ASME B89.1.7-2009

Performance Standard for Steel Measuring Tapes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Date of Issuance: September 18, 2009

This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Periodically, certain actions of the ASME B89 Committee may be published as Code Cases. Code Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

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

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FOREWORD

ASME Standards Committee B89 on Dimensional Metrology, under procedures approved by the American National Standards Institute (ANSI), prepares standards that encompass the inspection and the means of measuring characteristics of such various geometric parameters as diameter, length, flatness, parallelism, concentricity, and squareness. Because steel measuring tapes are widely used for the measurement and comparison of some of these features, the Chair of the B89 Division 1 — Length authorized the formation of Project Team B89.1.7 to prepare this Standard.

The overall scope of Dimensional Metrology Measuring Tape Project Team B89.1.7 is to define the requirements for steel measuring tapes for all units of measures in U.S. Customary units and SI units with respect to graduations, numbering, designations, and accuracy.

This Standard provides guidance to users and manufacturers of steel measuring tapes with respect to quality standards and preferred measuring units by specifying only the requirements that are essential for satisfactory performance. Presently, both SI (metric) and U.S. Customary (inch-based) graduations are in popular use.

Nonmandatory Appendices A and B discuss tape calibration uncertainties and provide general guidance and awareness regarding the determination and application of calibration uncertainties relative to tape calibrations. Nonmandatory Appendix A treats the subject of calibration of a tape by comparison to a master tape; Nonmandatory Appendix B discusses calibration of a tape using a laser interferometer.

Drafts of this Standard were proposed and discussed during project team meetings from January 1996 through October 2008.

This Standard was approved by the American National Standards Institute on June 15, 2009.

Suggestions for improvement of this Standard are welcome. They should be sent to the American Society of Mechanical Engineers, Secretary, B89 Committee, Three Park Avenue, New York, NY 10016-5990.

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General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Code to which the proposed Case applies.

Interpretations. Upon request, the B89 Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B89 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

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PERFORMANCE STANDARD FOR STEEL MEASURING TAPES

1 SCOPE

This Standard specifies the requirements for steel measuring tapes, with respect to units (SI and U.S. Customary), graduations, numbering, designations, and accuracy requirements.

2 DEFINITIONS

accuracy: closeness of agreement between a measured quantity value and a true quantity value of a measurand. Accuracy is a qualitative concept. (VIM 2.13)

graduations: marks or lines perpendicular to the edge of a measuring tape denoting increments of measure.

intermediate graduation: a graduation mark denoting an increment of measure that falls between the major and the minor graduations (e.g., inch or centimeter).

major graduation: a graduation mark denoting the largest increment of measure (e.g., feet or meter).

maximum permissible errors (MPE): extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system. (VIM 4.26)

minor graduation: a graduation mark denoting the smallest increment of measure (e.g., fraction of an inch, decimal inch, or millimeter).

plumb bob: when used with a measuring tape, a weight with a tapered or flat tip on the bottom that is suspended from the tape.

tension: a force that tends to stretch or elongate something, or a measure of such a force.

NOTE: The measure of force in the U.S. Customary system is the pound (lbf); the measure of force in the SI system is the newton (N). Traditionally, the tension (a force) has been referred to in units of pounds and kilograms. Pound (or pound-force) is proper. In the SI system of units, the kilogram is the unit of mass and the newton is the unit of force. In this Standard, the tension for tapes graduated in SI units is specified in kilograms, in order to maintain continuity of reference to master tape calibration data. The corresponding force in newtons is equal to the applied mass in kilograms multiplied by the acceleration due to gravity, g. By convention, $g = 9.80665\ m/s^2$ exactly. Thus, the force exerted on a tape by a 1 kg load is 9.80665 N. For highest accuracy, the local value of g should be used.

validity conditions: the set of values or range of values of the relevant influence quantities, e.g., environmental conditions, under which the performance specifications are valid.

zero reference mark: the location from which all graduation and numbering of the measuring tape is dimensioned.

3 REFERENCES

3.1 Normative References

If the American National Standard Institute (ANSI) and ISO standards referred to in this document are superseded by a revision, the revision shall apply.

IEEE/ASTM SI 10-2002, Standard for Use of the International System of Units (SI): The Modern Metric System
Publisher: Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Lane, Piscataway, NJ 08854-4141 (www.ieee.org)

ISO 1:2002, Geometrical Product Specifications (GPS) — Standard Reference Temperature for Geometrical Product Specification and Verification
ISO/IEC Guide 98-3:2008, Uncertainty of Measurement — Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995)
Publisher: International Organization for Standardization (ISO), 1 ch. de la Voie-Creuse, Case postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

JCGM 200:2008, International Vocabulary of Metrology — Basic and General Concepts and Associated Terms (VIM)
Publisher: Bureau International des Poids et Mesures (BIPM), Pavillon de Breteuil, 92312 Sèvres cedex, France (www.bipm.org)

3.2 Additional References

API MPMS 3.1A 2005, Manual of Petroleum Measurement Standards Chapter 3 — Tank Gauging Section 1A — Standard Practice for the Manual Gauging of Petroleum and Petroleum Products
Publisher: American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070 (www.api.org)

ASME B89.6.2, Temperature and Humidity Environment for Dimensional Measurement
ASME B89.7.3.1-2001, Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications
ASME B89.7.5-2006, Metrological Traceability of Dimensional Measurements to the SI Unit of Length, Technical Report

Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016-5990; Order Department: 22 Law Drive, P.O. Box 2300, Fairfield, NJ 07007-2300 (www.asme.org)

ISO/IEC 17025:2005, General Requirements for the Competence of Testing and Calibration Laboratories
Publisher: International Organization for Standardization (ISO), 1 rue de Varembé, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse (www.iso.org)

NIST SP 811 2008, Guide for the Use of the International System of Units (SI)
Publisher: National Institute of Standards and Technology (NIST), 100 Bureau Drive, Gaithersburg, MD 20899-1070 (www.nist.gov)

NOTE: ASME B89 documents may be found at http://catalog.asme.org/home.cfm?Search=B89

4 GENERAL REQUIREMENTS

All steel measuring tapes covered by this Standard shall conform to the requirements in paras. 4.1 through 4.9.

4.1 Straight and Parallel

Steel measuring tapes shall be made so that when stretched out on a flat surface the edges are nominally straight and parallel.

4.2 Ease of Reading

All steel measuring tapes shall be clearly marked to facilitate easy and correct reading.

