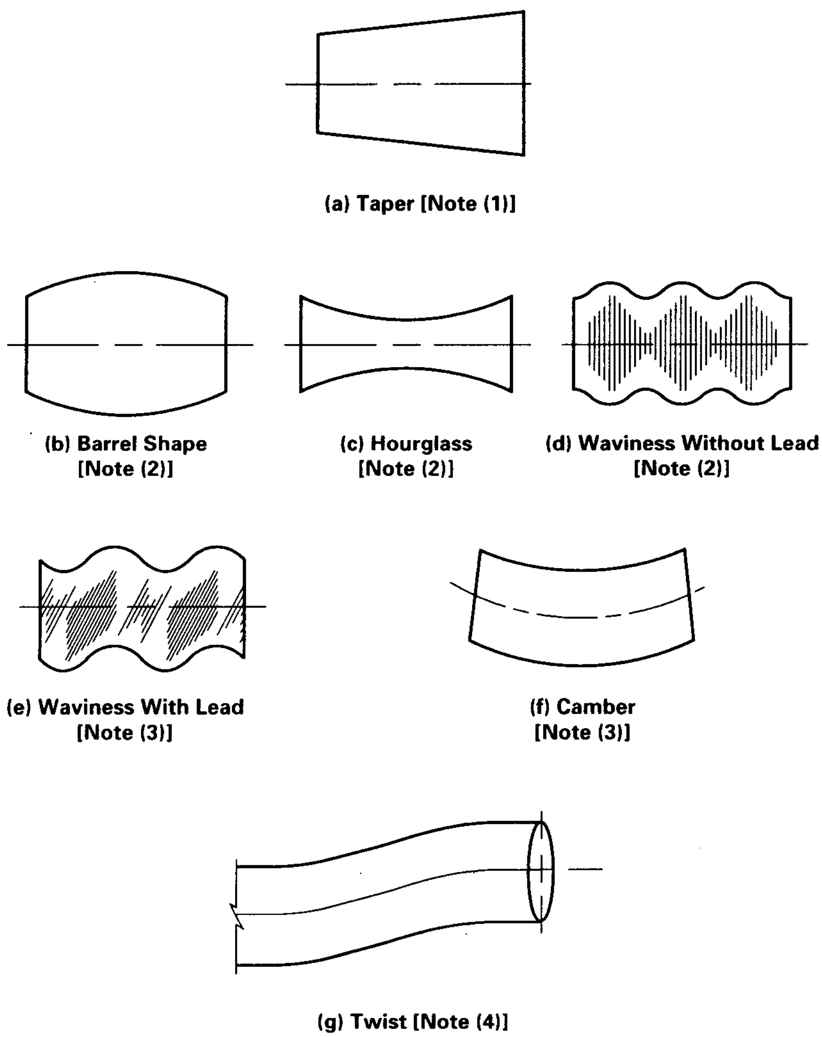
(e) Uniform Odd-Numbered Lobing Greater Than Three Lobes [Note (4)]



(f) Nonuniform Lobing [Note (5)]

NOTES:
(1) Diameter effect = 1 x roundness deviation (directly measurable with a two-point measuring device).
(2) Diameter effect = 2 x roundness deviation (directly measurable with a two-point measuring device).
(3) Diameter effect = 1 x roundness deviation (not directly measurable with a two-point measuring device, but directly measurable with a three-point measuring device).
(4) Diameter effect = 1 x roundness deviation (not directly measurable with a two- or three-point measuring device).
(5) Diameter effect = between 1 x and 2 x roundness deviation (may be partially measurable with a two-point measuring device).

FIG. A2 FORM INFLUENCES ON CIRCULAR SIZE



NOTES:

(1) Diameter effect = 2 x taper/side (directly measurable as a change in size).

(2) Diameter effect = 2 x straightness deviation/side (directly measurable as a change in size).

(3) Diameter effect = 1 x straightness deviation/side (not directly measurable as a change in size unless large anvil or platen is used).

(4) Diameter effect = the square root of the sum of the squares of *x* and *y* axes per side straightness deviation (not directly measurable as a change in size).

