	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 1 of 38**

Guidance on Uncertainty Budgets for Force Measurement and Calibration

December 2018

Written By

Henry Zumbrun

Morehouse Instrument Company

TABLE OF CONTENTS

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	Document Revised: DRAFT
	Force Measurement and Calibration	Page 3 of 38

1.0 Scope and Field of Application (or Introduction)

Introduction:
All calibration laboratories accredited by A2LA are required to submit uncertainty calculations for their Calibration and Measurement Capability (CMC) uncertainty claims included on the scope of accreditation. The assumptions made for the determination of the uncertainty budgets, if any, must be specified and documented. A2LA accredited calibration laboratories shall calculate measurement uncertainties using the method detailed in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM)[1].

ISO 17025:2017 requires:
"7.6.1 Laboratories shall identify the contributions to measurement uncertainty. When evaluating measurement uncertainty, all contributions that are of significance, including those arising from sampling, shall be taken into account using appropriate methods of analysis.
7.6.2 A laboratory performing calibrations, including of its own equipment, shall evaluate the measurement uncertainty for all calibrations."

ILAC P14:01/2013 requires:
"5.1 The scope of accreditation of an accredited calibration laboratory shall include the calibration and measurement capability (CMC) expressed in terms of:
a) measurand or reference material;
b) calibration/measurement method/procedure and/or type of
instrument/material to be calibrated/measured;
c) measurement range and additional parameters where applicable, e.g.,
frequency of applied voltage;
d) uncertainty of measurement."

A2LA R205 requires:
"6.3 Accredited Calibration Certificates
1) The laboratory shall meet the requirements of ILAC P14:01/2013 ILAC Policy for Uncertainty in Calibration section 6.1 to 6.5."
"6.8 Scopes of Accreditation
1) The laboratory shall meet the requirements of ILAC P14:01/2013 ILAC Policy for Uncertainty in Calibration section 5.1 to 5.4."

Purpose:
The purpose of this document is to provide guidance for identification of all significant contributions to measurement uncertainty in calibration of force measuring instruments. This document provides guidance for the evaluation of measurement uncertainty in the calibration of force measuring instruments to support CMC in scope of accreditation and

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 4 of 38**

calibration and/or measurement certificates/reports. This document also serves as a means for laboratories to be compliant with A2LA *R205 – Specific Requirements: Calibration Laboratory Accreditation Program*. Finally, for instruments that are calibrated in accordance with ASTM E74 or ISO 376, this document goes beyond R205 to include sections in ASTM E74 and ISO 376 that should be considered for determining uncertainty of measurement.

Background:

This document aims to improve the consistency in the assessment process among Assessors for the parameter of force. Currently, there are discrepancies regarding what is acceptable for a force calibration uncertainty budget. One of these issues involves how to calculate uncertainty properly when the lab is following a standard like ASTM E74, or ISO 376. If calibrating to ASTM E74, or ISO 376 standards, then contributions from Non-Linearity, Static Error Band or Hysteresis should not be considered for the uncertainty budget. For ASMT E74 calibrations, the contributors are replaced by the ASTM **llf** (lower limit factor). ISO 376 tests for relative error of repeatability, reproducibility, interpolation, zero, reversibility or creep, and includes the expanded uncertainty of the calibration force. Another common mistake is to include parameters from the force transducer specification sheet that are not needed. For example, if a force transducer is used to make ascending measurements only, the effect of the uncertainty contribution for hysteresis should not be included in the uncertainty budget.

Not understanding the force transducer specification terms is another inconsistency error source consideration. When the specification sheet states units of RO, this is a percentage of Rated Output of the force transducer. The percentage of RO is constant throughout the range, meaning 0.02 % of Rated Output at the instrument's capacity is 0.2 % at 10 % of the range. This document will provide four examples which should account for most instrumentation used for force measurements.

2.0   Definition of terms

Calibration and Measurement Capabilities should be calculated using A2LA document R205. Other documents may provide additional guidance such ILAC P-14, JCGM 100:2008, EURAMET cg-4, ISO 376 Annex C and the appendix in ASTM E74, which may call for the following:

ASTM E74 – Standard Practices for Calibration and Verification for Force-Measuring Instruments: ASTM E74 is a practice that specifies procedures for the calibration of force-measuring instruments.

Best existing force measuring instrument (ILAC P14): The term "best existing force measuring instrument" is understood as a force measuring instrument to be calibrated that is commercially or otherwise available for customers, even if it has a special performance (stability) or has a long history of calibration. For force calibrations this is often a very stable force transducer (load cell) and indicator with enough resolution to observe differences in repeatability conditions.

Calibration and Measurement Capability (ILAC-P14): A CMC is a Calibration and Measurement Capability available to customers under normal conditions:
   a) as described in the laboratory's scope of accreditation granted by a signatory to the ILAC Arrangement; or
   b) as published in the BIPM key comparison database (KCDB) of the CIPM MRA.

The scope of accreditation of an accredited calibration laboratory shall include the Calibration and Measurement Capability (CMC) expressed in terms of:
   a) measurand or reference material;
   b) calibration/measurement method/procedure and/or type of instrument/material to be calibrated/measured;
   c) measurement range and additional parameters where applicable, e.g., frequency of applied voltage;
   d) uncertainty of measurement.

Commercial Calibration or Quality Compliance Test: This is usually a 5-6-point calibration done by the manufacturer to verify the force measuring instrument is within the Manufacturer's specification in regard to non-linearity, Static Error Band (SEB), and Hysteresis. It does not give the expected performance of the force measuring instrument as it has not been subjected to testing repeatability and reproducibility during the calibration. ASTM E74 and ISO 376 are standards that give better guidance on what should be tested to determine expected performance of the force measuring instrument.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 6 of 38**

En Value:

$$E_n = \frac{x - X}{\sqrt{U_{LAB}^2 + U_{ref}^2}} \qquad |E_n| \le 1 = Satisfactory$$

$$|E_n| > 1 = Unsatisfactory$$

x: participant's result
X: Assigned Value

U^2_{LAB}: Uncertainty of participant's result

U^2_{ref}: Uncertainty of ref laboratory's assigned value

Environmental Factors: Environmental conditions, such as temperature, influences the force transducer output. The most common specification is temperature effect found on the force measuring instruments specification sheet. It is important to note that any deviation in environmental conditions from the temperature the force measuring instrument was calibrated at needs to be accounted for in the measurement uncertainty in measurements using the force transducer by the user.

Example: The calibration laboratory calibrated a force measuring instrument at 23 ^{0}C. The force measuring instrument is then used from 13 - 33 ^{0}C or ±10 ^{0}C from the calibration. Based on manufacturer's specification, this variation of temperature could cause an additional change on the force output by 0.015 percent reading per °C, or 0.15 percent reading for ±10 °C. This number is typically found on the force transducer specification sheet.

Temperature: Effect on Sensitivity, % Reading/100 ^{0}C or ^{0}F. It will vary depending on the force transducer used. The example uses a common specification found for most shear-web type force transducers.

Force Units: A force unit can be any unit representing a force. Common force units are N, kgf, lbf. The SI unit for force is N (Newton).

