How to Develop an Uncertainty Budget for a Morehouse Calibrating Machine

using ASTM E74 as the Calibration Standard

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Introduction

Many people often ask, "What is the best uncertainty I can expect to achieve when using a Morehouse calibrating machine?" It is indeed a great question, and the answer varies depending on several different factors. This article will identify all significant contributions to measurement uncertainty when using a Morehouse calibrating machine. It will cover what is needed to achieve a measurement uncertainty of better than 0.02 % of the applied force.

We achieve an uncertainty of better than 0.01 % of the applied force at Morehouse using very stringent guidelines and multiple load cell standards. However, we recommend laboratories use standard equipment capable of achieving uncertainty of better than 0.02 % of the applied force because the equipment required is at a price point that many can afford. For example, an uncertainty of better than 0.01 % of the applied force requires an indicator with six decimal places of precision at the cost of $50,000. In comparison, an uncertainty of better than 0.02 % of the applied force can be achieved with an indictor priced at under $3,000, such as the Morehouse 4215.

For Morehouse calibrations above 120,000 lbf, we send our standards to labs using deadweight primary standards. We use the National Institute of Standards and Technology (NIST) for our calibration laboratory with deadweight standards above 120,000 lbf. On calibrations under 120,000 lbf, we use our deadweight primary standards, and many of them are calibrated by NIST. The calibration using primary standards leads to the crucial first consideration, which is metrological traceability.

Figure 1: Morehouse Universal Calibrating Machine (UCM)

Figure 2: Morehouse [Portable Calibrating Machine (PCM)]

Consideration #1: Importance of Metrological Traceability

Metrological traceability is defined as the "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."**[1] This means that the laboratory using the equipment must consider the uncertainty of the measurement at the reference laboratory. You cannot have uncertainty or accuracy that is less than the measurement uncertainty of the reference laboratory. **For example, suppose the reference laboratory reports an uncertainty of 0.02 % of the applied force. In that case, the laboratory's uncertainty using the equipment must be higher than 0.02 % of the applied force. A laboratory cannot have an uncertainty of 0.0125 % of full scale when the reference laboratory performing the calibration is only capable of 0.02 % of the applied force.** The math does not work.

What does work is calculating the uncertainty following ISO/IEC 17025:2017, which states, "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."[2] and "A laboratory performing calibrations, including of its equipment, shall evaluate the measurement uncertainty for all calibrations."[3]

Consideration #2: Proper Adapters for Calibration

When performing a calibration, it is essential to replicate how the equipment is being used accurately. Using the proper adapters will help align the main loading force axis. Keeping the line of force pure (free from eccentric forces) is key to the calibration of load cells. ASTM E74-18 states, "Force-measuring instruments have sensitivity in varying degrees depending on design to mounting conditions and parasitic forces and moments due to misalignment. A measure of this sensitivity may be made by imposing conditions to simulate these factors, such as using fixtures with contact surfaces that are slightly convex or concave, or of varying stiffness or hardness, or with angular or eccentric misalignment, and so forth. They can replicate use, which then gives the end-user a much better probability of reproducing the calibration results."[4]

Figure 3: Morehouse Load Cell Indicating the Line of Force

Not using the proper adapters to calibrate load cells, truck and aircraft scales, tension links, dynamometers, and other force-measuring devices can produce significant measurement errors and pose serious safety concerns. The service life for force calibration adapters depends on several factors, including the material, design, manufacturing, number of load cycles, and magnitude of each load. There may come a time when the material begins to lose strength and eventually break due to fatigue.

There are material and manufacturing control processes in place today that provide design engineers with more reliable strength values than decades ago. Computer programs also greatly help in modeling and conducting all kinds of stress analysis. We often get asked, "What should we do with older adapters?" Our guidance is to visually inspect all adapters for wear or fatigue signs and replace them if they show any signs of potential failure. We recommend replacing adapters that have been in use for more than 20 years or 100,000 load cycles (10,000 calibrations). Adapters today are designed for a life cycle of at least 500,000 load cycles (50,000 calibrations) and failure at close to 1,000,000 load cycles.

In our technical paper on adapters, we cover error sources from proper alignment of various load cells, and how Morehouse adapters can be used to fix alignment issues on load cells, button cells, washer cells, and various other force-measuring instruments. There are adapters for replicating the tire footprint for aircraft and truck scales, as well as for handheld force gauges, tension links, and multi-axis load cells. These error sources can be very significant as shown below in one example of a tension link calibration.

If a calibration laboratory decides to use a pin that is different from manufacturer's recommendations, then there will be larger than expected bias. For example, the tension link below was loaded to 50,000 lbf with two different size load pins. When it was loaded with a 2-inch pin the device read 50,000 lbf, but with a 1.85-inch pin the device read 49,140 lbf. When the end user does not send in an adapter, the calibration laboratory must load the device with some pin, which may not be the correct size.

