Designation: E74 – 13a

Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines[1]

This standard is issued under the fixed designation E74; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 The purpose of this practice 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, Methods of Calibrating Weights for Piston Gages.[2]

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 This practice is 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 this practice 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 and health practices and determine the applicability of regulatory limitations prior to use.*

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 Specimen Alignment Under Tensile and Compressive Axial Force Application

2.2 *American National Standard:*

B46.1 Surface Texture[4]

ELASTIC FORCE-MEASURING INSTRUMENTS

3. Terminology

3.1 *Definitions:*

3.1.1 *elastic force-measuring instrument*—a device or system consisting of an elastic member combined with a device 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 determined by comparison with reference standards traceable to national standards 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 between 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 instument*—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.

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[1] This practice is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.01 on Calibration of Mechanical Testing Machines and Apparatus.

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[2] Available from National Institute for Standards and Technology, Gaithersburg, MD 20899.

[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.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

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 load cells, 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.

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 devices, 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 *loading range*—a range of forces within which the lower limit factor is less than the limits of error specified for the instrument application.

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 device*—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 devices.

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 this practice.

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 loading range, see 8.5. Other factors evaluated in establishing the lower limit of the loading 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 devices whose force characteristics are known to be traceable to national standards. Practice E74 describes how these devices 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, and service organizations that use the devices to verify testing machines.

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 of 125 or less as specified in ANSI B46.1.

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

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

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 national standards of 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 Center, National Oceanic and Atmospheric Administration.[5]

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:

$$1 \text{ lbf} = 4.448\,22\,N \tag{2}$$

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

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 elastic 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 Elastic force-measuring instruments used as secondary force standards shall be calibrated by primary force standards and used only over the Class AA loading range (see 8.6.2.1). 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:

$$LLF_c = \sqrt{LLF_o{}^2 + LLF_1{}^2 + LLF_2{}^2 + \ldots LLF_n{}^2} \tag{3}$$

where:

LLF_c = Lower Limit Factor of the combination, and

$LLF_{o,\,1,\,2\,.\,.\,.\,n}$ = 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 loading ranges 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 instrument. A polynomial equation is fitted to the calibration data by the least squares method to predict deflection values throughout the loading range. 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 99%. The LLF is, therefore, an estimate of one source of uncertainty contributed by the instrument when forces measured in service are calculated by means of the calibration equation. Actual errors in service are likely to be different if forces are applied under mechanical and environmental conditions differing from those of calibration. Other sources of uncertainty such as those listed in Appendix X1 could increase the uncertainty of measurement of the instrument in service.

NOTE 3—While it is the responsibility of the calibration laboratory to calibrate the instrument in accordance with the requirements of this practice, it is the responsibility of the user to determine the uncertainty of the instrument in service. Errors in service are likely to be different if forces are applied under mechanical and environmental conditions differing from those of calibration. Other sources of uncertainty, such as those listed in Appendix X1, must be considered by the user to determine the uncertainty of the instrument in service.

7.1.3 *Curve Fitting using polynomials of greater than 2nd degree*—The use of calibration equations of the 3rd, 4th, or 5th degree is restricted to devices having a resolution of 1 increment of count per 50000 or greater active counts at the maximum calibration force. Annex A1 specifies the procedure

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[5] Available from National Oceanic and Atmospheric Administration (NOAA), 14th St. and Constitution Ave., NW, Room 6217, Washington, DC 20230.

for obtaining the degree of the best fit calibration curve for these devices. Equations of greater than 5th degree shall not be used.

NOTE 4—Experimental work by several force calibration laboratories in fitting higher than second degree polynomials to the observed data indicates that, for some devices, use of a higher degree equation may 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 may occur if calculations are performed with insufficient precision.

A force measuring device 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 device 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 is made by the standardizing laboratory. An exception to this, and to the recommendations of 7.2.1 and 7.2.4, is made for specific force devices, 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 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 limit of the loading range of the device (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 limit. In no case should the smallest force applied be below the lower limit of the instrument as defined by the values:

$$400 \times \text{resolution for Class A loading range} \tag{4}$$

$$2000 \times \text{resolution for Class AA loading range}$$

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 load 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 center to center distance between two adjacent scale graduation marks. Recommended ratios are ½, ⅕, or 1⁄10 . A center to center 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 Devices (Limited Force Devices)*—Because these devices 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 assure 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 elastic device 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 during calibration.

7.3.4 Deflections of non-temperature compensated devices 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 devices must 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, preload the force-measuring instrument to the maximum force to be applied at least two times. Preloading 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 loading, as from compression to tension. Some instruments may require more than two preloads to achieve stability in zero-force indication.

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[6] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E28-1009. Contact ASTM Customer Service at service@astm.org.

NOTE 5—Overload or proof load tests are not required by this practice. 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 preloading, 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 instrument to zero before applying the second calibration force. Whenever possible, plan the loading schedule so that repetitions of the same calibration force do not follow in immediate succession.