Hydraulic amplification force standard machines: In a hydraulic amplification machine, a deadweight force is amplified using a hydraulic system with piston/cylinder assemblies of different effective areas, increasing the force by a factor approximately equal to the ratio of the two areas. Reference EURAMET cg-4 for uncertainty contributions and guidance on calculating uncertainties for Hydraulic amplification force standard machines.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 7 of 38**

Hysteresis: the phenomenon in which the value of a physical property lags behind changes in the effect causing it, as for instance when magnetic induction lags behind the magnetizing force. For Force measurements Hysteresis is often defined as the algebraic difference between output at a given load descending from the maximum load and output at the same load ascending from the minimum load. Normally expressed in units of % Full Scale. It is most commonly calculated between 40 - 60 % of full scale.

Lever amplification force standard machines: In a lever amplification machine, a deadweight force is amplified using one or more mechanical lever systems, increasing the force by a factor approximately equal to the ratio of the lever arm lengths, where the traceability of this larger force is directly derived from SI units. Reference EURAMET cg-4 for uncertainty contributions and guidance on calculating uncertainties for lever amplification force standard machines

lower limit factor (llf): ASTM specific term where the ASTM E74 standard uses a method of least squares to fit a polynomial function to the data points. The standard deviation of all the deviations from the predicted values by the fit function versus the observed values is found by taking the square root of the sum of all the squared deviations divided by the number of samples minus the degree of polynomial fit used minus one. This number is then multiplied by a coverage factor (k) of 2.4 and then multiplied by the average ratio of force to deflection from the calibration data. The **llf** is 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.

ISO 376 - **Calibration of force proving instruments used for the verification of uniaxial testing machines:** ISO 376 is an International Standard that specifies a method for the calibration of force-proving instruments used for the static verification of uniaxial testing machines (e.g. tension/compression testing machines) and describes a procedure for the classification of these instruments.

Metrological traceability (JCGM 200:2012, 2.41): property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Non-Linearity: The quality of a function that expresses a relationship that is not one of direct proportion. For Force measurements, Non-Linearity is defined as the algebraic difference between the output at a specific load and the corresponding point on the straight line drawn between the outputs at minimum load and maximum load. Normally expressed in units of % of Full Scale. It is most commonly calculated between 40 - 60 % of full scale.

Non-Repeatability (per force transducer specification and not JCGM 200:2012): The maximum difference between output readings for repeated loadings under identical

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for	Document Revised: DRAFT
Force Measurement and Calibration	Page 8 of 38

loading and environmental conditions. Normally expressed in units as a % of Rated Output (RO).

Other Force Measurement Errors: Most force measuring instruments are susceptible to misalignment error, errors from not exercising the force measuring instrument to full capacity, and errors from improper adapter use. In almost all cases, there will be additional errors if the end user fails to have the force measuring instrument calibrated with the same adapters being used in their application. Other errors may include temperature change under no load conditions. Errors from loading equipment not being level, square and rigid can have significant contributions.

Primary Standard: Per ASTM E74 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 the International System of Units (SI) of mass.

Note:
Weights used for force measurement require the correction for the effects of Local Gravity, Air Buoyancy and must be adjusted to within 0.005 % of nominal force value. The uncertainty budget for primary standards also needs to consider possible force-generating mechanisms other than gravity and air buoyancy, including magnetic, electrostatic and aerodynamic effects.

Rated Output or RO: The output corresponding to capacity, equal to the algebraic difference between the signal at "(minimal load + capacity)" and the signal at minimum load.

Reference Standard(s) Calibration Uncertainty: This is usually the measurement uncertainty in the calibration of reference standard(s) used to calibrate the force measuring instrument. It is the uncertainty contribution in the calibration of reference standard(s) used to calibrate the force measuring instrument.

Reference Standard(s) Stability: The change in output of the reference standard(s) from one calibration to another. This number is found by comparing multiple calibrations against one another over time. If the instrument is new, the suggestion is to contact the manufacturer for stability estimation on similar instruments.

Repeatability condition of measurement, repeatability condition (JCGM 200:2012, 2.20): condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time

Measurement repeatability, Repeatability (JCGM 200:2012, VIM 2.21):

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 9 of 38**

measurement precision under a set of repeatability conditions of measurement.

The example in this guidance document calculates repeatability by taking the sample standard deviation of a series of at least two measurements at the same test point (three or more are recommended). The overall repeatability of more than one group of data is calculated by taking the square root of the average of variances (also known as pooled standard deviation) The purpose of this test is for the determination of the uncertainty of force generation in a force calibrating machine or test frame. For laboratories testing multiple ranges, it is recommended that the measurement sequence takes a point for every ten percent of the ranges they calibrate.

Example: a laboratory performing calibrations from 10 N through 10,000 N. The ranges calibrated may be 10 N - 100 N, 100 N - 1,000 N, and 1 000 N – 10 000 N. Recommended practice would be to take test points at 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1 000, 2 000, 3 000, 4 000, 5 000, 6 000, 7 000, 8 000, 9 000, and 10 000 N.

Note 1:
For this application zero should never be considered as a first test point. A force measuring instrument should not be used to calibrate other force measuring instruments outside the range it was calibrated over.

Note 2:
A force measuring instrument calibrated from 10 % through 100 % of its range may not be capable of calibrating force measuring instruments outside of this range.

Resolution (JCGM 200:2012, VIM 4.14): Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

Resolution of a Displaying Device (JCGM 200:2012, VIM 4.15): smallest difference between displayed indications that can be meaningfully distinguished

Reproducibility condition of measurement, reproducibility condition (JCGM 200:2012, VIM 2.24): - condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

Measurement reproducibility, reproducibility (JCGM 200:2012, VIM 2.25): measurement precision under reproducibility conditions of measurement.

In the examples given Reproducibility calculations between technicians are found by taking the standard deviation of the averages of the same test point taken multiple times (multiple groups). There are other acceptable methods for determining reproducibility and it is up to the end user to evaluate their process and determine if the method presented makes

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised:** **DRAFT**
	Force Measurement and Calibration	**Page 10 of 38**

sense for them. For guidance on repeatability and reproducibility, the user should consult **ISO 5725 Parts 1 - 6**.

Secondary force standard (ASTM E74): an instrument or mechanism, the calibration of which has been established by comparison with primary force standards.

Static Error Band (SEB): The band of maximum deviations of the ascending and descending calibration points from a best-fit line through zero output. it includes the effects of nonlinearity, hysteresis, and non-return to minimum load. normally expressed in units of % of FS.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 11 of 38**

3.0   Guidance

Force measuring instruments generally fall into two categories.

a) Force measuring instruments for calibration of other force measuring equipment

Note: Any calibration laboratory performing calibration to further disseminate the unit of force would fall into this category.

b) Force measuring instruments for measurement of force.

Note: The end user of a force measuring instrument used for an application where there is a "go/no-go" or "Pass/Fail" scenario, where the testing stops and there is no further dissemination of force. Examples: material testing machines, weighing force measuring instruments

NPL Guide 102:
Calibration is required to ensure that the force measurement meets the needs of the user and achieves the required degree of uncertainty. The calibration of a force measurement system requires an understanding of traceability, standards, options, procedures and analysis of the data.

