

X-Ray Computed Tomography (CT) Performance Evaluation

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AN AMERICAN NATIONAL STANDARD



The American Society of
Mechanical Engineers

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FOREWORD

The application of X-ray computed tomography (CT) for dimensional metrology has become common in many industries. This is primarily due to the ability of CT systems to measure inside a workpiece without requiring tactile or optical access. However, there are currently no standards that address the performance evaluation of CT systems in a way that includes material influence, which is a dominant source of error when these systems are used to evaluate typical workpieces. For this reason, The American Society of Mechanical Engineers (ASME) decided to form the B89.4.23 Working Group to produce a standard for CT performance evaluation. This Standard is the result of significant effort by the working group to develop a performance evaluation that includes all known sources of error in CT systems.

This Standard provides definitions and a test procedure for the performance evaluation of X-ray CT systems used for dimensional measurements. Manufacturers and users of CT systems may use the results of the test procedure to fulfill contractual requirements or to compare the performance of systems from different suppliers or over time.

The test procedure described in this Standard is intended to report errors that are representative of typical use cases of CT systems. Users of this Standard seeking to determine measurement error or uncertainty for a particular workpiece or system configuration should perform a specific study for that case.

This Standard is available for public review on a continuing basis. This provides an opportunity for additional public review input from industry, academia, regulatory agencies, and the public-at-large.

This first edition of ASME B89.4.23 was approved by the American National Standards Institute on September 3, 2020.

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Dimensional Metrology

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This Standard is always open for comment, and the Committee welcomes proposals for revisions. 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.

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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.
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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.

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

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

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X-RAY COMPUTED TOMOGRAPHY (CT) PERFORMANCE EVALUATION

1 SCOPE

This Standard specifies the dimensional measurement accuracy of industrial X-ray computed tomography (CT) systems for length, size, and form measurands of sphere-based test objects made of homogeneous materials. Medical CT systems are outside the scope of this Standard. The material properties of the measured test objects are restricted to three classes of material selected to be representative of industrial materials: plastic polymers, aluminum alloys, and steel alloys; other materials are outside the scope of this Standard. However, this Standard may be used as a guide for testing the performance of a CT system for other materials. The evaluation of workpieces composed of multiple materials or of materials with density gradients, i.e., gradual density variations within the material, is outside the scope of this Standard.

This Standard is applicable to dimensional measurements made at the surface of the workpiece, i.e., at the workpiece material-air interface, including those of internal cavities. The effect of complex workpiece-material influence is simulated by test objects composed of spheres (serving as the metrological geometric elements) and an obstructing body; the obstructing body's dimensions are uncalibrated and its shape may be arbitrary. The spheres and obstructing body shall be of the same class of material and their combined length shall not exceed the maximum penetration length for this class of material, as stated by the CT system manufacturer.

This Standard applies to a variety of CT systems that may vary by scanning mode and system components involved in the acquisition of images. In cases where a system provides multiple configurations of X-ray sources, detectors, and scanning modes, the dimensional measurement accuracy may be specified for each scanning mode.

This Standard does not mandate testing (by either the CT manufacturer or the user) to verify CT performance. The amount of testing, and which party will bear the cost of testing, is a business decision and must be negotiated between the two parties. Calibrated test objects can be expensive; hence, the parties should recognize the costs involved and plan the testing accordingly.

Due to contrast sensitivity issues that can arise when X-rays must penetrate through large amounts of material, this Standard does not provide maximum permissible error specifications that apply to detecting high spatial-frequency form errors.

2 INTRODUCTION

ASME B89 performance evaluation standards for dimensional coordinate measuring systems specify the dimensional measuring accuracy for common measurements of industrial workpieces. Ideally the uncertainty associated with each point coordinate within the system's measurement work zone would be reported, but because the accuracy of an individual point coordinate in space is impossible to experimentally verify, ASME B89 standards typically use a point-to-point length measurand that is both realizable and practical for system testing. The advantage of evaluating test objects with point-to-point length measurands is twofold: first, test objects are simple to manufacture and calibrate, and second, different point-to-point length measurands can be used to evaluate different effects. Long-range effects are evaluated by the point-to-point length error between the center of two spheres on a test object, which can span the entire work zone. Short-range effects are evaluated by the errors in the point-to-point distance from the center of the test spheres to various points on their surface, i.e., sphere form measurands. Image thresholding issues that are associated with the determination of a surface are evaluated by the error of the size of the test spheres.

A primary goal of ASME B89.4 standards is to define maximum permissible error (MPE) specifications and their associated rated operating conditions, which are useful when the user is measuring similar measurands on a typical workpiece. For example, although a CT system might be tested with a calibrated steel test object, the user should be confident that the combined MPE specifications for center-to-center length, form, and size error would limit the error if a point-to-point length measurement were composed of a point on the exterior of a steel workpiece and a point on an interior surface of a fully enclosed cavity of the workpiece.

2.1 Organization

This Standard is organized into the following sections:

- (a) [Sections 1](#) and [2](#) provide the scope and introduction, respectively.
- (b) [Section 3](#) provides the normative references.
- (c) [Section 4](#) defines terminology specific to this Standard.
- (d) [Section 5](#) describes some examples of the rated operating conditions specified by the CT system manufacturer.
- (e) [Section 6](#) describes the required measurands for length, size, and form.
- (f) [Section 7](#) describes the test protocol.
- (g) [Section 8](#) provides the decision rules for determining whether a set of test values yields a test outcome that verifies the conformance of the CT system to its MPE specifications.
- (h) [Mandatory Appendix I](#) describes the material classes.
- (i) [Mandatory Appendix II](#) describes the mathematical adjustment needed for test objects with low-density and low-CTE (coefficient of thermal expansion) base materials.
- (j) [Mandatory Appendix III](#) provides a statement of metrological traceability described further in ASME B89.7.5-2006.
- (k) [Mandatory Appendix IV](#) describes test value uncertainty.
- (l) [Nonmandatory Appendix A](#) provides examples of test objects.
- (m) [Nonmandatory Appendix B](#) describes how to calculate a bidirectional length MPE.
- (o) [Nonmandatory Appendix C](#) describes a supplementary test procedure when using test objects with low-density and low-CTE base materials.

2.2 Specifications

The accuracy specifications are the MPEs associated with the measurement of the specific dimensional and geometric characteristics of the test objects. These values are specified by the CT system manufacturer, and they represent the largest CT measurement errors permitted when a CT system is tested per the ASME B89.4.23 test protocol. A CT system that generates measurement errors greater than the MPE values is not in conformance with this Standard. These MPEs may be of significant value when actual workpieces are measured. The rated operating conditions are specified by the CT system manufacturer and shall be satisfied for the MPE value (i.e., the “rating”) to be verified. The MPE can be thought of as a type of mathematical function over the domain of rated operating conditions, and it yields an interval of permitted errors that is bounded by the MPE value or values. Often the MPE function is just a single value; i.e., the function is a constant over all rated operating conditions. Typical rated operating conditions include such quantities as the size of the system work zone under specification, data collection speeds, ambient temperature conditions, the number of radiographs in a scan, X-ray source voltages and currents, operator training and skill requirements, and other metrological factors that are required to be satisfied for the system to function properly; these are described in [section 5](#).

2.3 Objectives of the Test Protocol

Testing is designed to verify the metrological specifications of the CT system. The test protocol described in this Standard has several objectives: to provide a thorough yet efficient test, to limit time and money spent on testing, and to assure users of the capabilities of their CT system. This Standard meets these objectives in several ways.