NOTE 6—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 should 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 device is calibrated with both increasing and decreasing forces, it is recommended that the same force increments be applied, but that separate calibration equations 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 Loading Conditions*—Shift the position of the instrument in the calibration machine before repeating any series of forces. In a compression calibration, rotate the instrument by an amount such as one-third, one-quarter, or one-half turn, keeping its force axis on the center force axis of the machine. In a tension calibration, rotate coupling rods by amounts such as one-third, one quarter, or one-half turn, and shift and realign any flexible connectors. In a calibration in both tension and compression, perform a part of the compression calibration, do the tension calibration, then finish the compression calibration afterward. Introduce variations in any other factors that normally are encountered in service, as for example, disconnecting and reconnecting electrical cables. Allow sufficient warmup time if electrical disconnections are made.

NOTE 7—A situation to be avoided is rotating the force-measuring instrument from 0° to 180° to 0° during calibration, since the final position duplicates the first, and reduces the randomization of loading conditions.

NOTE 8—Force measuring devices 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 measurment 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 measurement system. 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 insure that the zero return characteristic of the load cell 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 insure 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 devices, and for devices that have had major repairs, devices suspected of having been overloaded, or devices that show excessive non-return to zero following calibration. Creep and creep recovery are generally stable properties of a load cell unless the load cell is overloaded, has experienced moisture or other contaminant incursion, or is experiencing fatigue failure. If method *(b)* is used to determine deflections on a device 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 device 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 device and hold as constant as possible for 5 minutes. Remove the applied force as quickly as possible and record device 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 x (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 *Creep Recovery Error Limits:—*
Class AA Devices ± 0.02%
Class A Devices ± 0.05%.

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:

$$\text{Deflection} = A_0 + A_1 F + A_2 F^2 + \ldots A_5 F^5 \tag{5}$$

where:

F = force, and
A_0 through A_5 = coefficients.

A 2nd degree equation is recommended with coefficients A_3, A_4, and A_5 equal to zero. Other degree equations may be used. For example the coefficients A_2 through A_5 would be set equal to zero for a linearized load cell.

8.3.1 For high resolution devices (see 7.1.3), the procedure of Annex A1 may be used to obtain the best fit calibration curve. After determination of the best fit polynomial equation, fit the pooled calibration data to a polynomial equation of that degree per 8.3, and proceed to analyze the data per 8.4 – 8.6.2.2.

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:

$$s_m = \sqrt{\frac{d_1{}^2 + d_2{}^2 + \ldots + d_n{}^2}{n - m - 1}} \tag{6}$$

where:

d_1, d_2, 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 9—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 10—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 *Loading Range*—This is the range of forces within which the LLF of a force-measuring instrument does not exceed the maximum permissible limits of error specified as a fraction or percentage of force. Since the LLF for the instrument is of constant force value throughout the entire range of the instrument, it will characteristically be less than the specified percentage of force at instrument capacity but will begin to exceed the specified percentage at some point in the lower range of the instrument, as illustrated in Fig. 1. The loading range shown in the figure thus extends from the point, *A*, where the LLF and error limit lines intersect, up to the instrument capacity. The loading range shall not include forces outside the range of forces applied during the calibration.

8.6.1 *Lower Limit of Loading Range*—Calculate the lower end of the loading range for a specified percentage limit of error, *P*, as follows:

$$\text{Lower limit} = \frac{100 \times LLF}{P} \tag{7}$$

8.6.2 *Standard Loading Ranges*—Two standard loading ranges are listed as follows, but others may be used where special needs exist:

8.6.2.1 *Class AA*—For instruments used as secondary force standards, the LLF of the instrument shall not exceed 0.05 % of force. The lower force limit of the instrument is 2000 times the LLF, in force units, obtained from the calibration data.

NOTE 11—For example, an instrument calibrated using primary force standards had a calculated LLF of 16 N (3.7 lbf). The lower force limit for use as a Class AA device 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 capacity of the instrument. It is recommended that the lower force limit be not less than 2 % (1⁄50) of the capacity of the instrument.

8.6.2.2 *Class A*—For instruments used to verify testing machines in accordance with Practices E4, the LLF of the instrument shall not exceed 0.25 % of force. The lower force limit of the instrument is 400 times the LLF, in force units, obtained from the calibration data.

NOTE 12—In the example of Note 11 the lower force limit for use as a Class A device is 16 × 400 = 6400 N (3.7 × 400 = 1480 lbf). The LLF will be less than 0.25 % of force for forces greater than this lower force limit up the capacity of the instrument.

NOTE 13—The term "loading range" used in this practice is parallel in meaning to the same term in Practice E4. It is the range of forces over which it is permissible to use the instrument in verifying a testing machine or other similar device. When a loading range other than the two standard ranges given in 8.6.2 is desirable, the appropriate limit of error should be specified in the applicable method of test.

8.7 *Specific Force Devices*—Any force-measuring device may be calibrated as a specific force device. Elastic rings, loops, and columns with dial indicators as a means of sensing deformation are generally classed as specific force devices because the relatively large localized nonlinearities introduced by indicator gearing produce an LLF too great for an adequate loading range. These instruments are, therefore, used only at