SASO ASTM E74: 2020

ASTM E74:2018

Standard Practices for Calibration and Verification for Force-Measuring Instruments

ICS 17.0. 0

Saudi Standards, Metrology and Quality Org (SASO)

Foreword

The Saudi Standards ,Metrology and Quality Organization (SASO) has adopted the standard No. ASTM E74:2018 “Standard Practices for Calibration and Verification for Force-Measuring Instruments ” issued by the ASTM. The text of this international standard has been translated into Arabic so as to be approved as a Saudi standard without introducing any technical modification.

Standard Practices for Calibration and Verification for Force-Measuring Instruments

1. Scope

1.1 The purpose of these practices is to specify procedures for the calibration of force-measuring instruments. Procedures are included for the following types of instruments:

1.1.1 Elastic force-measuring instruments, and

1.1.2 Force-multiplying systems, such as balances and small platform scales.

NOTE 1—Verification by deadweight loading is also an acceptable method of verifying the force indication of a testing machine. Tolerances for weights for this purpose are given in Practices E4; methods for calibration of the weights are given in NIST Technical Note 577**(1)** [2)], Methods of Calibrating Weights for Piston Gages.

1.2 The values stated in SI units are to be regarded as the standard. Other metric and inch-pound values are regarded as equivalent when required.

1.3 These practices are intended for the calibration of static force-measuring instruments. It is not applicable for dynamic or high speed force calibrations, nor can the results of calibrations performed in accordance with these practices be assumed valid for dynamic or high speed force measurements.

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and deter- mine the applicability of regulatory limitations prior to use.

1.5 This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[3)]

E4 Practices for Force Verification of Testing Machines

E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

E1012 Practice for Verification of Testing Frame and Speci- men Alignment Under Tensile and Compressive Axial Force Application

2) The boldface numbers in parentheses refer to a list of references at the end of this standard.

3) ³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website

2.2 *ASME Standard:*

B46.1 Surface Texture, Surface Roughness, Waviness and Lay [4)]

FORCE-MEASURING INSTRUMENTS

3. Terminology

3.1 *Definitions:*

3.1.1 *force-measuring instrument*—a system consisting of an elastic member combined with an appropriate instrument for indicating the magnitude (or a quantity proportional to the magnitude) of deformation of the member under an applied force.

3.1.2 *primary force standard*—a deadweight force applied directly without intervening mechanisms such as levers, hydraulic multipliers, or the like, whose mass has been deter- mined by comparison with reference standards traceable to the International System of Units (SI) **(2)** of mass.

3.1.3 *secondary force standard*—an instrument or mechanism, the calibration of which has been established by comparison with primary force standards.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration equation*—a mathematical relationship be- tween deflection and force established from the calibration data for use with the instrument in service, sometimes called the calibration curve.

3.2.2 *continuous-reading instrument*—a class of instruments whose characteristics permit interpolation of forces between calibrated forces.

3.2.2.1 *Discussion*—Such instruments usually have force- to-deflection relationships that can be fitted to polynominal equations.

3.2.3 *creep*—The change in deflection of the force- measuring instrument under constant applied force.

3.2.3.1 *Discussion*—Creep is expressed as a percentage of the output change at a constant applied force from an initial time following the achievement of mechanical and electrical stability and the time at which the test is concluded. Valid creep tests may require the use of primary force standards to maintain adequate stability of the applied force during the test time interval. Creep results from a time dependent, elastic deformation of the instrument mechanical element. In the case of strain gage based force-measuring instruments, creep is adjusted by strain gage design and process modifications to reduce the strain gage response to the inherent time-dependent elastic deflection.

3.2.4 *creep recovery*—The change in deflection of the force- measuring instrument after the removal of force following a creep test.

[4)] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http:// www.asme.org.

3.2.4.1 *Discussion*—Creep recovery is expressed as a percentage difference of the output change at zero force following a creep test and the initial zero force output at the initiation of the creep test divided by the output during the creep test. The zero force measurement is taken at a time following the achievement of mechanical and electrical stability and a time equal to the creep test time. For many force-measuring instruments, the creep characteristic and the creep recovery characteristic are approximate mirror images.

3.2.5 *deflection*—the difference between the reading of an instrument under applied force and the reading with no applied force.

3.2.5.1 *Discussion*—This definition applies to instruments that have electrical outputs as well as those with mechanical deflections.

3.2.6 *verified range of forces*—in the case of force- measuring instruments, the range of indicated forces for which the force-measuring instrument gives results within the permissible variations specified.

3.2.7 *reading*—a numerical value indicated on the scale, dial, or digital display of a force-measuring instrument under a given force.

3.2.8 *resolution*—the smallest reading or indication appropriate to the scale, dial, or display of the force-measuring instrument.

3.2.9 *specific force-measuring instrument*—an alternative class of instruments not amenable to the use of a calibration equation.

3.2.9.1 *Discussion*—Such instruments, usually those in which the reading is taken from a dial indicator, are used only at the calibrated forces. These instruments are also called limited force-measuring instruments.

3.2.10 *lower limit factor, LLF*—a statistical estimate of the error in forces computed from the calibration equation of a force–measuring instrument when the instrument is calibrated in accordance with these practices.

3.2.10.1 *Discussion*—The lower limit factor was termed "Uncertainty" in previous editions of E74. The lower limit factor is used to calculate the lower end of the verified range of forces, see 8.5. Other factors evaluated in establishing the lower limit of the verified range of forces are the resolution of the instrument and the lowest non-zero force applied in the calibration force sequence, The lower limit factor is one component of the measurement uncertainty. Other uncertainty components should be included in a comprehensive measurement uncertainty analysis. See Appendix X1 for an example of measurement uncertainty analysis.

4. Significance and Use

4.1 Testing machines that apply and indicate force are in general use in many industries. Practices E4 has been written to provide a practice for the force verification of these machines. A necessary element in Practices E4 is the use of force- measuring instruments whose force characteristics are known to be traceable to the SI. Practices

E74 describes how these force-measuring instruments are to be calibrated. The procedures are useful to users of testing machines, manufacturers and providers of force-measuring instruments, calibration laboratories that provide the calibration of the instruments and the documents of traceability, service organizations that use the force-measuring instruments to verify testing machines, and testing laboratories performing general structural test measurements.

5. Reference Standards

5.1 Force-measuring instruments used for the verification of the force indication systems of testing machines may be calibrated by either primary or secondary force standards.

5.2 Force-measuring instruments used as secondary force standards for the calibration of other force-measuring instruments shall be calibrated by primary force standards. An exception to this rule is made for instruments having capacities exceeding the range of available primary force standards. Currently the maximum primary force-standard facility in the United States is 1 000 000-lbf (4.4-MN) deadweight calibration machine at the National Institute of Standards and Technology.

6. Requirements for Force Standards

6.1 *Primary Force Standards*—Weights used as primary force standards shall be made of rolled, forged, or cast metal. Adjustment cavities shall be closed by threaded plugs or suitable seals. External surfaces of weights shall have a finish (Roughness Average or R_a) of 3.2 µm (125 µin.) or less as specified in ASME B46.1.

6.1.1 The force exerted by a weight in air is calculated as follows:

$$Force = \frac{Mg}{9.80665}\left(1 - \frac{d}{D}\right) \qquad (1)$$

Where:

M = mass of the weight,

g = local acceleration due to gravity, m/s^2,

d = air density (approximately 0.0012 Mg/m^3),

D = density of the weight in the same units as d, and 9.80665 = the factor converting SI units of force into the customary units of force. For SI units, this factor is not used.

6.1.2 The masses of the weights shall be determined within 0.005 % of their values by comparison with reference standards traceable to the International System of Units (SI) **(2)** for mass. The local value of the acceleration due to gravity, calculated within 0.0001 m/s^2 (10 milligals), may be obtained from the National Geodetic Information Centre , National Oceanic and Atmospheric Administration.

NOTE 2—If M, the mass of the weight, is in pounds, the force will be in pound-force units (lbf). If M is in kilograms, the force will be in kilogram-force units (kgf). These customary force units are related to the newton (N), the SI unit of force, by the following relationships:

$$1 \text{ kgf} = 9.806\,65 \text{ N (exact)} \qquad (2)$$

$$1 \text{ lbf} = 4.448\,22 \text{ N}$$

The Newton is defined as that force which, applied to a 1-kg mass, would produce an acceleration of 1 m/s/s.

The pound-force (lbf) is defined as that force which, applied to a 1-lb mass, would produce an acceleration of 9.80665 m/s/s.

The kilogram-force (kgf) is defined as that force which, applied to a 1-kg mass, would produce an acceleration of 9.80665 m/s/s.

6.2 *Secondary Force Standards*—Secondary force standards may be either force-measuring instruments used in conjunction with a machine or mechanism for applying force, or some form of mechanical or hydraulic mechanism to multiply a relatively small deadweight force. Examples of the latter form include single- and multiple-lever systems or systems in which a force acting on a small piston transmits hydraulic pressure to a larger piston.

6.2.1 Force-measuring instruments used as secondary force standards shall be calibrated by primary force standards and used only over the Class AA verified range of forces (see 8.6.3.1). Secondary force standards having capacities exceeding 1 000 000 lbf (4.4 MN) are not required to be calibrated by primary force standards. Several secondary force standards of equal compliance may be combined and loaded in parallel to meet special needs for higher capacities. The lower limit factor (see 8.5) of such a combination shall be calculated by adding in quadrature using the following equation:

$$LLF_c = \sqrt{LLF_0^2 + LLF_1^2 + LLF_2^2 + \cdots LLF_n^2} \qquad (3)$$

Where

LLF_c = lower limit factor of the combination, and

$LLF_{0,\,1,\,2\,...\,n}$ = lower limit factor of the individual instruments.

6.2.2 The multiplying ratio of a force-multiplying system used as a secondary force standard shall be measured at not less than three points over its range with an accuracy of 0.05 % of ratio or better. Some systems may show a systematic change in ratio with increasing force. In such cases the ratio at intermediate points may be obtained by linear interpolation between measured values. Deadweights used with multiplying-type secondary force standards shall meet the requirements of 6.1 and 6.1.2. The force exerted on the system shall be calculated from the relationships given in 6.1.1. The force-multiplying system shall be checked annually by elastic force-measuring instruments used within their class AA verified range of forces to ascertain whether the forces applied by the system are within acceptable ranges as defined by this standard. Changes exceeding 0.05 % of applied force shall be cause for reverification of the force multiplying system.

7. Calibration

7.1 *Basic Principles*—The relationship between the applied force and the deflection of an elastic force-measuring instrument is, in general, not linear. As force is applied, the shape of the elastic element changes, progressively altering its resistance to deformation. The result is that the slope of the force-deflection curve changes gradually and continuously over the entire range of the instrument. This characteristic curve is a stable property of the instrument that is changed only by a severe overload or other similar cause.