(a) To facilitate commerce, both the CT system manufacturer and the user need an agreed-upon amount of testing to consider the system acceptable. A large amount of testing requested by a user can drive up the manufacturer’s costs, but insufficient testing might miss errors that could demonstrate nonconformance with MPE specifications. This Standard establishes the recommended amount of testing required to be reasonably thorough without being overly burdensome.

(b) By recommending test-object designs that can realize the measurands specified in this Standard, the CT system manufacturer need only maintain this limited set of test objects, thus avoiding the expense of multiple different test objects that might be otherwise requested by the user. Similarly, the user is protected because the manufacturer has used carefully designed test objects that reveal CT errors in an effective manner.

(c) The test protocol may require specific testing conditions (e.g., locations and orientations) for the test object that are sensitive to known error sources in the CT system and hence will reveal them with a minimum number of measurements. This well-crafted protocol protects the inexperienced user from performing a weak test but also saves on the cost of testing because it provides a targeted and acceptable testing procedure.

(d) The ASME B89.4 standards typically define test protocols with some user-selectable test conditions. These selectable test conditions ensure that the MPE specification is testable over any possible conditions within the rated conditions specified by the manufacturer, and not just those specific testing conditions required in this Standard. In particular, although the total number of test conditions required for an ASME B89 test may be relatively few compared to the near infinite number of potential conditions covered by the MPE specification, the fact that users may — at their discretion —

select a few specific conditions from this large collection of potential test conditions serves to verify the MPE is valid over the entire domain of rated conditions.

3 REFERENCES

The following is a list of publications referenced in this Standard. Where dates are noted, the specific edition applies.

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

ASME B89.7.5, Metrological Traceability of Dimensional Measurements to the SI Unit of Length (Technical Report)

ASME B89.7.6, Guidelines for the Evaluation of Uncertainty of Test Values Associated With the Verification of Indicating Dimensional Measuring Instruments to Their Performance Specifications

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.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), 3rd edition

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)

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

ISO 10360-5:2010, Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 5: CMMs using single and multiple stylus contacting probing systems

ISO 10360-7:2011, Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 7: CMMs equipped with imaging probing systems

ISO 10360-9:2013, Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 9: CMMs with multiple probing systems

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

4 DEFINITIONS

all surface points: the set of points extracted from a surface of a hemisphere according to a regular grid that has spacing not to exceed the voxel size. No extracted surface points from this set shall be excluded or refined when all surface points are used to evaluate a measurand.

NOTE: This type of surface point extraction is denoted by the subscript “all” in the symbol for an MPE specification, e.g., $P_{\text{size.sph.all:CT,MPE}}$; see [paras. 6.1 through 6.3](#).

base material: the part of the test object that holds the spheres used as metrological geometric elements. Base material shall be in the same material class as the spheres, or it shall be a material that is low-density and low-CTE. Use of a low-density and low-CTE base material shall be disclosed by the manufacturer in the specification sheet for the CT system in accordance with [Mandatory Appendix II](#).

fixturing material: any material other than the test object or obstructing body that is used to hold the test object in position during a CT scan. It may be any density or CTE as long as it is not in the X-ray material path.

low-CTE material: material with a coefficient of thermal expansion (CTE) less than $2 \times 10^{-6}/^{\circ}\text{C}$.

low-density material: material with a density less than 2 g/cm^3 .

maximum penetration length, $L_{p,\text{max}}$: the maximum allowed penetration length for a specific material class (plastic, aluminum, steel), as stated by the CT system manufacturer.

obstructing body: an uncalibrated and arbitrarily shaped material in the test object that is used to provide increased penetration length. It shall be in the same material class as the spheres used as metrological geometric elements. A sphere under measurement cannot be its own obstructing body.

NOTE: An obstructing body may comprise spheres other than those under measurement, base material, and/or fixturing material, or it may be a separate object.

penetration length, L_P : for any radiograph in a scan, the longest material path length through which the X-ray must penetrate; this length always includes the spheres used as metrological geometric elements and the obstructing body. It will also include the fixturing material if the fixturing material is of the same class of material as the test object and is in the X-ray material path.

NOTES:

- (1) If the base material, fixturing material, or both are less dense than the test object, the less dense material(s) shall be excluded from the penetration length even though the less dense material(s) may influence the surface determination.
- (2) Fixturing material denser than the test object material class shall not be used in the X-ray material path.

pixel size: the horizontal or vertical center-to-center distance between adjacent pixels in an X-ray detector.

NOTE: If the detector pixels are nonsquare, the pixel size is the smaller of horizontal or vertical center-to-center distance between adjacent pixels.

preknowledge: the nominal geometry, surface normal vectors, dimensions, chemical composition, or reference dimensional measurements of a workpiece or test object acquired by means other than the sensors of the CT system under verification.

NOTE: The use of preknowledge is denoted in the symbol for an MPE specification by the subscript "CAD" (computer-aided design), e.g., $P_{\text{size.sph.all:CAD,CT,MPE}}$.

rated operating condition: operating condition that must be fulfilled during measurement in order that a measuring instrument or measuring system perform [sic] as designed.

NOTES:

- (1) Rated operating conditions generally specify intervals of values for a quantity being measured and for any influence quantity.
- (2) In this Standard, "as designed" means "to meet the specified MPE values."
- (3) Conditions that are not explicitly constrained by the CT system manufacturer are acceptable conditions under which the system can be tested.
- (4) In this Standard, "rated operating condition" is also referred to as "rated condition."

[This definition, including [Note \(1\)](#), is identical to JCGM 200:2012, definition 4.9. [Notes \(2\)](#) through [\(4\)](#) are specific to this Standard.]

sphericity: spherical form.

NOTE: The sphericity of a test object may pertain to a portion of a sphere, e.g., a hemisphere.

voxel: a unit in a three-dimensional (3D) array that discretizes a reconstructed work zone using the principle of computed tomography.

voxel size: the size of a magnified pixel for a CT scan, which is calculated as pixel size divided by magnification.

NOTES:

- (1) Magnification is the X-ray source-to-detector distance divided by the X-ray source-to-object distance.
- (2) Other definitions of voxel size are possible. This definition is common and chosen for convenience. It is expressed as a unit of length rather than volume, e.g., in millimeters rather than in cubic millimeters.

work zone: a rated operating condition that is the boundary of the physical region within which measurements can be performed.

NOTE: In this Standard, the work zone may depend on the magnification used for the test.

5 EXAMPLES OF RATED OPERATING CONDITIONS

The rated operating conditions are stated by the CT system manufacturer and represent the conditions for which the CT system has MPE values. Although a CT system may be capable of obtaining measurements outside its rated operating conditions, the user cannot be sure of the accuracy of such measurements. The rated conditions make up the applicable domain where measurements can be accurately obtained. Consequently, when selecting a CT system, users should review all the rated operating conditions and especially the rated material classes and their maximum penetration lengths. If the largest penetration length of a workpiece, in any radiograph, exceeds the maximum penetration length (stated by the CT system manufacturer) for that material class, then that measurement is outside the rated operating conditions of the CT system. Since material effects are a major source of error in CT measurements, the user should ensure that the accuracy of the CT system is sufficient at the largest penetration length of any workpiece measurement anticipated and should also test the system at this condition. Any condition that is specified by the CT system manufacturer for the proper operation of the system is a rated condition — this includes requirements described in the operating manual. [Paragraphs 5.1](#) through [5.7](#) list examples of rated operating conditions.

