

Guidelines for the Evaluation of Uncertainty of Test Values Associated With the Verification of Dimensional Measuring Instruments to Their Performance Specifications

AN AMERICAN NATIONAL STANDARD



The American Society of
Mechanical Engineers

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Mechanical Engineers**

Two Park Avenue • New York, NY • 10016 USA

Date of Issuance: June 12, 2020

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FOREWORD

JCGM 100:2008, "Evaluation of measurement data — Guide to the expression of uncertainty in measurement," known as GUM, contains the internationally accepted method of expressing measurement uncertainty. The United States has adopted GUM as a national standard. The evaluation of measurement uncertainty has been applied for some time at national measurement institutes, but more recently, issues such as measurement traceability and laboratory accreditation are resulting in its widespread use in calibration laboratories.

Given the potential impact to business practices, national and international standards committees are working to publish new standards that will facilitate the integration of the GUM approach and the consideration of measurement uncertainty. In support of this effort, the ASME B89 Committee for Dimensional Metrology has formed Division 7, Measurement Uncertainty.

Measurement uncertainty has important economic consequences for calibration and measurement activities. In calibration reports, the magnitude of the uncertainty is often taken as an indication of the quality of the laboratory, and smaller uncertainty values generally are of higher value and higher cost. ASME B89.7.1, Guidelines for Addressing Measurement Uncertainty in the Development and Application of ASME B89 Documents, provides recommendations associated with measurement uncertainty for use in the development of ASME B89 documents and in the application of the existing ASME B89.7 series of uncertainty-related documents. ASME B89.7.2, Dimensional Measurement Planning, gives a high-level outline of what to consider when making measurements and provides examples of how measurement uncertainty is addressed for workpiece acceptance decisions. ASME B89.7.3.1, Guidelines to Decision Rules in Determining Conformance to Specifications, addresses the role of measurement uncertainty when accepting or rejecting products based on a measurement result and a product specification and provides the language to communicate what decision rule is used. ASME B89.7.3.2, Guidelines for the Evaluation of Dimensional Measurement Uncertainty, provides a simplified approach (relative to GUM) to the evaluation of dimensional measurement uncertainty associated with measurement results on workpieces. ASME B89.7.3.3, Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements, examines how to resolve disagreements concerning the magnitude of the measurement uncertainty statement. ASME B89.7.4.1, Measurement Uncertainty and Conformance Testing: Risk Analysis, provides guidance on evaluating the risks involved in any product acceptance/rejection decision. Finally, ASME B89.7.5, Metrological Traceability of Dimensional Measurement to the SI Unit of Length, provides one specific definition of metrological traceability and several examples demonstrating the concept.

This Standard provides guidance for the specific case of evaluating the uncertainty of test values associated with testing dimensional measuring instruments to their ASME B89 performance specifications.

ASME B89.7.6 was approved by the American National Standards Institute (ANSI) on October 31, 2019.

Acknowledgment. This work was initiated and chaired by the late Dr. Steven D. Phillips. The ASME B89 Committee recognizes his inspiring zeal, his tireless commitment, and his inestimable contribution to this Committee and to the dimensional metrology community at large.

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Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
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. Please provide a condensed and precise question, composed in such a way that a "yes" or "no" reply is acceptable.
Proposed Reply(ies):	Provide a proposed reply(ies) in the form of "Yes" or "No," with explanation as needed. If entering replies to more than one question, please number the questions and replies.
Background Information:	Provide the Committee with any background information that will assist the Committee in understanding the inquiry. 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.

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PREFACE

The primary purpose of this Standard is to provide guidance for assessing the uncertainty of test values associated with the verification of dimensional instruments to their ASME B89 performance specifications. This guidance is fully consistent with the GUM methodology and philosophy. The particular case of verifying dimensional instruments is frequently misunderstood by practitioners. This confusion arises primarily because the measurand of the verification is the instrument's measurement error when measuring the calibrated reference quantity specified in the testing protocol. The test values produced during ASME B89 testing are estimates of these measurement errors. Hence, in verification testing, the performance of the instrument is the quantity being measured. The instrument is verified as complying with its ASME B89 performance specification if the test values are within the instrument's maximum permissible error (MPE) and satisfy the decision rule stated in the testing protocol. To ensure that this verification is metrologically traceable, the uncertainty in the test values must be evaluated, i.e., the practitioner must determine how well each test value estimates the measurement error made by the instrument under verification when it is used to measure the reference quantity specified by the testing protocol. By distinguishing the instrument under verification from the measurement system performing the verification, the evaluation of the uncertainty of the test values is shown to follow the GUM procedure. ASME B89.7.6 provides both detailed discussions and worked examples to clarify this issue and should prove valuable to both novice and experienced metrologists.