FIG. A3 FORM INFLUENCES ON CYLINDRICAL SIZE

TABLE A1 DEVIATION OF GAGE FORM ERRORS
(Deviation From True Cylindrical Form)

Type of Form Error	Figure and Sketch	Appropriate Measurement Method: Note (1)	Note (2)	Note (3)	Note (4)	Note (5)	Note (6)	Note (7)	Note (8)
Roundness									
Single flat	A2(a)	X	...	...	...	...	...	X	X
Single hump	A2(b)	X	...	...	...	...	...	X	X
Ovality	A2(c)	X	...	...	...	...	...	X	X
Trilobed	A2(d)	...	X	...	...	...	...	X	X
Odd-numbered lobes	A2(e)	...	...	X	...	...	...	X	X
Irregular lobes	A2(f)	...	...	...	...	...	...	X	X
Taper	A3(a)	...	...	...	X	X	...	...	X
Straightness									
Barrel shaped	A3(b)	...	...	...	...	X	...	...	X
Hourglass	A3(c)	...	...	...	...	X	...	...	X
Convoluted	A3(d)	...	...	...	...	X	...	X	X
Barber pole	A3(e)	...	...	...	...	...	...	X	X
Camber	A3(f)	...	...	...	...	...	X	X	X
Twist	A3(g)	...	...	...	...	...	...	X	X
Combinations of Above	A1	...	...	...	...	...	...	...	X

NOTES:

(1) Two-point (180 deg apart) variables diameter measurement with 180 deg rotation of workpiece. Observe maximum and minimum measured values.

(2) Three-point (120 deg apart) variables diameter measurement with 120 deg rotation of workpiece. Observe maximum and minimum measured values.

(3) Single-point variables measurement with 360 deg rotation of workpiece supported in a V-block(s) with appropriate included angle (see Table A6).

(4) Variables diameter measurement at or near both ends of the workpiece.

(5) Variables diameter measurement scanning the entire length of the workpiece.

(6) Single-point variables measurement at the midpoint of the workpiece while rotated in an L-block or on a flat surface.

(7) Precision rotating spindle or rotating table instrument.

(8) Precision rotating spindle or rotating table instrument with a precision axial slide (cylindricity analyzer).

TABLE A2 GAGE GEOMETRY EFFECT ON CYLINDRICAL GO PLUG GAGES

Type of Form Error	Figure and Sketch	Appropriate Note(s) Note (1)	Note (2)	Note (3)	Note (4)	Note (5)	Note (6)
Roundness							
Single flat	A2(a)	...	...	...	...	X	...
Single hump	A2(b)	X	...	...	...	X	X
Ovality	A2(c)	X	...	...	...	X	X
Trilobed	A2(d)	X	...	...	...	X	X
Odd-numbered lobes	A2(e)	X	...	...	...	X	X
Irregular lobes	A2(f)	X	...	...	...	X	X
Taper	A3(a)	X	X	X	...	...	X
Straightness							
Barrel shaped	A3(b)	X	X	X	...	...	X
Hourglass	A3(c)	X	...	...	...	...	X
Convoluted	A3(d)	X	X	X	...	...	X
Barber pole	A3(e)	...	...	...	X	...	X
Camber	A3(f)	...	...	...	X	...	X
Twist	A3(g)	...	...	...	X	...	X

NOTES:

(1) Largest effective diameter of gage may exceed measured size of gage and could exceed upper limit of gage size tolerance. This increases probability of fail error and may increase manufacturing cost.

(2) Effective diameter at end of gage may be less than measured size of gage and could be less than lower limit of gage size tolerance. This increases probability of pass error on shallow, blind holes or counterbores.

(3) Workpiece may appear to be tapered or bell-mouthed when it is not. User will assume workpiece is tapered. This increases probability of fail error and may increase manufacturing cost.

(4) Virtual condition of gage may exceed measured size of gage and could exceed upper limit of gage size tolerance. This increases probability of fail error and may increase manufacturing cost.

(5) May accept a correspondingly out-of-round workpiece if the form error of the workpiece is aligned with the form error of the gage. This increased probability of pass error can be avoided by rotating the gage while it is engaged with the workpiece.

(6) Form error may reduce gage life because less surface material is available at the gage/workpiece interface and wear rates could increase.