Machines capable of undertaking force calibrations are known as force standard machines and they may be categorized as either primary or secondary. Primary standards in force measurement are machines whose uncertainty can be verified through physical principles directly to the fundamental base units of mass, length and time. Secondary standards are machines which can reliably reproduce forces and can be compared to primary standards by the use of a force transfer standard which is a calibrated force transducer, frequently a strain gauge force transducer. Types of force standards machine include:

Machine Type	Principle of operation	Uncertainty attainable	Category
Deadweight machines	A known mass is suspended in the Earth's gravitational field and generates a force on the support.	+/- 0.001%.	Primary or Secondary
Hydraulic amplification machines	A small deadweight machine applies a force to a piston-cylinder assembly and the pressure thus generated is applied to a larger piston-cylinder assembly.	+/- 0.02 %.	Secondary

Lever amplification machines	A small deadweight machine with a set of levers which amplify the force	+/- 0.02%.	Secondary
Strain-gauged hydraulic machines	The force applied to an instrument is reacted against by strain-gauged columns in the machine's framework.	+/- 0.05%.	Secondary
Reference force transducer machines	A force transfer standard is placed in series with the instrument to be calibrated (typically in a materials testing machine).	+/- 0.05%.	Secondary

EURAMET-cg-04 version 3 Typical force calibration machine CMCs
**Type of machine Typical range of CMCs (expanded relative uncertainty in percentage)**

Deadweight: 5×10^{-5} to 1×10^{-4}
Hydraulic amplification: 1×10^{-4} to 5×10^{-4}
Lever amplification: 1×10^{-4} to $5 \times 10{-4}$
Comparator with one or three reference force transducers: 2×10^{-4} to 5×10^{-3}

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for	Document Revised: DRAFT
Force Measurement and Calibration	Page 13 of 38

3.1   General Guidance

Metrological Traceability
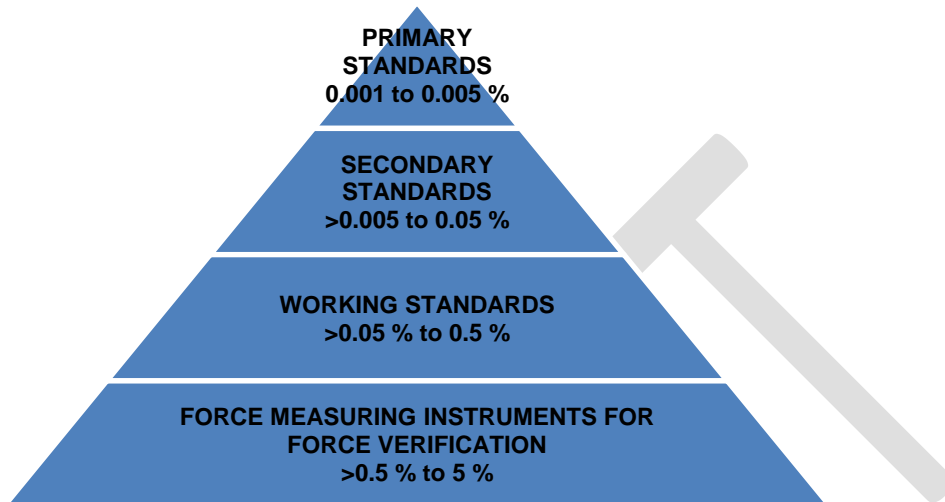
- All force measurements are traceable to SI Units of time, length, and mass. When electronics is involved, they are also traceable to the Ampere. The progression of traceability for force is primary deadweight standards which generally have the lowest uncertainties between 0.001 % to 0.005 % of applied force.

- A Primary Standard is required to calibrate Secondary Standards such as force transducers, proving rings and other force-measuring instruments. The uncertainties at this level are generally between 0.01 % to 0.05 % of applied force. To achieve less than 0.025 % is extremely difficult and calls for rigorous control of environmental conditions, adapters, and having force machines that are level, rigid, and square in regard to the position of the unit under test. Most laboratories will fall between 0.03 % to 0.05 % of applied force.

- Either Primary or Secondary Standards can be used to calibrate force measuring instruments referred to as working standards. The working standards can be force measuring instruments such as force transducers, force gages, crane scales, dynamometers etc., Working standards typically have uncertainties of greater than 0.05 % through 0.5 % of applied force. Where the laboratory falls into this range largely depends on the reference standard used to calibrate the force measuring instrument as well as calibration equipment, adapters and environmental conditions. To achieve 0.1 % uncertainty may require very stable force measuring instruments and calibration by primary standards.

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for	Document Revised: DRAFT
Force Measurement and Calibration	Page 14 of 38

- Force measuring instruments for Force Verification/Testing/Measurement – These force measuring instruments typically have uncertainties of 0.5 % or higher. They are used to verify the force applied. The most common example would be a force testing machine where material samples are tested with an uncertainty of approximately 1 %.

Note: Secondary standards cannot be used to calibrate other secondary standards and working standards cannot be used to calibrate other working standards. The force measuring instruments calibrated by working standards cannot be used to further disseminate the unit of force for calibration purposes.

Published standards for force calibration include ASTM E-74 or ISO 376

Documents referencing ASTM E74 directly or indirectly include:
- AASHTO T22
- AASHTO T68
- ASTM E4
- ASTM C39
- ASTM E10
- ASTM E18 – This document requires calibration by Primary Standards in accordance with ASTM E74. It is important as only calibration laboratories with deadweights calibrated in accordance with the ASTM E74 requirements can calibrate these force measuring instruments and assign the Class AA verified range of forces as required by section A2.6.2.1.

Documents referencing ISO 376 directly or indirectly include:
- ISO 7500
- ISO 6508-2

Note:
This may need to be expanded as most laboratories in North America reference ASTM E74

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	Document Revised: DRAFT
	Force Measurement and Calibration	Page 15 of 38

Guidelines for calculating CMC uncertainty

Type A Uncertainty Contributions

The GUM states that all data that is analyzed statistically is treated as a Type A contribution with a normal statistical distribution. Typical examples are:

1) Repeatability
2) Reproducibility
*3) Stability / Drift **
4) others (This would include ASTM E74 **llf**, ISO 376 Uncertainty, Non-Linearity, or SEB for commercial calibrations)

Repeatability contribution is required by the GUM, A2LA R205 and UKAS M3003.

*Note 1:
For our example, stability shall be treated as type B because we are taking values over a range using previous measurement data.

*Note 2:
Stability data may be treated as Type A if an evaluation is made using statistical methods.

Type B uncertainty contributions

Per section 4.3 of the GUM Type B evaluation of standard uncertainty may include:

- previous measurement data;
- experience with or general knowledge of the behavior and properties of relevant materials and instruments;
- manufacturer's specifications;
- data provided in calibration and other certificate(s);
- uncertainties assigned to reference data taken from handbooks.

A2LA R205 clarifies these type B contributions by requiring:

- Resolution of the Reference Standard
- Resolution of The Best Existing Force measuring instrument or Force measuring instrument used for Repeatability Studies
- Reference Standard Uncertainty
- Reference Standard Stability
- Environmental Factors
- Other Error Sources

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for	Document Revised: DRAFT
Force Measurement and Calibration	Page 16 of 38

Other Error Sources: When evaluating other error sources, it is important that the end user of the force measuring instrument is replicating how the force measuring instrument was calibrated or that the laboratory performing the calibration is replicating how the instrument is going to be used. Fixturing and adapters used with the force measuring instrument may have a significant contribution to the overall uncertainty of the force measuring instrument.

Note 1:
For the parameter of force, some laboratories have top-quality force calibration machines such as deadweight machines. These machines are classified as primary standards and if designed correctly some of the above error sources can be found to be insignificant. If complying with A2LA R205 requirements, these error sources should be considered.

