ISO 376 Guidance and Uncertainty Measurements Relating to Force Equipment

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Introduction

In past articles and blogs, we examined ISO 376 and ASTM E74 and the differences between these internationally recognized standards. However, one aspect we have not covered is the meaning of compliance with ISO 376.

Specifically, there is a common misconception about equipment "being compliant" with ISO 376. This may come from some testing criteria that are found in Euramet cg-4, which has best practices to evaluate force equipment and ensure your equipment can calibrate following the practices found in ISO 376.

It is important to note that ISO 376 does not relate to the force calibration equipment that is used to apply the forces; ISO 376 relates to the instruments used as reference standards in those transfer machines. It is comparable to ISO 9000 and ISO/IEC 17025. These accreditations do not ensure a quality product. However, they may help ensure that you have a quality system consisting of the validated procedures, adequate Measuring and Test Equipment (M&TE), and trained personnel performing the calibrations.

The purpose of this document is to guide the identification of all significant contributions to measurement uncertainty in the 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 the scope of accreditation and calibration and/or measurement certificates/reports. It also serves as a means for laboratories to be compliant with various accreditation bodies, including A2LA R205 – Specific Requirements: Calibration Laboratory Accreditation Program. Finally, for instruments calibrated following 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 measurement uncertainty.

There are discrepancies regarding what is acceptable for a force calibration uncertainty budget. Our goal is to improve the consistency in the assessment process among assessors regarding the parameter of force.

One of these issues involves correctly calculating uncertainty when the lab follows a standard like ASTM E74 or ISO 376. If calibrating to ASTM E74 or ISO 376 standards, 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 the 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 consider ISO 376 criteria as it applies to reference standards, such as Morehouse load cells. It will also cover proper adapters for calibration, what criteria make for great force equipment, and some information on common errors, measurement uncertainty, and Euramet cg-4.

ISO 376:2011 Standard Explained

The ISO 376:2011 standard is titled "Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines standard requirements." It focuses on force-proving instruments, not calibration machines such as the Morehouse Universal Calibration Machine (UCM) or Portable Calibration Machine (PCM).

In section 6.1 it states, "All the elements of the force-proving instrument (including the cables for electrical connection) shall be individually and uniquely identified, e.g., by the name of the Manufacturer, the model, and the serial number. For the force transducer, the maximum working force shall be indicated."[1]

In section 6.2 the standard addresses the application of force, "The force transducer and its loading fittings shall be designed so as to ensure axial application of force, whether in tension or compression."[2]

Later in section 7.1, it instructs to ensure "that the attachment system of the force-proving instrument allows axial application of the force when the instrument is used for tensile testing; that there is no interaction between the force transducer and its support on the calibration machine when the instrument is used for compression testing."[3]

Figure 1: ISO 376 Expanded Uncertainty Required to Classify a Force-Proving Instrument

The illustration above shows the typical range of reference uncertainties that are needed to achieve each ISO 376 classification. For *Class 00*, deadweight primary standards are highly recommended because most can achieve better than 0.003 % of applied force throughout the loading range.

Reference standard load cells can achieve the uncertainty needed. However, it is more likely that multiple reference standard load cell changes will be required, and several inefficiencies with timing may impact the Unit Under Test (UUT).

All calibration laboratories accredited to ISO/IEC 17025 must submit uncertainty calculations for their Calibration and Measurement Capability (CMC) uncertainty claims, which are included in the scope of accreditation. The assumptions made for the determination of the uncertainty budgets, if any, must be specified and documented. ISO/IEC 17025 accredited calibration laboratories shall calculate measurement uncertainties using the method detailed in the JCGM 100:2008 Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurement (GUM).

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." [4]

ILAC P14:09/2020 states, "The Accreditation Body shall ensure that an accredited calibration laboratory reports the measurement uncertainty in compliance with the GUM."[5]

Accreditation Bodies require the laboratory shall meet the requirements of ILAC P14.
Note: Any accreditation body is going to require any accredited laboratory to follow ILAC guidelines.