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Guidelines for the Evaluation of Uncertainty of Test Values Associated With the Verification of Dimensional Measuring Instruments to Their Performance Specifications

1 SCOPE

This Standard provides guidelines for evaluating the uncertainty of test values obtained when verifying dimensional measuring instruments¹ to an ASME B89 testing protocol. The scope is limited to the case in which the test measurand is the error of indication at a rated operating condition; hence, test measurands such as the “worst possible” error of indication that might occur at any operating condition (including those conditions that are not tested) are outside the scope of this Standard.

ASME B89 testing protocols are composed of many individual tests, each test yielding one test value that is an estimate of the instrument’s measurement error at the particular operating condition tested, and this test value is compared against the maximum permissible error (MPE) (specified for that rated operating condition) using the protocol’s decision rule. Although the MPE is specified by the instrument manufacturer for all rated operating conditions, the test value uncertainty is associated only with the test value obtained at the particular operating condition prevailing at the moment the test value was obtained (unless a correction to the indication is performed that is allowed by the test protocol).

Because each test investigates the error of indication at a particular rated operating condition, the test value uncertainty does not include the robustness or comprehensiveness of the testing protocol, i.e., it does not address the number of tests or their distribution over different rated operating conditions. This issue is addressed by the standardization committee creating the testing protocol; the committee balances the number of tests against the amount of time and effort to complete the testing protocol.

The scope of this Standard excludes issues associated with the evaluation of the uncertainty of future measurement results on workpieces and focuses solely on the test value uncertainties used to verify the instrument’s performance specification. Typically, the test value uncertainty is much smaller than the associated MPE value of the verification test.

2 DEFINITIONS

The following definitions are specific to this Standard:

instrument: the measuring system that is under verification to its performance specification.

NOTE: In this Standard, the term “instrument” is equivalent to “instrument under verification.”

verification system: the measuring system that is used to verify an instrument to its performance specification.

NOTE: In this Standard, the verification system includes everything necessary to execute the testing protocol. This includes the calibrated reference quantity, equipment used in the transfer process, the human operator (if one is involved), computations and any other analysis needed, environmental and other conditions required by the instrument under verification, and any input quantities required to realize the measurand of the verification test.

3 REFERENCES

The following is a list of publications referenced in this Standard:

ASME B89.1.13-2013, Micrometers

ASME B89.1.14-2018, Calipers

ASME B89.4.10360.2-2008, Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs) — Part 2: CMMs Used for Measuring Linear Dimensions (Technical Report)

¹ In this Standard, the term “instrument” is exclusively used to refer to the device under verification to its performance specification; hence the term “instrument” always means “instrument under the verification test.” In contrast, the measuring system providing the calibrated reference value used in the verification test is referred to as a “verification system.”

ASME B89.7.1-2016, Guidelines for Addressing Measurement Uncertainty in the Development and Application of ASME B89 Documents

ASME B89.7.2-2014, Dimensional Measurement Planning

ASME B89.7.3.1-2001, Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications

ASME B89.7.3.2-2007, Guidelines for the Evaluation of Dimensional Measurement Uncertainty

ASME B89.7.3.3-2017, Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements

ASME B89.7.4.1-2005, Measurement Uncertainty and Conformance Testing: Risk Analysis

ASME B89.7.5-2006, Metrological Traceability of Dimensional Measurement to the SI Unit of Length

ASME Y14.5-2018, Dimensioning and Tolerancing

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

ISO 1:2016, Geometrical product specifications (GPS) — Standard reference temperature for the specification of geometrical and dimensional properties

Publisher: International Organization for Standardization (ISO), Central Secretariat, Chemin de Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland (www.iso.org)

JCGM 100:2008, Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM)

JCGM 200:2012, International vocabulary of metrology — Basic and general concepts and associated terms (VIM)

Publisher: Joint Committee for Guides in Metrology (JCGM), Bureau International des Poids et Mesures (BIPM), Pavillon de Breteuil, F-92312 Sèvres Cedex, France (www.bipm.org)