Note 2:
Repeatability of a top-quality force measuring instrument in a deadweight machine (Several laboratories using primary standards have found this to be less than 2 ppm). Resolution of a top quality force measuring instrument can be better than 1 ppm, if high-quality indicators reading six decimal places or more are used. It is also common to find reproducibility and repeatability between technicians to be insignificant. It is important to note that these three error sources may be found to be insignificant using deadweight primary standards, may become significant at the next measurement tier.

Common error sources for force include:
- Alignment
- Using a different hardness of adapter than was used for calibration
- Using different size adapters than what were used for calibration
- Loading against the threads instead of the shoulder
- Loading through the bottom threads in compression
- Temperature effects on non-compensated force measuring instruments
- Temperature effect coefficients on zero and rated output
- Cable length errors on a four-wire system
- Using Electronic Instruments (Indicators) that were not used during calibration
- Using an excitation voltage that is different from the voltage used at the time of calibration
- Variations in bolting a force transducer to a base for calibration while application is different
- Not replicating via calibration how the equipment is being used
- Electronic cabling regarding shielding, proper grounding, use or non-use of sensing lines, cable length.
- Failure to exercise the force measuring instrument to the capacity it was calibrated at, prior to use.
- Difference between the output of a high quality force transducer when compared against the current machine and the realized value from the deadweight calibration.

3.2   Specific Guidance

Force measuring instruments for Calibration of Other Force Measuring Equipment are:

    a) **Force measuring instruments calibrated in accordance with the ASTM E74 Standard**
    b) **Force measuring instruments not calibrated to any known standard**
    c) **Force measuring instruments for Measurement or Verification of Force**
    d) **Force measuring instruments calibrated in Accordance with ISO 376**

Note:
It is highly recommended that all force measuring instruments for calibration of other force measuring equipment be calibrated in accordance with the ASTM E74 standard or a comparable standard. There are several other published standards for force measurements followed in other regions. European nations typically follow ISO 376. The ISO 376 standard annex C includes uncertainty contributions for the following: calibration force, repeatability, reproducibility, resolution, creep, zero drift, reversibility, temperature, and interpolation. The intent of this Guidance Document is to address specific guidelines for force measuring instruments in North America where ASTM standards are predominately followed. Laboratories following the ISO 376 standard should follow the guidelines outlined in annex C as well as the requirements of ILAC-P14 and ISO/IEC 17025.

Force measuring instruments Calibrated in Accordance with the ASTM E74 Standard

Note:
This section can be used as guidance for the force measuring instruments calibrated in accordance with ASTM E74 and used for ASTM E4 and other calibrations for determination of the laboratory's CMC. The ASTM E4 Annex gives additional detail on how to calculate the measurement uncertainty for the ASTM E4 verification/calibration.

The contributions for the CMC uncertainty are:

Type A Uncertainty Contributions
    1) ASTM **llf** reported as 1 Standard Deviation (k=1). ASTM **llf** is reported with k= 2.4.
       Note:
       *The reason ASTM **llf** is called out is because many reports do not list the standard deviation. In actuality, the Standard Deviation per section 8 of the ASTM E74 standard is what is required.*
    2) Repeatability conducted with the Best Existing Force measuring instrument
    3) Repeatability and Reproducibility

Note:

Repeatability and Reproducibility are from an R & R study and should not be confused with Repeatability with the Best Existing Force measuring instrument as noted in 2. It is up to the end user to determine if these errors are significant and should be included in the final uncertainty budget.

Type B Uncertainty Contributors
1) Resolution of the Best Existing Force measuring instrument
2) Reference Standard Resolution* *If Applicable*
3) Reference Standard Uncertainty
4) Reference Standard Stability
5) Environmental Factors
6) Other Error Sources

All uncertainty contributions should be combined, and if appropriate, the Welch-Satterthwaite equation as described in **JCGM 100:2008** should be used to determine the effective degrees of freedom for the appropriate coverage factor for a 95 % confidence interval.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Repeatability Between Techs	0.032435888	A	Normal	1.000	1	32.44E-3	1.05E-3	0.24%
Reproducibility Between Techs	0.006481823	A	Normal	1.000	10	6.48E-3	42.01E-6	0.01%
Repeatability	577.3503E-3	A	Normal	1.000	3	577.35E-3	333.33E-3	75.52%
ASTM LLF at 1 Standard Deviation	104.1667E-3	A	Normal	1.000	32	104.17E-3	10.85E-3	2.46%
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.19%
Environmental Factors	75.0000E-3	B	Rectangular	1.732	200	43.30E-3	1.88E-3	0.42%
Reference Standard Stability	500.0000E-3	B	Rectangular	1.732	200	288.68E-3	83.33E-3	18.88%
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.01%
Other Error Sources	150.0000E-3	B	Rectangular	1.7321E+0	200	86.60E-3	7.50E-3	1.70%
Reference Standard Uncertainty	100.0000E-3	B	Expanded (95.45% k=2)	2.000		50.00E-3	2.50E-3	0.57%
			Combined Uncertainty (u_c)=			664.36E-3	441.37E-3	100.00%
			Effective Degrees of Freedom			5		
			Coverage Factor (k) =			2.57		
			Expanded Uncertainty (U) K =			1.71	0.03416%	

Table 1 Example of a Single Point Uncertainty Analysis for Force measuring instruments Calibrated in Accordance with the ASTM E74 Standard

Note 1:
Force measuring instruments calibrated in accordance with the ASTM E74 standard are continuous reading force measuring instruments and any uncertainty analysis should be conducted on several test points used throughout the loading range.

Note 2:
There are Excel spreadsheets available for calculating measurement uncertainty from various force calibration laboratories. If the spreadsheets are used, the laboratory should conduct validation of the spreadsheet templates.

Note 3:
The **% Contribution** *Column is useful in determining significant contributors to uncertainty.*

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 19 of 38**

DRAFT

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 20 of 38**

Data to Support Table 1

Repeatability and Reproducibility between technicians: This should be performed whenever there is a change in personnel or the first time a budget is established.

This example uses two technicians recording readings at the same measurement point on the same equipment. The readings were taken in mV/V and were then converted to force units. Repeatability between technicians can be found by taken the square root of the averages of the variances of the readings from the technicians (Pooled Standard Deviation). Reproducibility between technicians is found by taking the standard deviation of the averages of readings for each technician.

	Technician 1	Technician 2	Technician 3	Technician 4	Technician 5
1	2.00000	2.00000			
2	2.00000	2.00000			
3	2.00000	2.00000			
4	2.00000	2.00000			
5	1.99999	2.00000			
6	2.00000	1.99998			
Std. Dev.	4.1833E-06	8.16497E-06			
Average	1.9999985	1.999996667			
Variance	1.75E-11	6.66667E-11			
Repeatability		6.48717E-06		5000.01	0.032435888
Reproducibility		1.29636E-06			0.006481823

Repeatability Data: Data needs to be taken for various test points throughout the loading range. This example only shows one data point. Calculations should be performed for several data points throughout the loading range.