7.1.1 Superposed on this curve are local variations of instrument readings introduced by imperfections in the force- indicating system of the instrument. Examples of imperfections include: non-uniform scale or dial graduations, irregular wear between the contacting surfaces of the vibrating reed and button in a proving ring, and instabilities in excitation voltage, voltage measurement, or ratio-metric voltage measurement in a load cell system. Some of these imperfections are less stable than the characteristic curve and may change significantly from one calibration to another.

7.1.2 *Curve Fitting*—To determine the force-deflection curve of the force-measuring instrument, known forces are applied and the resulting deflections are measured throughout the range of the force-measuring instrument. A polynomial equation is fitted to the calibration data by the least squares method to predict deflection values throughout the verified range of force. Such an equation compensates effectively for the nonlinearity of the calibration curve. The standard deviation determined from the difference of each measured deflection value from the value derived from the polynomial curve at that force provides a measure of the error of the data to the curve fit equation. A statistical estimate, called the lower limit factor, LLF, is derived from the calculated standard deviation and represents the width of the band of these deviations about the basic curve with a probability of approximately 99 %. The LLF is, therefore, an estimate of one source of measurement uncertainty contributed by the force-measuring instrument when forces measured in service are calculated by means of the calibration equation. Actual measurement uncertainty in service is likely to be different if forces are applied under mechanical and environmental conditions differing from those of calibration. Other sources of measurement uncertainty such as those listed in Appendix X1 could increase the measurement uncertainty of measurement of the force-measuring instrument in service. While it is the responsibility of the calibration laboratory to calibrate the force-measuring instrument in accordance with the requirements of these practices, it is the responsibility of the user to determine the measurement uncertainty of the instrument in service.

7.1.3 *Curve Fitting using polynomials of greater than 2^{nd} degree*—The use of calibration equations of the 3rd, 4th, or 5th degree is restricted to force-measuring instruments having a resolution of 1 increment of count per 50000 or greater active counts at the maximum calibration force. Annex A1 specifies the procedure for obtaining the degree of the best fit calibration curve for these force-measuring instruments. Equations of greater than 5th degree shall not be used.

NOTE 3—Experimental work by several force calibration laboratories in fitting higher than second degree polynomials to the observed data indicates that, for some force-measuring instruments, use of a higher degree equation can result in a lower LLF than that derived from the second degree fit. (ASTM RR:E28-1009)[6] Overfitting should be avoided. Equations of greater than 5th degree cannot be justified due to the limited number of force increments in the calibration protocol. Errors caused by round-off can occur if calculations are performed with insufficient precision.

A force-measuring instrument not subjected to repair, overloading, modifications, or other significant influence factors which alter its elastic properties or its sensing characteristics will likely exhibit the same degree of best fit on each succeeding calibration as was determined during its initial calibration using this procedure. A force-measuring instrument not subjected to the influence factors outlined above which exhibits continued change of degree of best fit with several successive calibrations may not have sufficient performance stability to allow application of the curve fitting procedure of Annex A1.

7.2 *Selection of Calibration Forces*— A careful selection of the different forces to be applied in a calibration is essential to provide an adequate and unbiased sample of the full range of the deviations discussed in 7.1 and 7.1.1. For this reason, the selection of the calibration forces shall be made by the calibration laboratory. An exception to this, and to the recommendations of 7.2.1 and 7.2.4, is made for specific force- measuring instruments, where the selection of the forces is dictated by the needs of the user.

7.2.1 *Distribution of Calibration Forces*—Distribute the calibration forces over the full range of the force-measuring instrument, providing, if possible, at least one calibration force for every 10 % interval throughout the range. It is not necessary, however that these forces be equally spaced. Calibration forces at less than one tenth of capacity are permissible and tend to give added assurance to the fitting of the calibration equation. If the lower force limit of the verified range of forces of the force-measuring instrument (see 8.6.1) is anticipated to be less than one tenth of the maximum force applied during calibration, then forces should be applied at or below this lower force limit. In no case should the smallest force applied be below the lower force limit of the force-measuring instrument as defined by the values:

$400 \times$ resolution for Class A verified range of forces (4)

$2000 \times$ resolution for Class AA verified range of forces

An example of a situation to be avoided is the calibration at ten equally spaced force increments of a proving ring having a capacity deflection of 2000 divisions, where the program will fail to sample the wear pattern at the contacting surfaces of the micrometer screw tip and vibrating reed because the orientation of the two surfaces will be nearly the same at all ten forces as at zero force. In force-measuring instruments cell calibration with electrical instruments capable of linearizing the output signal, whenever possible, select calibration forces other than those at which the linearity corrections were made.

7.2.2 The resolution of an analog type force-measuring instrument is determined by the ratio between the width of the pointer or index and the centre to centre distance between two adjacent scale graduation marks. Recommended ratios are $1/2$, $1/5$, or $1/10$. A centre to centre graduation spacing of at least 1.25 mm is required for the estimation of $1/10$ of a scale division. To express the resolution in force units, multiply the ratio by the number of force units per scale graduation. A vernier scale of dimensions appropriate to the analog scale may be used to allow direct fractional reading of the least main instrument scale division. The vernier scale may allow a main scale division to be read to a ratio smaller than that obtained without its use.

7.2.3 The resolution of a digital instrument is considered to be one increment of the last active number on the numerical indicator, provided that the reading does not fluctuate by more than plus or minus one increment when no force is applied to the instrument. If the readings fluctuate by more than plus or minus one increment, the resolution will be equal to half the range of fluctuation.

7.2.4 *Number of Calibration Forces*—A total of at least 30 force applications is required for a calibration and, of these, at least 10 must be at different forces. Apply each force at least twice during the calibration.

7.2.5 *Specific Force-Measuring Instruments (Limited Force-Measuring Instruments)*—Because these force- measuring instruments are used only at the calibrated forces, select those forces which would be most useful in the service function of the instrument. Coordinate the selection of the calibration forces with the submitting organization. Apply each calibration force at least three times in order to provide sufficient data for the calculation of the standard deviation of the observed deflections about their average values.

7.3 *Temperature Equalization During Calibration:*

7.3.1 Allow the force-measuring instrument sufficient time to adjust to the ambient temperature in the calibration machine prior to calibration in order to ensure stable instrument response.

7.3.2 The recommended value for room temperature calibrations is 23 °C (73.4 °F) but other temperatures may be used.

7.3.3 During calibration, monitor and record the temperature as close to the force-measuring instrument as possible. It is recommended that the test temperature not change more than ±0.5 °C (1 °F) during calibration. In no case shall the ambient temperature change by more than ±1.0 °C (2 °F) during calibration.

7.3.4 Deflections of non-temperature compensated force- measuring instruments may be normalized in accordance with Section 9 to a temperature other than that existing during calibration.

7.3.5 Deflections of non-temperature compensated force- measuring instruments shall be corrected in accordance with Section 9 to a nominal calibration temperature if the temperature changes more than ± 0.2 °C during calibration.

7.4 *Procedural Order in Calibration*—Immediately before starting the calibration, slowly and smoothly apply the maxi- mum force in the calibration sequence to the force-measuring instrument at least two times. This procedure is referred to as exercising the force-measuring instrument. Exercising is necessary to reestablish the hysteresis pattern that tends to disappear during periods of disuse, and is particularly necessary following a change in the mode of force application, as from compression to tension. Some force-measuring instruments may require more than two exercise cycles to achieve stability in zero-force indication.

NOTE 4—Overload or proof load tests are not required by these practices. It must be emphasized that an essential part of the manufacturing process for a force-measuring instrument is the application of a series of overloads to at least 10 % in excess of rated capacity. This must be done by the manufacturer before the instrument is released for calibration or service.

7.4.1 After exercising, apply the calibration forces, approaching each force from a lesser force. Forces shall be applied and removed slowly and smoothly, without inducing shock or vibration to the force-measuring instrument. The time interval between successive applications or removals of forces, and in obtaining readings from the force-measuring instrument, shall be as uniform as possible. If a calibration force is to be followed by another calibration force of lesser magnitude, reduce the applied force on the force-measuring instrument to zero before applying the second calibration force. Whenever possible, plan the force application schedule so that repetitions of the same calibration force do not follow in immediate succession. For any force-measuring instrument, the errors observed at corresponding forces taken first by increasing the force to any given test force and then by decreasing the force to that test force may not agree. Force-measuring instruments are usually used under increasing forces, but if a force- measuring instrument is to be used under decreasing force, it shall be calibrated under decreasing forces as well as under increasing force. Use the procedures for calibration and analysis of data given in Sections 7 and 8 except where otherwise noted. When a force-measuring instrument is calibrated with both increasing and decreasing forces, the same force values should be applied for the increasing and decreasing directions of force application, but separate calibration equations should be developed.

7.4.2 The calibration laboratory shall decide whether or not a zero force reading is to be taken after each calibration force. Factors such as the stability of the zero force reading and the presence of noticeable creep under applied force are to be considered in making this decision. It is pointed out, however, that a lengthy series of incremental forces applied without return to zero reduces the amount of sampling of instrument performance. The operation of removing all force from the instrument permits small readjustments at the load contacting surfaces, increasing the amount of random sampling and thus producing a better appraisal of the performance of the instrument. It is recommended that not more than five incremental forces be applied without return to zero. This is not necessary when the instrument is calibrated with decreasing forces;

however, any return to zero prior to application of all the individual force increments must be followed by application of the maximum force before continuing the sequence.

7.5 *Randomization of Force Application Conditions*— During the calibration sequence, maintain the force measurement axis of the force-measuring instrument coincident with the force axis of the machine. Shift the position of the force-measuring instrument in the calibration machine before repeating any series of forces. Introduce variations in any other factors that normally are encountered in service, as for example, disconnecting and reconnecting electrical cables. Allow sufficient warm up time if electrical disconnections are made.

7.5.1 In a compression calibration, position the force- measuring instrument to a 0 degree reference position, and then rotate to positions of approximately 120 degrees and 240 degrees. An exception is made for force-measuring instruments that cannot be rotated by 120 degrees such as some proving rings, force dynamometers, and Brinell Hardness Test Calibrators. For these types of force-measuring instruments, position the force-measuring instrument at 0 degrees, and then rotate to positions of approximately 60 degrees and 300 degrees, keeping its force axis on the centre force axis of the machine. This exception is made to minimize parallax error.

7.5.2 In a tension calibration, position the force-measuring instrument to a 0 degree reference position, and then rotate to positions of approximately 120 degrees and 240 degrees. An exception is made for force-measuring instruments that cannot be rotated by 120 degrees such as some proving rings and force dynamometers. For these types of force-measuring instruments, position the force-measuring instrument at 0 degrees, and then rotate to positions of approximately 60 degrees and 300 degrees, keeping its force axis on the centre force axis of the machine. Shift and realign any flexible connectors between positions. This exception is made to minimize parallax error.