Common Error Sources in Force Calibration

The force-measuring instrument's end-user must ensure the laboratory performing the calibration replicates how the instrument will be used. Calibrating machines that perform tension and compression in the same setup do not replicate use.

Fixturing and adapters used with a force-measuring instrument may significantly contribute to the force-measuring instrument's overall uncertainty. Morehouse has observed errors higher than 0.05 % of the output from using top blocks of different hardness. Common error sources for force calibration include:

- Not replicating via calibration how the equipment is being used
- Not using independent setups for compression and tension when calibrating to ASTM E74 or ISO 376.
- Alignment, which can be overcome with proper adapters
- Using a different hardness of adapter than what was used for calibration
- Using different size adapters than what was 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 that was used at the time of calibration
- Variations in bolting a force transducer to a base for calibration that is different from the application
- Electronic cabling such as 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 before use
- Difference between the output of a high-quality force transducer when compared to the current machine and realized value from the deadweight calibration
- Untrained Technicians
- Overshooting a test point
- And many more…

Morehouse has several articles, videos, webinars, and training courses, including on-site courses that focus on these error sources and how to correct them.

Selection of Load Cells for Your Morehouse UCM

Class	Relative error of the force-proving instrument %						Expanded uncertainty of applied calibration force (95 % level of confidence) %
	of reproducibility b	of repeatability b'	of interpolation f_c	of zero f_0	of reversibility v	of creep c	
00	0,05	0,025	±0,025	±0,012	0,07	0,025	±0,01
0,5	0,10	0,05	±0,05	±0,025	0,15	0,05	±0,02
1	0,20	0,10	±0,10	±0,050	0,30	0,10	±0,05
2	0,40	0,20	±0,20	±0,10	0,50	0,20	±0,10

Figure 2: ISO 376 Relative Error Needed to Achieve Classification

The selection of reference standards will vary depending on what is needed using Case C or Case D and the Class. Uncertainties relating to Calibration and Measurement Capability Uncertainty and what can be achieved have been covered in previous papers and guidance documents.

For example, if Class 00 is required, then the expanded uncertainty of applied calibration force of ± 0.01 % is needed. To achieve this, 2-3 reference standards will most likely be needed for a standard change at every 40 % of the desired capacity.

Achieving Class 0.5 may require a standard change at every 20 % of the capacity being calibrated, with 2 reference standards needed. For Class 1, 0.05 % could be accomplished with 1-2 reference standards. Class 2 would only require 1 reference standard.

Typical recommendations for achieving Class 00 calibrations are as follows, in order of importance:

1. Use a reference laboratory using deadweight primary standards or with the lowest CMC uncertainty parameter
2. Select instrumentation with excellent hysteresis specifications for Case D, as well as nonlinearity specification, non-repeatability, and temperature specification for Case C or D.
3. Use of transfer standards in the range above 40 % of their maximum capacity. This helps minimize interaction effects; it also reduces uncertainty from resolution. *
4. Select instrumentation with a resolution of 1 part in 200 000 at each calibration force (this is a primary reason a 4 mV/V load cell can cover 50 % to 100 %, thus leaving a need for the 40 % test point).

***Note: Obtaining Class 00 of better than 20 % is achievable with special load cells that are about double the price of the Morehouse UPC load cell. Ask us for more information if interested**

Several of these recommendations are found or elaborated upon in Euramet cg-04.

If Euramet cg-04 is the requirement, a different method will be discussed later. Most non-Euramet national laboratories and accreditation bodies will audit, assuming ASTM E74 or ISO 376 is used as a calibration method to determine the CMC uncertainty parameter. Verifying the CMC Uncertainty Parameter is often done by comparing two standards calibrated in deadweight machines against one another.