5.1 Typical Rated Characteristics of CT Systems

The CT system manufacturer typically provides rated values for the following system characteristics:

- (a) distance from X-ray source to detector
- (b) distance from X-ray source to object
- (c) geometric magnification
- (d) physical filtering of X-rays (e.g., copper, aluminum, range of thicknesses)
- (e) manipulator speed
- (f) scanning mode (see also para. 5.3)
 - (1) detector configuration (binning, integration time, sensitivity, region of interest)
 - (2) minimum number of radiographs during acquisition
 - (3) radiograph averaging
 - (4) continuous or stepped radiograph acquisition
 - (5) X-ray source configuration (voltage, current, and focal-spot size)
 - (6) trajectory (circular, helical, detector translation)
- (g) work-zone dimensions (see also para. 5.4)
- (h) test object material classes (e.g., plastic, aluminum, steel; see also para. 5.6)
- (i) maximum penetration length
- (j) requirements on operator-supplied values, e.g., coefficients of thermal expansion values

5.2 Typical Rated Environmental Conditions

The CT system manufacturer typically provides rated values for the following environmental conditions:

- (a) temperature
- (b) humidity
- (c) vibration at the site of installation

5.3 Scanning Mode

CT systems offering multiple scanning modes shall specify an MPE for each rated mode. Scanning modes are defined by the following:

- (a) the components involved. For systems with multiple detectors and sources, the manufacturer shall provide an MPE for each rated combination.
- (b) the configuration used (e.g., detector frame rate and binning, X-ray source energy, and focal-spot size).
- (c) the movement and trajectory of the components (e.g., any combination of rotary table, detector, and X-ray source movement).

5.4 Work Zone

The work zone is the boundary of the physical space in the CT system within which a measurement can be performed; it has an MPE rating. The CT system manufacturer shall specify the work zone as a rated condition. Work-zone size and shape are generally constrained by the maximum reconstructed volume from a CT scan. For each rated material and scanning mode, the rated work zone shall be unambiguously defined. The work zone may be parameterized by the following:

- (a) size and shape (e.g., cylindrical work zone with height and radius determined by the X-ray detector dimensions and magnification)
- (b) location within the CT system (e.g., elevation from the rotary table)
- (c) distance from the X-ray source to detector
- (d) magnification

5.5 Operating Procedures

When the test is performed, the CT system shall be operated according to the manufacturer's operating manual. The instructions in the operating manual are considered part of the rated conditions; i.e., they are required to be satisfied for the MPE value to be valid. Specific operating procedures may include, but are not limited to, the following:

- (a) start-up and stability evaluation of the X-ray source.
- (b) qualification and correction of the X-ray detector.
- (c) estimation and assessment of the CT geometry.
- (d) thermal stabilization of the machine prior to data collection.

(e) technique-development requirements (penetration, contrast, noise, geometric unsharpness). These requirements are not operator competency requirements and may be individually specified.

In addition, the CT system manufacturer shall specify any required information that the operator must supply as a rated condition, e.g., the CTE of the test object.

5.6 Test-Object Material

The material properties of the object under measurement are considered rated operating conditions. Material conditions are subdivided into the following three classes:

- (a) plastic
- (b) aluminum
- (c) steel

Each class is defined in [Mandatory Appendix I](#), which provides a detailed description of the allowed polymers or alloys within each class.

5.7 Maximum Loading

The maximum loading mass that can be on the CT system during a measurement shall be specified as a rated condition. The CT system manufacturer may specify a maximum load per unit area (in kilograms per square centimeter) in addition to the maximum load.

6 METROLOGICAL SPECIFICATIONS

This Standard describes the following metrological specifications:

- (a) center-to-center length error
- (b) sphere size error
- (c) sphere form error

Because the absorption of X-rays by material is a significant influence quantity, the CT system manufacturer shall state the MPE for each measurand, for each standardized material class (plastic, aluminum, and steel, as described in [Mandatory Appendix I](#)). The MPE specifications may differ for each of the materials the CT system is designed to measure; i.e., the MPEs for plastic may differ from those for aluminum, which may differ from those for steel. If the system is designed to measure only one material, e.g., plastic workpieces, then the CT system manufacturer shall specify the MPEs for that material.

The MPE specifications may be specific to measurement conditions such as the work zone (see [para. 5.4](#)), provided these are within the rated conditions of the CT system as stated by the CT system manufacturer. A CT system shall be in conformance with the MPE specification if, when tested by a properly trained user, it generates no errors in measurement (of length, diameter, or form) greater than the MPE value (evaluated at the measurement conditions). A properly trained user is a user who is capable of selecting the CT system parameters (e.g., voltage, current, spot size) according to the CT system manufacturer's operating procedures.

The CT system manufacturer is free to choose any specification format (table, formula, etc.) for stating the MPEs that are applicable within the range of rated conditions for the measurands identified in this Standard. MPE specifications may include MPEs for measurements taken at subranges of the rated conditions, e.g., for work zones that vary in size based on CT geometry, detector cropping, and region of interest.

The work zone may be affected by the CT scanning mode. For example, helical scanning mode may provide an elongated work-zone cylinder. The CT system manufacturer shall provide an MPE for a work zone that, regardless of scanning mode, is compatible with test objects specified by this Standard (see [section 7](#) and [Nonmandatory Appendix A](#)).

MPE specifications and corresponding test value symbols shall have a "CAD" (computer-aided design) designation, e.g., $P_{\text{size.sph.all:CAD,CT,MPE}}$ and $P_{\text{size.sph.all:CAD,CT}}$, if preknowledge (see [section 4](#)) is used in any way prior to or during CT scan acquisition, radiograph processing (e.g., filtering), volume reconstruction, surface determination, or any surface-point processing (e.g., filtering). See [para. 7.3](#) for requirements for the use of preknowledge during testing.

For each individual scan, the same CT system settings (software filtering, reconstruction, surface algorithm, etc.) shall be used to produce the surface points and to evaluate the measurands (length, size, and form).

All spheres used as metrological geometric elements shall have a minimum diameter specified in voxels by the manufacturer in the rated conditions. No sphere shall exceed 51 mm in diameter, which is the same maximum used in ISO 10360-5, ISO 10360-7, and ISO 10360-9.

6.1 Center-to-Center Length Error

The center-to-center length error specification, given by the value $E_{\text{Vol:L:CT,MPE}}$, shall bound all rated center-to-center length measurement errors in the measurement volume. The center-to-center length measurand is defined as the point-to-point length, L , between two least-squares-determined sphere centers, ($\vec{c}_1, \vec{c}_2$):

$$L = \|\vec{c}_1 - \vec{c}_2\| \quad (6-1)$$

The least-squares sphere center is defined as the center obtained from all surface points on a hemisphere that is only in contact with air. The center-to-center length error in a measurement volume between measured length, L_a , and calibrated length, L_r , is defined as

$$E_{\text{Vol:L:CT}} = L_a - L_r \quad (6-2)$$

where

Vol = subscript denoting measurement volume

The length, diameter, and form measurands for the specifications are defined and evaluated using the same points.

The center-to-center length error specification, $E_{\text{Vol:L:CT,MPE}}$, shall be valid for all rated lengths, L , and penetration lengths, L_p . The specification may be given as a function of these quantities, e.g., $E_{\text{Vol:L:CT,MPE}} = a + Lb + L_p c$, where a , b , and c are constants specified by the manufacturer; and $0 < L < \text{work-zone size}$; and $0 < L_p < L_{p,\text{max}}$. If the MPE specification does not explicitly include the quantities L and L_p , then the MPE specification shall be valid for all values of these quantities up to their maximum values.