TABLE A3 GAGE GEOMETRY EFFECT ON CYLINDRICAL NOGO PLUG GAGES

Type of Form Error	Figure and Sketch	Appropriate Note			
		Note (1)	Note (2)	Note (3)	Note (4)
Roundness					
Single flat	A2(a)	...	...	...	X
Single hump	A2(b)	X	...	X	...
Ovality	A2(c)	X	...	X	...
Trilobed	A2(d)	X	...	X	...
Odd-numbered lobes	A2(e)	X	...	X	...
Irregular lobes	A2(f)	X	...	X	...
Taper	A3(a)	X	X	...	...
Straightness					
Barrel shaped	A3(b)	...	X	...	...
Hourglass	A3(c)	X	...	...	...
Convoluted	A3(d)	X	X	...	...
Barber pole	A3(e)	...	...	...	X
Camber	A3(f)	...	...	...	X
Twist	A3(g)	...	...	...	X

NOTES:

(1) Largest effective diameter at end of gage may exceed measured size of gage and could exceed upper limit of gage size tolerance. This increases probability of pass error.

(2) Effective diameter at end of gage may be less than measured size of gage and could be less than lower limit of gage size tolerance. This increases probability of fail error and may increase manufacturing cost.

(3) This increased probability of pass error can be minimized by reducing the width of the gage member to approach single-element gaging. See Appendix C (flatted or diamond NOGO).

(4) Other conditions of form error that may produce a difference between the actual mating size and the measured size of a NOGO gage are not applicable because the gage is not intended to enter the workpiece.

TABLE A4 GAGE GEOMETRY EFFECT ON CYLINDRICAL MASTER DISCS

Type of Form Error	Figure and Sketch	Appropriate Measurement Method Note (1)	Note (2)	Note (3)	Note (4)	Note (5)	Note (6)	Note (7)	Note (8)	Note (9)	Note (10)	Note (11)	Note (12)	Note (13)	Note (14)	Note (15)
Roundness																
Single flat	A2(a)	X	...	X	X	...	...	...	...	...	...	...	...	...	...	...
Single hump	A2(b)	...	X	X	X	...	...	...	...	...	...	...	...	...	...	...
Ovality	A2(c)	...	...	...	...	X	X	...	X	...	...	...	...	X	...	...
Trilobed	A2(d)	...	...	...	...	X	X	X	...	...	...	...	...	X	...	...
Odd-numbered lobes	A2(e)	...	...	...	...	X	X	X	...	...	...	...	...	X	...	...
Irregular lobes	A2(f)	...	...	...	...	X	X	...	...	...	...	...	X	X	...	...
Taper	A3(a)	...	...	...	...	...	...	...	...	X	...	X	...	X	...	...
Straightness																
Barrel shaped	A3(b)	...	...	...	...	...	...	...	...	X	X	X	...	X	...	...
Hourglass	A3(c)	...	...	...	...	...	...	...	...	X	X	X	...	X	...	...
Convoluted	A3(d)	...	...	...	...	...	...	...	...	X	X	X	...	X	...	...
Barber pole	A3(e)	...	...	...	...	...	...	...	...	X	X	X	...	...	...	X
Camber	A3(f)	...	...	...	...	...	...	...	...	...	X	...	...	...	X	X
Twist	A3(g)	...	...	...	...	...	...	...	...	X	X	X	...	...	...	X

NOTES:
(1) Diameter across the flat may be less than the measured size of the master and less than the lower limit of gage size tolerance.
(2) Diameter across the hump may exceed the measured size of the master and exceed upper limit of gage size tolerance.
(3) Gage reading will change abruptly when master is rotated across the flat or hump.
(4) Inaccurate gage setting can be avoided by not setting the gage at a localized high or low reading.
(5) Circumscribed circle size of the master may be greater than the measured size of the master and could exceed upper limit of gage size tolerance.
(6) Inscribed circle size of the master may be smaller than the measured size of the master and could be less than the lower limit of gage size tolerance.
(7) Regularly spaced odd-numbered lobes are not a factor when setting a two-point measuring device. Form error may be magnified when used with V-blocks or a measuring device having more than two contacts.
(8) Gage reading will change slowly from high to low twice with each full rotation of the master disc.
(9) Gage reading will change as the master disc is moved lengthwise through the gage.
(10) Virtual condition of the master may exceed the measured diameter of the master and could exceed the upper limit of gage size tolerance. This will cause the gage to be set larger than intended and workpiece measurements will read smaller than the true size.
(11) Inaccurate gage setting can be avoided by using narrow contacts.
(12) Gage reading may fluctuate between high and low with rotation of the master.
(13) Inaccurate gage settting can be avoided by rotating or moving the master and setting the gage at the midpoint reading.
(14) Gage reading will change slowly from high to low once with each full rotation of the master disc.
(15) Inaccurate gage setting can be avoided by rotating the master and setting the gage at the lowest reading.