4.3 Background

The graduations and numbering shall be in sharp visual contrast with the background.

4.4 Compatibility

There shall be compatibility between the legibility of graduations and the size and form of numbers, when related to the distance at which the measuring tape is normally read.

4.5 Measurement Units

Unit names and symbols displayed on metric measuring tapes covered by this Standard shall be consistent with IEEE/ASTM SI 10-2002.

4.6 Graduation Requirements

Along the nominal length, the measuring tape shall carry clear, regular, and indelible graduations and numbering, to ensure simple and unambiguous reading. Some unnumbered graduations may extend beyond the major graduation marks at the ends of the measuring tape. Graduations extending to the left of zero and to the right of the last major graduation are not to be considered part of the tape for calibration purposes.

4.6.1 Graduation Quality. When the graduations are lines, they shall be visually straight, perpendicular to the axis of the measuring tape, and all of the same thickness. The thickness of each line shall be constant throughout its length. The lines shall be such that they form a distinct and clear graduation and that their thickness does not cause inaccuracy of measurement.

Certain sections of the measuring tape, especially towards the ends, may be subdivided into submultiples of the graduation interval adopted for the whole measure. In that case, the thickness of the lines may be less in the areas of reduced graduation intervals than in the rest of the measuring tape.

4.6.2 Arrangement. The measuring tape shall be divided by graduations of units consistent with the SI system or U.S. Customary system. The SI units shall be in meters, centimeters, millimeters, and multiples or subdivisions thereof. The U.S. Customary units shall be in feet, inches, and multiples or subdivisions thereof, to include decimal or fractional divisions.

4.6.3 Length of Graduations. In general, as the subdivision of length becomes smaller, the subdivisions should be indicated by using graduations of shorter length. However, in no case should the length of graduations be less than 0.7 mm or 0.03 in.

4.6.4 Width. The graduation marks shall not be wider than 50% of the distance between two consecutive minor graduations.

4.7 Additional Markings

All markings, other than graduations and numbering, should be so positioned and of such a size as not to interfere with the legibility of the steel measuring tapes.

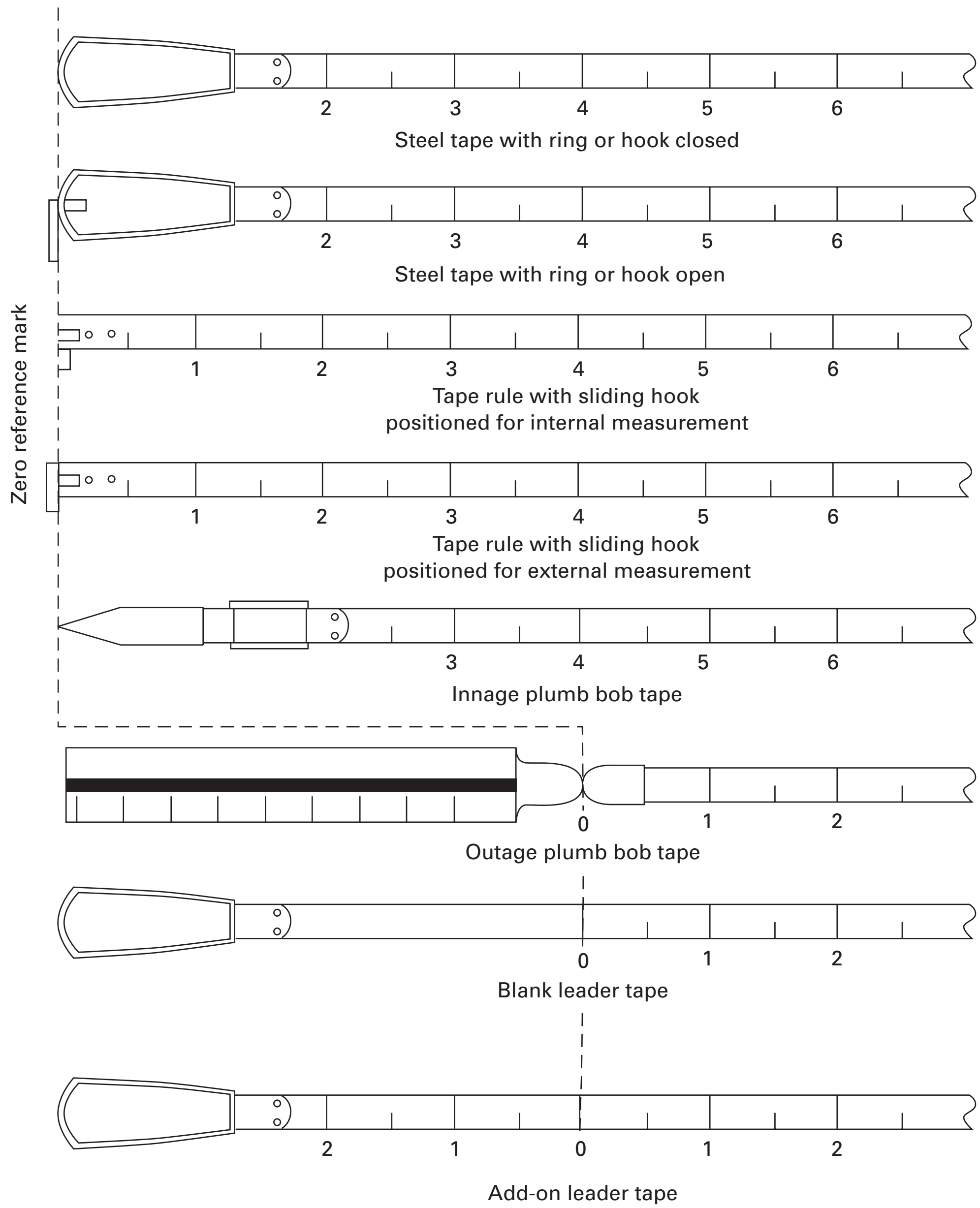
4.8 Numbering

4.8.1 Size of Numbers. The size of the numbers denoting the major graduations shall be as large as practical without reducing the legibility of the graduations. All digits shall be of a style that distinctly differentiates one number from another.

4.8.2 Zero Reference Mark. A tip, ring, hook, or end fitting may be included as a zero reference mark on the measuring tape. In this case, the numbering shall be positioned to accommodate the zero reference mark. Figure 1 illustrates the standard practice for the zero reference marking on various styles of tapes.