Figure 4: Tension Link Loaded into a Morehouse Deadweight Machine with Accuracy of Better than 0.002 % of the Applied Force

Finding the right pin size can be tricky because the manufacturer's recommendations may be counter intuitive. For example, a 20-ton tension link may require a 2.0-inch pin and a 25 ton tension link may require a 1.97 (50mm) pin. It may seem like 0.03 inches will not make a difference and the laboratory should go ahead and test it. However, on a device with an accuracy specification of 0.1 % of full scale, Morehouse has observed a change of 0.03 inches to use up 70 % of that specification.

Knowing these issues, Morehouse has designed clevis assemblies for use with our quick-change tension adapters. These assemblies' cross reference the manufacturer's recommended pin size and allow the calibration laboratory to calibrate hundreds of tension links, crane scales, dynamometers, and rod-end load cells with the same clevis. Not only does this simplify the logistics of having the proper adapter, but it also improves cycle time and standardizes the calibration process.

Figure 5: Morehouse Clevis Assemblies

For more Information on the selection of proper adapters, read the Morehouse technical paper on Recommended Compression and Tension Adapters for Force Calibration found at https://www.mhforce.com/Files/TechnicalPaper/16/TechnicalPaper.pdf

Consideration #3: Accuracy is not a Method of Validation

Many calibration laboratories have standard practices to use accuracies as a method of validation. When the device does not meet the specification, the technician will adjust it in their machine, which has unknown errors, to meet the tolerance requirements. The main problem with this method is that you will not know the calibration laboratory used to deem the necessary adjustments. If you use the wrong pin size on a tension link, you could adjust something out of tolerance because of the technician's mistake. For example, if they used a pin size that was too small to measure 1 %, and they adjusted it back to 0.1 % of full scale, they have now created a device that is likely in error by 0.9 % or more.

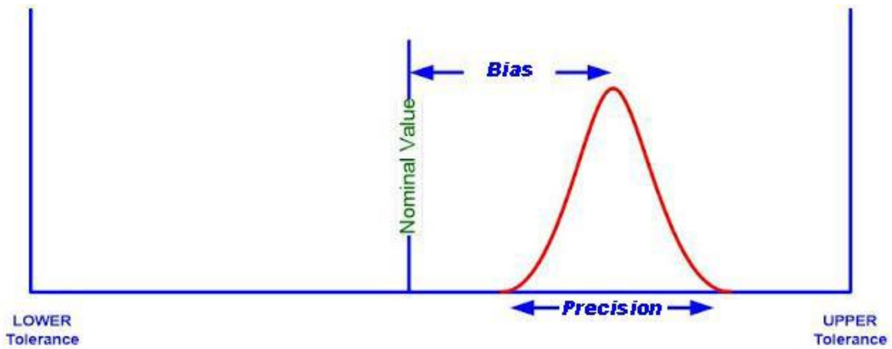

Figure 6: Accuracy

Accuracy is many times confused with uncertainty. Accuracy is defined as "Closeness of agreement between a measured quantity value and a true quantity value of a Measurand."[5] It does not usually include any additional contributors to measurement uncertainty. Therefore, it is likely that an accuracy report will tell you how far the measurement is from the actual value when it is tested, also known as bias. However, it is not likely to include additional Information on measurement uncertainty, such as

- reference standard uncertainty
- reproducibility
- influence of the operator
- resolution of the system
- stability from one calibration to the next
- environmental errors
- error sources from adapters, machines, or the overall process

Consideration #4: Contributions to Uncertainty

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 will likely be much more than any accuracy statement. Uncertainty may not include the bias from accuracy and will be broken down into several contributors. Of these contributors, uncertainty is often broken down into two types: 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)

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 force-measuring instrument used for repeatability studies
- Reference standard uncertainty
- Reference standard stability
- Environmental factors
- Other error sources

Consideration #5: Reducing Error Sources

Figure 7: Morehouse Primary Standard [Deadweight Calibrating Machine (DCM)]

Laboratories with top-quality force calibration machines, such as deadweight machines, are classified as primary standards. If designed correctly, error sources such as these can be reduced:

- Repeatability of the force measurement instrument: Several laboratories have found the repeatability of a top-quality force-measuring instrument using primary standards to be less than 0.0005 %.
- Resolution: The resolution of a top-quality force-measuring instrument can be better than 0.0002 % if high-quality indicators reading six decimals places are used.
- Reproducibility and repeatability between technicians: When combined with the proper adapters, reproducibility and repeatability between technicians are often insignificant. The Morehouse force measurement uncertainty tool has methods for testing reproducibility and repeatability between technicians using ANOVA (Analysis of Variances). Tests must be performed to prove the appropriate significance of these errors.

It is essential to understand that these three error sources may be insignificant using deadweight primary standards but can become significant at the next measurement tier, which often involves more factors than just alignment and proper adapters. For example, it likely that there will be some sort of control, whether manual or automatic. Timing and the inability to hold the force point for 20 seconds can be problematic.