NOTE: For the center-to-center length measurand, the errors from surface determination are expected to expand homogeneously in all directions when points are evenly distributed over each sphere, and therefore the error in the center location due to surface determination will be minimal and hence the error in the center-to-center length due to surface determination will be minimal.

6.2 Sphere-Size Error

The sphere-size error specification, given by the value $P_{\text{size.sph.all:CT,MPE}}$, is the maximum allowed value of the sphere-diameter error. The measurand is defined as the diameter of a least-squares sphere evaluated with all surface points on a hemisphere that is only in contact with air. The sphere-diameter error between measured diameter, D_a , and calibrated diameter, D_r , is defined as

$$P_{\text{size.sph.all:CT}} = D_a - D_r \quad (6-3)$$

The sphere-size error specification, $P_{\text{size.sph.all:CT,MPE}}$, shall be valid for all spheres with a diameter larger than the manufacturer-rated minimum diameter (specified in voxels) and for all rated penetration lengths, L_p . The specification may be given as a function of these quantities, e.g., $P_{\text{size.sph.all:CT,MPE}} = a + L_p b$, where a and b are constants specified by the manufacturer and $0 < L_p < L_{p,\text{max}}$. If the MPE specification does not explicitly include L_p , then the MPE specification shall be valid for all values of L_p up to the maximum value.

6.3 Sphere-Form Error

The sphere-form error specification, given by the value $P_{\text{form.sph.all:CT,MPE}}$, is the maximum allowed value of the sphere-form error, i.e., the error in sphericity, of a least-squares sphere evaluated with all surface points on a hemisphere that is only in contact with air. The measurand is defined as the difference between the largest and smallest radial distances ($R_{\text{max}}, R_{\text{min}}$) from the calculated sphere center to each of the surface points:

$$P_{\text{form.sph.all:CT}} = R_{\text{max}} - R_{\text{min}} \quad (6-4)$$

The sphere-form error specification, $P_{\text{form.sph.all:CT,MPE}}$, shall be valid for all spheres with a diameter larger than the manufacturer-rated minimum diameter (specified in voxels) and for all rated penetration lengths, L_p . The specification may be given as a function of these quantities, e.g., $P_{\text{form.sph.all:CT,MPE}} = a + L_p b$, where a and b are constants specified by the manufacturer and $0 < L_p < L_{p,\text{max}}$. If the MPE specification does not explicitly include L_p , then the MPE specification shall be valid for all values of L_p up to the maximum value, $L_{p,\text{max}}$.

7 TESTING

This Standard provides a test protocol for verifying the metrological specifications required by [section 6](#). A test produces a set of test values that are estimates of the error of indication from the CT system, i.e., a test value is the difference between a measured value and the calibrated value (at 20°C) of a measurand on the test object. The test shall be conducted within the system's rated operating conditions; only test values obtained at the rated operating conditions can be compared to the MPE values associated with the test measurands.

A test instance is a snapshot in time of the CT system's performance under the set of rated operating conditions that prevails at the time of testing. A single test instance cannot test the CT system's performance over all rated conditions. The protocol provided is a balance between the time and cost of testing and the comprehensiveness of the test. This protocol is the default procedure designed to expedite testing; however, other testing conditions (e.g., test objects of other sizes or orientations, other testing locations) are also valid if they are in compliance with the CT system's rated operating conditions.

7.1 Test Object

All test objects shall have characteristics that are within the CT system's rated operating conditions. Test objects can have penetration lengths from near zero up to the maximum penetration length specified by the CT system manufacturer. In particular, the largest penetration length of X-rays through the test object (and fixturing material, if applicable) in any radiograph of a CT scan shall not exceed the system's maximum penetration length as stated by the manufacturer.

7.1.1 Material Requirements. Test objects shall be made of a single material class with near constant density for scales of a voxel and larger. The standardized materials for constructing test objects are plastic polymers, aluminum alloys, and steel alloys; refer to [Mandatory Appendix I](#) for material class details.

Test objects shall be composed of spheres (serving as the metrological geometric elements), base material, and the obstructing body. The purpose of the obstructing body is to test in the presence of material effects. The combination of the spheres under measurement and the obstructing body shall not have a penetration length that exceeds the system's maximum penetration length for the class of material, as stated by the CT system manufacturer.

Test objects shall have a base material that is in the same material class as the spheres and obstructing body. If this condition cannot be met, the base material shall be a low-density and low-CTE material and its use shall be disclosed by the manufacturer in the specification sheet for the CT system in accordance with [Mandatory Appendix II](#). Tests conducted using test objects with a base material that is low-density and low-CTE may not reveal some errors in a CT system that might occur during a CT scan due to temperature variation. [Nonmandatory Appendix C](#) describes a test procedure that may reveal these errors.

7.1.2 Test Object Design. A test object shall consist of calibrated spheres used to determine the metrological fiducial points (sphere centers) and an uncalibrated obstructing body, which is introduced to test penetration length and beam-hardening effects. The spheres and obstructing body in a test object shall be made from the same class of material, which shall be one of the three rated material classes: plastic, aluminum, or steel. See [Mandatory Appendix I](#) for a discussion of material similarity. All spheres of a test object shall be made of the same material, e.g., aluminum oxide.

The test object shall consist of at least eight coplanar spheres. The spheres shall have a diameter larger than the manufacturer-rated minimum diameter (specified in voxels). No sphere shall exceed 51 mm in diameter, which is the same maximum used in ISO 10360-5, ISO 10360-7, and ISO 10360-9. The spheres may have the same nominal diameter, but this is not a requirement. The eight coplanar spheres shall provide at least 28 point-to-point lengths that align with the six independent measurement lines of one work-zone measurement plane shown in [Figure 7.4.1-1](#).

NOTE: A test object may have more than eight spheres and provide point-to-point lengths for more than one measurement plane in [Figure 7.4.1-1](#).

If a test object has more than the required number of spheres and point-to-point lengths, the spheres and lengths used for the test shall be selected by the user prior to the test. These selections shall be within the constraints of the test object design and test protocol. Only these selections shall be used to generate test values for comparison to MPEs.

To test for material effects, every tested measurement plane shall have at least one sphere that satisfies all of the following constraints during all scans of the test:

(a) At least one radiograph of the scan shall have a ray passing through the sphere center and obstructing body with a penetration length that is at least 80% of the maximum penetration length. Additionally, the proportion of the material penetration length through the obstructing body for this ray shall be at least 3 times that of the sphere diameter.

(b) At least one radiograph of the scan shall have a ray passing through the sphere center and optionally the obstructing body with a material path distance that is no greater than 20% of the maximum penetration length.

(c) The gap between the obstructing body and the sphere shall be at least 50% of the sphere diameter.

[Nonmandatory Appendix A](#) gives examples of test objects.

The thermal characteristics of every rated material class shall be tested. This requirement shall be satisfied if the coefficient of thermal expansion (CTE) of the test object's base material is within the range of CTEs given for the material class it represents; see [Mandatory Appendix I](#) for the associated requirements.

7.1.3 Test Object Calibration. The test object shall be calibrated for sphere center-to-center lengths. The test object shall have at least 28 calibrated center-to-center lengths. The calibrated lengths shall be clearly identified on a report of calibration. Each of the eight spheres shall be calibrated for their diameter and their spherical form, i.e., sphericity. The effect of imperfect sphericity of the spheres on the test object shall be included in the test value uncertainty evaluation and taken into account by the decision rule (see [section 8](#)).