TABLE A5 TYPICAL CAUSES OF LOBING CONDITIONS ON CIRCULAR PARTS

Number of Lobes	Causes
2	Inaccuracy in tooling (elliptical). Part not square in machine. Part not square in measuring machine.
3 to 4	Distortion of part due to clamping in machine or measuring system. Commonly caused by three- or four-jaw chuck.
3 to 15	Machining process (centerless grinding produces an odd number of lobes)
Over 15	Process and material parameters. Common process parameters include vibration, tool condition, spindle speed, feed rates, and medium to high frequency chatter.

TABLE A6 THE APPRAISAL OF THE V-BLOCK ROUNDNESS INSPECTION PROCESS

Number of Uniformly Spaced Undulations on the Object Surface	Appropriate Included Angle of the V-Block, deg	Factor by Which Indicator Readings Are Increased Over the Actual Radial Out-of-Roundness
3	60	3.00
5	108	2.24
7	129	2.11
9	140	2.06

APPENDIX B
MEASUREMENT UNCERTAINTY

(This Appendix is not part of ASME B89.1.5-1998, and is included for information purposes only.)

B1 EXAMPLE

In this example we develop an uncertainty budget for the calibration of a single diameter of a cylinder by comparison to a gage block stack using a gage block comparator. We will assume that the gage block stack and cylinder are the same nominal size.

Relevant inputs:

(a) Tungsten Carbide Cylinder

(1) diameter: 25.01 mm

(2) thermal expansion coefficient: 4.6×10^{-6}/°C ±10%

(b) Gage Blocks

(1) Block 1: 23 mm ± 0.1 μm

(2) Block 2: 2.01 mm ± 0.1 μm

(3) thermal expansion coefficient: 11.5×10^{-6}/°C ±10%

(c) room temperature: 23 ± 1°C

(d) thermometer uncertainty: ±0.1°C

Using this information, we will now develop the uncertainty budget according to the outline of uncertainty sources listed above.

B2 REFERENCE MASTER GAGE BLOCK STACK LENGTH

(a) Gage blocks are calibrated at a typical commercial laboratory, the total uncertainty on each block being 0.1 μm. We assume that this represents the 95% confidence level (2σ). This yields the standard uncertainty (1σ) u = 0.05 μm.

(b) The gage blocks are calibrated at their gage points. Since the blocks are not perfectly flat, when wrung together the distance between the gage block stack gage points may not be the sum of the two separate gage block lengths. The gaging surfaces are also not parallel. Between the flatness and parallelism, gage blocks wrung together do not generally produce a length exactly the sum of the lengths of the two blocks added together. The added uncertainty from wringing imperfect gage blocks together depends on the geometry of the block. Blocks that are very parallel and flat produce much less uncertainty than those of lesser quality.

A simple test for these effects is to wring up stacks of the same length made from two or three blocks. For example, the millimeter stacks of 1 + 9, 2 + 8, 3 + 7, 4 + 6, 5 + 5 could be made from two sets and compared to the 10 mm block. For our example, we find 0.030 μm as the extra variation in length for one wring. For two or more wrings we get an uncertainty of 0.030 μm for each wring.

Our example has only one wring, but for multiple wrings the uncertainties are uncorrelated and would be combined in quadrature.

B3 MECHANICAL DEFORMATION CORRECTION

The deformation geometries occurring in our calibrations include:

(a) sphere in contact with a plane: comparator contacts to gage block;

(b) sphere in contact with an external cylinder: comparator contact to cylinder.

All of the corrections are calculated from Puttock and Thwaite's CSIRO Technical Paper No. 25. The main source of uncertainty is from the elastic modulus, which is usually taken from a table. We assume that these values are good to about 5%, the variation we find between a number of standard references.

The corrections needed in this case are:

deformation of gage block: 0.24 μm

deformation of cylinder: 0.25 μm

For this size cylinder, the correction is about the size of the accuracy of the calculation and probably is not needed. For smaller diameter cylinders this is not the case. From the elastic constant uncertainty we assume the distribution to be rectangular with a range of 10%, that is for this case 0.01 μm.

B4 THERMAL UNCERTAINTY

There are three components of uncertainty related to temperature: the uncertainty in the thermometer calibration, the uncertainty of the coefficient of thermal expansion (CTE) of the material, and temperature differences between the thermometer and the part (or between part and master in comparison measurements).