Measurement errors due to timing are addressed in ISO 376, "The time interval between two successive loadings shall be as uniform as possible, and no reading shall be taken within 30 s of the start of the force change."[6] Most automated machines take on the fly or measurements close to the desired force point, and the data is corrected at the end of the run. It is a requirement of the ISO standard for all raw data to be kept and stored. Per ISO/IEC 17025:2017, "Original observations, data and calculations shall be recorded at the time they are made and shall be identifiable with the specific task." [8] Therefore, anyone using automated machines must ensure the raw data is being stored properly and available to the end-user, if requested.

Consideration #6: Common Error Sources

The force-measuring instrument's end-user must ensure the laboratory performing the calibration replicates how the instrument will be used. Fixturing and adapters used with a force-measuring instrument may significantly contribute to the force-measuring instrument's overall uncertainty. Morehouse has observed errors as high as 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
- Alignment (this can be overcome with proper adapters)
- Using a different hardness of adapter than was used for calibration
- Using different size adapters than what was used for calibration as shown in Consideration #2
- 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 the application is different
- 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 to the current machine and realized value from the deadweight calibration

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

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Figure 8: Morehouse Universal Calibrating Machine (UCM)

This section will give specific guidance for Consideration #4: Contributions to Uncertainty and includes the best methods to develop a measurement uncertainty budget when using a Morehouse calibrating machine. Morehouse has developed a force measurement uncertainty tool that contains mathematical and statistical equations to help the end-user calculate measurement uncertainty correctly. The user can enter calibration data to determine each test point's uncertainty. The data is automatically calculated and graphed for easy analysis! Many of the tables below are excerpts from this tool. The spreadsheet is available for downloaded at measurementuncertainty.info. There are other Excel spreadsheets available from various force calibration laboratories to calculate measurement uncertainty. When a spreadsheet is used, the laboratory should conduct validation of the spreadsheet templates.

The CMC uncertainty parameter contributions are similar to the Type A and Type B contributions outlined above.

Morehouse Guidance for Type A Uncertainty Contributions

- ASTM **llf needs to be reduced to** 1 Standard Deviation (*k*=1) as the ASTM **llf** is reported on calibration certificates with *k*= 2.4.
  Note: ASTM **llf** is called out 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.
- Repeatability conducted with the best existing force-measuring instrument
- Repeatability and reproducibility between technicians
  Note: Repeatability and Reproducibility are from an R & R study and should not be confused with repeatability conducted with the best existing force-measuring instrument. The end-user must determine if these errors are significant and should be included in the final uncertainty budget.

Morehouse Guidance for Type B Uncertainty Contributors

- Resolution of the best existing force-measuring instrument
- Reference standard resolution (if applicable)
- Reference standard uncertainty
- Reference standard stability
- Environmental factors
- Other error sources (typically side load sensitivity for a Morehouse calibrating machine)

All uncertainty contributions should be combined. 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.

Force-measuring instruments calibrated according to the ASTM E74 standard are continuous reading force-measuring instruments, and uncertainty analysis should be conducted on several test points used throughout the loading range. The % Contribution Column in the table below is useful in determining significant contributors to uncertainty.

	Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
1	**Repeatability Between Techs**	**0.032435888**	**A**	Normal	1.000	1	32.44E-3	1.05E-3	0.24%
2	**Reproducibility Between Techs**	**0.006481823**	**A**	Normal	1.000	10	6.48E-3	42.01E-6	0.01%
3	**Repeatability**	577.3503E-3	A	Normal	1.000	3	577.35E-3	333.33E-3	75.66%
4	**ASTM LLF at 1 Standard Deviation**	104.1667E-3	A	Normal	1.000	32	104.17E-3	10.85E-3	2.46%
5	**Resolution of UUT**	25.0000E-3	B	Resolution	3.464	200	7.22E-3	52.08E-6	0.01%
6	**Environmental Factors**	75.0000E-3	B	Rectangular	1.732	200	43.30E-3	1.88E-3	0.43%
7	**Reference Standard Stability**	500.0000E-3	B	Rectangular	1.732	200	288.68E-3	83.33E-3	18.91%
8	**Ref Standard Resolution**	25.0000E-3	B	Resolution	3.464	200	7.22E-3	52.08E-6	0.01%
9	**Other Error Sources**	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	1.70%
10	**Reference Standard Uncertainty**	100.0000E-3	B	Expanded (95.45% k=2)	2.000	200	50.00E-3	2.50E-3	0.57%
				Combined Uncertainty (u_c)=			**663.77E-3**	**440.59E-3**	**100.00%**
				Effective Degrees of Freedom			**5**		
				Coverage Factor (k) =			**2.57**		
				Expanded Uncertainty (U) K =			**1.71**	**0.03413%**	

Table 1: Single point uncertainty analysis for a force-measuring instrument calibrated following the ASTM E74 standard

Data Utilized for Uncertainty Analysis in Table 1

1 & 2: Repeatability and Reproducibility between Technicians 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 taking 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.