7.2 Loading Requirements

The total mass of the test object plus any loading mass shall not exceed the CT system's rated operating conditions. Any loading mass used with a test object shall not obstruct the X-rays used to measure the test object; e.g., the loading mass could be a disk of material placed directly on the rotary table with the test object mounted above it. The loading mass can be made of any material. The loading mass shall not extend beyond the rotary table; i.e., the mass shall not be cantilevered, and the loading mass shall be free standing. For point loads, the load at any one point shall not exceed twice the load at any other contact point and at least three contact points shall be present.

7.3 Preknowledge Requirements

Preknowledge may be used during testing. In this case, the symbols for the MPEs and corresponding test values shall have a "CAD" (computer-aided design) designation, e.g., $P_{\text{Size.Sph.all:CAD,CT,MPE}}$.

For the case of no CAD designation in the MPE and corresponding test value symbols, then preknowledge can only be used for the purpose of automating the localization of surface points that will be used to calculate the values of measurands. In this case no preknowledge shall be used prior to or during CT scan acquisition, radiograph processing (e.g., filtering), volume reconstruction, surface determination, or any other surface point processing (e.g., filtering). Preknowledge shall not be used to refine the location of a surface point or to exclude surface points. The error of indication shall not be improved by use of preknowledge in this case.

For ASME B89.4.23 testing, test objects do not have tolerances, so no tolerance information shall be included as preknowledge during any part of the acquisition, reconstruction, surface determination, or extraction of the values of the measurands.

7.4 Test Protocol

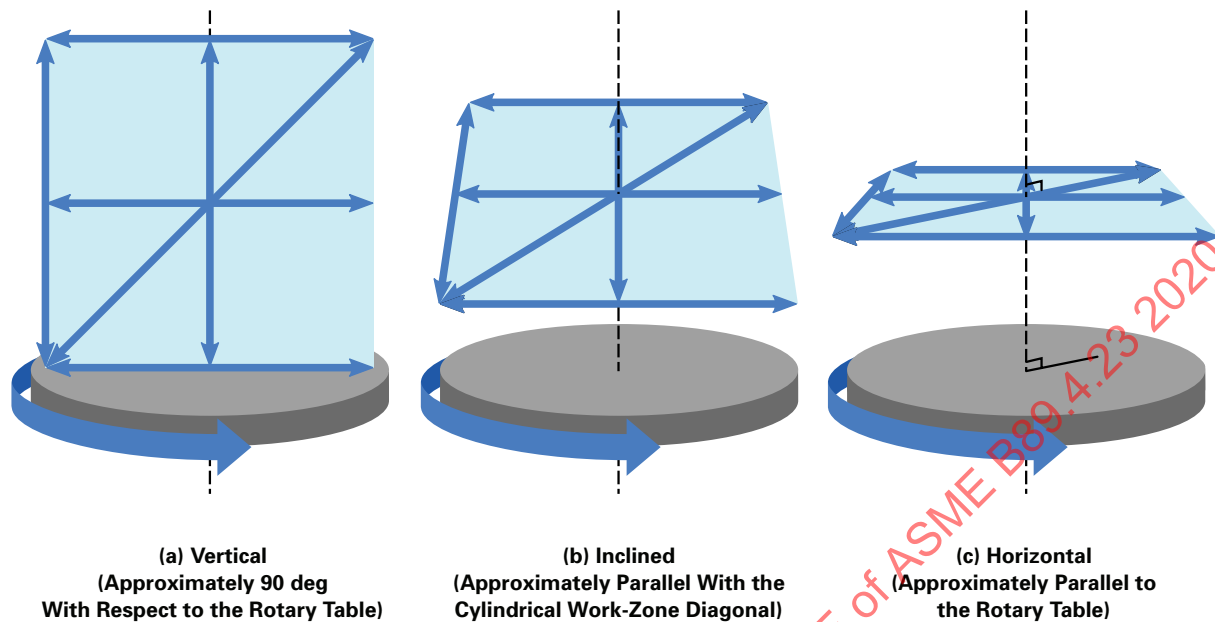
[Paragraphs 7.4.1 and 7.4.2](#) describe the default test protocol. All measurements of the measurands within the rated operating conditions shall yield errors that are within the MPE specifications for a conforming CT system. The default test protocol shall be used for verifying the CT manufacturer's specifications and testing unless otherwise agreed to by the user and manufacturer.

7.4.1 Mandatory Work Zone Measurement Lines. The testing of a specified work zone shall require measuring in three nonparallel planes and along six mandatory lines per plane. The mandatory measurement lines and planes to be tested in a work zone are shown in [Figure 7.4.1-1](#).

NOTE: Additional work-zone measurement planes and lines may be selected with prior agreement between the user and manufacturer.

The testing of a specified work zone shall also require measuring at least one calibrated length per measurement plane, i.e., at least 66% of the maximum length in the work zone's intersection with the measurement plane. Hence a larger work zone means testing with a larger test object, and, typically, the larger the test object, the greater its X-ray penetration length. Most CT systems can be tested with the test objects described in [para. 7.4.2](#), [Mandatory Appendix I](#), and [Nonmandatory Appendix A](#), but in the special case where the CT manufacturer has specified a large work zone but a small maximum penetration length, special test objects may need to be constructed.

Figure 7.4.1-1 Mandatory Work-Zone Measurement Planes and Lines



As an example, consider a 1 920 pixel $\times$ 1 536 pixel detector with 0.127-mm pixel pitch and the following rated operating conditions and test conditions:

Cylindrical Work-Zone Parameter	Rated Operating Condition	Test Condition
Magnification	1.5X to 10.0X	2.8X
Height	1 920 $\times$ 0.127 mm/magnification	87.1 mm
Diameter	1 536 $\times$ 0.127 mm/magnification	69.7 mm
Elevation from rotary table	≤ 200 mm	150 mm
X-ray source-to-detector distance	1 200 mm	1 200 mm

A test performed at 2.8X magnification would yield a cylindrical work-zone diagonal of approximately 111.5 mm ($\text{height}^2 + \text{diameter}^2 = \text{diagonal}^2$), implying that a test object having a test length of at least 73.6 mm (66% work-zone diagonal) would be needed. The test object shall not exceed the maximum penetration length, so if the default sphere plate exceeds the rated maximum penetration length, a suitable alternative test object from [Nonmandatory Appendix A](#) may be used.

A CT system shall be tested within the rated operating conditions and the resulting test values compared with their corresponding MPE values. However, users should be aware that calibrated test objects might not be available for all test conditions. If users supply their own test objects, these objects shall conform to this Standard both in design and in their calibration as defined in [para. 7.1](#). The test uncertainty shall satisfy the 4:1 simple acceptance decision rule described in [section 8](#).

7.4.2 Measurements and Scans

(a) *Number of Required Measurements.* Every scan shall measure at least one work-zone measurement plane that contains the 28 calibrated center-to-center lengths and 8 calibrated sphere diameters and sphere form values evaluated from all surface points on each sphere. The settings (software filtering, reconstruction, surface algorithm, etc.) used to produce the surface points shall also be used to evaluate all measurands (length, size, and form) for an individual scan.