7.5.3 In a two-mode calibration (compression and tension), perform a part of the calibration in one mode, switch modes and continue the calibration, then finish the calibration in the initial calibration mode. It is acceptable practice to change modes at each rotational position

NOTE 5—Force-measuring instruments have sensitivity in varying degrees depending on design to mounting conditions and parasitic forces and moments due to misalignment. A measure of this sensitivity may be made by imposing conditions to simulate these factors such as using fixtures with contact surfaces that are slightly convex or concave, or of varying stiffness or hardness, or with angular or eccentric misalignment, and so forth. Such factors can sometimes be significant contributors to measurement uncertainty and should be reflected in comprehensive measurement uncertainty analyses.

8. Calculation and Analysis of Data

8.1 *Deflection*—Calculate the deflection values for the force-measuring instrument as the differences between the readings of an instrument under applied force and the reading with no applied force. The method selected for treatment of zero should reflect anticipated usage of the force-measuring instrument. The deflection calculation shall *(a)* utilize the initial zero value only or *(b)* a value derived from readings taken before and after the application of a force or series of forces. For method *(a)*, the deflection is calculated as the difference between the deflection at the applied force and the initial deflection at zero force. For method *(b)*, when it is elected to return to zero after each applied force, the average of the two zero values shall be used to determine the deflection.

For method *(b)* when a series of applied forces are applied before return to zero force, a series of interpolated zero force readings may be used for the calculations. In calculating the average zero force readings and deflections, express the values to the nearest unit in the same number of places as estimated in reading the instrument scale. Follow the instructions for the rounding method given in Practice E29. If method (*a*) is elected, a creep recovery test is required per the criteria of 8.2 to ensure that the zero return characteristic of the forcemeasuring instrument does not result in excessive error.

8.2 *Determination of Creep Recovery*—Creep affects the deflection calculation. Excessive creep is indicated if large non-return to zero is observed following force application during calibration. A creep recovery test is required to ensure that the creep characteristic of the device does not have a significant effect on calculated deflections when method *(a)* is used to determine deflections. The creep test is to be performed for new force-measuring instruments, and for force-measuring instruments that have had major repairs, force-measuring instruments suspected of having been overloaded, or forcemeasuring instruments that show excessive non-return to zero following calibration. Creep and creep recovery are generally stable properties of a force-measuring instrument unless the force-measuring instrument is overloaded, has experienced moisture or other contaminant incursion, or is experiencing fatigue failure. If method *(b)* is used to determine deflections on a force-measuring instrument both during calibration and subsequent use, the creep recovery test is not required. The creep recovery test is performed as follows:

8.2.1 Exercise the force-measuring instrument to the maximum applied force in calibration at least two times. Allow the zero reading to stabilize and record the value. Apply the maximum applied force used in calibration of the forcemeasuring instrument and hold as constant as possible for 5 minutes. Remove the applied force smoothly, but as quickly as possible and record output at 30 seconds and 5 minutes. Creep recovery error is calculated as follows:

8.2.1.1 Creep Recovery Error, % of Output at Maximum Applied Force = 100 × (Output 30 seconds after zero force is achieved – Initial zero reading) /Output at Maximum Applied Force

8.2.2 A zero return error shall be calculated as follows:

8.2.2.1 Zero Return Error, % of Output at Applied Force = 100 × (Initial zero reading – Final zero reading 5 minutes after the applied force is removed) /Output at Applied Force. The creep test shall be repeated if the zero return error exceeds 50% of the creep recovery error limits.

8.2.3 For force-measuring instruments calibrated for use over the following verified ranges of forces, the creep recovery error limits of the output at the applied force are:

Class AA: 6 0.020 %

Class A: 6 0.050 %.

8.3 *Calibration Equation*—Fit a polynomial equation of the following form to the force and deflection values obtained in the calibration using the method of least squares:

$$\text{Deflection} = A_0 + A_1F + A_2F^2 + \ldots A_5F^5 \quad (5)$$

where:

F = force, and

A_0 through A_5 = coefficients.

A 2nd degree equation is recommended with coefficients $A3$,

$A4$, and $A5$ equal to zero. Other degree equations may be used.

For example the coefficients $A2$ through $A5$ would be set equal to zero for a linearized force-measuring instrument.

8.3.1 For high resolution force-measuring instruments (see 7.1.3), the procedure of Annex A1 shall be used to obtain the maximum degree of the best fit polynomial equation statistically supported by the calibration data set. This calculation is performed with a polynomial equation fitted to the average data at each applied force following the method of Annex A1. After determination of the degree of the best fit polynomial equation, fit a polynomial equation of that degree, or a lower degree, to the entire data set (not the averaged data set) in accordance with 8.3, and proceed to analyze the data in accordance with 8.4 – 8.6.3.2.

8.4 *Standard Deviation*—Calculate a standard deviation from the differences between the individual values observed in the calibration and the corresponding values taken from the calibration equation. Calculate a standard deviation as follows:

$$S_m = \sqrt{\frac{d_1^2 + d_2^2 + \cdots + d_n^2}{n-m-1}} \quad (6)$$

where:

d 1, d2, etc. = differences between the fitted curve and the n

observed values from the calibration data,

n = number of deflection values, and

m = the degree of polynomial fit.

NOTE 6—It is recognized that the departures of the observed deflections from the calibration equation values are not purely random, as they arise partly from the localized variation in instrument readings discussed in 7.1.1. As a consequence, the distributions of the residuals from the least squares fit may not follow the normal curve of error and the customary estimates based on the statistics of random variables may not be strictly applicable.

8.5 *Determination of Lower Limit Factor, LLF*—LLF is calculated as 2.4 times the standard deviation. If the calculated LLF is less than the instrument resolution, the LLF is then defined as that value equal to the resolution. Express the LLF in force units, using the average ratio of force to deflection from the calibration data.

NOTE 7—Of historical interest, the limit of 2.4 standard deviations was originally determined empirically from an analysis of a large number of force-measuring instrument calibrations and contains approximately 99 % of the residuals from least-squares fits of that sample of data.

8.6 *Verified Range of Forces*—Calculate the verified range of forces of the force-measuring instrument as follows:

8.6.1 *Lower Force Limit of the Verified Range of Forces*— Calculate the lower force limit to the verified range of forces for a specified percentage limit of error, *P*, as follows:

$$Lower\ force\ limit = \frac{100 \times LLF}{P} \qquad (7)$$

8.6.2 The verified range of forces shall not include forces outside the range of forces applied during the calibration. If the lower force limit is less than the lowest non-zero calibration force applied, then the lower force limit of the verified range of forces is equal to the lowest calibration force applied. 8.6.3 *Standard Verified Ranges of Forces*—Two standard verified ranges of forces are listed as follows, but others may be used where special needs exist:

Class AA: 6 0.050 %

Class A: 6 0.25 %.

8.6.3.1 *Class AA*—For force-measuring instruments used as secondary force standards, the LLF of the instrument shall not exceed 0.05 % of force. The lower force limit of the force measuring instrument as expressed by Equation (7) over the Class AA verified range of forces is therefore 2000 times the LLF, in force units, obtained from the calibration data.

NOTE 8—For example, a force-measuring instrument calibrated using primary force standards had a calculated LLF of 16 N (3.7 lbf). The lower force limit for the Class AA verified range of forces is therefore 16 × 2000 = 32 000 N (3.7 × 2000 = 7400 lbf). The LLF will be less than 0.05 % of force for forces greater than this lower force limit to the maximum force applied during calibration of the force-measuring instrument. It is recommended that the lower force limit be not less than 2 % (1⁄50) of the capacity of the force-measuring instrument.

8.6.3.2 *Class A*—For force-measuring instruments used to verify testing machines in accordance with Practices E4, or similar applications, the LLF of the force-measuring instrument shall not exceed 0.25 % of force. The lower force limit for use over the Class A verified range of forces is therefore 400 times the LLF, in force units, obtained from the calibration data.

NOTE 9—In the example of Note 8, the lower force limit for force measuring instruments calibrated for use over the Class A verified range of forces is 16 N × 400 = 6400 N (3.7 lbf × 400 = 1480 lbf). The LLF will be less than 0.25 % of force for forces greater than this lower force limit up the maximum force applied during calibration of the instrument.

NOTE 10—The term "verified range of forces" used in these practices are parallel in meaning to the same term in Practice E4. It is the range of forces over which it is permissible to use the force-measuring instrument in verifying a testing machine or other similar device. When a verified range of forces other than the two standard ranges given in 8.6.3 is desirable, the appropriate limit of error should be specified in the applicable method of test.

8.7 *Specific Force-Measuring Instruments*—Any force measuring instrument may be calibrated as a specific force measuring instrument. Elastic rings, loops, and columns with dial indicators as a means of sensing deformation are generally classed as specific force-measuring instruments because the relatively large localized nonlinearities introduced by indicator gearing produce an LLF too large for an adequate verified range of forces. These instruments are, therefore, used only at the calibrated forces and the curve-fitting and analytical procedures of 8.3 – 8.5 are replaced by the following procedures:

8.7.1 *Calculation of Nominal Force Deflection*—From the calibration data, calculate the average value of the deflections corresponding to the nominal force. If the calibration forces applied differ from the nominal value of the force, as may occur in the case of a calibration by secondary force standards, adjust the observed deflections to values corresponding to the nominal force by linear interpolation provided that the force differences do not exceed 61 % of capacity force. The average value of the nominal force deflection is the calibrated value for that force.

8.7.2 *Standard Deviation for a Specific Force-Measuring Instrument*—Calculate the range of the nominal force deflections for each calibration force as the difference between the largest and smallest deflections for the force. Multiply the average value of the ranges for all the calibration forces by the appropriate factor from Table 1 to obtain the estimated standard deviation of an individual deflection about the mean value.

TABLE 1 Estimates of Standard Deviation from the Range of Small Samples

Number of Observations at Each Force	Multiplying Factor for Range
3	**0.591**
4	**0.480**
5	**0.430**
6	**0.395**

8.7.3 *Lower Limit Factor for Specific Force-Measuring Instrument*—The LLF for a specific force-measuring instrument is defined as 2.0 times the standard deviation, plus the resolution. Convert the LLF into force units by means of a suitable factor and round to the number of significant figures appropriate to the resolution. The LLF is expressed as follows:

$$LLF = (2s + r)\,f \qquad (8)$$

where:

s = standard deviation,

r = resolution

f = average ratio of force to deflection from the calibration data.

8.7.4 *Precision Force*—A specific force-measuring instrument does not have a verified range of forces as specified in 8.6, since it can be used only at the forces for which it was calibrated. The use is restricted, however, to those calibrated forces that would be included in a verified range of forces are calculated in 8.6 – 8.6.3.2.

9. Temperature Corrections for Force-Measuring Instruments During Use

9.1 *Referenced Temperature of Calibration*—It is recommended that the temperature to which the calibration is referenced be 23 °C (73 °F), although other temperatures may be referenced (see 7.3.2).