4.8.3 Distinguishing of Numbers. Numbers denoting each multiple or subdivision of a unit of length shall be distinguishable from each other by one or more of the following: size, color, or style. The numbers designating the same multiple or subdivision shall be of the

Fig. 1 Standard Practice for Zero Reference Marking



same size and style, except where these are reduced to accommodate other markings.

4.9 Definition of the Calibrated Distance

The calibrated distance between graduations shall be taken as the intervals between the centerlines of pairs of graduations at the edge of the tape where the shortest graduations appear.

In the absence of short graduations, the calibrated distance is defined to be the intervals between centerlines of the graduations at the bottom edge of the tape when viewed with the numbers right side up. The distance is defined at 20°C, when the tape is fully supported with specified tension (possibly zero) applied (see section 6).

It should be noted that cases exist that are not covered above. In these cases the owner should specify the definition of the calibrated distance. In the absence of a clear definition, the calibrating technician shall use his or her discretion in defining the calibrated distance, and the definition of the calibrated distance shall be documented in the calibration report.

5 STEEL MEASURING TAPES

This Standard applies to numerous tapes, as described in paras. 5.1 through 5.4.

5.1 Retractable Steel Tape Rule

A retractable steel tape rule is a graduated and numbered flexible steel blade with either a curved cross section that provides a measurable degree of stiffness, or a flat rectangular cross section, with an end fitting and optionally a spring motor within a case. It is to be constructed in a manner that allows easy extension and provides for quick retraction into the case.

5.2 Measuring Tape — Steel General Purpose

A steel general purpose tape is a graduated and numbered flexible steel blade with an end fitting and a case or reel having a winding drum and handle, or other mechanism, for retraction of the tape into the case.

5.3 Measuring Tape — Surveying/Engineering

A surveying/engineering tape is a graduated and numbered flexible steel blade that may be fitted with clips at one or both ends to permit attachment of handles and tensioning devices. It usually is attached to a reel having a winding drum and handle in such a way as to be easily removable.

5.4 Measuring Tape — Liquid Gaging

A liquid gaging tape is a graduated and numbered flexible steel blade with an end fitting to which a plumb bob is attached. Liquid gaging tapes are either innage tapes or outage tapes. The tapes are similar in design but differ in their mode of use.

Table 1 Tension Requirements for Steel Measuring Tapes With Flat Rectangular Cross Section

Tapes Graduated in SI Units	Tapes Graduated in U.S. Customary Units
0 m to 30 m overall length — 5 kg	0 ft to 100 ft overall length — 10 lbf
Length > 30 m — 10 kg	Length > 100 ft — 20 lbf

GENERAL NOTES:

(a) Tapes manufactured to other tensions must specify the tension on the tape near the zero end.

(b) Curved cross section tapes, regardless of length, are to be calibrated without tension.

Innage tapes measure the depth of the product from its surface to the tank bottom or datum plate. Therefore, the end (tip) of the plumb bob, when the tape is hung vertically, is the zero reference mark for an innage tape (see Fig. 1).

Outage tapes measure the height of space above the liquid from a reference point on the tank to the surface of the product. The outage tape is lowered into the tank until the plumb bob breaks the surface of the liquid. The zero reference mark on an outage tape is located on the hook where the plumb bob is attached (see Fig. 1).

6 CALIBRATION AND MAXIMUM PERMISSIBLE ERRORS

6.1 Tension

Steel tapes with a flat rectangular cross section shall be calibrated while fully supported on a horizontal surface with tension applied as given in Table 1. Tapes with a curved cross section, regardless of length, shall be calibrated without tension.

6.2 Calibration Procedure

The measuring tape to be calibrated shall be laid out flat on a smooth horizontal surface and compared to a length standard whose uncertainty has been evaluated. Specified tension (possibly zero) shall be applied. Friction between the surface and tapeline shall be minimized. If the comparison is between two tapes, a correction for differential expansion of the materials should be applied.

For the most accurate results, the tape to be calibrated should be tested against an interferometer system (see Nonmandatory Appendix B). The interferometer measurements shall be corrected for the environmental conditions.

In all cases, the uncertainties associated with measured errors shall be evaluated (see Mandatory Appendix I and Nonmandatory Appendices A and B).

6.3 Decision Rule

Each length under test, L_j, has a corresponding error, δ_j, equal to the nominal value of the length, indicated on the tape, minus the measured value for that length. Each of these errors has an associated standard uncertainty, $u(\delta_j)$ (see Nonmandatory Appendix A or B). The index $j = 1, 2, ..., n$, where n is the total number of lengths under test.

Because there is uncertainty associated with the error values, a decision rule needs to be applied that describes the way in which those uncertainty values are accounted for when deciding acceptance or rejection. In this Standard, a simple 4:1 acceptance decision rule applies as defined in ASME B89.7.3.1.

(a) The measuring tape under test is accepted (i.e., conformance to specifications is considered verified) when both of the following are true:

(1) for each length under test, L_j, the uncertainty associated with the determined error is sufficiently small to satisfy $C_m = MPE_j/2u(\delta_j) \geq 4$, where C_m = the measurement capability index

(2) for each length under test, L_j, the determined error is sufficiently small to satisfy $|\delta_j| \leq MPE_j$

(b) The measuring tape under test is rejected when there is at least one length under test, L_j, for which its determined error, δ_j, and associated uncertainty, $u(\delta_j)$, satisfy both of the following:

(1) the uncertainty associated with the determined error, $u(\delta_j)$, is sufficiently small to satisfy $C_m = MPE_j/2u(\delta_j) \geq 4$, where C_m = the measurement capability index

(2) the determined error is sufficiently large in magnitude to satisfy $|\delta_j| > MPE_j$

Since the uncertainties of the errors can generally be evaluated before the test begins, it can be determined beforehand if the uncertainties are sufficiently small to ensure $C_m \geq 4$ for each length under test, and thus if the testing apparatus or procedure is sufficiently accurate to test for acceptance. When the uncertainties are not small enough to ensure such C_m values, the uncertainty requirement for simple 4:1 acceptance has not been met, meaning that the testing apparatus or procedure is not sufficiently accurate to test for acceptance of the tape under test.

The quantity MPE_j is the specified maximum permissible error in the length of the tape between the zero graduation and graduation L_j. The magnitude of MPE_j depends on the nominal length, L_j, as described in para. 6.4 and shown in examples in Tables 2 and 3.