The following number of measurement planes (center-to-center lengths, sphere diameters, and sphere form values) shall be measured during the test:

Number of Rated Materials	Required Number of Measurement Planes	Required Number of Length Measurements	Required Number of Diameter and Form Measurements
1	4	$28 \times 4 = 112$	$8 \times 4 = 32$
2	6	$28 \times 6 = 168$	$8 \times 6 = 48$
3	8	$28 \times 8 = 224$	$8 \times 8 = 64$

(b) *Evaluation of Measurands.* All measurands (length, size, and form) shall be evaluated with all surface points on a hemisphere of each sphere (see [section 6](#)). The location of the hemisphere should be chosen by the user prior to testing and shall only be in contact with air; it shall not be in contact with the base material and/or adhesive.

(c) *Number of Scans and Required Magnifications.* The CT system shall be tested with scans of test objects made from each rated material. The total number of scans required depends on the number of rated materials and the number of measurement planes in the test object, as follows:

Number of Measurement Planes in Test Object	Number of Rated Materials	Required Number of Scans
1	1	4
	2	6
	3	8
2	1	3
	2	5
	3	7
3	1	2
	2	4
	3	6

Every rated material shall be scanned at least twice.

The user shall scan at least one of the rated materials at two magnifications; these scans count toward the required number of scans. The user is free to choose any rated magnification for testing [see [Note \(1\)](#)]; however, testing at the ends of the rated magnification range is recommended. For example, if the rated magnification range is from 2X to 20X, then the user should test at 2X and 20X magnifications.

Every scan of a test object shall include at least one calibrated length per measurement plane that is at least 66% of the maximum length in the work zone's intersection with the measurement plane. [See [Note \(2\)](#).]

NOTES:

- (1) The user can achieve a particular magnification by changing either the X-ray source-to-detector distance or the X-ray source-to-object distance. The user is free to choose how to achieve the magnification to be tested as long as it is within the CT system's rated operating conditions for source-to-detector and source-to-object distance. However, different combinations of source-to-detector and source-to-object distances that produce the same magnification may lead to different test results.
- (2) Different test objects may be used during the test. For example, it may be necessary to use a different size test object for each magnification tested to meet the test length requirements.

The user shall clock a test object approximately 45 deg about the rotation axis between scans.

The user and manufacturer may agree to perform additional scans beyond those required for the test. Additional scans may address concerns about repeatability due to variation between scans from sources such as temperature, vibration, hysteresis, or X-ray source stability.

(d) *Mandatory Work-Zone Measurement Planes.* For the required number of scans, the user shall select the test-object orientations that meet the following mandatory work-zone measurement planes (see [Figure 7.4.1-1](#)), at minimum:

(1) one vertical work-zone measurement plane (approximately 90 deg with respect to the rotary table). The user shall orient the test object to measure one vertical measurement plane for each rated material at one of the recommended magnifications.

(2) one inclined work-zone measurement plane (approximately parallel with the cylindrical work-zone diagonal). The user shall orient the test object to measure one inclined measurement plane at one of the recommended magnifications.

(3) one horizontal work-zone measurement plane (approximately parallel to the rotary table). The user shall orient the test object to measure one horizontal measurement plane at one of the recommended magnifications.

These orientations will reveal artifacts related to cone-beam CT, geometric errors, beam hardening, and other penetration-length issues.

Within the constraints described in (a) through (d), and within the rated conditions of the CT system, the user is free to choose the remaining scan magnification(s), test object orientation(s), and test object material(s).

NOTE: The user should recognize that calibrated test objects can be expensive and the cost of the test may only include a choice of test objects of particular sizes.

7.4.3 Test Protocol Example. Form 7.4.3-1 provides an example template for documenting a test involving a test object with one measurement plane and up to three rated materials. Figure 7.4.3-1 shows an example usage of the template for a test involving one rated material (aluminum).

8 COMPLIANCE WITH SPECIFICATIONS

8.1 Decision Rule

The decision rule for acceptance and rejection shall be simple 4:1 acceptance (see ASME B89.7.3.4) where the test value uncertainty is evaluated according to ASME B89.7.6.

8.2 Acceptance Criteria

The CT system shall be in compliance with MPE specifications if the test values (i.e., measurements of the test object) satisfy the following two acceptance criteria:

(a) No test value for center-to-center length, sphere diameter, or sphere form exceeds the MPE specified by the CT system manufacturer for the rated conditions.

(b) The test value uncertainty satisfies the decision rule requirement (see para. 8.1).

A rescan is permitted if any test value obtained from the measurement of a test object in a particular scan exceeds the MPE specified by the manufacturer due to an assignable cause (such as improper fixturing or poor technique) or as otherwise agreed to by the user.

A rescan shall have the same configuration (test-object material, position, and orientation, and system magnification) as the scan being discarded.

All test values (length, form, and size) shall be measured from a rescan, and no test value with an uncertainty that satisfies the decision rule requirement shall exceed the MPE; otherwise the test is a failure.

Additional confirming rescans may be agreed to by the manufacturer and the user.

8.3 Reverification Test

The performance of the CT system is considered to have been reverified if $E_{Vol:L:CT}$, $P_{Size.Sph.all:CT}$, and $P_{Form.Sph.all:CT}$, described in paras. 6.1 through 6.3, are not greater than the MPEs, $E_{Vol:L:CT,MPE}$, $P_{Size.Sph.all:CT,MPE}$, and $P_{Form.Sph.all:CT,MPE}$, as stated by the user.

**Form 7.4.3-1 Test Protocol Template for Up to Three Rated Materials and a Test Object
With One Measurement Plane**

Rated Material	Scans			MPE			Maximum Test Values		
	Magnification (User- specified)	Orientation	L_p	$E_{Vol:L:CT, MPE}$	$P_{size.sph.all:CT,MPE}$	$P_{form.sph.all:CT,MPE}$	$E_{Vol:L:CT}$	$P_{size.sph.all:CT}$	$P_{form.sph.all:CT}$
1	Mag 1:	Vertical							
		Inclined							
		Horizontal							
	Mag 2:	User- specified							
2	Mag 1:	Vertical							
	Mag 2:	User- specified							
3	Mag 1:	Vertical							
	Mag 2:	User- specified							

Figure 7.4.3-1 Example Test Protocol for One Rated Material

Rated Material	Scans			MPE [Note (1)]			Maximum Test Values		
	Magnification (User-specified)	Orientation	L_p	$E_{Vol:L:CT, MPE}$	$P_{size.sph.all:CT,MPE}$	$P_{form.sph.all:CT,MPE}$	$E_{Vol:L:CT}$	$P_{size.sph.all:CT}$	$P_{form.sph.all:CT}$
Aluminum	Mag 1: 3.3X	Vertical	46 mm	$15 + L/50 \mu m$	12 μm	40 μm	10 μm	8 μm	31 μm
		Inclined	48 mm				6 μm	4 μm	31 μm
		Horizontal	57 mm				8 μm	2 μm	26 μm
	Mag 2: 6.6X	User-specified	45 mm				8 μm	4 μm	26 μm

NOTE: (1) MPE applies to all penetration lengths, L , up to the maximum penetration length, $L_{P,max}$, specified by the manufacturer as one of the rated conditions.

MANDATORY APPENDIX I

TEST OBJECT MATERIALS

I-1 MATERIALS, SURROGATES, AND EXCLUSIONS

The goal of specifications per this Standard is to provide the CT system user with reasonable estimates of the accuracy obtainable from CT measurements on industrial workpieces for selected measurands. The role of the test object, e.g., the sphere plate, is to represent the properties of a workpiece and provide well-defined measurands in a physical form that can be economically produced and calibrated.