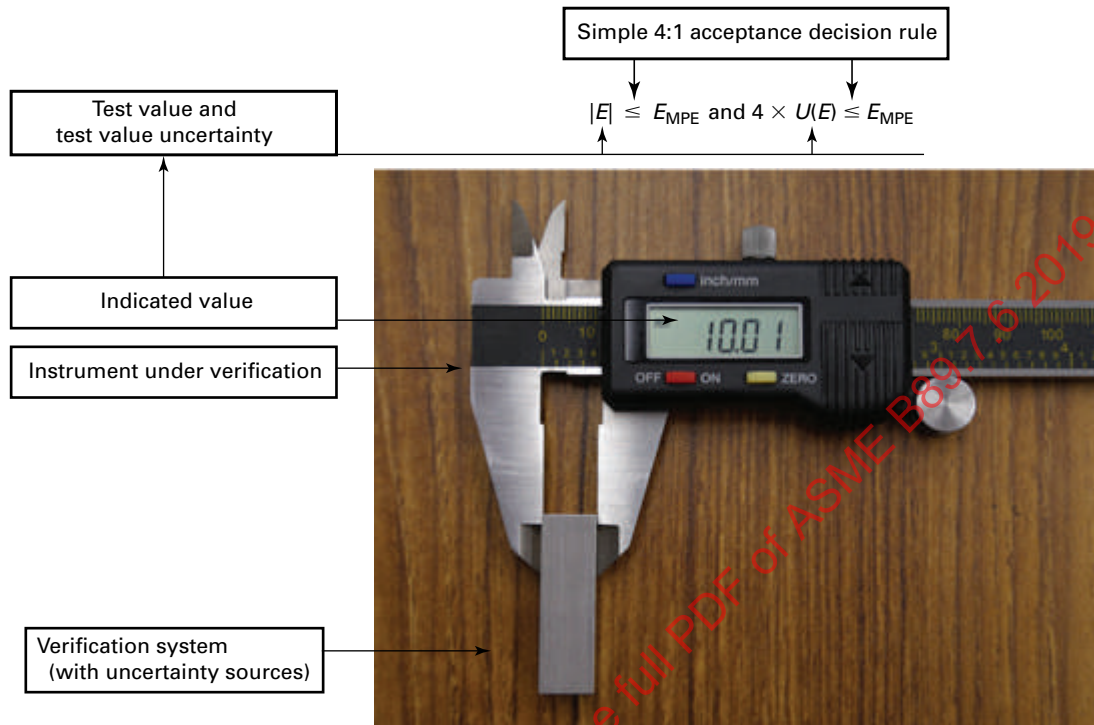
4 BASIC CONCEPTS OF TEST VALUES AND TEST VALUE UNCERTAINTY

4.1 Introduction

ASME B89 standards describe the testing protocols used to specify the performance of dimensional measuring instruments. Verification of an instrument to its MPE is based on a decision rule (e.g., see ASME B89.7.3.1) that determines whether a test value (obtained per the testing protocol) is within its MPE specification. Different test values may have different test value uncertainties, e.g., due to different testing temperatures or different uncertainties of calibrated gauges used in the verification.

It is important that the test value uncertainty not be confused with the measurement uncertainty associated with a future workpiece measurement. The uncertainty of a workpiece measurement, having a measurand similar to that used in the ASME B89 testing protocol and obtained within the rated conditions of the instrument, is primarily determined by the instrument's MPE. In contrast, the test value uncertainty is associated with uncertainty of the test values obtained when verifying the MPE; it is independent of the MPE and hence has nothing to do with the accuracy of future workpiece measurements. An inaccurate instrument, with a large MPE, might have a relatively small test value uncertainty. The test value uncertainty does not describe the accuracy of the instrument's measurement results, but rather describes the accuracy of the test values obtained in a verification test. Figure 4.1-1 illustrates the distinction between the instrument under verification that produces an error of indication and the verification system that includes a calibrated reference quantity.

Figure 4.1-1 A Caliper Under Verification to Its MPE Specification by a Verification System Composed of Calibrated Gauge Blocks Using a Simple Acceptance Decision Rule



4.2 Rated Operating Conditions

The rated operating conditions are generally stated by the instrument manufacturer. They are the conditions under which the instrument has a performance specification, i.e., the MPE specification exists only within the rated operating conditions. The rated operating conditions can be considered the domain of a function whose value is the MPE.

Often the MPE value is constant or slowly varies over wide ranges of an operating condition; e.g., the same MPE value might be quoted for the performance of an instrument over the entire range of the rated ambient temperatures. Environmental conditions are frequently included among the rated operating conditions; however, many other factors can also be included. The quantity under measurement is a rated condition, e.g., the MPE for a micrometer generally increases as the length of the calibrated reference length increases. Any influence that is specified or constrained in some manner as a requirement to achieve the instrument's performance specification is an operating condition; this includes requirements described in the instrument's operating manual. When tested under conditions that satisfy the rated operating conditions, an instrument conforming to its performance specification shall yield an error of indication no greater than its MPE value.

4.3 Test Conditions

The test conditions are the particular conditions that prevail at the moment the test value is obtained. Often the test conditions are within the rated operating conditions of the instrument under test. In some cases, the test conditions will — as explicitly permitted by the testing protocol — be outside the rated operating conditions and require a correction to create an indicated value from the instrument that is associated with conditions that are within the rated operating conditions. As described in [para. 5.3](#), in some cases this correction is numerically zero, but there are still test value uncertainties associated with the zero correction. Conceptually, the correction creates an indicated value that is associated with conditions within the rated operating conditions and hence can be compared to the MPE. For example, ASME B89.1.13 has (for historical reasons) defined the test measurand as the measurement error of a micrometer at (and only at) 20°C. Hence an MPE specification exists only at the operating condition of 20°C, whereas test conditions will inevitably occur at other temperatures. In this case, corrections are required — and permitted by the protocol — to adjust the indicated value of the instrument to produce a value the instrument would have produced if the test had been conducted at 20°C (thus satisfying the rated operating conditions) and producing a test value that can be compared to the MPE specification.