6.4 Maximum Permissible Errors (MPE) Requirements

In this Standard, the MPE for steel tapes are based on the formula $MPE = \pm(A + B \cdot L)$, where A and B are specified constants and L is the length being checked.

NOTE: There are other standards that may apply to specific types of steel measuring tapes such as API MPMS 3.1A 2005.

6.4.1 Curved Cross Section Without Tension. For measuring tapes with curved cross sections, A = 0.300 mm (0.0118 in.) and B = 0.150 mm/m (0.0020 in./ft), thus the formula for the MPE becomes

(SI Units)

$$MPE_{\text{mm}} = \pm(0.300 \text{ mm} + 0.150 \text{ mm/m} \cdot L \text{ m})$$

(U.S. Customary Units)

$$MPE_{\text{in.}} = \pm(0.0118 \text{ in.} + 0.0020 \text{ in./ft} \cdot L \text{ ft})$$

Representative values of the MPE for various tape lengths are given in Table 2.

6.4.2 Flat Rectangular Cross Section With Tension. For measuring tapes with flat rectangular cross sections, A = 0.300 mm (0.0118 in.) and B = 0.127 mm/m (0.0015 in./ft), thus the formula for the MPE becomes

(SI Units)

$$MPE_{\text{mm}} = \pm(0.300 \text{ mm} + 0.127 \text{ mm/m} \cdot L \text{ m})$$

(U.S. Customary Units)

$$MPE_{\text{in.}} = \pm(0.0118 \text{ in.} + 0.0015 \text{ in./ft} \cdot L \text{ ft})$$

Representative values of the MPE for various tape lengths are given in Table 3.

6.4.3 With End Fittings. When the calibrated length includes a tip, ring, hook, or end fitting, the calibration shall include an additional point at the 100 mm or 4 in. graduation.

6.4.4 MPE for Tapes With End Fittings. To determine the MPE for these tapes, add 0.300 mm (0.0118 in.) to the A constant in the MPE formulas in paras. 6.4.1 and 6.4.2 (see Tables 2 and 3).

Table 2 MPE for Representative Lengths of Curved Cross Section Tapes

SI Units			U.S. Customary Units		
Length Being Checked, m	MPE, ±mm	MPE (With End Fitting), ±mm	Length Being Checked, ft	MPE, ±in.	MPE (With End Fitting), ±in.
1	0.450	0.750	1	0.0138	0.0256
2	0.600	0.900	2	0.0158	0.0276
3	0.750	1.050	3	0.0178	0.0296
4	0.900	1.200	4	0.0198	0.0316
5	1.050	1.350	5	0.0218	0.0336
6	1.200	1.500	20	0.0518	0.0636
8	1.500	1.800	25	0.0618	0.0736
10	1.800	2.100	30	0.0718	0.0836
15	2.550	2.850	50	0.1118	0.1236
20	3.300	3.600	75	0.1618	0.1736
30	4.800	5.100	100	0.2118	0.2236
40	6.300	6.600	125	0.2618	0.2736
50	7.800	8.100	150	0.3118	0.3236
100	15.300	15.600	200	0.4118	0.4236

Table 3 MPE for Representative Lengths of Flat Rectangular Cross Section Tapes

SI Units			U.S. Customary Units		
Length Being Checked, m	MPE, ±mm	MPE (With End Fitting), ±mm	Length Being Checked, ft	MPE, ±in.	MPE (With End Fitting), ±in.
1	0.427	0.727	1	0.0133	0.0251
2	0.554	0.854	2	0.0148	0.0266
3	0.681	0.981	3	0.0163	0.0281
4	0.808	1.108	4	0.0178	0.0296
5	0.935	1.235	5	0.0193	0.0311
6	1.062	1.362	20	0.0418	0.0536
8	1.316	1.616	25	0.0493	0.0611
10	1.570	1.870	30	0.0568	0.0686
15	2.205	2.505	50	0.0868	0.0986
20	2.840	3.140	75	0.1243	0.1361
30	4.110	4.410	100	0.1618	0.1736
40	5.380	5.680	125	0.1993	0.2111
50	6.650	6.950	150	0.2368	0.2486
100	13.000	13.300	200	0.3118	0.3236

MANDATORY APPENDIX I REFERENCE STANDARD TRACEABILITY

I-1 GENERAL TRACEABILITY ISSUES

This Standard employs the interpretation of traceability described in ASME B89.7.5. In this Standard, traceability issues arise in calibration of tapes through comparisons to either a master tape or an interferometer. The reference standard (master tape or interferometer) used for comparison to a test tape must satisfy the traceability requirements of section I-2 of this document. This requirement provides the connection back to the SI meter and allows a comparison of the measured length errors with the specified MPE values.

The traceability of the reference standard must be documented. The documentation traceability requirement describes how the connection to the SI meter is achieved. If a master tape is employed, the documentation traceability is the calibration certificate of the master tape to an appropriate metrological terminus (see section I-3). If the reference standard is an interferometer, then this interferometer must have metrological traceability to an appropriate metrological terminus, either a calibration certificate or documentation describing the means of realizing the SI meter (ASME B89.7.5, section 2).

I-2 REFERENCE STANDARD TRACEABILITY

Each measurement system used in the calibration, for example, a master tape and a height gage used to measure the length of the plumb bob attached to end fittings, must be traceable per ASME B89.7.5. Typically, it is not necessary to separately document the traceability of each calibrated distance on a tape unless multiple measurement systems are used in the calibration.

Supplying the information below for each measurement system employed will satisfy the traceability requirements for the tape calibration. Information on evaluating the uncertainty of the reference length is given in Nonmandatory Appendices A and B.

(a) State the quantity under measurement, for example, the specified intervals between the centerlines of pairs of graduations at the edge of the master tape where the shortest graduations appear.

NOTE: The calibrated distance always refers to the standard temperature of 20°C.

(b) Identify the measurement system or standard used, for example, a master steel tape with serial number 12345.

(c) State the expanded ($k = 2$) uncertainty associated with the calibrated distance of the reference standard as used at the time of measurement.

NOTE: This includes both the uncertainty on the calibration certificate and effects such as the prevailing thermal conditions at the time of the calibration, and associated equipment used to transfer the value from the master to the tape under calibration, for example, a microscope carriage system.

(d) Provide an uncertainty budget describing the uncertainty components used to compute the statement of uncertainty. For a master tape, the typical uncertainty components are the calibration uncertainty, the uncertainty in the master tape temperature (used to make the nominal thermal expansion correction), and the uncertainty in the coefficient of thermal expansion of the master tape. Additional uncertainty components may include fixturing effects.