Per Point Example							
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.
1	5000.00	5001.00	5000.00	5001.00	5000.00	**5000.5**	**0.5774**
Repeatability Of Best Existing Device			Average Standard Deviation of Runs			0.577350	

ASTM llf = 0.25 FORCE UNITS (This is Divided by 2.4 to get 1 Standard Deviation and the value shown is the result of dividing 0.25 by 2.4) and is found on the calibration report. If the report lists the standard deviation as calculated per section 8 of the ASTM standard, use as reported. (0.25/2.4 = 0.104166)

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
ASTM LLF at 1 Standard Deviation	104.1667E-3	A	Normal	1.000	32	104.17E-3	10.85E-3	2.46%

Resolution of Unit Under Test (Best Existing Force measuring instrument) = 0.1 FORCE UNITS

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for Force Measurement and Calibration	Document Revised: DRAFT
	Page 21 of 38

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.19%

Environmental Factors +/- 1 ^{0}C was used and this is found on the manufacturer's specification sheet. The temperature effect is 0.0015 percent per ^{0}C. If the reference laboratory controls the temperature to within +/- 1 ^{0}C, the contribution formula is Force Applied Temperature Specification per 1 ^{0}C = Environmental Factor Error. 5 000 Force Units * 0.0015 % = 0.075 FORCE UNITS

+/- 1 ^{0}C was used and this is found on the manufacturer's specification sheet. The temperature effect is 0.075 FORCE UNITS

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Environmental Factors	75.0000E-3	B	Rectangular	1.732	200	43.30E-3	1.88E-3	0.42%

Reference Standard Stability: This is calculated per point and 0.01 % change between the same 5 000 FORCE UNITS calibration point was used which corresponded to 0.5 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Stability	500.0000E-3	B	Rectangular	1.732	200	288.68E-3	83.33E-3	18.88%

Reference Standard Resolution: Resolution of the reference standard. In this example the resolution is 0.024 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.01%

Other Error Sources: In this example the alignment of the force transfer machine 1/16th inch measured off centerline of the force transducer (From the specification sheet side load sensitivity 0.05 % * 0.0 625 = 0.003 % = 0.15 FORCE UNITS). Other Error Sources could include geometric alignment, timing and contributions associated with using different indicators; if the force measuring instrument is calibrated with a different indicator than was used for calibration. Other errors may include temperature change under no load conditions. Errors from loading equipment not being level, square, and rigid can have significant contributions.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Other Error Sources	150.0000E-3	B	Rectangular	1.7321E+0	200	86.60E-3	7.50E-3	1.70%

	American Association for Laboratory Accreditation
Guidance on Uncertainty Budgets for	Document Revised: DRAFT
Force Measurement and Calibration	Page 22 of 38

Reference Standard Uncertainty: The laboratory performing the calibration of this force measuring instrument used deadweight primary standards with a CMC of 0.002 % of applied. 5 000 FORCE UNITS * 0.002 % = 0.1 FORCE UNITS and this is then divided by the appropriate coverage factor to get the standard uncertainty.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Uncertainty	100.0000E-3	B	Expanded (95.45% k=2)	2.000		50.00E-3	2.50E-3	0.57%

Indicator: If the force measuring instrument is not used with the same indicator that was used for calibration and additional error source will need to be accounted for and measurement traceability for the indicator will have to be verified.

*Note: On any Force Calibrating Machine, comparisons should be made against at least two high-quality transfer standards calibrated by primary standards to determine any additional deviation from the reference value. One method for assessing this involves determining whether the **E**n values calculated across the range of applied force exceed unity. If these values do exceed unity, it is not sufficient simply to increase the CMC to reduce the **E**n value to an acceptable level, but the whole uncertainty budget associated with the Force Calibrating Machine should be reviewed to the satisfaction of the National Accreditation Body.*

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 23 of 38**

Force measuring instruments Not Calibrated to a Published Standard or Commercial Calibrations

Note:

If further dissemination of force is required, ASTM E74 or ISO 376 should be followed. The intent of the commercial calibration or quality conformance test is to verify manufacturer's specifications only. It is not intended as a calibration to disseminate the unit of force. Only to prove the force transducer is fit for use. If a laboratory chooses to define its own procedure, the force measuring instrument should be tested for all applicable contributions below.

The contributions for the CMC uncertainty are:

Type A Uncertainty Contributions
1) Non-Repeatability
2) Repeatability or Non-Repeatability of the Reference Standard.
3) Repeatability of the Best Existing Force measuring instrument (and technician)
4) Repeatability and Reproducibility

Type B Uncertainty Contributions
5) Resolution of the Best Existing Force measuring instrument
6) Reference Standard Resolution* *If Applicable*
7) Reference Standard Uncertainty
8) Reference Standard Stability
9) Environmental Factors
10) Other Error Sources
11) Specified Tolerance * If Not Listed and making ascending measurements only. If making Ascending and Descending Measurements Use Static Error Band (SEB) or a combination of Non-Linearity and Hysteresis. If the force measuring instrument is calibrated with an indicator and setup to have a tolerance, then it may not be necessary to include non-linearity, hysteresis, or SEB.
    Note: if the force measuring instrument is going to be used at points different from the points it was calibrated at, then SEB, Non-Linearity, or Hysteresis may need to be used.
12) Hysteresis * (Only if the Force measuring instrument is Used to Measure Decreasing Forces and SEB was not used)

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	**0.645497224**	**A**	Normal	1.000	1	645.50E-3	416.67E-3	4.85%	173.6E-3
Reproducibility Between Techs	**0.11785113**	**A**	Normal	1.000	10	117.85E-3	13.89E-3	0.16%	19.3E-6
Repeatability of Best Existing Device	500.0000E-3	A	Normal	1.000	3	500.00E-3	250.00E-3	2.91%	20.8E-3
Non-Repeatability of Reference	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	15.52%	8.9E-3
Resolution of UUT	1.0000E+0	B	Resolution	3.464	200	288.68E-3	83.33E-3	0.97%	34.7E-6
Environmental Factors	300.0000E-3	B	Rectangular	1.732	200	173.21E-3	30.00E-3	0.35%	4.5E-6
Reference Standard Stability	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	15.52%	8.9E-3
Ref Standard Resolution	50.0000E-3	B	Resolution	3.464	200	14.43E-3	208.33E-6	0.00%	217.0E-12
Specified Tolerance or Non-Linearity	2.1000E+0	B	Rectangular	1.732	200	1.21E+0	1.47E+0	17.11%	10.8E-3
Hysteresis	2.3000E+0	B	Rectangular	1.732	200	1.33E+0	1.76E+0	20.53%	15.5E-3
Other Error Sources	1.0000E+0	B	Rectangular	1.7321E+0	200.0000E+0	577.35E-3	333.33E-3	3.88%	555.6E-6
Reference Standard Uncertainty	2.5000E+0	B	Expanded (95.45% k=2)	2.000		1.25E+0	1.56E+0	18.19%	
			Combined Uncertainty (u_c)=			2.93E+0	8.59E+0	100.00%	239.2E-3
			Effective Degrees of Freedom			308			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			5.77	0.05767%		

Table 2 Example of a Single Point Uncertainty Analysis for a 10,000 FORCE UNITS Force measuring instrument with Not Calibrated to a Published Standard. In This Example Hysteresis Was Included in The Uncertainty Budget.

Data to Support Table 2

In this example the force measuring instrument supplied had a capacity of 10,000 Force Units and an indicator was supplied. The customer wanted to use the force measuring instrument throughout the loading range and to make both ascending and descending measurements. Therefore, contributions from Non-Linearity and Hysteresis were used.

The calibration was performed taking readings at 1 000, 2 000, 3 000, 4 000, 5 000, 6 000, 7 000, 8 000, 9 000, 10 000, 9 000, 8 000, 7 000, 6 000, 5 000, 4 000, 3 000, 2 000, 1 000 Force Units and three repeated readings were taken at each force point.