(a) The uncertainty in the thermometer calibration generates an uncertainty in length according to the formula:

$$\Delta L = L\alpha\Delta T$$

where L is the length, ΔT the change in temperature, and α the CTE. For our case we are comparing two gages, one of steel and one of tungsten carbide, and the correction must be made for both. Thus the total correction depends only on the difference in thermal expansion between the gage and master.

$$\Delta L = (\alpha_{WC} - \alpha_{\text{steel}})L\Delta T$$

The length is 25 mm and the thermometer calibration will be assumed to be as good as the least significant digit, 0.1°C. The uncertainty becomes:

$$\Delta L = (11.5\times10^{-6} - 4.6\times10^{-6})(0.1°\text{C})(25\text{ mm}) = 0.017\ \mu\text{m}$$

If we assume that the uncertainty is from a rectangular distribution with width ±0.017 μm, we can get an uncertainty of:

$$U_t = \frac{0.017\ \mu\text{m}}{\sqrt{3}} = 0.01\ \mu\text{m}$$

(b) The second source of thermal error is from our uncertainty about the CTE of the two materials. The gage block standard gives the tolerance on steel gage blocks as 10% of the nominal value supplied by the manufacturer. Measurements on real gage blocks show variations of this magnitude. We will assume that the distribution of the gage block expansion coefficients is rectangular with a width of $\pm1\times10^{-6}$/°C for steel and $\pm0.5\times10^{-6}$/°C for tungsten carbide. This gives the uncertainty in thermal expansion coefficient of steel as 0.6×10^{-6}/°C and of tungsten carbide as 0.4×10^{-6}/°C.

Measuring 3°C from 20°C, we have:

$$\Delta L = L(20 - T)\Delta\alpha$$

For tungsten carbide:

$$u_{\alpha,WC} = (25\text{ mm})(20 - 23)(0.4\times10^{-6}) = 0.030\ \mu\text{m}$$

For steel:

$$u_{\alpha,\text{steel}} = (25\text{ mm})(20 - 23)(0.6\times10^{-6}) = 0.045\ \mu\text{m}$$

(c) Differences in temperature between the gage and the gage block stack will cause an error in the measurement. Even in rooms with excellent temperature control, gradients will inevitably exist which are large enough to affect the measurements. Particular concerns are exhausts of cooling fans of computers, lighting fixtures, and of course the metrologist. In our example we will assume that our thermometer has a resolution of 0.1°C, which limits our knowledge of gradients to this figure. Thus we must assume that gradients of up to ±0.5°C could exist and use this in our error budget. Using this as the span of a rectangular distribution, we get a temperature uncertainty of ±0.03°C. The differential thermal expansion between our steel gage block stack and the gage is 6.9×10^{-6} μm/m°C, which gives a standard uncertainty of 0.2 μm/m. For a 25 mm gage, this is 0.005 μm.

B5 INSTRUMENT GEOMETRY

When measuring a cylinder between two point contacts, it is critical that the two contacts be aligned and that the anvil holding the cylinder be square to the line between the contacts. In general, this alignment is not perfect. From experience, we have found that using our gage block comparators as installed and varying the placement of cylinders can change the reading by up to 0.25 μm (10 μin.). Taking the smallest maximum as the correct answer, the value could still be off by one or more microinches. Using 0.25 μm

TABLE B1 SUMMARY OF UNCERTAINTIES

Source of Uncertainty	u, µm (µin.)	u^2, µm^2
Master block 1 calibration	0.050 (2.0)	0.0025
Master block 2 calibration	0.050 (2.0)	0.0025
Block geometry effects	0.030 (1.2)	0.0009
Mechanical deformation	0.010 (0.4)	0.0001
Thermometer calibration	0.010 (0.4)	0.0001
Thermal expansion of block stack	0.045 (1.8)	0.0020
Thermal expansion of cylinder	0.030 (1.2)	0.0009
Temperature difference (block stack – cylinder)	0.005 (0.2)	0.0000
Instrument geometry	0.015 (0.6)	0.0002
Reproducibility	0.040 (1.6)	0.0016
Total (RSS)	0.104 (4.1)	0.0108

(2 µin.) as the possible range of errors, and assuming a square distribution, we obtain an uncertainty for geometry of:

$$u_g = 0.015 \ \mu\text{m}$$

B6 REPRODUCIBILITY OF MECHANICAL COMPARISON

This value is very dependent on the type of comparator, the operator skill, and number of repetitions of the measurement. In general, the reproducibility will be somewhat worse than for gage block calibrations. From round-robin data, it appears that most competent labs making two comparisons of a master and unknown gage blocks have an uncertainty (1σ) of about 0.03 µm (1.25 µin.). We will use a slightly higher amount of 0.04 µm (1.5 µin.) as our uncertainty of the comparison between a block and a cylinder.