This can be thought of as an Intra Laboratory Comparison or ILC, though the number is used and referenced in Euramet cg-04. Unfortunately, there is often a lack of good enough reference standards for claiming uncertainties lower than 0.01 %. Hence, the recommendation is to have additional standards calibrated by deadweight and make the comparison in the machine. Furthermore, this practice, whether in line with Euramet cg-04 or done in-house, can satisfy an ISO/IEC 17025 requirement found in Section 7.7.2 of ISO/IEC 17025:2017, which states, "The laboratory shall monitor its performance by comparison with results of other laboratories, where available and appropriate. This monitoring shall be planned and reviewed and shall include, but not be limited to, either or both of the following:

a) participation in proficiency testing;

Note: ISO/IEC 17043 contains additional information on proficiency tests and proficiency testing providers. Proficiency testing providers that meet the requirements of ISO/IEC 17043 are considered to be competent.

b) participation in interlaboratory comparisons other than proficiency testing." - The deadweight ILC is a great way to help mitigate risk.

Morehouse has done this on our machines, and the values typically agree to within 0.005 to 0.02 % throughout the loading range. When we do the test, we use the recommended adapters and skilled technicians. These numbers have been confirmed independently with two Morehouse-calibrated load cells in our deadweight systems compared with two load cells calibrated by PTB.

The equipment manufacturer should not do this test because it would not involve your technicians, who need to be part of the overall measurement uncertainty. An additional advantage of a spare reference load cell or two is that they can be used to set up cross-checks and SPC (statistical process control), which can be used to monitor and spot trends and reduce measurement uncertainty if done correctly.

Uncertainty Calculations

Uncertainty is the value assigned to "doubt" about the validity of an assigned calibration value. Documented measurement uncertainties are required on a calibration certificate to support metrological traceability. Uncertainty is much more than any accuracy statement. Uncertainty is often broken down into two types of contributors: Type A and Type B.

Type A is often derived from statistical data or evaluation of uncertainty by the statistical analysis of a series of observations. Type B is an evaluation of uncertainty by means other than the statistical analysis of a series of observations. Examples of both types are below.

Type A Uncertainty Contributions

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

- Repeatability (required by the GUM, A2LA R205, and UKAS M3003)
- Reproducibility
- Stability / Drift
- 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. For our example, stability shall be treated as Type B because we are taking values over a range using previous measurement data. 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 certificates
- Uncertainties assigned to reference data taken from handbooks
- Resolution of the reference standard
- Resolution of the best existing force-measuring instrument or the force-measuring instrument used for repeatability studies
- Reference standard uncertainty
- Reference standard stability
- Environmental factors
- Other error sources

When evaluating other error sources, the end-user of the force-measuring instrument must replicate how the force-measuring instrument was calibrated, or the laboratory performing the calibration must replicate 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.

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.

Repeatability of a top-quality force-measuring instrument in a deadweight machine (Several laboratories using primary standards have found this to be less than 5 ppm). The 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 if the Morehouse automation system is used with proper adapters and alignment. It is important to note that these three error sources may be found to be insignificant using deadweight primary standards, and 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.
- Untrained Technicians
- Overshooting a test point if not using Morehouse Automation
- And many more…

A more thorough analysis on calculating CMC uncertainty was written by Morehouse and published by A2LA.

Guidelines for Calculating CMC Uncertainty

It is highly recommended that all force-measuring instruments for the calibration of other force-measuring equipment be calibrated following the ASTM E74 or ISO 376 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. Laboratories following the ISO 376 standard should follow the guidelines outlined in Annex C and the requirements of ILAC-P14 and ISO/IEC 17025.

Cases a-c are discussed in the uncertainty guidance written for A2LA found with several other Morehouse Guidance Documents https://mhforce.com/documentation-tools/?_sft_support-item-tag=guidance-document

The next section provides an example of force-measuring instruments calibrated following the ISO 376 Standard.