Repeatability and Reproducibility between technicians: This should be performed whenever there is a change in personnel or the first time a budget is established.

This example uses two technicians recording readings at the same measurement point on the same equipment. The readings were taken in lbf. Repeatability between technicians can be found by taken the square root of the averages of the variances of the readings from the technicians (Pooled Standard Deviation). Reproducibility between technicians is found by taking the standard deviation of the averages of readings for each technician.

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for Force Measurement and Calibration	Document Revised: DRAFT
	Page 25 of 38

	Technician 1	Technician 2
1	5010.00000	5010.00000
2	5011.00000	5012.00000
3	5010.00000	5010.00000
4	5010.00000	5010.00000
5	5010.00000	5010.00000
6	5010.00000	5010.00000
Std. Dev.	0.40824829	0.816496581
Average	5010.166667	5010.333333
Variance	0.166666667	0.666666667
Repeatability		0.645497224
Reproducibility		0.11785113

Repeatability of the Best Existing Device:

Repeatability of Best Existing Force measuring instrument showing one point in the loading range (several points need to be taken to comply with ILAC P-14. This example only shows one data point. Calculations should be run for several data points throughout the loading range.

Per Point Example							
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.
1	10000.00	10001.00	10001.00	10000.00	10001.00	**10000.75**	**0.5000**
Repeatability of Best Existing Device			Average Standard Deviation of Runs			0.500000	

Non-Repeatability of Reference:

Used Data from Manufactures Specification sheet of 0.02 % of Rated Output (RO) which equates to 10 000 Force Units * 0.02 % = 2 Force Units

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Non-Repeatability of Reference	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	15.52%

Note:
This test should be done by the reference laboratory in lieu of using manufacture's specifications. It could be taking additional runs of data, rotating the force measuring instrument, or taking multiple readings of one point and if it applies to all points (not recommended).

Resolution of Unit Under Test (Best Existing Force measuring instrument) = 1 Force Units

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Resolution of UUT	1.0000E+0	B	Resolution	3.464	200	288.68E-3	83.33E-3	0.97%

Environmental Factors: +/- 1 ^{0}C was used, and this is found on the manufacturer's specification sheet. The temperature effect is 0.0 015 percent per ^{0}C. If the reference laboratory controls the temperature to within +/- 2 ^{0}C, the contribution formula is Force Applied * Temperature Specification per 2 ^{0}C = Environmental Error. 10 000 Force Units * 0.003 % = 0.3 Force Units

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Environmental Factors	300.0000E-3	B	Rectangular	1.732	200	173.21E-3	30.00E-3	0.35%

Reference Standard Stability: This is calculated per point and 0.02 % change between the same 10 000 FORCE UNITS calibration point was used which corresponded to 2 FORCE UNITS. The number was found by comparing the output for the previous calibration 10 000 FORCE UNITS versus the same output from the current calibration 10 002 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Stability	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	15.52%

Reference Standard Resolution: For this example, the unit read by 0.5 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Standard Resolution	50.0000E-3	B	Resolution	3.464	200	14.43E-3	208.33E-6	0.00%

Specified Tolerance or Non-Linearity: Either one or the other should be used. In this example, Non-Linearity is 0.021 % of Full Scale. 10 000 FORCE UNITS * 0.021 % = 2.1 FORCE UNITS

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Specified Tolerance or Non-Linearity	2.1000E+0	B	Rectangular	1.732	200	1.21E+0	1.47E+0	17.11%

Note:
It is recommended the laboratory take the highest value for Non-Linearity per the loading range. Non-linearity should be verified by calibration and the specification sheet should not be used in lieu of actual calibration data.

L:\Guidance\

Hysteresis: Was reported at 0.023 % of Full Scale. 10 000 FORCE UNITS * 0.023 % = 2.3 FORCE UNITS *Note: If the end user is not using the force measuring instrument to make decreasing measurements, Hysteresis should not be included in the budget.*

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Hysteresis	2.3000E+0	B	Rectangular	1.732	200	1.33E+0	1.76E+0	20.53%

Other Error Sources: For this example, an arbitrary value was used.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Other Error Sources	1.0000E+0	B	Rectangular	1.7321E+0	200.0000E+0	577.35E-3	333.33E-3	4.88%

Reference Standard Uncertainty: The laboratory performing the calibration of this force measuring instrument used secondary standards with a CMC of 0.025 % of applied. 10 000 FORCE UNITS * 0.025 % = 2.5 FORCE UNITS. (CMC's of 0.01 – 0.05 % are common for reference laboratories using Secondary Standards)

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Uncertainty	2.5000E+0	B	Expanded (95.45% k=2)	2.000		1.25E+0	1.56E+0	22.89%

Specified Tolerance (Not used in this example):

The example given uses non-linearity and hysteresis. If the device has a specified tolerance, then it may not be appropriate to use non-linearity, hysteresis, or SEB.

Example: Data from the Manufactures Specification sheet of 0.5 % of full scale, which equates to 5 000 Force Units * 0.25 % = 2.5 Force Units was used. The calibration laboratory verifies this via calibration and issues a statement of compliance in agreement with the appropriate guard-banding method.

Indicator: If the force measuring instrument is not used with the same indicator that was used for calibration an additional error source will need to be accounted for and measurement traceability for the indicator will have to be verified.

Force measuring instruments for Measurement or Verification of Force

These force measuring instruments are typically used for weighing or for verification of a press or force application. They are not to be used to further disseminate the unit of force.

Measurement uncertainty in calibration of force measuring instruments is different than measurement uncertainty in the measurement of force.

Measurement uncertainty in the measurement of force:

(reference standard in this case is the measuring force measuring instrument used to measure force)

Type A Uncertainty Contributions
1) Repeatability
2) Repeatability and Reproducibility

Type B Uncertainty Contributions
3) Resolution of the Best Existing Force measuring instrument * If applicable
4) Reference Standard Resolution* *If Applicable*
5) Reference Standard Uncertainty
6) Reference Standard Stability
7) Environmental Factors
8) Other Error Sources
9) Specified Tolerance * *If a specified tolerance is not given, SEB, Non-Linearity, or Hysteresis could be used.*

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Repeatability Between Techs	**2.89**	**A**	Normal	1.000	1	2.89E+0	8.35E+0	2.55%
Reproducibility Between Techs	**1.18**	**A**	Normal	1.000	10	1.18E+0	1.39E+0	0.42%
Repeatability	8.1650E+0	A	Normal	1.000	3	8.16E+0	66.67E+0	20.33%
Specified Tolerance	25.0000E+0	B	Rectangular	1.732	200	14.43E+0	208.33E+0	63.52%
Environmental Factors	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	0.00%
Reference Standard Stability	10.0000E+0	B	Rectangular	1.732	200	5.77E+0	33.33E+0	10.16%
Ref Standard Resolution	10.0000E+0	B	Resolution	3.464	200	2.89E+0	8.33E+0	2.54%
Other Error Sources	000.0000E+0	B	Rectangular	1.7321E+0	200	000.00E+0	000.00E+0	0.00%
Reference Standard Uncertainty	2.5000E+0	B	Expanded (95.45% k=2)	2.000		1.25E+0	1.56E+0	0.48%
			Combined Uncertainty (u_c)=			18.11E+0	327.98E+0	100.00%
			Effective Degrees of Freedom			60		
			Coverage Factor (k) =			2.00		
			Expanded Uncertainty (U) K =			36.23	0.72452%	

Table 3 Example of a Single Point Uncertainty Analysis for a 5,000 FORCE UNITS Force measuring instrument with a Specified Tolerance of 0.5 % of Full Scale Used for Verification of Weight or Force Press.