4.4 Test Values

The test value in an ASME B89 standard is typically the measurement error associated with a single indicated value of the instrument under verification. However, in some cases it might be defined as the range or average of several indicated values. Since the instrument manufacturer specifies the MPE based on the testing protocol — and hence the testing protocol becomes the defining document for the instrument's MPE — no modification of the testing protocol is allowed. For example, if the testing protocol requires that a single indicated value be used for each test value, then the verification testing must similarly do so, and changing the procedure, e.g., averaging multiple indicated values, is not allowed.

Test values obtained during verification testing to an ASME B89 test protocol are estimates of the instrument's measurement error.² The measurement error is defined as the indicated value (obtained at a specific operating condition) minus the true value of the reference quantity; see eq. (1).

$$E|_{RC} = I|_{RC} - R_T \quad (1)$$

where

$E|_{RC}$ = error of indication at the rated operating conditions

$I|_{RC}$ = instrument indicated value at the rated operating conditions

R_T = measurement system (true) reference value

In eq. (1), “at the rated operating conditions” is a reminder that the measurement error and the indicated value are within the rated operating conditions.³ Note that the reference quantity is often defined at conditions other than the test conditions at which the indicated value is obtained. For example, an instrument's operating ambient conditions could be 15°C to 25°C and the indicated value obtained at 22°C when measuring a gauge block (the reference quantity) whose length is defined at 20°C.

In this Standard, the term “indicated value” is used exclusively to describe the value from the instrument under test. This value is produced by the instrument and represents its best estimated value of the reference quantity it has measured, after the operator has followed all the requirements of the testing protocol. For a digital instrument under verification, the indicated value is the value shown on the display. For an analog instrument under verification, the indicated value is the value recorded (written down) after the operator has completed the measurement; e.g., if the instrument's operating manual requires adjusting for parallax error (and hence this is an operating condition required to achieve the specified MPE performance), then the indicated value is that obtained after adjustment for the parallax effect.

In verification testing, the test value is an estimate of the measurement error defined in eq. (1); it is a well-defined quantity evaluated as

$$T|_{RC} = I|_{CRC} - R_C \quad (2)$$

where

$I|_{CRC}$ = instrument indicated value corrected to the rated operating conditions

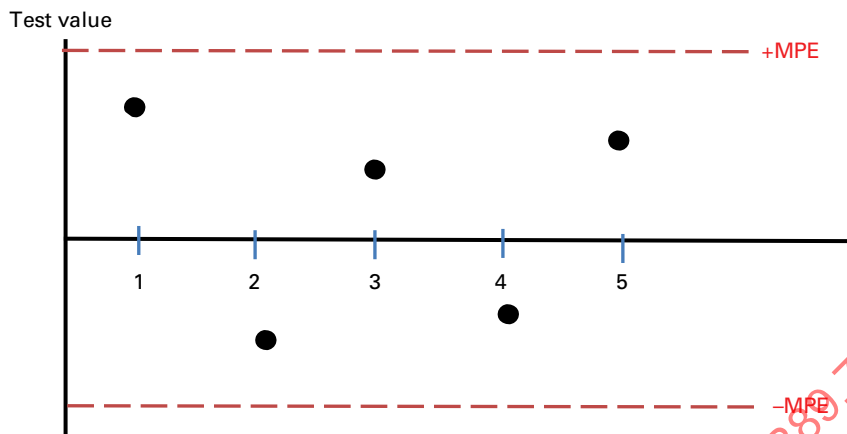
R_C = verification system (calibrated) reference value

$T|_{RC}$ = test value at the rated operating conditions

In eq. (2), “corrected to the rated operating conditions” is a reminder that in some cases the indicated value may require a correction — as permitted by the testing protocol — to yield the indicated value that the instrument would have indicated had the test been performed at a specific condition within the rated operating conditions. The calibrated reference standard that is used as an estimate of its true value does not require a correction, because it is reported at the standard reference conditions defined for length, e.g., 20°C (unless otherwise stated), and even if a length-measuring instrument had rated operating conditions of 21°C to 22°C, the instrument is required (by ISO 1) to report length at the standard reference temperature of 20°C unless another reference temperature is employed.

² In some cases, such as for verification of a repeatability specification of an instrument (see ASME B89.4.10360.2), the test value might be the range of a specified number of indications, so the test value uncertainty would involve only the stability (over the testing time) of the fixed reference quantity being measured.

³ The MPE of the instrument under verification is only specified, and so only defined, within the rated operating conditions; hence, the indicated value and corresponding measurement error must be within the rated conditions or corrected to be within the rated conditions. Measurement errors outside the rated operating conditions are irrelevant to the verification.