9.2 *Temperature Corrections*—Nearly all mechanical elastic force-measuring instruments require correction when used at a temperature other than the temperature to which the calibration is referenced. This category includes proving rings, Amsler boxes, and rings, loops, and columns equipped with dial indicators. Uncompensated instruments in which the elastic element is made of steel with not more than 5 % of alloying elements may be corrected on the basis that the deflection increases by 0.027 % for each 1 °C increase in temperature.

9.3 *Method of Applying Corrections:*

9.3.1 In using an uncompensated force-measuring instrument at a temperature other than the temperature of calibration, the correction may be made in the following manner:

9.3.1.1 Calculate a force value from the uncorrected observed deflection of the instrument using the working table or other media derived from the calibration equation.

9.3.1.2 Correct this force value for temperature by reducing it by 0.027 % for every 1 °C by which the ambient temperature exceeds the temperature of calibration. If the ambient temperature is less than the temperature of calibration, the force value would be increased by the appropriate amount.

9.4 *Temperature Effect on the Sensitivity of Temperature- Compensated Force-Measuring Instruments*—Force- measuring instruments such as load cells may have temperature compensation built in by the manufacturer.

9.4.1 For force-measuring instruments with such compensation calibrated for use over the following verified ranges of forces, the temperature error limits as a percent of reading are (See Note 11):

Class AA: ±0.010 % Class A: ±0.050 %

9.4.2 If a force-measuring instrument is used at temperatures other than the temperature at which it was calibrated, it is the user's responsibility to ensure that the performance of the force-measuring instrument does not exceed the limits of paragraphs 9.4.1, or if such limits would be exceeded, that the force-measuring instrument is calibrated at the expected temperature of use, or over a range of the expected temperatures of use and corrected accordingly.

NOTE 11—There is a negligible effect on the maximum values for force-measuring instruments calibrated for use over the Class AA, verified range of forces, LLF (0.05 % of applied force) and Class A, LLF (0.25 % of applied force) when these values are added as root-sum-squares with the values for temperature error given in 9.4.1. Such a combination of error sources is valid in the case of independent error sources. It should be noted the temperature differences between conditions of calibration and use may result in significant errors. This error source should be evaluated by users to assure compliance with these requirements, when such usage occurs. Adequate stabilization times are required to ensure that thermal gradients or transients in the force-measuring instrument have equilibrated with the environment in which testing is to be performed. Otherwise, thermal gradients may cause significant errors in both temperature compensated and uncompensated force-measuring instruments.

It is recommended that the effect of temperature on the sensitivity of force-measuring instruments calibrated for use over the Class AA verified range of forces not exceed 0.0030 %/°C (0.0017 %/°F) and for force- measuring instruments calibrated for use over the Class A verified range of forces, that the effect of temperature on the sensitivity not exceed 0.010 %/°C (0.0056 %/°F).

As an example, for the case of force-measuring instruments that have temperature coefficients equal to the maximum recommended values, the error due to the temperature is negligible within ±3 °C for force- measuring instruments calibrated for use over the Class AA verified range of forces and ±5 °C for force-measuring instruments calibrated for use over the Class A verified range of forces referenced to the temperature at which those force-measuring instruments were calibrated.

10. Force-Multiplying Systems

10.1 *Balances and Small Platform Scales:*

10.1.1 *General Principles*—Balances and small platform scales are sometimes useful for the verification at low forces of testing machines that respond to forces acting vertically upwards. The following procedures are verifications for the purpose of calibrating a balance or small platform scale used in verifying a testing machine, and do not replace or supplement established procedures, such as those set forth in NIST Handbook 44 **(3)**, Specifications, Tolerances and Other Technical Requirements for Commercial

Weighing and Measuring Devices, for the testing of commercial weighing equipment. The calibration of a balance or platform scale consists of a verification of the multiplying ratio of its lever system, using laboratory mass standards of National Institute of Standards and Technology (NIST) Class F (Note 12) or better. Masses used shall be traceable to the International System of Units (SI) **(2)**.

NOTE 12—Class F weights of 0.91 kg (2 lb) or greater have a tolerance of 0.01 %.

10.1.2 *Equal-Arm Balances*—With both pans empty, adjust the balance to bring the rest point to approximately the centre of the scale and note the value of the rest point. Place equal masses in each pan to an amount between three-quarters and full-balance capacity, then add to the appropriate pan to restore the rest point to the original value. Divide the mass in the pan that will eventually bear against the testing machine by the mass in the other pan and round the resulting quotient to the nearest 0.1 %. This value is the multiplying ratio and will generally be nearly 1.000 for a well-constructed balance. The test method with necessary modifications, may be employed for single-lever systems in general.

10.1.3 *Verification of a Platform Scale with counterpoise weights*—The counterpoise weights of a platform scale are usually marked with mass values that include the nominal multiplication ratio of the scale.

10.1.3.1 Set the weigh beam poise to zero and carefully balance the scale to bring the beam pointer to the centre of the trig loop.

10.1.3.2 Place standard weights (NIST Class F) or weights of equivalent or lower uncertainty on the centre of the scale platform and balance the scale using the counterpoise weights and weigh beam poise.

10.1.3.3 Divide the total mass on the platform by the sum of the counterpoise weight values and the weigh beam poise reading, rounding the quotient to the nearest 0.1 %. This value is the multiplication ratio correction factor and will be nearly 1.000 for a scale in good condition.

10.1.4 *Verification of a Direct Reading Platform Scale*— These scales are direct reading in mass units.

10.1.4.1 With no mass on the platform, tare the scale.

10.1.4.2 For each force, place standard weights (NIST Class F or weights of equivalent or lower uncertainty) on the centre of the scale platform and record the reading of the scale.

10.1.4.3 Divide the total mass on the platform by the scale reading, rounding the quotient to the nearest 0.1 %. This value is the multiplication ratio correction factor and will be nearly 1.000 for a scale in good condition

10.1.5 *Calculation of Forces*—The verification of a testing machine force by means of balances, levers, or platform scales is similar to verification by deadweight loading in that gravity and air buoyancy corrections shall be applied to the values indicated by these devices. For the verification of a testing machine, the multiplying factors given in Table 2 are sufficiently accurate. Always make corrections to primary force standards in accordance with the formula given in 6.1.1.

11. Time Interval Between Calibrations and Stability Criteria

11.1 All force-measuring instruments and systems shall meet the range, accuracy, resolution, and stability requirements of this standard, and shall be suitable for their intended use.

11.2 The calibration intervals for force-measuring instruments and systems used as secondary force standards or for the verification of force indication of testing machines shall be calibrated at intervals not exceeding two years after demonstration of stability supporting the adopted recalibration inter- val. New force-measuring instruments shall be calibrated at an interval not exceeding 1 year to determine stability per 11.2.1.

11.2.1 Force-measuring instruments shall demonstrate changes in the calibration values over the range of use during the recalibration interval of less than 0.032 % of reading for force-measuring instruments and systems used over the Class AA verified range of forces and less than 0.16 % of reading for those instruments and systems used over the Class A verified range of forces. See Note 13.

11.2.2 Force-measuring instruments not meeting the stability criteria of 11.2.1 shall be recalibrated at intervals that shall ensure the stability criteria are not exceeded during the recalibration interval. See Note 13.

NOTE 13—The above stability criteria provide minimum requirements for establishing calibration intervals for force-measuring instruments and systems used as secondary force standards and those used for the verification of the force indication of testing machines. Users specifying percentage limit of errors other than Class AA or Class A should determine stability criteria appropriate to the instruments employed. For secondary force standards, it is recommended that cross-checking be performed at periodic intervals using other standards to help ensure that standards are performing as expected.

11.2.3 *Balances, Scales, and Other Lever Systems*— Mechanical force-multiplying systems used for the verification of test machines shall be verified at intervals not exceeding 5 years. If a balance or platform scale shows evidence of binding or excessive friction in the lever pivots as demonstrated by a lack of free action in the balance beam before the unit is coupled to the testing machine, the system shall be examined to locate the source of friction and the condition corrected. However, once the system is coupled to the testing machine and force is applied, it is an acceptable condition that the balance beam is no longer free to swing in the normal manner characteristic of deadweight loading.

11.3 *Calibration Following Repairs or Overloads*—A force- measuring instrument or multiplying system shall be recalibrated following any repairs or modifications that might affect its response, or whenever the calibration of the force- measuring instrument might be suspect. Any instrument sustaining an overload that produces a permanent shift in the unadjusted zero force reading amounting to 1 % or more of the capacity deflection shall be recalibrated before further use.

NOTE 14—Certain indicators used with electrical force-measuring instruments can zero out or tare-out significant offsets at zero force. Certain mechanical force-measuring instruments can have their deflection measuring apparatus readjusted to positions or conditions, which can reset the zero force reading to approximate that prior to the overload. These operations can circumvent the requirement of 11.3. A means of establishing a true zero reference is required in order to assure that the zero balance of calibration has not been shifted by an amount greater than 1 %.

TABLE 2 Unit Force Exerted by a Unit Mass in Air at Various Latitudes

Latitude, deg	Elevation Above Sea Level, m (ft)					
	–30.5 to 152 (-100 to 500)	152 to 457 (500 to 1500)	457 to 762 (1500 to 2500)	762 to 1067 (2500 to 3500)	1067 to 1372 (3500 to 4500)	1372 to 1676 (4500 to 5500)
20	0.9978	0.9977	0.9976	0.9975	0.9975	0.9974
25	0.9981	0.9980	0.9979	0.9979	0.9978	0.9977
30	0.9985	0.9984	0.9983	0.9982	0.9982	0.9981
35	0.9989	0.9988	0.9987	0.9987	0.9986	0.9985
40	0.9993	0.9993	0.9992	0.9991	0.9990	0.9989
45	0.9998	0.9997	0.9996	0.9996	0.9995	0.9994
50	1.0003	1.0002	1.0001	1.0000	0.9999	0.9999
55	1.0007	1.0006	1.0005	1.0005	1.0004	1.0003

12. Substitution of Electronic Indicating Instruments Used with Force-Measuring Systems

12.1 It may be desirable to treat the calibration of the elastic member and the force-indicating instrument separately, thus allowing for the substitution or repair of the force-indicating instrument without the necessity for repeating an end-to-end system calibration. When such substitution or repair is made, the user assumes the responsibility to ensure that the accuracy of the force-measuring system is maintained. Substitution of the electronic indicating instrument shall not extend the system calibration/verification date. The following conditions shall be satisfied when substituting a metrologically significant element of the electronic indicating instrument.

12.1.1 The electronic-indicating instrument used in the initial calibration and the instrument to be substituted shall each have been calibrated and their measurement uncertainties determined. The electronic indicating instrument to be substituted shall be calibrated with traceability to the SI over the full range of its intended use including both positive and negative values if the system is used in tension and compression. The calibrated range shall include a point less than or equal to the output of the force transducer at the lower force limit and a point equal to or greater than the output of the force transducer at the maximum applied force. A minimum of five points shall be taken within this range. The measurement uncertainty of each electronic indicating instrument shall be less than or equal to one third of the uncertainty for the force-measuring system over the range from the lower force limit to the maximum force.