(e) Provide documentation of traceability back to an appropriate terminus of the standard used for the reference standard (see section I-3 for an appropriate metrological terminus). For example, for a master tape the calibration certificate would suffice assuming the certificate is from an appropriate metrological terminus.

(f) Show evidence of an internal quality assurance program so that the measurement uncertainty statement for the reference standard is assured. This may be a simple procedure to ensure that the reference standard is periodically recalibrated; other sensors, e.g., the weather station of a reference interferometer, are periodically recalibrated; and the artifact fixturing or other effects are in accordance with the calibration requirements or otherwise taken into account in the uncertainty budget.

I-3 METROLOGICAL TERMINUS

An appropriate metrological terminus for the documentation traceability is any one of the following sources (see ASME B89.7.5 for further details):

(a) a calibration report[1] from a national measurement institute (NMI) for the reference length (artifact or instrument) used in the testing

[1] For some instruments, accuracy is often specified by a grade or class. A document identifying compliance to a metrolgical grade or class is equivalent to a calibration report.

(b) a calibration report from a competent[2] laboratory fulfilling section 5.6 of ISO 17025 for the reference standard used in the testing

(c) documentation describing an independent realization of the SI meter[3] used to generate the reference standard, e.g., a laser interferometer. This documentation will include the measurement uncertainty of the calibration and evidence that the stated uncertainty is achievable, e.g., participation in a round robin or comparison against another independently calibrated length standard.

[2] A de facto means of demonstrating competence is through laboratory accreditation.

[3] In this Standard, an independent realization of the SI meter is considered a reproducible physical phenomenon that has its metrological characteristic (and reproducibility) measured and documented by an NMI. Hence, reproduction of this phenomenon represents an unbroken chain of information back to the SI unit of length; such a realization is sometimes referred to as a quantum-based standard.

NONMANDATORY APPENDIX A
CALIBRATION OF A TAPE BY COMPARISON TO A MASTER TAPE

A-1 TEST SETUP

See Fig. A-1.

A-2 NOTATION

L_M^0 = calibrated length of a master tape at 20°C
L_M = length of master tape at temperature T
α_{test} = coefficient of thermal expansion of test tape
α_M = coefficient of thermal expansion of master tape
δ_T = error of test tape measured at temperature T
δ_{20} = error of test tape at $T = 20°C$

A-3 CALIBRATION PROCEDURE

The test setup is illustrated in Fig. A-1. Assume that the right-hand edges of the two tapes correspond to the same length graduation, for example, the 10 m marks.

The difference in length, δ_T, at temperature T is measured with a comparator instrument, such as a measuring microscope. The relevant lengths are shown at the top of Fig. A-1. The length of the master tape at temperature T is

$$L_M = L_M^0(1 + \alpha_M \Delta T) \tag{A-1}$$

where
L_M^0 = the length of the master tape taken from its calibration report
ΔT = $T - 20°C$

The quantity of interest (the measurand) is δ_{20}, the error of the test tape at 20°C, which is the standard reference temperature for length measurements.

The bottom of Fig. A-1 shows the situation at $T = 20°C$. The master tape now has its calibrated length, L_M^0. The length of the test tape at 20°C, corrected for thermal expansion (or contraction) from its length at temperature T, is $(L_M + \delta_T)(1 - \alpha_{test}\Delta T)$, where $\Delta T = T - 20°C$. From the figure it is seen that

$$\delta_{20} = (L_M + \delta_T)(1 - \alpha_M \Delta T) - L_M^0 \tag{A-2}$$

and substituting for L_M using eq. (A-1) gives

$$\begin{aligned}\delta_{20} &= [L_M^0\,(1 + \alpha_M\Delta T) + \delta_T](1 - \alpha_{test}\Delta T) - L_M^0 \\ &= \delta_T + (\alpha_M - \alpha_{test})L_M^0\Delta T - \alpha_{test}\delta_T\Delta T - \alpha_M\alpha_{test}L_M^0(\Delta T)^2\end{aligned} \tag{A-3}$$

The last two terms in this equation are negligible and may be omitted, so that the desired error is

$$\delta_{20} = \delta_T + (\alpha_M - \alpha_{test})L_M^0\Delta T \tag{A-4}$$

Equation (A-4) is the fundamental result of a tape calibration performed by comparison with a master tape at temperature T. The first term is the measured error at the calibration temperature T. The second term is a correction for differential expansion (or contraction) of the test and master tapes between the calibration temperature and 20°C.

There are two cases of interest with respect to the differential expansion correction.

(a) If the test and master tapes are made of the same material (e.g., a steel tape calibrated against a steel master), then $\alpha_M = \alpha_{test}$ and the correction is equal to zero. There will still be uncertainty components associated with the correction because none of the quantities α_M, α_{test}, L_M^0, and ΔT are known exactly.

(b) If the test and master tapes are made of different materials (e.g., a steel tape calibrated against an Invar master), then the correction term must be calculated and the result used to adjust the measured error.

The two cases are illustrated in section A-4.

A-4 UNCERTAINTY EVALUATION

The standard uncertainty, $u(\delta_{20})$, associated with the result eq. (A-4) of the tape calibration is calculated using the law of propagation of uncertainty as described in ISO/IEC Guide 98-3:2008 (GUM). The result is

$$\begin{aligned}u^2(\delta_{20}) &= u^2(\delta_T) + (L_M^0\Delta T)^2[u^2(\alpha_M) + u^2(\alpha_{test})] \\ &\quad + (L_M^0\Delta\alpha)^2u^2(\Delta T) + (\Delta\alpha\Delta T)^2u^2(L_M^0)\end{aligned} \tag{A-5}$$