Since material properties of the workpiece have a significant impact on CT system measurement accuracy, this Standard provides for the MPE specifications for different classes of materials. The test object material classes are plastic, aluminum, and steel. These classes represent the workpiece materials most commonly used in industry. MPE specifications are required only for those materials that a CT system is designed to measure; e.g., if the CT system is designed only for plastic, then the CT system manufacturer shall specify the MPEs only for plastic.

Materials within a given class are considered to be identical. For example, a CT system measuring any plastic within the permitted plastic class can be expected to meet its MPE specifications for this class. Each material class is subject to some restrictions to make the class reasonably homogeneous. (Industrial users who have workpiece materials outside the specified classes should contact the CT system manufacturer for accuracy specifications of those materials.)

Each class of materials may also have specific surrogate materials allowed for the sphere material only, i.e., not for the obstructing body. These surrogate materials have X-ray properties similar to those of the material class but have metrological properties (e.g., hardness, dimensional stability) that are useful for the spheres used on test objects. Surrogate materials are considered equivalent to the material class, and ASME B89.4.23 test values obtained from the allowed surrogate materials are valid verifications of the MPE specifications. Allowed surrogate materials are listed in [Table I-1-1](#).

The coefficient of thermal expansion (CTE) associated with a material class is given in [Table I-1-1](#). The CTE of the base material affects the length between the spheres and shall be within the range of CTEs shown in [Table I-1-1](#). The CTE of the sphere material shall also be within this range except when the spheres are made of one of the surrogate materials shown in [Table I-1-1](#).

Table I-1-1 CTEs of Material Classes

Class	Examples	Surrogates	CTE, $\mu\text{m}/(\text{m } ^\circ\text{C})$
Plastic [Note (1)]	ABS, polycarbonate, POM, PEEK, polyethylene, PMMA, polypropylene	Graphite, B ₄ C, c-BN, Be	40 to 200
Aluminum [Note (2)]	Series 1XXX, 3XXX, 4XXX, 5XXX, 6XXX [Note (3)]	Fused quartz, Al ₂ O ₃ , SiC	20 to 26
Steel	Carbon steels, low alloy steels [Note (4)]	None	9 to 14

GENERAL NOTE: The abbreviations are defined as follows:

ABS = acrylonitrile butadiene styrene
 Al₂O₃ = aluminum oxide
 B₄C = boron carbide
 Be = beryllium
 c-BN = cubic boron nitride
 PEEK = polyether ether ketone
 PMMA = poly(methyl methacrylate)
 POM = polyoxymethylene
 PPS = polyphenylene sulfide
 SiC = silicon carbide

NOTES:

(1) This class excludes Teflon and polyphenylene sulfide (PPS).

(2) This class excludes Series 2XXX and 7XXX.

(3) The following compositions are excluded:

- (a) $\text{sum}(\text{Mn, Cr, Fe, Co, Ni, Cu}) > 1.5\%$
 (b) $\text{sum}(\text{Zn, Bi, Pb}) > 0.5\%$

where "sum" indicates the sum of the elements or compounds within the parentheses as a percentage of the alloy, and Bi = bismuth, Co = cobalt, Cr = chromium, Cu = copper, Fe = iron, Mn = manganese, Ni = nickel, Pb = lead, and Zn = zinc.

(4) The following compositions are excluded:

- (a) $\text{sum}(\text{W, Bi, Pb}) > 0.5\%$
 (b) $\text{sum}(\text{Cu, Zn, Mo}) > 1.5\%$
 (c) $\text{Fe} < 95\%$

where "sum" indicates the sum of the elements or compounds within the parentheses as a percentage of the alloy, and Mo = molybdenum and W = tungsten. See Note (3) for definitions of other abbreviations.

MANDATORY APPENDIX II

MATHEMATICAL ADJUSTMENTS TO TEST OBJECTS WITH A BASE MATERIAL THAT IS LOW-DENSITY AND LOW-CTE

II-1 GENERAL

For some test objects, use of a base material with low-density and low-CTE facilitates testing of CT systems.

Consider a CT system that is rated for scanning steel. Such a CT system requires a steel test object that meets the test protocol requirements of [para. 7.4.3](#). In this case, the base material of the test object may violate the rated maximum penetration length specified by the CT system manufacturer. For this reason, a low-density and low-CTE base material may be used. However, the thermal expansion correction ability of the CT system shall still be tested. Consequently, a mathematical adjustment to the calibrated values of the spheres mounted on the low-CTE base material shall be made, making it appear to the CT system as if the base material were steel.

Implementing such an adjustment requires that the temperature of the low-CTE base material be measured with a calibrated temperature sensor. The recorded temperature is used in conjunction with the synthetic CTE, $\alpha = 11.5 \times 10^{-6}/^{\circ}\text{C}$, to calculate a synthetic length equivalent to a steel gauge with an exactly known CTE. The effect of this adjustment is to change the calibration of the low-CTE test length such that it corresponds to a synthetic length, with a CTE of $11.5 \times 10^{-6}/^{\circ}\text{C}$, at the measured temperature. The advantage of this procedure is that the CT system rated to scan steel will be measuring a “synthetic steel” test length, and hence the measurements will not suffer the uncorrected thermal expansion error.

NOTE: The mathematical adjustment to the low-CTE artifact is performed by the tester according to the requirements of [section II-2](#). This adjustment is equivalent to a recalibration of the length between spheres in the test object.

II-2 REQUIREMENTS

When implementing the mathematical adjustment procedure for acceptance or reverification testing, the tester shall comply with the following requirements:

- (a) The mathematical adjustment shall be used only on test objects with low-density and low-CTE base material (i.e., base material with a $\text{CTE} \leq 2 \times 10^{-6}/^{\circ}\text{C}$).
- (b) The actual CTE of the test object and its uncertainty shall be stated on its calibration certificate prior to any measurements performed on the CT system.
- (c) The mathematical adjustment for each material class is as follows; in each case, no other synthetic CTE shall be used:

Material	Synthetic CTE, α
Plastic	$80 \times 10^{-6}/^{\circ}\text{C}$
Aluminum	$23 \times 10^{-6}/^{\circ}\text{C}$
Steel	$11.5 \times 10^{-6}/^{\circ}\text{C}$

- (d) The synthetic CTE used for mathematical adjustment shall be inputted into the CT system software if the software has an input option for such data.

- (e) The mathematical adjustment shall be performed only once for each scan. In each case, the temperature measurement shall occur before the beginning of each scan but after the test object has been positioned in the CT system for at least the period of time specified in the rated conditions.

- (f) The low-CTE test object shall be measured with a calibrated thermometer that is independent of the CT system.

- (g) When employing the mathematical adjustment procedure, both the actual CTE and the synthetic CTE of the test length shall be stated on the manufacturer's specification sheet and the test results page, e.g., “CTE of test length is $0.5 \times 10^{-6}/^{\circ}\text{C}$ mathematically adjusted to $11.5 \times 10^{-6}/^{\circ}\text{C}$.”

(h) The mathematical adjustment contributes to test uncertainty, and it must be considered.

NOTE: The effects of thermal gradients in the calibrated test length are greatly suppressed when a low-CTE artifact is used, but these effects may appear as length measurement errors when a normal, e.g., steel, artifact is used.

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MANDATORY APPENDIX III

METROLOGICAL TRACEABILITY OF ASME B89.4.23 TEST VALUES

III-1 TRACEABILITY REQUIREMENTS

This Standard uses the interpretation of metrological traceability described in ASME B89.7.5. The performance test values obtained in accordance with this Standard, i.e., the errors in the CT system's measurements of the calibrated test objects, are considered metrologically traceable when the calibrated values of the test objects satisfy the traceability requirements of ASME B89.7.5, section 2, at the time of testing. This provides the connection from the measurement errors of the CT system (expressed in micrometers) back to the SI meter and allows a comparison of the measured errors with the specified MPE values using the decision rule of the test protocol.