All technicians who perform force calibrations on the machine should participate in these tests. The test will show if there are differences between technicians and may lead to better training if one technician has measurement results that are not in line with others. Getting all technicians to have a close agreement with these measurements will improve measurement process uncertainty for the calibration laboratory.

	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**

Table 2: Repeatability and reproducibility between technicians

3: Repeatability data must 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. In a Morehouse calibrating machine, we recommend taking data points throughout the range that calibrations are performed. Most Morehouse calibrating machines can be used from about 0.2 - 0.3 % of rated capacity and achieve acceptable results. All Morehouse calibrating machines can apply force from 1 % of rated capacity to capacity.

In a machine with a tare weight of 750 lbf, a smaller capacity load cell should be avoided. To avoid overloading the load cell, the smallest load cell that should be used is one rated at 5 % of the total capacity. For example, in a 100,000 lbf Morehouse UCM, the load cell used should be more than 5,000 lbf. At 5,000 lbf, about 5,750 lbf will be applied to the load cell because of the machine's tare weight. Many load cells will not be hurt because they are designed to be loaded up to 140 % of capacity.

At around 150 % of capacity, the zero may shift, and the cell may become overloaded. It is essential to check the manufacturer's specification sheet for the exact safe overload because not all load cells can be taken this high. At Morehouse, we have tested our shear-type load cells and confirmed that zeroing or taring out up to 15 % of the load cell's capacity will produce the same output as with no tare load applied. However, not all load cells will perform the same way as the Morehouse tested load cells.

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**	

Table 3: Repeatability for one data point

4: ASTM llf = 0.25 force units is found on the calibration report. The standard uncertainty of 104.17E-3 is the result of dividing 0.25 by 2.4 to get one standard deviation. If the report lists the standard deviation as calculated per section 8 of the ASTM standard, use it 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%

Table 4: ASTM llf at one standard deviation

5: Resolution of Unit Under Test (best existing force-measuring instrument) = 0.25 force units. The resolution of any load cell can be calculated by dividing the force applied by the output of the load cell and then multiplying by the readability. For example, a 10,000 lbf load cell with a 4 mV/V output will have a resolution of 2,500 lbf per 1 mV/V. Multiply the 2,500 lbf by the readability of 0.00001 to get 0.025 lbf.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Resolution of UUT	25.0000E-3	B	Resolution	3.464	200	7.22E-3	52.08E-6	0.01%

Table 5: Resolution of the unit under test (UUT)

6: Environmental Factors data must be taken for various test points throughout the loading range. This example only shows one arbitrary data point. In this example, ± 1°C was used, which is found on the manufacturer's specification sheet. The temperature effect is 0.0015 percent per °C. If the reference laboratory controls the temperature to within ± 1°C, then the contribution formula is Force Applied * Temperature Specification per 1°C = Environmental Factor Error. 5,000 Force Units * 0.0015 % = 0.075 force units

Additional Example: If a calibration laboratory is operating at a temperature range of 20°C to 27°C, the maximum difference from the temperature at the time of calibration should be used. If Morehouse performed the calibration at 23°C ± 1, the worst-case scenario would be 27°C – 22°C = 5°C. Following the above guidance, If the reference laboratory controls the temperature to within + 5°C and -2°C of the reference laboratory, then the maximum difference from the reference laboratory should be used. The uncertainty contribution formula is Force Applied * Temperature Specification for 5°C = Environmental Factor Error. 5,000 Force Units * (0.0015 % * **5**) becomes 5,000 Force Units * (0.0075 %) = 0.375 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	0.43%

Table 6: Environmental factors

7: Reference Standard Stability data must be taken for various test points throughout the loading range. This example only shows one arbitrary data point. A 0.01 % change between the same 5,000 force units calibration point was used, which corresponded to 0.5 force units. It is worth noting that drift can be controlled by having calibrations performed at a more frequent interval. The stability is found by comparing the output of a force-measuring instrument from a previous calibration with the output from the current calibration throughout each point in the measurement range.

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	18.91%

Table 7: Reference standard stability

Additional Information on Reference Standard Stability:

There are several ways to calculate reference standard stability. The above example is the simplest in just comparing the percentage change of a force-measuring instrument from a previous calibration with the output from the current calibration throughout each point in the measurement range. The below guidance contains additional Information on the importance and magnitude reference standard stability can have on the overall measurement uncertainty. The Information is for informative purposes.