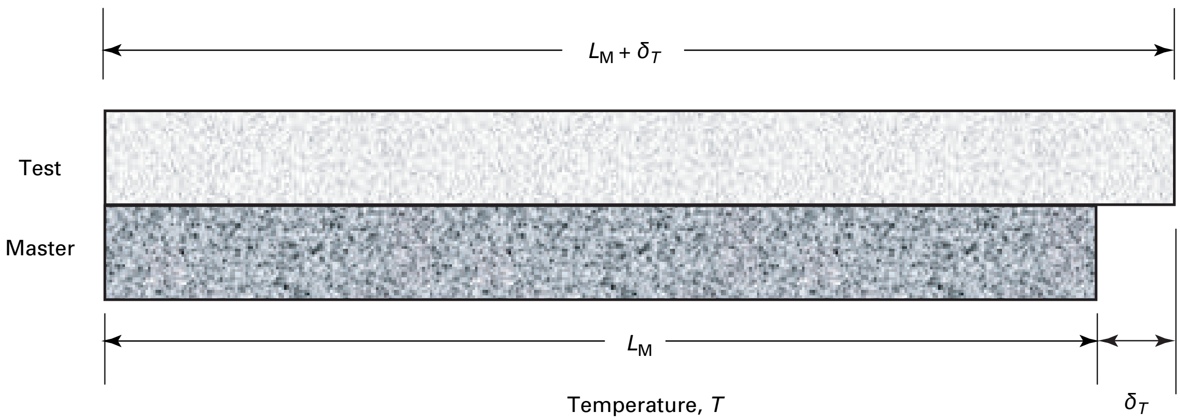
where $\Delta\alpha = \alpha_M - \alpha_{test}$. The first term on the right is associated with the procedure used to measure the error, δ_T, and includes components due to the comparator calibration and resolution, measurement repeatability, operator effects, etc.

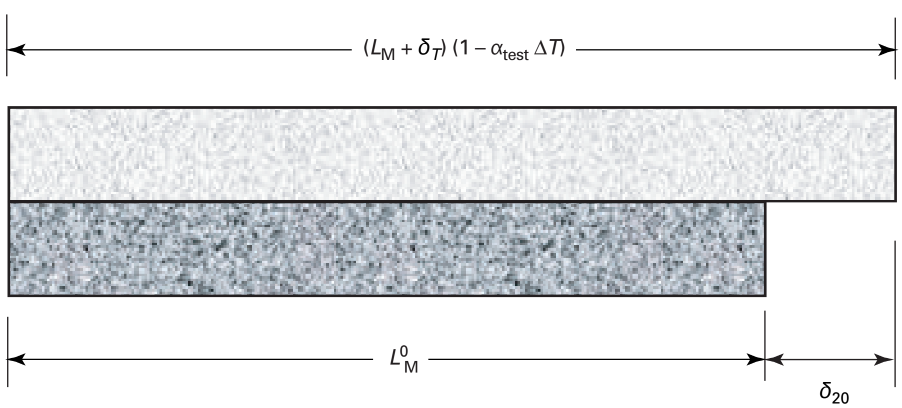
The remaining terms in eq. (A-5) arise from the imperfect correction for differential expansion (or contraction) between the two tapes. The two possibilities are

(a) test and master tapes of the same material (e.g., steel tape and steel master): In this case, $\alpha_M = \alpha_{test}$, $u(\alpha_M) = u(\alpha_{test}) = u(\alpha)$, and the last two terms in eq. (A-5) are equal to zero, so that

$$u^2(\delta_{20}) = u^2(\delta_T) + 2(L_M^0\Delta T)^2u^2(\alpha) \tag{A-6}$$

Fig. A-1 Test Setup





and

$$u(\delta_{20}) = \sqrt{u^2(\delta_T) + 2(L_M^0 \Delta T)^2 u^2(\alpha)} \quad \text{(A-7)}$$

(b) test and master tapes of different materials (e.g., steel tape and Invar master): In this case all terms in eq. (A-5) must be included, so that

$$u(\delta_{20}) = \begin{bmatrix} u^2(\delta_T) + (L_M^0 \Delta T)^2 [u^2(\alpha_M) + u^2(\alpha_{test})] \\ + (L_M^0 \Delta\alpha)^2 u^2(\Delta T) + (\Delta\alpha \Delta T)^2 u^2(L_M^0) \end{bmatrix}^{\frac{1}{2}} \quad \text{(A-8)}$$

A-5 DECISION RULE

Once the test tape error has been measured, one has to decide whether or not the MPE requirement has been met. Because of the uncertainty associated with the result of the error measurement, a decision rule according to ASME B89.7.3.1 must be specified. The stated decision rule describes the way in which measurement uncertainty will be accounted for in deciding if the tape is to be accepted as in compliance with its specification.

In this Standard, the decision rule is called simple 4:1 acceptance. This means that a tape for which $|\delta_{20}| \leq MPE$ is accepted as conforming with specification, as long as the measurement capability index, defined by $C_m = MPE/2u(\delta_{20}) = MPE/U$, satisfies the requirement

$$C_m = \frac{MPE}{U} \geq 4 \quad \text{(A-9)}$$

where $U = 2u(\delta_{20})$ is the $k = 2$ expanded uncertainty associated with the measurement of the error.

A-6 EXAMPLE: COMPARATOR REQUIREMENT FOR TAPE CALIBRATION

A manufacturer wishes to design a comparator system for calibrating 10 m curved cross section steel tapes. The calibrated master tape will also be made of steel. Calibrations will be performed in a laboratory where the temperature is maintained within the range 21°C ≤ T ≤ 25°C.

Tapes will be accepted or rejected using a simple 4:1 acceptance decision rule. From eq. (A-9) it is seen that the requirement $C_m = MPE/2u(\delta_{20}) \geq 4$ means that the standard uncertainty associated with the result of an error measurement must satisfy

$$u(\delta_{20}) \leq \frac{MPE}{8} \quad \text{(A-10)}$$

Because the master and test tapes are both made of steel, the correction for differential expansion is equal to zero. The standard uncertainty, $u(\delta_{20})$, is given by eq. (A-7).

The basic question facing the manufacturer is how well must the comparator measurement be performed. Or in other words, with what standard uncertainty, $u(\delta_T)$, must the errors be measured in order to satisfy the requirement of eq. (A-10)?

The question can be answered as follows. Combining eqs. (A-7) and (A-10) yields the requirement

$$u^2(\delta_{20}) = u^2(\delta_T) + 2(L_M^0 \Delta T)^2 u^2(\alpha) \leq \frac{MPE^2}{64} \quad \text{(A-11)}$$

Solving for $u(\delta_T)$ then gives

$$u(\delta_T) \leq \sqrt{\frac{MPE^2}{64} - 2(L_M^0 \Delta T)^2 u^2(\alpha)} \quad \text{(A-12)}$$

This can now be evaluated by putting in the numbers.

$$L_M^0 = 10 \text{ m}$$

From Table 2:

$$MPE = 1.8 \text{ mm}$$
$$\Delta T_{max} = 5°\text{C}$$
$$u(\alpha) = (1/\sqrt{3}) \times 10^{-6}°\text{C}^{-1}$$

The value for $u(\alpha)$ is the standard deviation of a uniform probability distribution of width 2×10^{-6}°C^{-1}, i.e., α is unknown by ±1 × 10^{-6}°C^{-1}.