B7 SUMMARY OF UNCERTAINTY

The total expanded uncertainty, using a coverage factor $k = 2$ (95% confidence level) is 0.2 µm (8 µin.). All sources of uncertainty discussed are listed in Table B1.

Note that the last column of Table B1 shows the weight of each source of uncertainty. Thus, the master block calibrations and the thermal expansion of the gage block stack are much more important to the result than any of the other effects. This shows which path should be followed to improve the process. If the gage block stack is measured by interferometry (as wrung), the uncertainty from the first three uncertainty sources will be reduced to the uncertainty of the interferometric measurement, or 0.015 µm. The second large source is from measuring at 23°C rather than 20°C. If the measurements were made at 20°C and the gage block stack measured by interferometry, the uncertainty would be reduced from 0.17 µm to 0.09 µm.

APPENDIX C
DEPTH STEPS, AIR GROOVES, AND FLATTED NOGO MEMBERS FOR PLUG GAGES

(This Appendix is not part of ASME B89.1.5-1998, and is included for information purposes only.)

Depth steps or notches on GO members are commonly used to visually check the depth of holes. The reference end of the gage must be perpendicular to the diameter of the gage. Steps are not recommended on small carbide gages or other brittle materials. The diameter of the gage must be considered when choosing to use depth steps.

In Fig. C1, perpendicularity (*) is 0.635*T* or 0.0127 mm, whichever is greater. The workpiece depth tolerance is *T*. Steps 90 deg apart are suggested when diameter size *A* is less than 4.45 mm. An alternative method is flatted style steps, also shown in Fig. C1.

Air grooves are suggested on the GO gage for air release when checking blind holes. Flatted or radius grooves work equally well. See Fig. C2.

Flatted or diamond shaped NOGO plug gages are commonly used to detect ovality of holes. It is suggested that the width of the remaining gaging surface be one-third of the gaging diameter (see Fig. C3). If geometry is critical, we recommend that holes be checked using single-element gaging. Flatted or diamond shaped members will not detect odd-numbered lobed conditions.

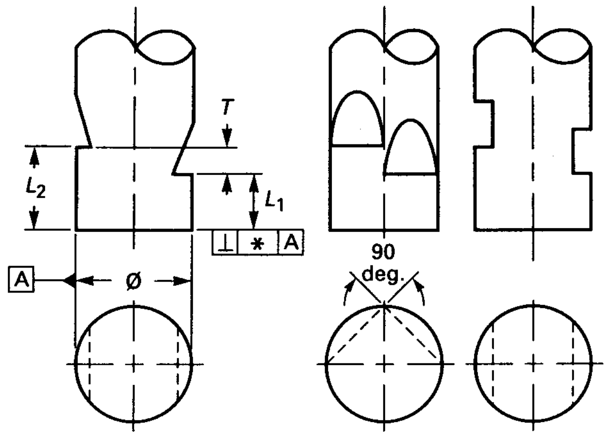


FIG. C1 STANDARD DEPTH STEPS (With Optional Flat Design)

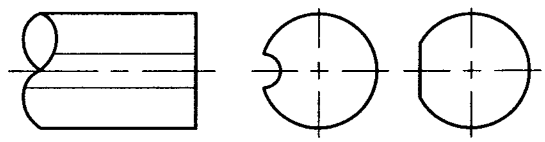


FIG. C2 AIR GROOVE DESIGNS

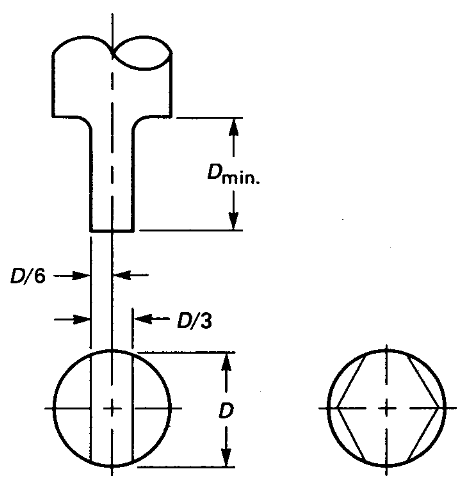


FIG. C3 FLATTED OR DIAMOND SHAPED NOGO

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