A load cell is a force-measuring instrument. It is a combination of metal, strain gauges, adhesive, and more. Like humans, every measuring instrument is subject to aging. Load cells age from mechanical stress or fatigue over time; this ensures that there will be some instability in the system. Instability cannot be prevented, but it can be detected and corrected by setting the appropriate calibration cycle. Load cell stability or drift is usually assumed to be the amount of change in the entire cell system from one calibration cycle to the next. It is the relative standard uncertainty of a reference force transducer's long-term instability. In an uncertainty budget, load cell drift can be referred to as either the reference standard instability or the reference standard stability.

Load cell instability can:

· Consume your uncertainty budget

· Cause the force-measuring device to be out of tolerance

· Cause all measurements between the last calibration and the current calibration to be recalled

· Raise the accuracy specification of the system

Calibrating load cells for more than 50 years, Morehouse has observed all kinds of instabilities from different load cell manufacturers. Most load cells we see are categorized as either general purpose or those calibrated in accordance with more stringent standards, such as ASTM E74 or ISO 376.

The load cell and indicating systems are broken down into excellent, good, common, and bad categories. The excellent category is typically a more expensive category with load cells, precisely trimmed and adjusted for optimal performance. Systems that fall into the good category are usually made by reputable manufacturers who understand load cells and indicating systems. The common category consists of suboptimal combinations, such as an excellent load cell and an average indicator, an excellent indicator, and an average load cell. In the poor category, one or both components are not suitable for the end user's overall uncertainty needs.

A Morehouse ultra-precision load cell and a high stability 4215 falls into the excellent category, with 1-year stability that is often between 0.005 % through 0.03 % from approximately 20 % of the rated output. A good system is a Morehouse Calibration Grade load cell, and a stable direct reading type indicator will typically have stability between 0.02 % - 0.1 %. A common system could be a standard column type or rod end load cell 0.05 % - 0.15 %. A bad system such as an S-type load cell with a meter that is not stable within 50,000 counts often has stability well above 0.1 % when using a 1-year calibration interval. We recommend the shear-type load cells when wanting to minimize the uncertainty parameter for drift, as shown in figure 8.

Figure 9: Ultra-Precision Load Cell and a High Stability 4215

For example, an excellent force-measuring system with a stability of 0.01 % may be achieved from year to year. On a two-year interval, that may rise to 0.025 %, at 100,000 lbf, which could almost double the overall uncertainty from less than 0.015 % to 0.03 %. Therefore, shortening the calibration interval can help control the overall drift.

The table below shows the change or drift of a new load cell system during the year. As time progresses, most load cell systems become more stable. Typically, stability is less than 0.01 % after a couple of years of use with a one-year calibration interval. The end-user should monitor the stability of their system and set the appropriate calibration intervals.

	3-Month Calibration Interval		6-Month Calibration Interval		9-Month Calibration Interval		12-Month Calibration Interval	
Applied	Stability %	Expanded Uncertainty	Stability %	Expanded Uncertainty	Stability %	Expanded Uncertainty	Stability %	Expanded Uncertainty
10000.00	0.005	1.93	0.010	2.16	0.020	3.69	0.030	4.69
20000.00	0.005	2.79	0.010	3.41	0.020	6.03	0.030	8.11
30000.00	0.005	3.81	0.010	4.81	0.020	8.37	0.030	11.53
40000.00	0.005	4.73	0.010	6.15	0.020	10.70	0.030	14.95
50000.00	0.005	5.78	0.010	7.58	0.020	13.04	0.030	18.37
60000.00	0.005	7.05	0.010	9.18	0.020	15.37	0.030	21.80
70000.00	0.005	8.03	0.010	10.57	0.020	17.71	0.030	25.22
80000.00	0.005	9.15	0.010	12.06	0.020	20.05	0.030	28.64
90000.00	0.005	10.23	0.010	13.52	0.020	22.38	0.030	32.06
100000.00	0.005	11.24	0.010	14.92	0.020	24.72	0.030	35.48
Note: This is an example of stability. Many load cell system become more stable over time.								

Table 8: Example of stability over a year for a load cell in a new force-measuring system

The additional uncertainty contribution to stability can be minimized by using the appropriate system. This would include a good, dedicated meter such as the Morehouse HADI or 4215, a precision class or better load cell, and the appropriate adapters. When this happens, the stability of a good system can drop to better than 0.01 % for almost all the points from 20 % of the capacity to 100 % of capacity. The smallest change in output at a low force point can impact the results.

8: Reference Standard Resolution is the resolution of the reference standard. In this example, the resolution is 0.025 force units as our load cell output is slightly higher at 4.00214 mV/V. Example ((10,000/4.00214) *0.00001) =0.02498 and when rounded to significant digits becomes 0.025.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Ref Standard Resolution	25.0000E-3	B	Resolution	3.464	200	7.22E-3	52.08E-6	0.01%

Table 9: Reference standard resolution

Additional Information on Reference Standard Resolution:

Resolution of the force-measuring system can change the overall system uncertainty. A 100,000-force measuring system can resolve 6 decimal places 0.000001 mV/V and has an output at capacity of 4.000000 mV/V is going to have a resolution = 100,000 / 4 mV/V * Readability (0.000001 mV/V) 0.025 lbf. If a meter such as the Morehouse 4215 is used with a readability of 5 decimal places or 0.00001 mV/V, then the resolution becomes 100,000 / 4 mV/V * Readability (0.000001 mV/V) 0.25 lbf. Percentagewise at 1,000 lbf force, 0.25 lbf resolution is 0.025 %.