The two terms under the square root in eq. (A-12) are then

$$\frac{MPE^2}{64} = 50625 \ \mu\text{m}^2$$

$$2(L_M^0 \Delta T_{max})^2 u^2(\alpha) = \frac{2 \cdot 50^2}{3} \times 10^{-12} \text{ m}^2 = 1670 \ \mu\text{m}^2$$

Then

$$u(\delta_T) \leq \sqrt{50625 - 1670} \ \mu\text{m} \leq 221 \ \mu\text{m} \quad \text{(A-13)}$$

The comparator measurement process used to measure the distance between the 10 m marks on the test and master tapes must have an associated standard uncertainty of about 0.22 mm in order to satisfy the requirements for simple 4:1 acceptance.

NONMANDATORY APPENDIX B
CALIBRATION OF A TAPE USING A LASER INTERFEROMETER

B-1 TEST SETUP

See Fig. B-1.

B-2 NOTATION

L_j = numbered tape graduations, $j = 1, 2, ..., n$. Numerically, L_j is equal to the nominal length from the zero graduation to graduation L_j at 20°C

l_j^{nom} = nominal length of tape from the zero graduation to graduation L_j at the calibration temperature, T

l_j^{cal} = calibrated length of tape from the zero graduation to graduation L_j at the calibration temperature, T

α_{test} = coefficient of thermal expansion of the test tape

δ_j = error in nominal length l_j^{nom}

d_j = measured displacement from zero graduation to graduation L_j

θ_0 = microscope pitch angle at zero graduation

θ_j = microscope pitch angle at graduation L_j

$\Delta\theta_j$ = $\theta_j - \theta_0$
= change in microscope pitch angle between zero graduation and graduation L_j

z = vertical (Abbe) offset between tape and laser beam axis

B-3 LASER INTERFEROMETER TAPE CALIBRATION SETUP

A typical tape calibration setup using a laser interferometer is shown in Fig. B-1. A reticule microscope is arranged so as to be sequentially centered on the tape graduations to be calibrated. (For clarity, the traveling microscope carriage is not shown in the diagram.)

The displacement of the microscope along the test tape is measured by a laser displacement interferometer, corrected for wavelength changes due to the refractive index of air. The target reflector (typically a cube-corner retroreflector) is attached to the microscope carriage.

For a typical two-beam interferometer with retroreflector target, as shown in the diagram, the measurement axis is a straight line parallel to the laser beams through the retroreflector vertex.

The measurement axis is offset from the tape surface by an amount z, called an Abbe offset. Any angular (pitch) motion of the microscope carriage between measurement locations will cause a length measurement error called an Abbe error.

The pitch of the carriage can be adjusted and maintained approximately constant using a bubble level and an adjustment screw. Such adjustments cannot be done perfectly so that residual Abbe errors will, in principle, contribute to the measurement uncertainty.

The tape calibration is carried out at temperature T, with an associated standard uncertainty, $u(T)$.

B-4 CALIBRATION PROCEDURE

The procedure for calibrating a tape is as follows:

(a) Level the microscope carriage using the adjusting screw.

(b) Center the microscope reticule on the tape zero graduation and zero the laser displacement measuring system. This is illustrated at the top of Fig. B-1.

(c) Move the carriage to the first graduation, level the carriage, and center the microscope reticule on the graduation.

(d) Record the measured displacement, d_1.

(e) Move the carriage to the next desired graduation, level the carriage, and center the microscope reticule on the graduation.

(f) Record the measured displacement, d_2.

(g) Repeat steps (e) and (f) until all desired graduations have been sampled.

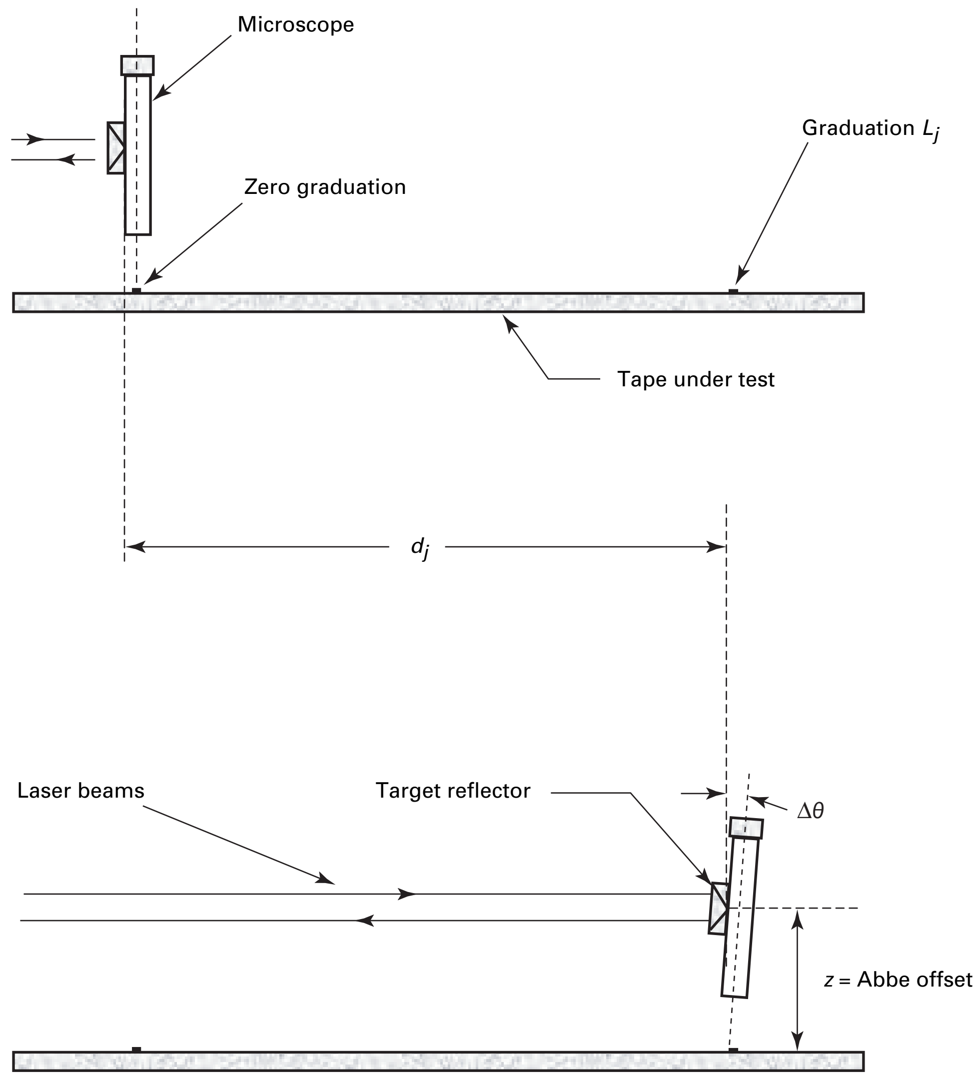
The measurement data consist of the measured displacements $d_1, d_2, ..., d_n$ between the tape zero graduation and the numbered graduations $L_1, L_2, ..., L_n$.