12.1.2 The measurement uncertainty of the force-indicating instrument shall be determined by one of the methods outlined in Appendix X2. It is recommended that a transducer simulator capable of providing a series of input mV/V steps over the range of measurement and with impedance characteristics similar to that of the force transducer be employed as a check standard to verify calibration of the electronic indicating instrument and in establishing the measurement uncertainty. The measurement uncertainty of the transducer simulator shall be less than or equal to one tenth of the uncertainty for the force-measuring instrument.

12.1.3 Excitation voltage amplitude, frequency, and wave- form shall be maintained in the substitution within limits to ensure that the affect on the calibration is negligible. It is a user responsibility to determine limits on these parameters through measurement uncertainty analysis and appropriate tests to ensure that this requirement is met. Substitution of an inter- connect cable can have a significant affect on calibration. If an interconnect cable is to be substituted, see Note 15.

12.2 A report of calibration for the original and electronic substitute indicating instruments shall be generated. The report shall include the identification of the item calibrated, date of calibration, calibration technician, test readings, the identification of the test equipment used to verify the performance of the electronic indicating instrument, and the measurement uncertainty and traceability. The report shall be available for reference as required.

NOTE 15—If an interconnect cable is substituted, care should be taken to ensure that the new cable matches the original in all aspects significant to the measurement. (Such factors as the point of excitation voltage sensing and the impedance between the point of excitation voltage sensing and the elastic force-measuring element of the force-measuring instrument can affect the sensitivity of the electronic indicating instrument to changes in applied force.) It is recommended that the electronic indicating instrument/cable performance be verified using a transducer simulator or other appropriate laboratory, instruments.

12.3 Metrologically insignificant elements of force- measuring instrument systems such as digital displays, printers, and computer monitors may be substituted following verification of proper function.

13. Report

13.1 The report issued by the calibration laboratory on the calibration of a force-measuring instrument shall be error-free and contain no alteration of dates, data, etc. The report shall contain the following information:

13.1.1 Statement that the calibration has been performed in accordance with Practices E74. It is recommended that the calibration be performed in accordance with the latest published issue of Practices E74.

13.1.2 Manufacturer and identifying serial numbers of the instrument calibrated,

13.1.3 Name of the laboratory performing the calibration,

13.1.4 Date of the calibration,

13.1.5 Type of reference standard used in the calibration with a statement of the limiting errors or uncertainty,

13.1.6 Temperature at which the calibration was referenced, 13.1.7 Listing of the calibration forces applied and the corresponding deflections, at each rotational position, including the initial and return zero forces and measured deflections.

13.1.8 Treatment of zero in determining deflections 8.1*(a)* or *(b)*, and if method *(b)* is elected if zero was determined by the average or interpolated method.

13.1.9 List of the coefficients for any fitted calibration equation and the deviations of the experimental data from the fitted curve,

13.1.10 Force-measuring instrument resolution, the measurement uncertainty associated with the calibration results, and the verified range of forces or verified ranges of forces,

13.1.11 The result of the creep recovery test, when performed,

13.1.12 The excitation voltage and wave form used for calibration when known,

13.1.13 Statement that the lower force limit expressed in this report applies only when the calibration equation is used to determine the force.

NOTE 16—For force-measuring instruments and systems in which deflections are displayed in engineering units (that is, lbf, kgf, N) users are cautioned that the lower force limit expressed in the calibration report applies only when the calibration equation is used to determine the force, that is, the direct reading should be incorporated into the calibration equation to determine the applied force.

13.1.14 Tabulation of values from the fitted calibration equation for each force applied during calibration and, if available and suitable for comparison, a tabulation of the change in calibrated values since the last calibration for other than new instruments.

NOTE 17—The comparison should be made between the unsynthesized calibration data sets, not between data sets derived from the calibration curves, unless the same degree of fit is used in both calibrations under comparison.

13.1.15 Working table of forces, or a correction curve from a nominal factor, or other device to facilitate use of the instrument in service.

NOTE 18—It is advised that a working table of forces versus deflections be supplied, as many users may not have access to data processing at the point of use. The minimum tabular increment of force should not be less than the resolution, nor greater than 10 % of the maximum force applied during calibration.

14. Keywords

14.1 force-measuring instrument; force standard; load cell; proving ring; testing machine.

ANNEX

(Mandatory Information)

A1. PROCEDURE FOR DETERMINING DEGREE OF BEST FITTING POLYNOMIAL

A1.1 This procedure may be used to determine the degree of best fitting polynomial for high-resolution force-measuring instruments (see 7.1.3).

A1.2 The procedure assumes that a force-measuring instrument has been measured at n distinct, non-zero forces, and that the series of n measurements has been replicated k times at the same forces. At each force, the mean of k measurements is computed. (The value k is not otherwise used here.) These n values are referred to as the mean data. The following analysis is to be applied only to the mean data, and is used only to determine the degree of best fitting polynomial.

A1.3 Fit separate polynomials of degree 1, 2, 3, 4, and 5 to the mean data. Denote the computed residual standard deviations by s_1, s_2, s_3, s_4, and s_5 respectively. The residual standard deviation from an m_1-degree fit is:

$$S_{m_1} = \sqrt{\frac{d_1^2 + d_2^2 + \cdots + d_n^2}{n_1 - m_1 - 1}} \qquad \text{(A.1.1)}$$

Where

d_1, d_2, etc. = differences between the fitted curve and the n observed mean values from the calibration data,

n_1 = number of distinct non-zero force increments, and

m_1 = the degree of polynomial fit.

A1.4 These values for residual standard deviation are used in a sequential procedure to test whether the coefficient of the highest order term in the current fit is significant. Use will be made of the constants $C(n_1, m_1)$ in Table A1.1. Quantities of the F distribution were used in computing these constants.

A1.5 Compute s_4 / s_5 and compare it to $C(n_1, 5)$. If $s_4 / s_5 > C(n_1, 5)$ then the coefficient of the 5th-degree term is significant and the 5th-degree fit is determined to be best. Otherwise,

TABLE A1.1 - Factors $C(n_1, m_1) = (1 + [F_{.975}(1, n_1 - m_1 - 1) - 1]/(n_1 - m_1))^{1/2}$ for Determining the Best Degree of Polynomial Fit

n_1	$m_1 = 2$	$m_1 = 3$	$m_1 = 4$	$m_1 = 5$
10	1.373	1.455	1.582	1.801
11	1.315	1.373	1.455	1.582
12	1.273	1.315	1.373	1.455
15	1.195	1.215	1.241	1.273
20	1.131	1.141	1.151	1.163

compute s_3 / s_4 and compare it to $C(n_1, 4)$. Continue the procedure in the same manner until the coefficient of the highest-degree term in the current fit is determined to be compute s_3 / s_4 and compare it to $C(n_1, 4)$. Continue the procedure in the same manner until the coefficient of the highest-degree term in the current fit is determined to be significant. To state the rule generally, if $\frac{s_{m_1-1}}{s_{m_1}} > C(n1, m1)$ then the coefficient of the m_1 th degree term is significant and the m_1 degree fit is determined to be best. Otherwise, reduce $m1$ by one and repeat the test ($m1$ = 5, 4, 3, 2).

A1.5.1 To illustrate the procedure, let:

n_1 = 11,

s_1 = 1.484,

s_2 = 0.7544,

s_3 = 0.2044,

s_4 = 0.1460, and

s_5 = 0.1020 (see NIST Technical Note 1246 **(4)**, A New Statistical Model for Force Sensors).

Compute $s4/s5$ = 1.431 < 1.582 = $C(11, 5)$. This indicates the 5th degree term is not significant, therefore compute $s3/s4$ = 1.400 < 1.455 = $C(11, 4)$.

This indicates the 4th degree term is not significant, therefore compute

$s2/s3$ = 3.691 > 1.373 = $C(11, 3)$.

This indicates the 3rd degree term is significant, and the 3rd degree fit is determined to be the best degree of polynomial fit.

A1.6 After determination of the degree of best fit, return to 8.3.1 of these practices to continue calculation and analysis of the calibration data.

APPENDIXES

(Nonmandatory Information)

X1. SAMPLE MEASUREMENT UNCERTAINTY ANALYSES FOR PRIMARY AND SECONDARY FORCE CALIBRATION METHODS

X1.1 Scope

X1.1.1 This appendix provides sample procedures and examples of calculations to assist in determining the measurement uncertainty for primary and secondary force standards and for force-measuring instruments used to verify the force indications of material testing machines. Examples are provided for determining the measurement uncertainty in applied forces associated with primary force standards, secondary force standards used over the Class AA verified range of forces and force-measuring instruments used for verifying the force indications of testing machines used over the Class A verified range of forces. Potential sources of uncertainty are identified and evaluated in order to estimate the measurement uncertainty according to the method of NIST Technical Note 1297 **(5)** "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results". Other methods of analysis may be used when appropriate. The user should determine and analyze all sources of uncertainty pertinent to the specific application. The uncertainty sources and the sample calculations and values presented are examples only and should not be assumed as inclusive of all uncertainty components particular to a given force-measuring instrument and calibration process.

X1.2 Sources of Measurement Uncertainty

X1.2.1 All relevant sources of uncertainty should be evaluated. The examples presented are samples and may not include all potentially significant uncertainties for the user's calibration process, apparatus, and personnel. The user should evaluate and identify any other uncertainties which are significant to the calibration result and incorporate them into the measurement uncertainty analysis.

X1.3 Uncertainty of the Applied Force of Primary Force Standards

X1.3.1 The formula to determine the force exerted by a weight in air is given in paragraph 6.1.1 of these practices. This formula contains four independent variables: mass of the weight, local gravity where the weights are used, air density, and density of the weight. The measurement uncertainty analysis shall include the uncertainties of these variables, taking into account their variation over time. Other components should be evaluated and included in the measurement uncertainty where appropriate.