9: Other Error Sources: In this example, the force transfer machine's alignment is 1/16th inch measured off the force transducer's centerline. From the specification sheet side load sensitivity 0.05 % * 0.0625 = 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 what was used for calibration). Another error source may be temperature change under no-load conditions. Loading equipment that is not level, square, and rigid can have significant error contributions.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
Other Error Sources	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	1.70%

Table 10: Other error sources

10: Reference Standard Uncertainty The reference standard uncertainty is often found on the Certificate of Calibrate as what equipment was used to calibrate the Unit Under Test.

TYPE	SERIAL NO.	CMC	NIST NO.	CALIBRATED DATE	CALIBRATION DUE DATE
PRIMARY FORCE STANDARD	M-4930	0.002 % OF APPLIED FORCE (*k*=2)	822/254341-94	9/16/1994	8/26/2030
TEMPERATURE STANDARD	A21299/A782932	0.2 °C (*k*=2)	01145353	7/28/2020	7/28/2021

Figure 10: Example of the CMC Uncertainty on a Certificate of Calibration

This example uses a primary laboratory performing the force-measuring instrument's calibration using deadweight primary standards with a CMC of 0.002 % of applied force. If you had a load cell calibrated in a Morehouse primary standard deadweight machine with an uncertainty of 0.002 % of applied force, Figure 6 above shows. One would take the capacity for the point in question and multiple that by the CMC uncertainty parameter of the standard used at the time of calibration. 5,000 force units * 0.002 % = 0.1 force units divided by the appropriate coverage factor *k* also reported on the calibration certificate 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	200	50.00E-3	2.50E-3	0.57%

Table 11: Reference standard uncertainty

We have stepped through the 10 steps shown in table 1 for a 5,000 lbf force point. When the user is doing their uncertainty budget, they will want to use several points throughout the range. More Information and examples below.

Additional Information comparing Reference Standard Uncertainty

The difference in expanded uncertainty in the table below is shown only by changing the reference standard used to perform the calibration. In this example, we are using a 100,000 lbf load cell and comparing the calibration results using the Morehouse 120,000 lbf primary standard deadweight machine versus a secondary standard Universal Calibrating Machine. Regardless of the capacity, the results between primary and secondary standards are significant. We chose a 100,000 lbf for comparison because we have both primary and secondary standards at this capacity to compare against one another. The previous example used a 10,000 lbf load cell calibrated using a different Morehouse Primary Standard Machine.

In the second column, deadweight standards are used, which are known to within 0.0016 % of applied force. This is compared with the calibration of a laboratory using secondary standards, which are known to within 0.025 % of applied force.

	Deadweight 0.0016 %	Calibration Machine 0.025 %	Difference	Difference	Difference
Applied	Expanded Uncertainty	Calibration Machine 0.025 %	In Uncertainty lbf	In Uncertainty % of Applied	In Uncertainty %
1000.00	1.58	1.59	0.02	0.002%	1.1%
10000.00	1.85	3.05	1.20	0.012%	39.3%
20000.00	2.57	5.51	2.94	0.015%	53.4%
30000.00	3.43	8.09	4.65	0.016%	57.5%
40000.00	4.18	10.63	6.45	0.016%	60.7%
50000.00	5.07	13.23	8.15	0.016%	61.7%
60000.00	6.22	15.91	9.69	0.016%	60.9%
70000.00	7.04	18.49	11.45	0.016%	61.9%
80000.00	8.01	21.12	13.11	0.016%	62.1%
90000.00	8.94	23.73	14.79	0.016%	62.3%
100000.00	9.78	26.32	16.54	0.017%	62.8%

Table 12: Comparison of a 100,000 lbf load cell calibrated with deadweight standards versus secondary standards (calibration machine)

When using secondary standards to calibrate a reference standard, the expanded uncertainty is an additional 0.016 % at full scale. The overall uncertainty will jump from 0.01 % of full scale to 0.026 % of full scale, just from using secondary standards instead of primary standards. The differences shown below are staggering once past the 10 % of capacity force point.