ISO 376 Uncertainty Example

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 Between Technicians

Type A and B Uncertainty per ISO 376 with a coverage factor of 2

1. Combined uncertainty from ISO 376 Annex C includes contributions for calibration force (reference standard uncertainty), Repeatability, Reproducibility, resolution, creep, zero drift, reversibility, temperature, and interpolation.

Type B Uncertainty Contributors

1. Resolution of the Best Existing Force-Measuring Instrument
2. Reference Standard Stability
3. Environmental Factors
4. Other Error Sources

The following example is for a force-measuring instrument calibrated using a force transducer (reference standard), 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.

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%**	

Figure 3: Example of a Single Point Uncertainty Analysis for Force-measuring instruments Calibrated following the ISO 376 Standard

Force-measuring instruments calibrated following the ISO 376 standard are continuous reading force-measuring instruments. Any uncertainty analysis should be conducted on several test points used throughout the loading range.

Data to Support Figure 3

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

This example uses two technicians recording readings on the same equipment at the same measurement point. The readings were taken in mV/V and were then converted to force units. Repeatability between technicians can be found by taking 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 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 call 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%

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, corresponding 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 the 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 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%

Reference Standard Uncertainty: The laboratory calibrating 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 used for calibration, additional error sources will need to be accounted for, and measurement traceability for the indicator will have to be verified.

Figure 4: A Morehouse 30K Automation Setup.

Note: Automation will typically reduce Type A uncertainties for repeatability and reproducibility.

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.

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.

$$E_n = \frac{x_{Lab} - x_{Ref}}{\sqrt{U_{Lab}^2 + U_{Ref}^2}}$$

Where,
x_{Lab} = measurement result of participating lab
x_{Ref} = measurement result of reference lab
U_{Lab} = Expanded Uncertainty (i.e. 95%) of participating lab
U_{Ref} = Expanded Uncertainty (i.e. 95%) of reference lab

Figure 5 Example of En Ratio.

One method for assessing this involves determining whether the En values calculated across the range of applied force exceed unity. If these values do exceed unity, it is not enough to increase the CMC to reduce the En value to an acceptable level. The entire uncertainty budget associated with the Force Calibrating Machine should be reviewed to satisfy the National Accreditation Body.

Download the Excel sheet developed by Morehouse to help build a force uncertainty budget.

Additional Euramet cg-4 Information for Force Uncertainties

Euramet cg-4 Uncertainty of Force Measurements is a calibration guide. The standard provides guidance on establishing traceability through the country's National Metrology Institute (NMI). The standard relies on a Force Standard Machine (FSM) such as Morehouse machines to be used with force-proving instruments and calibrated or verified by additional reference load cells calibrated by the NMI's National Force Standard Machines (NSFM). The two examples listed in Euramet cg-4 are as follows:

1. When the machines are calibrated using reference load cells calibrated by the NFSM Euramet cg-4 states, "The forces generated within calibration laboratory FSMs are usually traceable to those generated within NFSMs (or other FSMs of the required uncertainty in generated force) through exercises using force transfer standards, and the accredited calibration and measurement capability (CMC) of the calibration laboratory will be based on the results of these exercises."[6]
2. When one purchases equipment with Calibration from Morehouse and verifies their CMC claims, Euramet cg-4 states, "The Calibration of a force-measuring instrument in an FSM will generally be carried out in accordance with a documented procedure, such as ISO 376, and the uncertainty of the calibration results will be dependent on the machine's CMC, as well as on the performance of the instrument during the calibration. ISO 376 classification criteria include the magnitude of the uncertainty of the applied force and, for high-quality force transducers, this value is often the dominant uncertainty contribution. For this reason, the CMC of an FSM is often set to be equal to the uncertainty of the applied force, ignoring any other uncertainty contributions that may be present during the calibration."[7]

Many of the European laboratories that Morehouse has provided force equipment to are NMIs, or labs that use Morehouse for Calibration of the references to ISO 376 and the NMI to validate their CMC claims.