X1.3.1.1 *Uncertainty of the mass of the weights*—The un- certainty of the mass of the weights is treated as a Type A uncertainty with a normal probability distribution and is designated u_W. For an expanded uncertainty of 0.0020 %, with a 95 % confidence level, as an example, the standard uncertainty is:

$$U_w = 0.0020\ \% \,/\, 2.0 = 0.0010\ \% \qquad \text{(X1.1)}$$

X1.3.1.2 *Uncertainty of the determination of local gravity*— The local value for the acceleration due to gravity, calculated within 0.0001 m/s^2, may be obtained from the National Geodetic Information Centre , National Ocean and Atmospheric Administration (NOAA). For a more accurate determination, gravity can be measured at the site where the weights are to be used. When determined by actual measurement the probability distribution of this component of the measurement uncertainty will be normal, and if the NOAA value is used the distribution will be rectangular. For this example the gravity value was obtained by local measurement with an uncertainty of 0.0001 % with a 95 % confidence level. This is a Type A uncertainty and is treated as having a rectangular probability distribution and is designated u_{g1}. The standard uncertainty is:

$$u_{g1} = 0.0001\ \% \,/\, 2 = 0.00005\ \% \qquad \text{(X1.2)}$$

X1.3.1.3 *Uncertainty of the gravity correction for the height of the weight stack*—The gravity field varies with height above or below the reference plane. This variation is approximately 0.000032 %/m. When weights are used above or the below the reference plane the difference in gravity must be evaluated and included in the calculation of the measurement uncertainty when necessary. Corrections can be applied to the individual weights or can be included in the uncertainty analysis. For this example a weight will be used at an elevation three meters below the reference plane for which the gravity was deter- mined. This is a Type B uncertainty and is treated as having a rectangular probability distribution and is designated u_{g2}. The standard uncertainty is:

$$u_{g2} = (0.000032\ \%\ \text{x}\ 3) \,/\, 1.732 = 0.000055\ \% \qquad \text{(X1.3)}$$

X1.3.1.4 *Uncertainty due to variation of the buoyant force*—Buoyant forces equal to the weight of the air displaced are exerted on the weights. This force varies with atmospheric pressure and humidity. The correction factor is($(1- d \,/\, D$) where d = air density and D = weight density. The air density equation can be found in NIST Special Publication 700-1**(6)**. Following are examples of the uncertainty contribution due to variations in air density and the uncertainty in the determination of the density material from which the weights are made.

X1.3.1.5 *Uncertainty of the air density*—Air density varies with fluctuations in barometric pressure, humidity, and temperature. According to NBS Monograph 133**(7)** at a constant temperature of 23 °C, changes in barometric pressure and humidity may cause the actual air density to vary as much as 3 % in either direction from the average air density at a given time and place. Where the masses are maintained in an environment at 23 °C 6 2 °C the variation in air density will cause a change in mass of the weight of 5.47 ppm (0.000547 %). This is a Type B uncertainty and is treated as having a rectangular probability distribution. This uncertainty is designated u_d. The standard uncertainty is:

$$u_d = 0.000547\ \% \,/\, 1.732 = 0.000316\ \% \qquad (X1.4)$$

X1.3.1.6 *Uncertainty in determination of the density of* material may be determined by actual measurement or hand*material from which weights are made*—The density of the book values may be used. When determined by actual measurement the probability of this component of the measurement uncertainty will be normal. When handbook values are used the uncertainty is treated as having rectangular probability. For this example the material density was determined by actual measurement to be 7.903 g/cm^3 with an uncertainty 0.007 % for k=2. A variation in material density of 0.0035 % will cause a change in the mass of the applied force of 0.000007 %. This is a Type A uncertainty and is treated as having a normal probability distribution and is designated u_D. The standard uncertainty is:

$$u_D = (0.000007\ \% \,/\, 2) = 0.0000035\ \% \qquad (X1.5)$$

X1.3.1.7 *Uncertainty due to stability of mass values with time*—The stability of the masses with time can be determined experimentally and may depend on the material and processing of the masses. Other factors including the finish of the weights, the design and operation of the machine using the weights, the environment, and the care and maintenance of the weights and the machine can also influence stability. Studies performed on masses made from austenitic stainless steel alloy at the National Institute of Standards and Technology showed no significant change in the masses with time. The National Physical Laboratory in England reports experience with austenitic stainless steel masses shows the mass is likely to be stable to better than 0.2 ppm over a period of ten years. For the purpose of this example a stability of 0.2 ppm (0.00002 %) for ten years will be used. For this example a ten-year calibration interval will be used and it will be assumed that the change of mass is directly proportional to time. This is a Type B uncertainty and is treated as having a rectangular probability distribution and is designated u_s. The standard uncertainty is:

$$u_s = 0.00002/1.732 = 0.000012 \qquad (X1.6)$$

X1.3.1.8 *Uncertainty due to misalignment*—Misalignment may cause unintended forces and moments to be applied to the instrument affecting its sensitivity and is an often overlooked significant error source. This may occur with both tension and compression calibrations. Some assessment of the error can be inferred from the differences in the calibrations performed in relatively good or not based on whether the load string is perturbed showing motion perpendicular to the load axis as load is engaged. In this example, it is assumed that the LLF determined in the rotational test is low and no other indications are evident in indicating that this error source is minimal. If there are indications that alignment is not what it should be, multi-axis force-measuring instruments or alignment specimens such as used in Practice E1012 may provide a means of measuring the magnitude of the problem and a verification that suitable alignment has been achieved after adjustments have been made to the machine.

X1.3.1.9 *Combined and Expanded Uncertainty*—The combined uncertainty in this example is:

$$u_c = \sqrt{u_w^2 + u_{g1}^2 + u_{g2}^2 + u_d^2 + u_D^2 + u_s^2} \quad \text{(X1.7)}$$

$$u_c = \sqrt{\begin{matrix} 0.0010\ \%^2 + 0.00005\ \%^2 + 0.000055\ \%^2 + \\ 0.000316\ \%^2 + 0.0000035\ \%^2 + 0.000012\ \%^2 \end{matrix}} = 0.00105\ \% \quad \text{(X1.8)}$$

The expanded uncertainty is:

$$U = k \times u_c \quad \text{(X1.9)}$$

$$U = 2.0 \times 0.00105\ \% = 0.0021\ \% \quad \text{(X1.10)}$$

where *k* is the coverage factor. For a coverage factor of 2.0, the confidence level that the true force value lies within the range of the measured value 6*U* is approximately 95 %.

X1.4 Uncertainty of Calibration of Secondary Force Standards and Force-Measuring Instruments Used for Verifying the Force Indication of Testing Ma- chines by Primary Force Standards

X1.4.1 *Uncertainty of the Applied Force*—Secondary force standards are required to be calibrated by primary force standards. Other force-measuring instruments may also be calibrated by primary force standards. The measurement un- certainty analysis for these secondary force standards and other force-measuring instruments when calibrated by primary force standards shall include the uncertainty of the applied calibration force, uncertainty of reproducibility (differences in calibration values measured when the force-measuring instrument is rotated in the calibration machine as required by the standard) and curve fitting errors, uncertainty due to temperature, uncertainty due to misalignment. Other components should be evaluated and included in the measurement uncertainty when relevant.

X1.4.1.1 *Uncertainty of the calibration forces applied during calibration of the secondary force standard or of force- measuring instruments used for verifying the force indications of testing machines by primary force standards*—The uncertainty in the calibration forces applied by the primary force standards force calibration lab is 0.0021 % over the verified range of forces with a 95 % confidence factor as determined in X1.3. the primary calibration example. This is treated as a Type A uncertainty with a normal probability function

$$u_{\mathrm{cal}} = 0.0021\,\% - 2 = 0.00105\,\% \qquad \text{(X1.11)}$$

X1.4.1.2 *Uncertainty due to force-measuring instrument responses during calibration and curve fitting errors*—This uncertainty includes errors due to reproducibility (which encompasses errors due to repositioning the force-measuring instrument in the calibration load frame as required in 7.5), and interpolation errors which are the result of a lack of perfect representation of the calibration curve by a polynomial. This uncertainty is evaluated as the standard deviation determined in the curve fit process used to establish the LLF. This uncertainty is treated as a Type A uncertainty with a normal probability distribution and is assumed constant over the range. The measurement uncertainty must be evaluated at the lowest calibration force at which the secondary force standard is used.

For the example, this uncertainty is evaluated as 0.0020 % of the maximum calibration force and as 0.020 % of reading when the secondary force standard is used at 10 % of range.

$$u_{\mathrm{r}} = 0.0020\,\%/0.1 = 0.020\% \quad \text{reading at 10 % of range} \qquad \text{(X1.12)}$$

X1.4.1.3 *Uncertainty due to effect of temperature on sensitivity and zero*—Temperature differences in the secondary laboratory from the temperature at which the secondary force standard was calibrated in the primary lab result in additional uncertainty in the applied force. For this example the secondary force standard has a sensitivity temperature coefficient of 0.0015 % /°C and a zero temperature coefficient of 0.0015 % /°C. The temperature effect on sensitivity is evaluated at the next level in the uncertainty analysis (see Appendix X1) and it is only necessary that the temperature during the secondary calibration be noted on the primary lab calibration report as required by 13.1.6. The uncertainty due to temperature effect on zero is usually small, since the zero shift occurring with temperature becomes the reference for that calibration run and only the zero shift due to temperature during a calibration run is of consequence. Monitoring zero return after the calibration provides a basis for uncertainty evaluation for change of zero during the calibration process. The return to zero error observed has both creep recovery error and thermal zero shift measurement uncertainty components. The zero-shift should be treated appropriately depending on the method of treatment of zero selected. For example, if it is elected to use method *(b)* averaging the initial and final zero data, then the zero return error could reasonably be evaluated as one half of the difference in these readings. If method *(a)* is chosen, the difference in initial and final zero data provides an estimate of error. For the example, zero return 30 seconds after force removal has been measured as 0.00005 mV/V for a 2 mV/V sensitivity force-measuring instrument and it is elected to use method *(b)* for deflection calculation. The return to zero uncertainty is treated as a Type B uncertainty with rectangular distribution.

$$u_z = (100 \times 0.00005 \text{ mV/V} / 2.00000 \text{ mV/V})/(2 \times 1.732)$$
$$= 0.00072 \text{ \% Rated} \qquad \text{(X1.13)}$$

or for lower force limit of 10 % of range:

$$u_z = 0.00072 \text{ \%} \frac{}{0.1} = 0.0072\% \qquad \text{(X1.14)}$$

X1.4.1.4 *Uncertainty due to misalignment*—Evaluation of alignment uncertainty sources is often problematic and can lead to significant errors. Evaluation should take into account the misalignment in the load frame and fixtures and the effect of that misalignment on the secondary force standard and the unit being calibrated. Observing the alignment as force is applied to the load string (fixtures, unit being calibrated, and secondary force standard) for motion perpendicular to the loading axis should always be performed. Such motion should be adjusted out before proceeding. Concentricity and angular misalignment uncertainty can be estimated based on fixture tolerances and platen levelness. Some secondary force standards have a specified maximum error due to side force and moment, or this can be determined experimentally. This information taken together provides a means for estimating the uncertainty due to misalignment. This uncertainty cannot be separated from errors determined in the rotational tests and is not evaluated separately. This paragraph is intended to be informational and call attention to what can be a significant contributor to measurement uncertainty.