	Deadweight 0.0016 %	Expanded Uncertainty	Calibration Machine 0.025 %	Expanded Uncertainty
Applied	Expanded Uncertainty	% of Applied	Calibration Machine 0.025 %	% of Applied
1000.00	1.58	0.158%	1.59	0.159%
10000.00	1.85	0.019%	3.05	0.031%
20000.00	2.57	0.013%	5.51	0.028%
30000.00	3.43	0.011%	8.09	0.027%
40000.00	4.18	0.010%	10.63	0.027%
50000.00	5.07	0.010%	13.23	0.026%
60000.00	6.22	0.010%	15.91	0.027%
70000.00	7.04	0.010%	18.49	0.026%
80000.00	8.01	0.010%	21.12	0.026%
90000.00	8.94	0.010%	23.73	0.026%
100000.00	9.78	0.010%	26.32	0.026%

Table 13: Expanded uncertainty of a 100,000 lbf load cell with deadweight standards and secondary standards (calibration machine)

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. Additionally, measurement traceability for the indicator will have to be verified to maintain the force measuring system's accuracy.

Example of Morehouse Calibrating Machine Uncertainty

Pictured below is a sample uncertainty summary of what many laboratories expect to see when using standard equipment. The screengrab is from our force measurement uncertainty tool. We are looking specifically at the 100,000 lbf test point. The error sources throughout the range are constant, though they will vary.

Morehouse Sample UCM Uncertainty			
	Applied	Expanded Uncertainty	% Percentage
1	1000.00	1.92	0.1919%
2	10000.00	1.93	0.0193%
3	20000.00	2.57	0.0128%
4	30000.00	3.43	0.0114%
5	40000.00	4.25	0.0106%
6	50000.00	5.16	0.0103%
7	60000.00	6.22	0.0104%
8	70000.00	7.00	0.0100%
9	80000.00	7.96	0.0100%
10	90000.00	8.94	0.0099%
11	100000.00	9.78	0.0098%

Table 14: Universal Calibrating Machine uncertainty

One of the largest error sources in the table below is the miscellaneous error from comparing similar capacity load cells calibrated by deadweight primary standards. If we use this test's error, we no longer need to worry about side load sensitivity because that error and several others will be captured. If we do not use this test, we should add the error due to sideload sensitivity.

Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	0.603909823	A	Normal	1.000	2	603.91E-3	364.71E-3	1.48%	66.5E-3
Reproducibility Between Techs	0.432403257	A	Normal	1.000	27	432.40E-3	186.97E-3	0.76%	1.3E-3
Repeatability	975.7344E-3	A	Normal	1.000	3	975.73E-3	952.06E-3	3.86%	302.1E-3
Standard Deviation	766.6667E-3	A	Normal	1.000	32	766.67E-3	587.78E-3	2.39%	10.8E-3
Resolution of UUT	250.0000E-3	B	Resolution	3.464	200	72.17E-3	5.21E-3	0.02%	135.6E-9
Environmental Conditions	825.0000E-3	B	Rectangular	1.732	200	476.31E-3	226.88E-3	0.92%	257.4E-6
Stability of Ref Standard	1.0000E+0	B	Rectangular	1.732	200	577.35E-3	333.33E-3	1.35%	555.6E-6
Ref Standard Resolution	250.0000E-3	B	Resolution	3.464	200	72.17E-3	5.21E-3	0.02%	135.6E-9
Miscellaneous Error	8.0000E+0	B	Rectangular	1.7321E+0	200.0000E+0	4.62E+0	21.33E+0	86.60%	2.3E+0
Morehouse CMC	1.6000E+0	B	Expanded (95.45% k=2)	2.000		800.00E-3	640.00E-3	2.60%	
			Combined Uncertainty (u_c)=			4.96E+0	24.64E+0	100.00%	2.7E+0
			Effective Degrees of Freedom			228			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			9.78	0.00978%		
Slope Regression Worksheet									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	100000.00	100001.33	99999.01	99999.66	99999.88	99999.97	0.9757	0.0016%	1.6
Repeatability (Of Error)			Average Standard Deviation of Runs			0.975734			

Table 15: Uncertainty contributors

The problem is simple. Without comparing two load cells calibrated by primary standards as shown below in compression, we would have to make a guesstimate and hope we pass any proficiency test. The other benefit of using this comparison test is that if we know about an error, then we can make changes and repeat the test. It is common to purchase better alignment adapters and have a much better result because force measurement is all about keeping the line of force pure, free from eccentric forces.

Figure 11: Primary Standards Calibration in Compression

On any force calibrating machine, comparisons should be made against at least two high-quality reference standards calibrated by primary standards to determine any additional deviation from the reference value. 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, then it is not sufficient simply to increase the CMC to reduce the En value to an acceptable level. Still, the whole uncertainty budget associated with the force calibrating machine should be reviewed to satisfy the National Accreditation Body.

The best method to determine the machine's uncertainty with reference standards is to conduct a test comparing two secondary standards, which are calibrated by primary standards, against each other. Per ASTM E74 appendix X1.5.1.3, the best method to account for the uncertainty related to differences in characteristics of the load frame and measurement system is disseminating calibration values from the primary force standards calibration to secondary force standards calibration. At Morehouse, we typically find these tests to yield results better than 0.01 % of reading when the appropriate adapters and reference load cells are used. This test is very similar to a good PT and helps ensure the overall calculation of uncertainty is correct.