Figure 5.1-1 An Example of Five Test Values, All From the Same Reference Length

5 EVALUATION OF TEST VALUE UNCERTAINTY

5.1 General Test Value Uncertainty Guidelines

The evaluation of the uncertainty associated with a test value obtained from an instrument under verification follows the usual methodology of JCGM 100 (GUM); however, it is important to clearly identify the instrument as the device under verification and the calibrated reference standards (e.g., gauge blocks) as part of the verification system performing the test. It is the verification system that is measuring the error of indication of the instrument, and when the test conditions are fully within the rated operating conditions, the test value uncertainty arises solely from the verification system, not from the instrument being verified.

Factors affecting only the performance of the instrument are manifested in the test value and are not contributors to the test value uncertainty. The resolution of the instrument under verification is not an uncertainty source; it is an error source, and a low-resolution instrument under verification will generally have a larger test value than a high-resolution instrument. For example, if a caliper with a 1-cm resolution were tested with a 4-mm calibrated gauge block and an indicated value at 0 cm, a -4-mm error would be reported as the test value; however, the test value uncertainty would be very small and mostly due to the uncertainty of the calibrated value of the gauge block.

Similarly, the lack of repeatability of the instrument, e.g., the instrument generates different test values when measuring the same reference quantity under nominally the same conditions, is not a test value uncertainty source. Each “repeated” test value corresponds to a different test, and each test value is compared to its MPE using the decision rule. For example, Figure 5.1-1 shows a hypothetical testing protocol that requires five repeated measurements of a calibrated gauge and the associated MPE for this measurement. Each test value corresponds to a different test with a different indicated value, and each must be within the MPE for a conforming instrument. The test values are not a source of test value uncertainty; rather they are estimates of the measurand under specification by the MPE. Including the standard deviation of the different test values as a test value uncertainty source is a mistake.

5.2 Test Value Uncertainty When Test Conditions Are Within the Rated Operating Conditions

When the test conditions (at the time the test value is obtained) are within the rated operating conditions, the MPE function is evaluated at this test condition, and it is to this MPE the test value will be compared using the protocol’s decision rule. Because the test conditions are within the rated operating conditions, no correction to the indicated value of the instrument under verification is required or allowed. Since there are no corrections to the indicated value, there is no uncertainty associated with the indicated value. (This does not mean the instrument under verification is accurate; it only means that the indicated value produced by the instrument under verification is indicative of the instrument’s performance when the instrument is properly used.)

Since there is no uncertainty in the indicated value, the test value uncertainty is solely associated with the verification system. Using the example in Nonmandatory Appendix A of a coordinate measuring machine (CMM) length test per ASME B89.4.10360.2, the verification system is composed of a calibrated gauge block and the uncertainty in the block’s calibrated value at the moment of testing is a contributor to the test value uncertainty. The main contributor to the test value uncertainty is the uncertainty stated on the gauge block calibration report. Other contributors include any degradation in

the reference value such as distortion in the gauge block due to its fixturing or drift in the length of the gauge block since the time its calibration report was issued. In principle, the resolution of the verification system, e.g., the last significant digit of the gauge block length as stated on its calibration report, is also an uncertainty source, as is the repeatability of the gauge block length;⁴ however, these are usually negligible for reference values embodied in mechanical gauges. It is also noteworthy to point out that there are no thermal uncertainties associated with the length of the gauge block. The instrument under verification (the CMM) should produce an indicated value that yields the gauge block's length, which is defined by ISO 1 to be its length at 20°C. The verification system (the calibrated gauge block) is required to have a reference value that is the block's length at 20°C. Because the calibration report for the gauge block already states the block's length at 20°C, there is no thermal uncertainty associated with the length of the gauge block to be included in the test value uncertainty evaluation.

5.3 Test Value Uncertainty When Test Conditions Are Outside the Rated Operating Conditions

5.3.1 General. There are several subtle issues to consider when the test conditions are outside the rated operating conditions. Since an MPE specification of the instrument does not exist outside the rated operating conditions, test values obtained outside the rated operating conditions cannot directly be used to verify the instrument's MPE specification. The test can proceed only if the testing protocol (within an ASME B89 standard) specifically allows test values to be obtained outside the rated operating conditions. In this case, corrections are applied to obtain a corrected indicated value that corresponds to what the instrument under verification would have indicated at a specified condition within the rated operating conditions. Since all corrections to the indicated value have an associated uncertainty, this must be included in the evaluation of the test value uncertainty.

5.3.2 Test Conditions Outside the Rated Operating Conditions Due to the Tester-Supplied Coefficient of Thermal Expansion (CTE) Value. Some instruments under verification include a means of performing a thermal expansion compensation, e.g., an instrument that includes a temperature probe as part of its normal operation and yields an indicated value that is compensated for thermal expansion. Such compensation allows the instrument to indicate a more accurate value (specifically compensated to 20°C to satisfy the ISO 1 requirement) and will typically allow the instrument to have a smaller MPE value than an uncompensated instrument. If the instrument requires the user to input a CTE (i.e., such input is part of the normal operation of the instrument as stated in its operating manual), supplying an accurate CTE value is part of the rated operating conditions of the instrument and is required to meet its MPE specification.