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for Force Measurement and Calibration	Document Revised: DRAFT
	Page 29 of 38

Data to Support Table 3

Repeatability and Reproducibility between technicians: This should be performed whenever there is a change in personnel or the first time a budget is established.

This example uses two technicians recording readings at the same measurement point on the same equipment. The readings were taken in lbf. Repeatability between technicians can be found by taken the square root of the averages of the variances of the readings from the technicians. Reproducibility between technicians is found by taking the standard deviation of the averages of readings for each technician.

	Technician 1	Technician 2
1	5010.00000	5010.00000
2	5011.00000	5012.00000
3	5010.00000	5010.00000
4	5010.00000	5010.00000
5	5010.00000	5010.00000
6	5010.00000	5010.00000
Std. Dev.	0.40824829	0.816496581
Average	5010.166667	5010.333333
Variance	0.166666667	0.666666667
Repeatability		0.645497224
Reproducibility		0.11785113

Repeatability: In this example the force measuring instrument is a crane scale. The repeatability study could be performed weighing a mass without a resolution.

Per Point Example							
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.
1	5000.00	5010.00	5010.00	5020.00	5000.00	**5010**	**8.1650**
Repeatability			Average Standard Deviation of Runs			8.164966	

Specified Tolerance:
Data from Manufactures Specification sheet of 0.5 % of full scale, which equates to 5 000 * 0.25 % = 2.5 FORCE UNITS was used.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Specified Tolerance	25.0000E+0	B	Rectangular	1.732	200	14.43E+0	208.33E+0	63.52%

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
Force Measurement and Calibration	**Page 30 of 38**

Resolution of Unit Under Test: * This example is a crane scale used for a weighing application. The Unit Under Test does not have a resolution.

Environmental Factors: +/- 1 ^{0}C was used, and this is found on the manufacturer's specification sheet. The temperature effect is 0.0015 percent per ^{0}C. If the reference laboratory controls the temperature to within +/- 2 ^{0}C, the contribution formula is Force Applied * Temperature Specification per 2 ^{0}C = Environmental Error. 5 000 Force Units * 0.003 % = 0.15 FORCE UNITS

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Environmental Factors	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	0.00%

Reference Standard Stability: This is calculated per point and is the change between the same 5 000 FORCE UNITS calibration point. The number was found by comparing the output for the previous calibration 5 000 FORCE UNITS versus the same output from the current calibration 5 010 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Stability	10.0000E+0	B	Rectangular	1.732	200	5.77E+0	33.33E+0	10.16%

Reference Standard Resolution: For this example, the unit read by 10 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Standard Resolution	10.0000E+0	B	Resolution	3.464	200	2.89E+0	8.33E+0	2.54%

Other Error Sources: In this example the Repeatability test and R & R between technicians can account for other error sources. The end user should evaluate use and make the appropriate decision.

Note:
If the end user is changing adapters or using different adapters such as pins of a different width than what was used at the time of calibration, the resulting error could be quite high. Substituting different pin sizes in Tension Links can result in errors well above 1 %.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 31 of 38**

Reference Standard Uncertainty: The laboratory performing the calibration of this force measuring instrument used secondary standards with a CMC of 0.025 % of applied. 10 000 FORCE UNITS * 0.025 % = 2.5 FORCE UNITS. (CMC's of 0.01 – 0.05 % are common for reference laboratories using Secondary Standards)

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Uncertainty	2.5000E+0	B	Expanded (95.45% k=2)	2.000		1.25E+0	1.56E+0	0.48%

Indicator: If the force measuring instrument is not used with the same indicator that was used for calibration and additional error source will need to be accounted for and measurement traceability for the indicator will have to be verified.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	Document Revised: DRAFT
	Force Measurement and Calibration	Page 32 of 38

Force measuring instruments Calibrated in Accordance with the ISO 376 Standard

Per EURAMET-cg-04 the evaluation of measurement uncertainty in calibrations of transducers per ISO 376 should account the following uncertainty contributions in relative terms:

w1 = relative standard uncertainty associated with applied calibration force
w2 = relative standard uncertainty associated with reproducibility of calibration results
w3 = relative standard uncertainty associated with repeatability of calibration results
w4 = relative standard uncertainty associated with resolution of indicator
w5 = relative standard uncertainty associated with creep of instrument
w6 = relative standard uncertainty associated with drift in zero output
w7 = relative standard uncertainty associated with temperature of instrument
w8 = relative standard uncertainty associated with interpolation Calibration force.

Type A Uncertainty Contributions
　　1) Repeatability of the Best Existing Force measuring instrument
　　2) Repeatability and Reproducibility

Type A and B Uncertainty per ISO 376 with a coverage factor of 2
　　3) Combined Uncertainty from ISO 376 Annex C which includes contributions for *calibration force (reference standard uncertainty), repeatability, reproducibility, resolution, creep, zero drift, reversibility, temperature, and interpolation.*

Type B Uncertainty Contributors
　　4) Resolution of the Best Existing Force Measuring Instrument
　　5) Reference Standard Stability
　　6) Environmental Factors
　　7) Other Error Sources

The following example is for a force measuring instrument calibrated using a force transducer (reference standard), which was calibrated per ISO 376. All uncertainty contributions should be combined, and the Welch-Satterthwaite equation should be used to determine the effective degrees of freedom for the appropriate coverage factor for a 95 % confidence interval.

American Association for Laboratory Accreditation

Guidance on Uncertainty Budgets for

Force Measurement and Calibration

Document Revised:
DRAFT

Page 33 of 38

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Repeatability Between Techs	0.032435888	A	Normal	1.000	1	32.44E-3	1.05E-3	0.03%
Reproducibility Between Techs	0.006481823	A	Normal	1.000	10	6.48E-3	42.01E-6	0.00%
Repeatability	577.3503E-3	A	Normal	1.000	3	577.35E-3	333.33E-3	8.87%
ISO 376 Uncertainty	1.8250E+0	A	Normal	1.000	32	1.83E+0	3.33E+0	88.61%
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.02%
Environmental Factors	75.0000E-3	B	Rectangular	1.732	200	43.30E-3	1.88E-3	0.05%
Stability of Ref Standard	500.0000E-3	B	Rectangular	1.732	200	288.68E-3	83.33E-3	2.22%
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.00%
Other Error Sources	150.0000E-3	B	Rectangular	1.7321E+0	200	86.60E-3	7.50E-3	0.20%
Ref Std Unc (Inc in ISO 376 data)	000.0000E+0	B	Expanded (95.45% k=2)	2.000		000.00E+0	000.00E+0	0.00%
			Combined Uncertainty (u_c)=			1.94E+0	3.76E+0	100.00%
			Effective Degrees of Freedom		36			
			Coverage Factor (k) =		2.03			
			Expanded Uncertainty (U) K =		3.93		0.07864%	

Table 4 Example of a Single Point Uncertainty Analysis for Force measuring instruments Calibrated in Accordance with the ISO 376 Standard

Note: Force measuring instruments Calibrated in Accordance with the ISO 376 standard are continuous reading force measuring instruments and any uncertainty analysis should be conducted on several test points used throughout the loading range. There are Excel spreadsheets available for calculating CMC from certain force calibration laboratories.