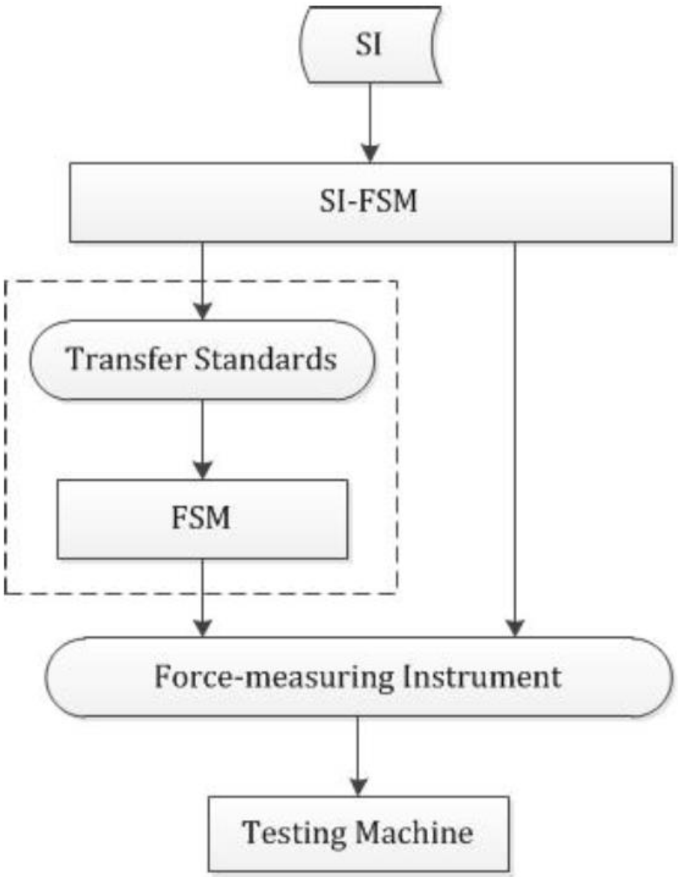

Figure 6: Force Traceability to the SI from Euramet cg-4

If the machine purchased from Morehouse is a deadweight primary standard machine, then it would be designated as a SI-FSM (SI-reference Force Standard Machine).

Deadweight SI-FSM Machines

The unit of force is realized through SI units of Time, Mass, and Length.

$$F = mg\left(1 - \frac{\rho_a}{\rho_m}\right)$$

Figure 7: Equation to Determine Force

$$\left(\frac{u(F)}{F}\right)^2 \approx \left(\frac{u(m)}{m}\right)^2 + \left(\frac{u(g)}{g}\right)^2 + \left(\frac{u(\rho_{\mathrm{a}})}{\rho_{\mathrm{m}}}\right)^2 + \frac{\rho_{\mathrm{a}}^2}{\rho_{\mathrm{m}}^2}\left(\frac{u(\rho_{\mathrm{m}})}{\rho_{\mathrm{m}}}\right)^2$$

Figure 8: Uncertainty Equation in Euramet cg-4 for SI-FSM Deadweight Machines

The uncertainty for Morehouse deadweight machines includes the standard mass uncertainty, the determination of the acceleration of gravity, standard uncertainty of air density, standard uncertainty of the density of the weight.

The uncertainty budget for the machine also needs to consider possible force-generating mechanisms other than gravity and air buoyancy, including magnetic, electrostatic, and aerodynamic effects.