X1.4.1.5 *Combined and expanded uncertainty*—The combined and expanded uncertainty in this example evaluated at 10 % of range is:

$$u_c = \sqrt{u_{cal}^2 + u_r^2 + u_z^2} \qquad \text{(X1.15)}$$

$$u_c = \sqrt{0.00105 \text{ \%}^2 + 0.0200 \text{ \%}^2 + 0.0072 \text{ \%}^2 = 0.0212 \text{ \%}} \qquad \text{(X1.16)}$$

The expanded uncertainty is:

$$U = k \times u_c \qquad \text{(X1.17)}$$
$$U = 2.0 \times 0.0212 \text{ \%} = 0.0424 \text{ \%} \qquad \text{(X1.18)}$$

where *k* is the coverage factor. For a coverage factor of 2.0, the confidence level that the true force value lies within the range of the measured value 6 *U* is approximately 95 %.

X1.4.2 *Uncertainty of the Electrical Measurement*—See Appendix X2 for an example method of determining the measurement uncertainty of the electrical measurement. Note that when force calibration instruments are calibrated as a system with a read out instrument, such factors as the uncertainty of the calibration of the instrument and instrument non-linearity are accounted for in the calibration process and should not be double counted. If the calibration is a mV/V calibration using instrumentation provided by the primary lab, the electrical measurement uncertainty is reported by the calibration laboratory and should be combined with the uncertainty calculated for the force-measuring instrument.

X1.5 Uncertainty of Applied Force during Calibration by Secondary Force Standards

X1.5.1 *Uncertainty of the Applied Force during calibration*—The measurement uncertainty analysis of the applied forces for calibrations performed using secondary force standards shall include the uncertainty of the calibration forces applied when the secondary force standard was calibrated at the primary lab, uncertainty due to stability, uncertainty due to temperature, uncertainty due to misalignment, and uncertainty in dissemination of calibration values. Other components should be evaluated and included in the measurement uncertainty when relevant.

X1.5.1.1 *Uncertainty in the calibration forces applied during calibration of the secondary force standard as reported by the calibration laboratory*—The uncertainty in the calibration of the secondary force standard by the primary force standards is 0.0021 % over the verified range of force with a 95 % confidence factor as determined in the primary calibration example. This is treated as a Type A uncertainty with a normal probability function. For use at 10 % of rated range,

$$U_{cal} = 0.0424\ \% / 2.0 = 0.0212\ \% \qquad (X1.19)$$

X1.5.1.2 *Uncertainty due to the stability of the secondary force standard with time*—The stability of the secondary force standard with time is estimated based on experience for a new secondary force standard and by measured calibration data for a device that has a calibration history. For new devices, the estimate can be based on similar standards made from the same materials and processed similarly. Manufacturers may be able to provide an estimate of stability, recognizing that stability is partially dependent on environment and usage, which are under the laboratory's control. For force-measuring instruments that have been in service, stability is determined by measured calibration data for the force-measuring instrument by comparing previous calibrations with the current calibration. For this example, assume the change in the sensitivity of the standard with time has been determined to be 0.005 % of reading over a one year recalibration interval. This uncertainty will be treated as a Type B uncertainty with a rectangular probability function.

$$u_s = 0.005\ \% / 1.732 = 0.00289\ \% \text{ of reading at } 10\ \% \text{ of range} \qquad (X1.20)$$

X1.5.1.3 *Uncertainty in disseminating calibration values from the primary force standards calibration to secondary force standards calibration*—The uncertainty in disseminating calibration values is an attempt to account for the uncertainty related to differences in characteristics of the load frame and measurement system of the primary force standards calibration and the secondary force standard calibration. This uncertainty can be estimated by comparing the result of two secondary force standards calibrated by primary force standards using one as the reference standard and the other as the unit under test.

An alternative approach to identifying the dissemination uncertainty component is to perform a proficiency test throughout the calibration range of use, utilizing a primary calibration laboratory as the reference laboratory.

The difference in measured values derived from the calibration with primary force standards and the measured values determined in calibration with secondary force standards is determined for each point in the calibration sequence. The ratio in the maximum difference of the measured values to the deflection value at that force multiplied by 100 represents an estimate of the dissemination uncertainty as a percent of reading. For this example suppose that the result is 0.005 % reading. This uncertainty is treated as a Type B uncertainty with a rectangular probability distribution.

$$U_d = 0.005\ \%\ \text{reading}/1.732 = 0.00289\ \%\ \text{reading} \qquad \text{(X1.21)}$$

X1.5.1.4 *Uncertainty due to temperature on sensitivity and zero*—Temperature differences in the secondary laboratory from the temperature at which the secondary force standard was calibrated in the primary lab result in additional uncertainty in the applied force. The temperature effect on zero has been evaluated in X1.4.1.3. For mechanical force-measuring instruments, corrections were made during primary calibration to a reference temperature per the requirements of 9.1–9.4 and an additional correction should be applied using the 0.0270 %⁄□‹C sensitivity temperature coefficient to correct for temperature difference between the reference temperature of calibration at the primary lab and the temperature during calibration at the secondary lab. For this example using a temperature compensated force-measuring instrument, assume the secondary force standard has a sensitivity temperature coefficient of 0.0015 %⁄□‹C and the difference in the secondary laboratory temperature and the temperature measured during the primary lab calibration of the secondary force standard does not exceed 2 °C. The uncertainty is treated as a Type B uncertainty with rectangular distribution.

$$u_t = \frac{0.0015\%/°\text{C reading} \times 2\ °\text{C}}{\sqrt{3}} = 0.00173\%\ \text{reading} \qquad \text{(X1.22)}$$

X1.5.1.5 *Uncertainty due to misalignment*—Evaluation of alignment uncertainty sources may be a significant source of error for secondary force standard calibrations and can lead to significant errors. Evaluation should take into account the misalignment in the load frame and fixtures and the effect of that misalignment on the secondary force standard and the unit being calibrated. Observing the alignment as force is applied to the load string (fixtures, unit being calibrated, and secondary force standard) for motion perpendicular to the loading axis should always be done. Such motion should be adjusted out before proceeding. The best evaluation is to physically measure the misalignment in the load frame using methods described in Practice E1012, or similar methods using multiaxis load cells. A well-aligned calibration load frame may demonstrate less than 2 % bending (100 × moments applied to the secondary force standard in in-lbf divided by the axial force in lbf). Concentricity and angular misalignment uncertainty can be estimated based on fixture tolerances. Some secondary force standards have a specified maximum error due to side force and moment, or this can be determined experimentally.

This information taken together provides a means for estimating the uncertainty due to misalignment. This uncertainty cannot be separated from errors determined in the rotational tests and dissemination of calibration values and is not evaluated separately.

X1.5.1.6 *Combined and expanded uncertainty*—The combined and expanded uncertainty in this example evaluated at 10 % of range is

$$u_c = \sqrt{u_{cal}^2 + u_s^2 + u_d^2 + u_t^2} \quad \text{(X1.23)}$$

$$u_c = \sqrt{0.0212\ \%^2 + 0.00289\ \%^2 + 0.00289\ \%^2 + 0.00173\ \%^2}$$

$$= 0.0216\ \%\ \text{reading} \quad \text{(X1.24)}$$

over the range from 10 % to 100 % of rated force. The expanded uncertainty evaluated at 10 % of range is

$$U = k \times u_c \quad \text{(X1.25)}$$

$$U = 2.0 \times 0.02126 = 0.0433\ \%\ \text{reading} \quad \text{(X1.26)}$$

over the range of 10 % to 100 % of rated force, where *k* is the coverage factor. For a coverage factor of 2.0, the confidence level that the true force value lies within the range of the measured value 6 *U* is approximately 95 %

X1.5.2 *Uncertainty of the Electrical Measurement*—See X1.1 for an example method of determining the measurement uncertainty of the electrical measurement. Note that when force calibration instruments are calibrated as a system with a read out instrument, such factors as the uncertainty of the calibration of the instrument and instrument non-linearity are accounted for in the calibration process and should not be double counted. The uncertainty of the electrical measurement should be combined with the uncertainty of applied force for a system measurement uncertainty if a mV/V calibration is reported by the calibration laboratory using a calibration laboratory instrument.

X1.6 Uncertainty of Calibration Using Secondary Force Standards to Calibrate Force-Measuring Instruments Used for Verification of the Force Indication of Testing Machines Over the Class A Verified Range of Forces

X1.6.1 *Uncertainty of the Applied Force during calibration by the secondary calibration laboratory*—The measurement uncertainty analysis performed using secondary force standards shall include the uncertainty of the calibration forces applied when the secondary force standard was calibrated by the primary lab, uncertainty due to errors in the polynomial curve fit, uncertainty due to temperature, and uncertainty due to misalignment. Other components should be evaluated and included in the measurement uncertainty when relevant.

X1.6.1.1 *Uncertainty in the calibration forces applied during calibration of the secondary force standard as reported by the calibration laboratory*—The uncertainty in the calibration of the secondary force standard by the primary lab is 0.0021 % over the verified range of forces with a 95 % confidence factor as determined in the primary calibration example. This is treated as a Type A uncertainty with a normal probability function. For use at 10 % of rated range,

$$u_{cal} = 0.0433\ \% / 2.0 = 0.0217\ \% \qquad (X1.27)$$

X1.6.1.2 *Uncertainty due to force-measuring instrument responses during calibration and curve fitting errors*—This uncertainty includes errors due to reproducibility (which encompasses errors due to repositioning the force-measuring instrument in the calibration load frame as required in 7.5), and interpolation errors which are the result of a lack of perfect representation of the calibration curve by a polynomial. This uncertainty is evaluated as the standard deviation determined in the curve fit process used to establish the lower limit factor.

This uncertainty is treated as a Type A uncertainty with a normal probability distribution and is assumed constant over the range. The measurement uncertainty must be evaluated at the lowest calibration force at which the secondary force standard is used. For the example, this uncertainty is evaluated as 0.004 % of the maximum calibration force and as 0.04 % of reading when the secondary force standard is used at 10 % of range.

$$U_r = 0.0040\ \% / 0.1 = 0.04\ \% \text{ reading at } 10\ \% \text{ of range} \qquad (X1.28)$$

X1.6.1.3 *Uncertainty due to effects of temperature on sensitivity and zero*—Temperature differences in the secondary laboratory from the temperature at which the secondary force standard was calibrated in the primary lab result in additional uncertainty in the applied force. For this example the secondary force standard has a sensitivity temperature coefficient of 0.0015 %/°C and a zero temperature coefficient of 0.0015 %/°C. The temperature effect on sensitivity for the device that is undergoing calibration is evaluated at the next level in the uncertainty analysis, and it is only necessary that the temperature during the secondary lab calibration be noted on the primary lab calibration report as required by 13.1.6. The uncertainty due to temperature effect on zero is usually small, since the zero-shift occurring with temperature becomes the reference for that calibration run and only the zero shift due to temperature during a calibration run is of consequence. Monitoring zero return after the calibration provides a basis for uncertainty evaluation for change of zero during the calibration process. The return to zero error observed has both creep recovery error and thermal zero shift error components. The zero-shift should be treated appropriately depending on the method of treatment of zero selected. For example, if it is elected to use method *(b)* averaging the initial and final zero data, then the zero return error could reasonably be evaluated as one half of the difference in these readings. If method *(a)* is chosen, the difference in initial and final zero data provides an estimate of error. For the example, assume that zero return 30 seconds after force removal has been measured as 0.00010 mV/V for a 2 mV/V sensitivity force-measuring instrument and it is elected to use method *(b)* for deflection calculation. The return to zero uncertainty is treated as a Type B uncertainty with rectangular distribution.

$$u_z = (100 \times 0.00010 \text{ mV/V} / 2.0 \text{ mV/V}) / (2 \times 1.732)$$
$$= 0.00144 \text{ \% Rated Output} \quad (X1.29)$$

or for lower force limit of 10 % of range

$$u_z = 0.00144 \text{ \%} / 0.10 = 0.0144 \text{ \%} \quad (X1.30)$$

X1.6.1.4 *Uncertainty due to misalignment*—See discussion of uncertainty due to misalignment in X1.5.1.5. This uncertainty cannot be separated from errors determined in the rotational tests and dissemination of calibration values and is not evaluated separately.