If an imperfect (uncertain) CTE value is outside the rated operating conditions, then it may produce an incorrect thermal compensation, thus creating an incorrect indicated value and hence a potentially large test value that is due to this faulty information. Hence, it is a test value uncertainty source. Although the tester-supplied CTE value is a best estimate of the true CTE of the reference quantity, it is still considered a correction to the indicated value, where the correction is typically zero (because the best estimate of the CTE was supplied), but there is still an uncertainty in this correction that must be taken into account and combined with the uncertainty in the calibrated reference value.

The standard uncertainty associated with the indicated value due to the uncertain tester-supplied CTE value of the reference standard (u_{CTE}) is given by

$$u_{CTE} = L|T - 20^\circ\text{C}|u(\alpha_R) \quad (3)$$

where

L = reference length

T = ambient testing temperature as measured by the instrument under verification

$u(\alpha_R)$ = standard uncertainty in the CTE of the reference standard; see ASME B89.7.3.2 for details

If the tester is required to select a CTE from a series of menu choices, e.g., "steel," "aluminum," or "plastic," then the situation is more complex and requires a careful GUM analysis. Note that any issues associated with the instrument's temperature probe are not uncertainty sources because the temperature probe is part of the instrument under verification and incorrect temperature readings will appear as incorrect indication values, which are then compared to the MPE specification.

5.3.3 Test Conditions Outside the Rated Operating Conditions Due to the Tester-Supplied Temperature Value. Some instruments include a means of performing a thermal expansion compensation that requires the tester to input the temperature of the reference standard being measured. (If it also requires the CTE value, then this is also an uncertainty source; see [para. 5.3.2](#).) When part of the normal operation of this instrument (as stated in its operating manual) is

⁴ For example, there might be microscopic length changes in the gauge block due to chemical changes in the steel and its crystal structure, but these are negligible over the duration of the measurement when compared to either the workpiece tolerance or the uncertainty of a caliper measurement.

supplying an accurate temperature value, this is part of the rated operating conditions of the instrument and is required to meet its MPE specification. Analogous to [para. 5.3.2](#), the tester-supplied temperature is a best estimate of the true temperature of the reference standard, but the uncertainty in the temperature becomes a test value uncertainty source and is evaluated in the usual methodology of GUM and combined with the uncertainty in the reference value.

For a CMM being verified by a gauge block (as the reference standard), when the temperature is supplied by the tester, the standard uncertainty due to an uncertain temperature value (u_{temp}) is given by

$$u_{\text{temp}} = L|\alpha_I - \alpha_R|u(T) \quad (4)$$

where

L = reference length

$u(T)$ = standard uncertainty of the temperature value

α_I = the CTE of the instrument, typically supplied by the instrument manufacturer, possibly with its magnitude constrained by the testing protocol

α_R = the CTE of the reference standard; see ASME B89.7.3.2 for details

5.3.4 Test Conditions Outside the Rated Operating Conditions Due to the Ambient Temperature. When an instrument under verification has an operating condition for the ambient temperature of exactly 20°C, this means that the MPE value exists only at 20°C. Since any actual test condition cannot meet this operating condition, a correction — as permitted by the testing protocol — to the instrument's indicated value is required. A perfect correction would yield an indicated value that the instrument under verification would have indicated had it been at the rated condition of 20°C. The magnitude of the correction and the uncertainty of the correction will depend on the instrument under test and the testing temperature; the following examples elucidate the situation:

(a) A simple example is the verification of a micrometer made entirely of steel. (A steel caliper could also be used per ASME B89.1.14.) The micrometer is the instrument under verification, and the verification system includes a calibrated steel gauge block that provides the reference value. The micrometer's rated operating conditions include both the micrometer and the gauge block at a temperature of exactly 20°C, i.e., the micrometer's MPE exists only at 20°C. Suppose the testing condition of the verification test is 22°C and ASME B89.1.13 allows this as a test condition. Following the testing protocol, the micrometer indicates the length associated with the reference quantity, but the indication cannot yet be used to evaluate the test value because the testing conditions are not within the rated operating conditions of the micrometer, i.e., there is no MPE value at 22°C. The test value requires the corrected indicated value and the testing protocol specifies the correction⁵ (ΔL) as

$$\Delta L = L(\alpha_I - \alpha_R)(T - 20^\circ\text{C}) \quad (5)$$

where

L = reference length

T = temperature

α_I = the CTE of the micrometer

α_R = the CTE of the calibrated reference standard (gauge block)

In this example, the micrometer and the gauge block are both steel, and (for this example) it is assumed they have the same CTE value, so the correction is zero. However, the uncertainty of the correction is not zero. The GUM methodology is applied to the correction formula and evaluates the uncertainties associated with α_I , α_R , and T . The uncertainty of the

correction is $L|T - 20^\circ\text{C}| \sqrt{u^2(\alpha_I) + u^2(\alpha_R)}$; the GUM evaluation will also show that the temperature and reference length uncertainties do not contribute any test value uncertainty in this example because $\alpha_I = \alpha_R$. The uncertainty in the correction formula itself (i.e., the mathematical model), while in principle an uncertainty source, is negligible in this example, because it describes the physics of the actual measurement due to the uniform materials of the micrometer and the gauge block. In addition to the uncertainty of the correction, there is another source of test value uncertainty associated with the uncertainty in the reference value of the calibrated gauge block at the moment the indication was obtained.