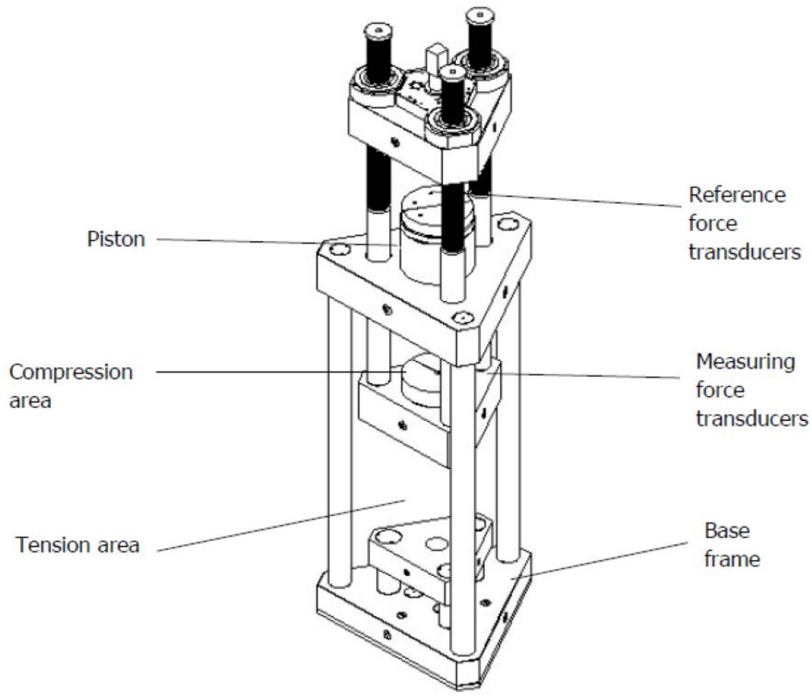

Figure 9: Example of a Typical FSM Type Machine

Morehouse Calibrating Machines (FSMs)

The figure above shows distinct areas for compression and tension calibration. Other manufacturers may try to combine the compression and tension area, but Morehouse does not. This design is not shown in Euramet cg-4 because these machines do not replicate how the equipment is typically used in the field.

The Morehouse machine also only has two bars. We built a three-bar machine and ran tests to see if there was a difference. Our two-bar machine has a lighter tare weight and performs just as well as a three-bar machine.

Download the Test Paper for the Morehouse 3 Bar Versus 2 Bar Universal Calibrating Machines Comparison.

To determine the uncertainty of the Morehouse (FSM), Euramet recommends these 5 steps.

1. Determination of the uncertainty of the force generated by the SI-FSM (reference standard used for Calibration, like a Morehouse Deadweight Machine)
2. Determination of the calibration uncertainty of the transfer standard in the SI-FSM (Use the Morehouse Deadweight Machine to calibrate the load cell. Rotate the load cell and take several readings. This is where ASTM E74 data or ISO 376 reproducibility can be used.)
3. Determination of the uncertainty of the transfer standard's reference value (This step deals with the stability of the reference load cells over a short period of time)
4. Determination of the uncertainty of force generation in the FSM (Here a comparison is made between the machine using an additional set of transfer standards calibrating in the SI-FSM)
5. Determination of the FSM's CMC (calibration uncertainty of the reference load cell, and long-term instability)

Morehouse has observed various ways to calculate the uncertainty of the FSM and reference standards. We believe the method described in our uncertainty guidance meets most accreditation guidelines. If you are unsure, please check with your accreditation body to determine the required method.

Summary

Figure 10: Morehouse Universal Calibrating Machine, Portable Calibrating Machine, and Benchtop Calibrating Machine

Morehouse calibrating machines like the UCM, PCM, and BCM simplify force calibration by reducing rework, errors from misalignment, and problematic setups. These machines rank among the most versatile and cost-effective solutions to calibrate all types of force instruments. The operator can replicate how the force instruments are used in the field by using different setups for tension and compression and proper adapters recommended by several standards, including ISO 376. Both the Morehouse UCM and PCM have options that allow calibration automation. These machines are built with the finest precision and will help you improve measurement accuracy and grow your business.

Figure 11: Morehouse Deadweight Machine

If the goal is the lowest possible uncertainty, then Morehouse deadweight machines can achieve better than 0.0025 % of applied force. It also eliminates the need to use several standards in the same machine, and calibration is often faster. Many of these machines are installed in National Metrology Institutes worldwide. They are the best standard for force calibration, allowing the end-user to calibrate devices to Class 00 following ISO 376.