Data to Support Table 4

Repeatability and Reproducibility between technicians: This should be performed whenever there is a change in personnel or the first time a budget is established.

This example uses two technicians recording readings at the same measurement point on the same equipment. The readings were taken in mV/V and were then converted to force units. Repeatability between technicians can be found by taken the square root of the averages of the variances of the readings from the technicians. Reproducibility between technicians is found by taking the standard deviation of the averages of readings for each technician.

Repeatability and Reproducibility						
	Technician 1	Technician 2	Technician 3	Technician 4	Technician 5	Technician 6
1	2.00000	2.00000				
2	2.00000	2.00000				
3	2.00000	2.00000				
4	2.00000	2.00000				
5	1.99999	2.00000				
6	2.00000	1.99998				
Std. Dev.	4.1833E-06	8.16497E-06				
Average	1.9999985	1.999996667				
Variance	1.75E-11	6.66667E-11				
Repeatability		6.48717E-06		5000.01	0.032435888 LBF	
Reproducibility		1.29636E-06			0.006481823 LBF	

Repeatability Data: Data needs to be taken for various test points throughout the loading range. This example only shows one data point. Calculations should be run for several data points throughout the loading range.

Per Point Example							
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.
1	5000.00	5001.00	5000.00	5001.00	5000.00	5000.5	0.5774
Repeatability Of Best Existing Device			Average Standard Deviation of Runs			0.577350	

Combined Uncertainty from ISO 376 Annex C which includes contributions for *calibration force (reference standard uncertainty), repeatability, reproducibility, resolution, creep, zero drift, reversibility, temperature, and interpolation.*

At each calibration force, F, a combined standard uncertainty, u_c, expressed in units of force, is calculated from the readings obtained during the calibration. These combined standard uncertainties are plotted against force, and a least-squares fit covering all the values is calculated. The coefficients of this fit are then multiplied by the coverage factor k = 2 to give an expanded uncertainty value, **U**, for any force within the calibration range. The form of the fitted line (e.g. linear, polynomial, exponential) will depend on the calibration results. This line equation should be used to derive the uncertainty per point and additional contributions to uncertainty should be considered. We are calling this the ISO 376 Uncertainty and have reduced the number to a standard uncertainty to use the Welsh-Satterthwaite formula.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
ISO 376 Uncertainty	1.8250E+0	A	Normal	1.000	32	1.83E+0	3.33E+0	88.55%

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 35 of 38**

Resolution of Unit Under Test (Best Existing Force measuring instrument): 0.1 FORCE UNITS

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.02%

Environmental Factors: +/- 1 ^{0}C was used and this is found on the manufacturer's specification sheet. The temperature effect is 0.0015 percent per ^{0}C. If the reference laboratory controls the temperature to within +/- 1 ^{0}C, the contribution formula is Force Applied * Temperature Specification per 1 ^{0}C = Environmental Error. 5 000 Force Units * 0.0015 % = 0.075 FORCE UNITS

 +/- 1 ^{0}C was used and this is found on the manufacturer's specification sheet. The temperature effect is 0.075 FORCE UNITS

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Environmental Factors	75.0000E-3	B	Rectangular	1.732	200	43.30E-3	1.88E-3	0.05%

Reference Standard Stability: This is calculated per point and 0.01 % change between the same 5 000 FORCE UNITS calibration point was used which corresponded to 0.5 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Reference Standard Stability	500.0000E-3	B	Rectangular	1.732	200	288.68E-3	83.33E-3	2.22%

Reference Standard Resolution: For this example, the unit read by 0.24 FORCE UNITS.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.00%

Other Error Sources: In this example the alignment of the force transfer machine 1/16th inch measured off centerline of the force transducer (From the specification sheet side load sensitivity 0.05 % * 0.0 625 = 0.003 % = 0.15 FORCE UNITS). Other Error Sources could include contributions associated with using different indicators, if the force measuring instrument is calibrated with a different indicator than was used for calibration.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Other Error Sources	150.0000E-3	B	Rectangular	1.7321E+0	200	86.60E-3	7.50E-3	0.20%

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 36 of 38**

Reference Standard Uncertainty: The laboratory performing the calibration of this force measuring instrument used deadweight primary standards with a CMC of 0.002 % of applied. This number was figured into the ISO 376 uncertainty per Annex C and therefore the value for the reference is in the ISO 376 Uncertainty line above. The ISO 376 Uncertainty at 1 standard deviation is 1.825 Force Units at the 5 000 Force Units test point. The reference standard uncertainty is included in the ISO 376 Uncertainty from above.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Std Unc (Inc in ISO 376 data)	000.0000E+0	B	Expanded (95.45% k=2)	2.000		000.00E+0	000.00E+0	0.00%

Indicator: If the force measuring instrument is not used with the same indicator that was used for calibration and additional error source will need to be accounted for and measurement traceability for the indicator will have to be verified.

Measurement uncertainty for actual calibrations reported on the Calibration Certificate should include the same type uncertainties contributions (as above) but using actual calibration data and conditions, such as the actual repeatability, reproducibility and resolution for the actual force measuring instrument under calibration and environment conditions.

Note:
On any Force Calibrating Machine, comparisons should be made against at least two high-quality transfer standards calibrated by primary standards to determine any additional deviation from the reference value. One method for assessing this involves determining whether the E_n values calculated across the range of applied force exceed unity. If these values do exceed unity, it is not enough to simply increase the CMC to reduce the E_n value to an acceptable level, but the whole uncertainty budget associated with the Force Calibrating Machine should be reviewed to the satisfaction of the National Accreditation Body.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	Document Revised: DRAFT
	Force Measurement and Calibration	Page 37 of 38

4.0 References

JCGM 100:2008 Evaluation of measurement data — Guide to the expression of uncertainty in measurement.
https://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

ILAC P14:01/2013 ILAC Policy for Uncertainty in Calibration
https://ilac.org/publications-and-resources/ilac-policy-series/

ASTM E74-18 Standard Practices for Calibration and Verification for Force-Measuring Instruments

A2LA R205 R205 - Specific Requirements: Calibration Laboratory Accreditation Program, American Association for Laboratory Accreditation, 2015
https://portal.a2la.org/requirements/A2LA_R205.pdf

ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories

ANSI/NCSLI Z540.3-2006 Requirements for the Calibration of Measuring and Test Equipment Handbook, 2013.

JCGM 200:2012 International vocabulary of metrology – Basic and general concepts and associated terms
https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

EURAMET cg-4 Version 2.0 Uncertainty of Force Measurements
https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-4__v_2.0_Uncertainty_of_Force_Measurements.pdf

ISO 376 Fourth Edition Metallic material – Calibration of force-proving instrument used for the verification of uniaxial testing machine

UKAS M3003 Edition 3 The Expression of Uncertainty and Confidence in Measurement
https://www.ukas.com/technical-services/publications/

Morehouse Uncertainty Propagation for Force Calibration Systems by Henry Zumbrun and Alireza Zeinali https://www.mhforce.com/Files/TechnicalPaper/11/TechnicalPaper.pdf

Note: All free standards have links to them. Those standards without links are available for sale only.

	American Association for Laboratory Accreditation	
	Guidance on Uncertainty Budgets for	**Document Revised: DRAFT**
	Force Measurement and Calibration	**Page 38 of 38**

5.0 Document Revision History

Date	Description
DRAFT	Dave Kreitlow, Klaus Jaeger, Andy Knott, Carlos Silva, Vincent Pugh all helped bringing this draft to initial release