Assuming the gauge block is dimensionally stable and undistorted by fixturing, the gauge block calibration uncertainty is the only uncertainty source associated with the reference value.

(b) A slightly more complex example is a steel micrometer instrument and a verification system including a ceramic gauge block. In this example, $\alpha_I \neq \alpha_R$ and the correction is nonzero. The corrected indicated value is used in the test value calculation, as seen in [eq. \(2\)](#). Note also that in this example, the uncertainty in the temperature becomes a test value

⁵ The correction is a value that is added to the indicated value.

uncertainty source, because the two CTEs are not equal, and the correction uncertainty will include a contributor similar to that described in [para. 5.3.3](#). Again, the test value uncertainty contributor associated with the calibrated reference value is only due to the gauge blocks.

(c) A subtler issue in the example in (b) arises when the verification system's thermometer reads 20°C. Even though the thermometer reads 20°C, there is still some uncertainty in this temperature, and although the indicated value of the micrometer would not be changed, i.e., a correction of zero, this uncertainty must still be included in the test value uncertainty evaluation. The uncertainty of this (zero) correction is nonzero because when the GUM evaluation of the correction formula [eq. (5)] is evaluated for $T = 20^\circ\text{C}$, the uncertainty is as shown in eq. (4) and remains nonzero at $T = 20^\circ\text{C}$. For example, suppose the verification system provides an environment of 20.1°C but the thermometer reads 20°C. A perfect correction to the indication of the instrument would apply the 0.1°C offset, but due to the imperfect thermometer (part of the verification system), this correction is not applied; it is, however, accounted for in the uncertainty of the correction, which is a test value uncertainty contributor.

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NONMANDATORY APPENDIX A

EXAMPLE: VERIFICATION OF A CMM TO ITS ASME B89.4.10360.2 PERFORMANCE SPECIFICATIONS

A-1 INTRODUCTION

Consider a CMM with an integrated workpiece thermal compensation system that has its performance specified to ASME B89.4.10360.2. Consider the E_0 test protocol and associated specification; this protocol involves 105 CMM bidirectional length errors, each estimated by a test value compared to the corresponding MPE (E_0), as stated by the CMM manufacturer. Assume the MPE is 10 μm for all rated operating conditions. The tester selects ceramic gauge blocks as the reference standard (which is permitted by the protocol). The blocks have a CTE of $9 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$. The CMM manufacturer has specified the thermal rated operating conditions allowed for testing as 15°C to 25°C. The temperature at the time of testing is 23°C, which is within the rated operating conditions. Other rated operating conditions are satisfied, such as the probe configuration and general operation of the CMM, using the procedures given in the manufacturer's operating manual including machine start-up, warm-up cycles, and probing system qualification.

Following the protocol, 105 test values are obtained, each of which is an estimate of the error of indication in the measurement of a gauge block length. The protocol requires the test value uncertainty to be evaluated for each of the 105 test values and the decision rule requires $U \leq \frac{1}{4}$ MPE for each test value. There could be 105 different test value uncertainties, but typically there is one for each calibrated gauge block length used. In this example, the test value uncertainty budget will be stated for one particular gauge block length of 500 mm. The 500-mm gauge block has a calibration certificate reporting an expanded uncertainty of 0.5 μm . Sections A-2 through A-5 discuss what factors are included in the test value uncertainty budget and, for instructive purposes, what factors are not included in the budget. A final uncertainty budget is presented in Table A-1-1.

A-2 REFERENCE STANDARD CALIBRATED VALUE

(a) *Included in Test Value Uncertainty.* The reference value is obtained from a gauge block whose length is uncertain by an amount stated on its calibration certificate, i.e., the true value of the reference length is uncertain. Dividing the expanded uncertainty (shown on the gauge block calibration report) by the coverage factor (e.g., $k = 2$) yields the standard uncertainty of 0.25 μm . Since this gauge block has been recalibrated several times and it consistently yields the same calibrated value (within the 0.5- μm calibration uncertainty), there is no additional uncertainty due to dimensional instability of the block, and hence the reference value of the gauge block at the time of testing is taken to be its calibrated value with the uncertainty shown on the calibration report.