Force measurement can be complex. Morehouse has additional spreadsheets, tools, and guidance to simplify the process on our website.

Definition of Terms

Calibration and Measurement Capabilities should be calculated using the accreditation bodies document relating to CMC. 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 regarding Nonlinearity, 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 the expected performance of the force-measuring instrument.

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

For example, a calibration laboratory calibrated a force-measuring instrument at 23 °C. The force-measuring instrument is then used from 13 - 33 0 °C or ±10 °C from the calibration. Based on Manufacturer's specification, this variation of temperature could cause an additional change in 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 (FU): 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.

Hysteresis: The phenomenon in which the value of a physical property lags changes in the effect causing it. An example is when magnetic induction lags the magnetizing force.
For force measurements, Hysteresis is defined as the difference between two responses of a single given load, one ascending from the lowest non-zero load applied, the other descending from the full-scale load. Hysteresis is typically calculated at a 40 % load. The purpose of calculating Hysteresis is to identify how well the materials of the device recover after fully loaded. Hysteresis is typically expressed as a positive value and in percent of full-scale (% FS).

Two responses must be recorded for the same load applied to calculate Hysteresis. Following the below equation, the full-scale response should be subtracted from the ascending load's response. The difference should be divided by the descending load's response. To ensure Hysteresis is a positive value, the absolute value of the quotient is used.

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 following 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. It is usually calculated between 40 - 60 % of the full scale.
An ideal measurement device has a perfectly linear response to force applied ratio. However, this is rarely true; most devices have a non-linear ratio. The purpose of the non-linearity calculation is to show how the recorded responses deviate from the ideal ratio. Non-linearity is typically expressed in the percent of full-scale (% FS).

Non-Repeatability (per force transducer specification and not JCGM 200:2012): The maximum difference between output readings for repeated loadings under identical loading and environmental conditions. Non-Repeatability is normally expressed in units as a % of Rated Output (RO).

Other Force Measurement Errors: Most force-measuring instruments are susceptible to misalignment errors, errors from not exercising the instrument to full capacity, and improper adapter use. There will be additional errors in almost all cases 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, rigid, and not having low torsion 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 that 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 the reference standard(s) used to calibrate the force-measuring instrument. It is the uncertainty contribution in the calibration of the 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): 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.

For 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 sense to 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 Non-Linearity, Hysteresis, and non-return to minimum load. It is usually expressed in units of % of full scale.

If the load cell is always used to make ascending and descending measurements, this term best describes the load cell's actual error from the straight line drawn between the ascending and descending curves.

Additional Recommended Reading

Morehouse Calculation Guidance Morehouse Calculations found on Certificates of Calibration

Force Calibration for Technicians and Quality Managers – 333 pages + E-book

Additional Information

Visit www.mhforce.com for additional guidance on adapters, uncertainty, calibration techniques, etc.

Your time is valuable. Morehouse wishes to thank you for taking the time to read this document.

About Morehouse Instrument Company

Our purpose is to create a safer world by helping companies improve their force and torque measurements. We have several other technical papers, guidance documents, and blogs that can add to your knowledge base. To learn more and stay up to date on future documents and training, subscribe to our newsletter and follow us on social media.

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Follow us on social media.

Contact Morehouse at info@mhforce.com or 717-843-0081.

References

[1] ISO 376, https://www.iso.org/standard/44661.html
[2] ISO 376, https://www.iso.org/standard/44661.html
[3] ISO 376, https://www.iso.org/standard/44661.html
[4] ISO 17025:2017 https://www.iso.org/standard/66912.html
[5] ILAC P14:09/2020 section 5.1 0 https://ilac.org/publications-and-resources/ilac-policy-series/
[6] EURAMET cg-4 https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-4__v_2.0_Uncertainty_of_Force_Measurements.pdf
[7] EURAMET cg-4 https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-4__v_2.0_Uncertainty_of_Force_Measurements.pdf