	Deadweight 0.0016 % Reference			
	Expanded Uncertainty		Expanded Uncertainty	
Applied	With 0.003 % Error	% of Applied	With 0.008 % Error	% of Applied
1000.00	1.57	0.157%	1.58	0.158%
10000.00	1.66	0.017%	1.85	0.019%
20000.00	1.97	0.010%	2.57	0.013%
30000.00	2.38	0.008%	3.43	0.011%
40000.00	2.50	0.006%	4.18	0.010%
50000.00	2.84	0.006%	5.07	0.010%
60000.00	3.77	0.006%	6.22	0.010%
70000.00	3.92	0.006%	7.04	0.010%
80000.00	4.43	0.006%	8.01	0.010%
90000.00	4.83	0.005%	8.94	0.010%
100000.00	4.99	0.005%	9.78	0.010%

Table 16: Typical values if additional errors have been eliminated or reduced.

Conclusion

To achieve an uncertainty of better than 0.01 % of full-scale, the laboratory must take the utmost care in using the proper adapters, having the force-measuring system calibrated at a frequent interval (likely 1-year), having the proper technician training, using the right indicating equipment, and running statistical process controls with an additional force measuring system. Additionally, their standard must be calibrated by primary deadweight standards. There is no secondary transfer machine or method available to produce expanded uncertainties of less than 0.01 % of applied force.

The examples provided above prove the importance of the reference standard in relation to overall expanded uncertainty. Deadweight primary standards are predictably the best possible reference standard. A laboratory using secondary standards calibrated by deadweight can achieve expanded uncertainties as low as 0.01 % of the applied load if using several standards. Our above example shows that standard changes may be required at every 30 – 40 % capacity to achieve an uncertainty of better than 0.01 % of applied force. If the target uncertainty is to be better than 0.025 % of the applied force, then one additional standard will need to be added at around 10 – 20 % of the capacity test point.

Overall, it depends on how the end-user controls the additional errors and how frequently calibration the force-measuring system will determine the number of standards required to maintain the appropriate uncertainty. The lower the measurement process uncertainty, the better the calibration, and the higher the likelihood of making the appropriate measurements and not failing as many instruments by making statements of conformance to a specification. Such as passing essential and vital equipment as part of the calibration procedure. Please contact us at info@mhforce.com with any additional questions.

Definition of Terms

- 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

  Note: The scope of calibration is where one will find the best capability a company can achieve. It is important to check this when deciding on who to use for a calibration laboratory. If the scope says the best a company can do is 0.02 % from 1,000 lbf through 100,000 lbf, you cannot have uncertainty or accuracy better than that. Also, the best a company can do is usually what is reported on the certificate, though that does not mean that your equipment will be put in the same equipment as used for the CMC. It is imperative to ask the calibration provider about their measurement capability. Morehouse can calibrate equipment up to 120,000 lbf known to within 0.0016 % of applied force. However, if someone sends in an instrument that is 36 inches long, we cannot fit it in that machine, and therefore, the best we can do is 0.01 % of applied in our elongated Universal Calibrating Machine.

- Environmental Factors: Environmental conditions, such as temperature, influence the force transducer output. The most common specification is the temperature effect found on the force-measuring instrument's specification sheet. It is important to note that any deviation in environmental conditions from the temperature that the force-measuring instrument was calibrated at must be accounted for in the measurement uncertainty, using the user's force transducer measurements.
  For example, the laboratory calibrated a force-measuring instrument at 23°C. The force-measuring instrument is then used from 13-33°C or ±10°C from the calibration. Based on the manufacturer's specification, this temperature variation could cause an additional change on the force output by 0.015 % reading per °C, or 0.15 % reading for ±10°C. This number is typically found on the force transducer's specification sheet as Temperature: Effect on Sensitivity, % Reading/100 °C or °F. The value 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).

- Hysteresis: The phenomenon in which the value of a physical property lags changes in the effect causing it, as for instance when magnetic induction lags 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 it is expressed in units of % full scale. It is normally calculated between 40 - 60 % of full scale.

- Lower limit factor (llf): This is an ASTM specific term. 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.

- 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 it is expressed in units of % of full scale. It is normally 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 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 errors from misalignment, not exercising the force-measuring 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 and rigid can have significant contributions.
- Primary Standard: Per ASTM E74, a deadweight force is 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 and 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.
- Reference Standard(s) Stability: The change in the 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): The 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 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, which is also known as pooled standard deviation. The purpose of this test is to determine 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 10% 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.

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. 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): The 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): The smallest difference between displayed indications that can be meaningfully distinguished.
- Reproducibility condition of measurement, reproducibility condition (JCGM 200:2012, VIM 2.24): The 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 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.

References

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