X1.6.1.5 *Combined and expanded uncertainty*—The combined and expanded uncertainty in this example evaluated at 10 % of range is

$$u_c = \sqrt{u_{cal}^2 + u_r^2 + u_z^2} \quad (X1.31)$$

$$u_c = \sqrt{0.0217\ \%^2 + 0.040\ \%^2 + 0.0144\ \%^2} = 0.0477\ \%\ \text{reading} \quad (X1.32)$$

over the range from 10 % to 100 % of rated force. The expanded uncertainty evaluated at 10 % of range is

$$U = k \times u_c \quad (X1.33)$$

$$U = 2.0 \times 0.0477 = 0.0954\ \%\ \text{reading} \quad (X1.34)$$

over the range of 10 % to 100 % of rated force, where k is the coverage factor. For a coverage factor of 2.0, the confidence level that the true force value lies within the range of the measured value 6 U is approximately 95 %.

X1.6.2 *Uncertainty of the Electrical Measurement*—See Appendix X2 for an example method of determining the measurement uncertainty of the electrical measurement. Note that when force calibration instruments are calibrated as a system with a read out instrument, such factors as the uncertainty of the calibration of the instrument and instrument non-linearity are accounted for in the calibration process and should not be double counted. The uncertainty of the electrical measurement should be combined with the uncertainty of applied force for a system measurement uncertainty if a mV/V calibration is reported by the calibration laboratory using a calibration laboratory instrument.

SAMPLE PROCEDURES FOR DETERMINING FORCE INDICATING INSTRUMENT UNCERTAINTY

X2. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC FORCE INDICATING INSTRUMENT FOR CLASS A VERIFIED RANGE OF FORCES USING A TRANSDUCER SIMULATOR AND THE METHOD OF MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH THE PROCEDURES OF ASTM E74

X2.1 The force-measuring instrument in the system for which it is desired to substitute the electronic force indicator has a 2 mV ⁄V output at full capacity. The force-measuring instrument is calibrated for use over the Class A verified range of forces with a lower force limit equal to 10 % of the force transducer's capacity. The LLF of the system is 0.25 %. The standard deviation is 0.104 %.

X2.2 A transducer simulator with a measurement uncertainty equal to or less than one tenth of the allowable standard uncertainty for the force-measuring system is used to provide a series of discrete mV/V steps over the range of measurement (see 8.6.3.1 and 8.6.3.2 for allowable uncertainty). The electronic indicating instrument and transducer simulator shall be connected and allowed to warm up according to manufacturer's recommendations. At least five readings taken three times for each polarity shall be acquired over the calibrated range for the original electronic indicating instrument and the electronic indicating instrument to be substituted. The readings shall include a point less than or equal to the lower force limit for the system, and another point equal to or greater than the maximum force for the system. The transducer simulator settings shall provide at least one point for every 20 % interval throughout this range. Care shall be taken that environmental conditions do not significantly affect the accuracy of measurements taken.

NOTE X2.1—It is desirable to use the same transducer simulator for determining the readings of both indicators; however, different simulators may be used provided their outputs for a given input are identical within one tenth of the allowable standard uncertainty for the force-measuring instrument.

X2.3 The electronic force indicator to be used as a substitute is evaluated to ensure that the electrical characteristics are the same, and that the interconnect cable is the same with respect to wiring, and wire types, sizes, and lengths.

X2.4 Atransducer simulator capable of providing 0.2 mV/V steps is selected.

X2.5 The transducer simulator is connected to the original force indicator and the reading at 0.2 mV/V and each 0.4 mV/V step between 0.4 and 2.0 mV/V are recorded. After the first run of readings, a second and third run are taken. This process is repeated for the opposite polarity. This process is repeated on the indicator to be used as a substitute. It is not required that the verification of the two indicators occur at the same time, provided the transducer simulator stability is evaluated over the relevant time period in the determination of its measurement uncertainty.

X2.6 Alinear least squares curve fit is performed on the data set according to the procedure set forth in 8.1 – 8.5. The standard deviation is determined to be 0.00005 mV/V, and the LLF is 0.00012 mV/V (2.4 times the standard deviation). This value must be less than or equal to one third of the system LLF at the lower force limit in electrical units, or less than

$$(0.25\ \% \times 0.2\ \text{mV/V})/3 = 0.000167\ \text{mV/V}$$

X3. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC FORCE INDICATING INSTRUMENT FOR CLASS A VERIFIED RANGE OF FORCES USING A MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH THE METHOD OF NIST TECHNICAL NOTE 1297 (5)

X3.1 Using the same example from Appendix X2, the method of NIST TN 1297 **(5)** is employed.

X3.2 The first step in a measurement uncertainty analysis of an electronic force indicator is to identify the sources of error.

The following are potential sources of measurement error in strain gage based force-measuring instrument electrical indicators:

Calibration Uncertainty (Gain Error)	Non-linearity
Zero Offset	Temperature Effect on Zero
Temperature Effect on Sensitivity	Gain and Zero Stability
Quantization Error	Common Mode Voltage
Normal Mode Voltage	Noise
Excitation Voltage Error	Electrical Loading
Power Line Voltage Variation	Error signals due to thermal EMF

X3.3 Each of these potential error sources, and any others of significance, should be evaluated for the conditions in which the indicator will operate. It is recommended that a transducer simulator or equivalent laboratory test instrumentation be used to verify indicator performance and assess errors. The same requirements for number and distribution of test points as given in the previous example apply.

X3.4 A Typical Analysis of the Major Error Sources as

Determined for an Indicator is given below:

Simulator uncertainty	uc = 20 ppm	Includes the ratio uncertainty
Indicator Nonlinearity	$u$nl = 116 ppm	For 0.005 % non-linearity and an assumed rectangular probability $\frac{0.005}{2\sqrt{3}}$ where a factor of 2 is specific to a particular indicator and shall be determined by test to reflect the error over the full range of indicator use.

		Nonlinearity is evaluated by test using a transducer simulator or other suitable instrument.
Temperature Effect on Gain	ut = 58 ppm	For a temperature coefficient of 20 ppm / °C and a temperature range of ±5 °C, and an assumed rectangular probability function, $(5 \times 20)/\sqrt{3} = 58.$
Gain Stability	Negligible	Gain stability is not a factor if calibrated on a simulator at the time of substitution as the gain error is incorporated in the transducer simulator uncertainty.
Noise	Evaluated	Noise is already incorporated in the uncertainty that determines the lower force limit. It is only necessary to adjust for noise if the noise exhibited by the substitute indicator exceeds that for the original indicator. The quantization error is often smaller than the noise and is included in the experimental determination of the noise. Noise for each indicator shall be determined by test.

X3.5 Errors from the other potential sources are found to be negligible for this indicator (less than 1⁄5 of the largest error source). For DC indicators, the thermal emf error source can be significant and should be evaluated experimentally.

X3.6 The Combined Uncertainty based on the error sources evaluated is,

Combined Uncertainty $u = \sqrt{u_c^2 + u_{nl}^2 + u_t^2} = 131 \text{ ppm of Reading}$

and the Expanded Uncertainty is,

Expanded Uncertainty U = ± 0.026 % of Reading over the range of 0.2

- 2.0 mV/V

Expressed in mV/V units, the uncertainty is 0.000052 mV/V at the 0.2 mV/V level.

The expanded uncertainty defines an interval within which the true value is expected to be contained with 95 % probability based on a coverage factor of 2.

The allowable uncertainty for this Class A verified range of forces, is 0.25 % of 0.2 mV/V, or expressed in electrical units, 0.0005 mV/V. Allowable uncertainty for the electronic indicating instrument is equal to or less than one third of this limit, or 0.000167 mV/V. If the uncertainty is less than 0.000167 mV/V as in this example, the substitution is permitted.

X4. UNCERTAINTY ANALYSIS FOR AN ELECTRONIC FORCE INDICATING INSTRUMENT FOR CLASS AA VERIFIED RANGE OF FORCES USING A MEASUREMENT UNCERTAINTY DETERMINATION IN ACCORDANCE WITH NIST TECHNICAL NOTE 1297 (5)

X4.1 Following the method in Appendix X3, an analysis is performed for an electronic indicating instrument calibrated for use over the ClassAA verified range of forces for a system with a 10 % lower force limit and a 2 mV/V sensitivity at maximum force.

Simulator uncertainty	uc = 10 ppm	Includes the ratio uncertainty
Indicator Nonlinearity	$u$nl = 58 ppm	For 0.005 % non-linearity and an assumed rectangular probability $\frac{0.001}{2\sqrt{3}}$ where a factor of 2 is specific to a particular indicator and shall be determined by test to reflect the error over the full range of indicator use.
Temperature Effect on Gain	ut = 12 ppm	For a temperature coefficient of 5 ppm / °C ±5 °C, Assumed rectangular probability distribution.

X4.2 Errors from the other potential sources are found to be negligible for this indicator (less than 1⁄5 of the largest error source).

X4.3 The Combined Uncertainty based on the error sources evaluated is,

Combined Uncertainty $u = \sqrt{u_{\mathrm{c}}^2 + u_{\mathrm{nl}}^2 + u_{\mathrm{t}}^2} = 60\ \mathrm{ppm\ of\ Reading}$

and the Expanded Uncertainty is,

Expanded Uncertainty U= ± 0.012 % of Reading in the range of 0.2

- 2.0 mV/V

Expressed in mV/V units the uncertainty is 0.000024 mV/V at the 0.2 mV/V level.

The expanded uncertainty defines an interval within which the true value is expected to be contained with 95 % probability based on a coverage factor of 2.

The allowable uncertainty for this electronic indicating instrument calibrated for use over the Class AA verified range of forces is 0.05 % of 0.2 mV/V expressed in electrical units, or 0.0001 mV/V. Allowable uncertainty for the force-indicating instrument is one third of this limit, or 0.000033 mV/V. If the uncertainty is less than 0.000033 mV/V, as in this example, the substitution is permitted.

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