(b) *Not Included in Test Value Uncertainty.* No additional test value uncertainty is allowed for the accuracy of the scales in the CMM as they are part of the system under test and their inaccuracies will appear as an error of indication, which is subject to the MPE specification being tested.

A-3 REPRODUCIBILITY AND RESOLUTION OF THE REFERENCE STANDARD

(a) *Included in Test Value Uncertainty.* Any influence that causes the reference value of the gauge block, at the moment it is presented to the CMM under verification, to vary from its calibrated value is an uncertainty contributor. In this example, an analysis of the fixturing holding the gauge block determines it is vibrating slightly due to excitations from the CMM motion. Since the rated operating conditions (required for the MPE) require a rigid reference standard, this is an uncertainty source; it is estimated to have a standard uncertainty of 0.1 μm . The resolution of the measuring system (the gauge block) is determined by the last digit shown on the gauge block calibration report. Since it is common practice to report the gauge block length with more precision than its associated uncertainty, this source is negligible.

(b) *Not Included in Test Value Uncertainty.* Most nonreproducible measurement results during testing are due to the CMM and thus are not a test value uncertainty source; i.e., they are part of the measurement error quantified by the test value and are subject to the MPE specification being tested. Similarly, the CMM resolution is part of the instrument and not

Table A-1-1 Test Value Uncertainty for Test Values Obtained Using a 500-mm Calibrated Gauge Block and a Test Condition of 23°C

Test Value Uncertainty Sources	Standard Uncertainty, μm
Reference value (calibration certificate)	0.25
Reproducibility and resolution (fixture vibration)	0.1
Deformation (of gauge and fixture)	0.3
Thermal considerations (CTE)	0.9
Combined standard test value uncertainty	1.0
Expanded test value uncertainty ($k = 2$)	2.0

part of the test value uncertainty because poor CMM resolution will be detected as a measurement error, i.e., it affects the indicated value and hence the test value subject to the MPE specification.

A-4 REFERENCE VALUE DEGRADATION

(a) *Included in Test Value Uncertainty.* The gauge block is held in a fixture that can cause gauge distortion (e.g., by the force from the fixturing bolts). This affects the reference length of the gauge block in an unknown manner and is therefore a source of test value uncertainty. Similarly, reorientation of the gauge block in the gravitational field may create additional distortions affecting the gauge block length and is also a source of test value uncertainty. The rated operating conditions for the MPE require noninfluencing reference standard fixturing; hence flimsy fixturing that deflects under fixturing forces, gravity, or CMM probing forces is a test value uncertainty source. If the CMM measurement is aligned (which is permitted by the test protocol) relying on the parallelism of the gauge block faces, then the imperfect parallelism is a test value uncertainty source. If the CMM requires knowledge of the mechanical properties of the gauge block, e.g., modulus of elasticity, to correct for the stylus ball penetration into the gauge block while probing, imperfect knowledge of this property is also a test value uncertainty source (see para. 5.3.2, which describes how the analogous CTE issue is addressed). In this example, a standard uncertainty of 0.3 μm is assumed for gauge deformation effects.

(b) *Not Included in Test Value Uncertainty.* The rated operating conditions of a CMM include its ability to measure engineering materials, including ceramics, according to ASME Y14.5, which states that ASME Y14.5 design specifications are defined in the free state, i.e., zero force.

Additionally, gauge blocks have their length defined with zero penetration into their surface at the gauging points; the calibrated length of the gauge block is the zero penetration length. Hence, unless the CMM requests a specific modulus of elasticity value of the gauge block (as required by the operating manual), the penetration by the CMM stylus is not a test value uncertainty because the material is within the rated operating conditions.

A-5 THERMAL EXPANSION ISSUES

(a) *Temperature Measurement.* Since the test values are obtained fully within the rated operating conditions, no thermal expansion issues are included in the test value uncertainty. The CMM temperature probes are part of the instrument under verification that are included in the test value, not in the test value uncertainty. Therefore, the gauge block temperature measurement is not a test value uncertainty source.

Since ISO 1 applies to the length of the gauge block, the true value of its length is the length at 20°C. The length of the gauge block shown on the calibration report is its 20°C length, hence there is no thermal correction to the length of the gauge block, and so there is no test value uncertainty contributor. Since this CMM includes automatic thermal compensation (a selling point of the instrument), it includes its own thermometer, which is part of the instrument under verification and hence is not a test value uncertainty source. (A miscalibrated CMM thermometer will create measurement errors that will be detected in the test values and then compared against the MPE.)

(b) *Coefficient of Thermal Expansion*

(1) *Included in Test Value Uncertainty.* The CMM operating manual (part of the rated operating conditions) states that to perform the thermal expansion compensation, an accurate CTE value is required. The reference standard's CTE is imperfectly known (see para. 5.3.2). Assuming a standard uncertainty of the CTE of $0.58 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ (from a $\pm 1 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ limit that is characterized by a uniform distribution of values), the standard uncertainty for a 500-mm gauge block at 23°C is 0.9 μm .