The ASME B89.7.5, section 2 requirements include the following:

- (a) a clear statement of the measurands, e.g., center-to-center length, sphere size, and sphere form.
- (b) identification of the CT system and the test objects used in the test, e.g., serial numbers.
- (c) a statement of the expanded ($k = 2$) uncertainty associated with the measurement errors the CT system obtained on the test object, consistent with the principles described in JCGM 100 (GUM).
- (d) an uncertainty budget that quantifies the significant uncertainty contributors to the expanded uncertainty of the calibrated test object at the time of the ASME B89.4.23 performance test. This includes the calibration uncertainty of the test object as reported on its calibration certificate, any drift from the calibrated values at the time of testing, any mathematical adjustments to test objects according to [Mandatory Appendix II](#), and the effects of other degradations, e.g., fixturing effects such as distortions of the test object, that occur at the time of testing.
- (e) documentation traceability of the test objects used in the ASME B89.4.23 test, showing an appropriate metrological terminus [see ASME B89.7.5, para. 2(c) for the terminus requirements], e.g., the calibration report for the test object from an accredited laboratory.
- (f) a measurement assurance program that ensures the calibrated test objects are within their calibration uncertainty, e.g., by requiring appropriate recalibration intervals, handling, and storage.

MANDATORY APPENDIX IV TEST VALUE UNCERTAINTY

IV-1 INTRODUCTION

This Standard uses a discrete test measurand approach (see ASME B89.7.6) to CT performance evaluation with a 4:1 simple acceptance decision rule (see ASME B89.7.3.1] to determine acceptance. Each test value is an estimate of an error of indication, e.g., a sphere-center-to-sphere-center length error, that is compared to the MPE evaluated at the rated operating conditions at which the test value was obtained. The test value uncertainty represents the uncertainty in that particular observed error of indication.

The evaluation of test value uncertainty in this Standard consists of two categories of contributors:

- (a) uncertainty associated with the reference value at the time the test value is obtained
- (b) uncertainty associated with any corrections applied to the indicated value when the test value is obtained outside the rated operating conditions, provided this test condition is explicitly permitted by the Standard

IV-2 UNCERTAINTY ASSOCIATED WITH THE REFERENCE VALUE

Uncertainty associated with the reference values refers to the following:

- (a) uncertainty associated with the calibrated value of the test measurand, e.g., the uncertainty as shown on the calibration certificate or report for the test object. Each length, sphere size, and sphere form and any other measurand specified by this Standard shall have a calibrated value with a stated uncertainty.
- (b) uncertainty associated with the degradation of the calibrated value at the time the test value is obtained. This can include drift in the value since the calibration was performed; changes in the value due to distortions, e.g., overconstrained fixturing that distorts the test object; mathematical adjustments to test objects according to [Mandatory Appendix II](#); and any other condition that effects the calibrated reference value at the time the test value is obtained. Note the thermal expansion of the artifact is not a source of test value uncertainty, provided the test value was obtained within the thermally rated operating environment. This is because the CT system reports its results in compliance with ISO 1, i.e., at 20°C, and the calibration certificate or report referred to in (a) has its values reported at 20°C, hence calibrated values are stated at the correct temperature.

IV-3 UNCERTAINTY ASSOCIATED WITH TEST VALUES OBTAINED OUTSIDE THE RATED OPERATING CONDITIONS

In this Standard, test values shall be reported within the rated operating conditions because they are to be compared to the MPE, which is only defined within these conditions. All rated operating conditions shall be satisfied except those that are “input values.” Some CT systems may require input information, e.g., the CTE of the test object, to achieve their MPE specification, and the uncertainty of the value input shall be accounted for in the test value uncertainty, unless otherwise stated. The requirement for input values shall be disclosed in the CT system’s operating manual or technical specification sheet to be considered part of the rated operating conditions. Since many input values are experimentally measured, they are inherently uncertain and so require a correction (usually a zero correction) to the indicated value measured by the CT system. This correction yields the best estimate of the indication that would have occurred at the specified rated operating condition had the input information been perfect, and thus it becomes the test value. Although the supplied input value is usually the best estimate of this quantity, and hence the correction is often zero, there is still the uncertainty in the correction. This uncertainty is to be combined in a root sum of squares manner with the uncertainty of the reference value to yield the test value uncertainty; see ASME B89.7.6 for details.

NONMANDATORY APPENDIX A DEFAULT TEST OBJECTS

A-1 SPHERE-HOLE PLATES

A calibrated sphere-hole plate may be used for testing. The plate may be either a single piece of material or a two-piece design that has an uncalibrated hole plate covering it (for examples of the latter, see [Figure A-1-1](#)). Each sphere is approximately centered inside a hole, and the ratio of sphere diameter to hole diameter shall be 50% to 75%.

A-2 SPHERE PLATES WITH OBSTRUCTING RODS OR BLOCKS

A calibrated sphere plate with obstructing rod or block may be used for testing. The test object may consist of a calibrated sphere plate and uncalibrated obstructing body, e.g., a rod [see [Figure A-2-1](#), illustration (b)]. The spheres and obstructing body shall belong to the same material class, which shall be one of the three rated material classes: plastic, aluminum, or steel. The maximum penetration length of the test object (combined spheres and obstructing body) shall adhere to the CT system's rated maximum penetration length for a given energy and material. Additionally, the maximum penetration length of the obstructing body shall be at least 3 times the sphere diameter. This test object has a scalable design, i.e., the sphere plate may be elongated in the vertical direction (along the rotational axis) or cut into pieces and mounted on the base material to cover the whole specified extended work zone vertically or horizontally (see [Figure A-2-2](#)). (See [para. 7.1](#) and [Mandatory Appendix II](#) for base material requirements.) In principle, the orientation of the sphere plate is variable, as shown in [Figure A-2-3](#).

NOTE: If the sphere plate is cut into pieces, it would require a new calibration.

A-3 3D TEST STRUCTURE

A calibrated 3D test structure may be used for testing. One example of an acceptable 3D test structure, which includes at least eight spheres in a plane parallel to the rotary axis, eight spheres in a plane perpendicular to the rotary axis, and eight spheres in an inclined plane, is detailed here. This type of test structure has the advantage that all three required orientations of a sphere plate can be obtained in a single scan.

[Figure A-3-1](#) shows an example of a 3D test object. For this particular 3D test structure design, the tube shape minimizes the maximum penetration length relative to the overall size of the object. There is a minimum of eight spheres per measurement plane (horizontal, vertical, and inclined). The nature of this 3D test structure allows for measurement of sphere-to-sphere lengths between spheres on different test planes, in addition to the required in-plane sphere-to-sphere lengths.

The example test object in [Figure A-3-1](#) shows an aluminum material design with fused silica spheres (a surrogate for aluminum), so that uncompensated thermal expansion effects of the test object will be manifested in the errors of the sphere-to-sphere lengths.

Figure A-1-1 A Square Two-Piece Sphere-Hole Plate With Covering Hole Plate



Figure A-1-1 A Square Two-Piece Sphere-Hole Plate With Covering Hole Plate (Cont'd)



GENERAL NOTE: Photos courtesy of the National Institute of Standards and Technology.