B-5 CALCULATION OF TEST TAPE ERRORS

The lower illustration in Fig. B-1 shows the setup when measuring graduation L_j. The interferometer measures a displacement, d_j, as the carriage moves from the zero graduation to graduation marking nominal length, L_j.

Due to pitch error in the motion of the carriage, the microscope is rotated relative to its initial position by a small angle, $\Delta\theta_j$. This rotation causes an Abbe error in the measured length. From the illustration, taking $\Delta\theta_j$ to be positive, it can be seen that the measured displaceent, d_j, is too large by an amount approximately equal to $z\Delta\theta_j$, where z is the offset from the measurement axis to the tape surface.

Fig. B-1 Test Setup



The calibrated length, l_j^{cal}, of the tape segment, corrected for Abbe error, is then given by

$$l_j^{cal} = d_j - z\Delta\theta_j \quad \text{(B-1)}$$

The nominal length, l_j^{nom}, of the tape segment at calibration temperature T is equal to its nominal length, L_j, at 20°C, corrected for thermal expansion (or contraction)

$$l_j^{nom} = L_j\,(1 + \alpha_{test}\Delta T) \quad \text{(B-2)}$$

where $\Delta T = T - 20°C$.

The error, δ_j, in length of the tape segment at temperature T is the difference between the measured value and the nominal value

$$\delta_j = l_j^{nom} - l_j^{cal} \quad \text{(B-3)}$$

Using eqs. (B-1) and (B-2) then gives

$$\delta_j = d_j - z\Delta\theta_j - L_j\,(1 + \alpha_{test}\Delta T) \quad \text{(B-4)}$$

Equation (B-4) is the general result for the error of the tape between the zero graduation and the graduation marking nominal length L_j.

NOTE: If the calibration temperature, T, is different from 20°C, the error, δ_j, should in principle be corrected for this temperature offset. In practice, however, such corrections are negligible because δ_j is typically a small error whose correction would be very much smaller.

For example, in calibrating a 10 m flat steel tape, Table 3 states an MPE requirement of ±1.57 mm. An error of this size, measured at 25°C, would be smaller at 20°C by an amount equal to $(MPE)\alpha_{test}\Delta T = (1.57\text{ mm}) \times 11 \times 10^{-6}{}°C^{-1} \times 5°C = 0.1\ \mu m$, which is negligible.

B-6 DECISION RULE

For a measured error, δ_j, and associated standard uncertainty, $u(\delta_j)$, the simple 4:1 acceptance decision rule used in this Standard requires both

(a) a measurement capability index, C_m, such that $C_m = MPE_j/2u(\delta_j) \geq 4$

(b) $|\delta_j| \leq MPE_j$ for every numbered graduation, L_j, $j = 1, 2, ..., n$ to be calibrated

The quantity MPE_j is the maximum permissible error in the length of the tape between the zero graduation and the graduation marked L_j. The magnitude of MPE_j depends on the nominal length, L_j, as shown in Tables 2 and 3.

B-7 UNCERTAINTY EVALUATION

The standard uncertainty, $u(\delta_j)$, associated with measured error δ_j follows from the law of propagation of uncertainty applied to the measurement model eq. (B-4)

$$u^2(\delta_j) = u^2(d_j) + (\Delta\theta_j)^2u^2(z) + z^2u^2(\Delta\theta_j) + (\alpha_{test}\Delta T)^2u^2(L_j) + (L_j\alpha_{test})^2u^2(\Delta T) + (L_j\Delta T)^2u^2(\alpha_{test}) \quad \text{(B-5)}$$

Two of the terms drop out of this equation.

(a) Because the carriage is leveled at each measurement position, the best estimate of the change in angle $\Delta\theta_j$ is equal to zero, so that the second term vanishes.

(b) The scale graduation marking, L_j, is a fixed constant, so that $u(L_j) = 0$ and the fourth term vanishes.

Then eq. (B-5) simplifies to

$$u^2(\delta_j) = u^2(d_j) + z^2u^2(\Delta\theta_j) + (L_j\alpha_{test})^2u^2(\Delta T) + (L_j\Delta T)^2u^2(\alpha_{test}) \quad \text{(B-6)}$$

Now since $\Delta\theta_j = \theta_j - \theta_0$, and these angles are independently adjusted, they are uncorrelated and

$$u^2(\Delta\theta_j) = u^2(\theta_j) + u^2(\theta_0) = 2u^2(\theta) \quad \text{(B-7)}$$

where $u(\theta)$ is the common standard uncertainty associated with leveling the microscope carriage at each measurement position. Using this result in eq. (B-6) then gives the central result of the uncertainty evaluation

$$u^2(\delta_j) = u^2(d_j) + 2z^2u^2(\theta) + (L_j\alpha_{test})^2u^2(\Delta T) + (L_j\Delta T)^2u^2(\alpha_{test}) \quad \text{(B-8)}$$

There are four standard uncertainties in the equation for $u^2(\delta_j)$

$u(d_j)$ = standard uncertainty in laser measurement of displacement, d_j

$u(\theta)$ = standard uncertainty in leveling the microscope carriage

$u(\Delta T)$ = standard uncertainty in temperature deviation from 20°C

$u(\alpha_{test})$ = standard uncertainty in tape coefficient of thermal expansion

The displacement measurement uncertainty, $u(d_j)$, will generally have components due to repeatability of the calibration process, as well as a component due to environmental effects (primarily the air temperature and pressure) on the wavelength of the laser interferometer.

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