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THE FORCE IN CALIBRATION SINCE 1925

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Force Calibration for Technicians and Quality Managers

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Top Conditions, Methods, and Systems that Impact Force Calibration Results

Calibration might not be glamorous, yet it matters!

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Introduction

Morehouse Instrument Company has shared tremendous knowledge throughout the years with blogs, technical papers, classes, and webinars. This education aligns with our purpose to create a safer world by helping companies improve their force and torque measurements.

The information can be overwhelming when someone is new to calibration or metrology. There is so much to digest that people can quickly become overwhelmed. Some have joked that an introduction to metrology is like drinking through a firehouse.

Morehouse has created this book to help anyone with their force measurement needs or challenges to simplify things. The book will help anyone from beginner to seasoned metrologists. It is a combination of a century of experience concerning making force measurements.

Even seasoned metrologists or technicians with years of experience may learn something new, or this document can be a refresher for more advanced people. In either case, the knowledge gained will help you become better and help make better force measurements to make the world safer.

We hope you enjoy it!

Note: The book revisits certain concepts and definitions multiple times. This deliberate choice aims to improve reader understanding. By grouping related information within specific sections, readers can easily navigate to a particular topic, ensuring they find the necessary information to comprehend that specific subject effectively.

Figure 1: Force Calibration Basics

Force Calibration and its Importance.

What is Force Calibration?

In his second law, Sir Isaac Newton stated that force controls motion; therefore, we must control the force if we are to control the motion. An example of force: I have an egg in my hand and want to break it by squeezing it in my hand. This egg will break at X known force. No matter where I am on Earth, the same force will be required to break the egg in my hand. It will not take less force to break this egg in Pennsylvania than in Peru.

A simple physics definition for force is mass times acceleration (F = m x a). As shown in the illustration below, force is a derived unit from the SI base units of Mass, Time, and Length. The International Committee for Weights and Measures in the Bureau International des Poids et Mesures (CIPM/BIPM) defines 1N as the force required to accelerate 1 kg to 1 meter per second per second in a vacuum.

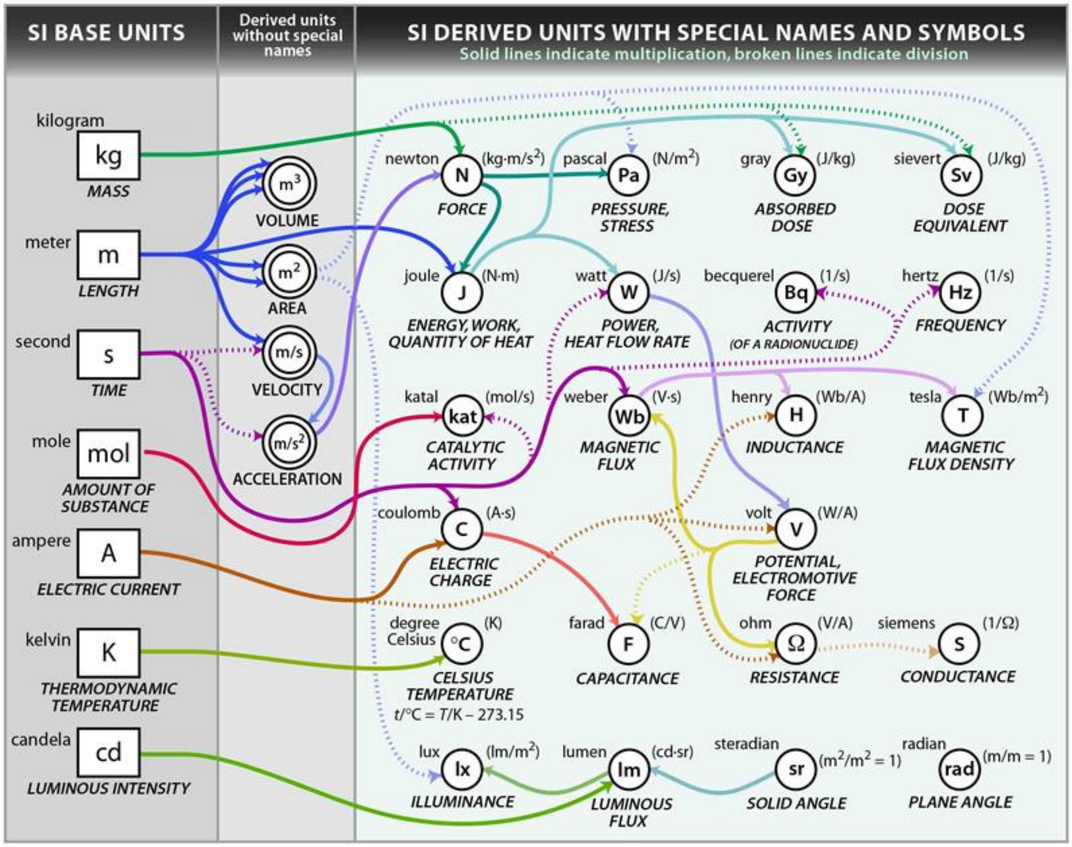


Figure 2: SI Units courtesy of NIST [1]

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a specific error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Therefore, force calibration compares a force instrument to a force reference standard to characterize the instrument.

Why is Force Measurement Important?

The most straightforward answer is that bridges and other objects do not collapse when forces are exerted upon them. When building a bridge, it is essential to get the concrete strength measurement correct. Ensuring the steel is tested, and the cables are appropriately checked for prestress or post-tension is essential. Bad things happen when these measurements are incorrectly done, as shown below.

Figure 3: Bridge Failure

In the example below, the ripeness of apples is being checked. Why may that be important? If you are in California and want to distribute apples nationwide, the harder ones will last longer and ripen during shipment. In contrast, the softer ones might be distributed locally.

Figure 4: Testing Apple Ripeness

The example below shows the fishing line being tested. I am sure any fisherman would not want the line to break as they haul in their prized fish.

Figure 5: Testing Fishing Line

In general, force measurement is performed so frequently that we take it for granted. However, almost every material item is tested using some form of traceable force measurement. Testing may vary from sample testing on manufactured lots, including anything from the materials used to build your house to the cardboard on a toilet paper roll.

How a Transducer Measures Force

What is a Transducer?
In the broad sense of the term, a transducer is a device that turns one type of energy into another. Some examples are:

Figure 6: A Battery is a Transducer

1. A battery is a transducer that converts chemical energy into electrical energy. The chemical reactions involve electrons flowing from one material to another through an external circuit.

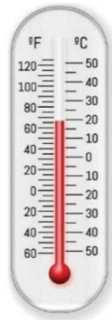


Figure 7: A Thermometer is Transducer

2. A thermometer is a transducer that converts heat energy into the mechanical displacement of a liquid column. As the temperature around the bulb heats up, the liquid expands and rises.

Figure 8: A Load Cell is a Transducer

3. A load cell is a transducer that converts mechanical energy into electrical signals. As compressive or tensile force is exerted on a load cell, the mechanical energy is converted into equivalent electrical signals.

Compression and Tension Force Calibration

This section covers compression and tension and how they relate to force calibration.

What is Compression Calibration?

When discussing compression calibration, we should think about something being compressed or squeezed. I like to describe compression calibration as pushing or squeezing something.

Figure 9: Compression Calibration Examples

Above are two examples of a compression setup in a calibrating machine. The machine on the left compresses both load cells by creating an upward force. The picture on the right shows a deadweight machine compression setup where a downward force compresses the load cell.

The key to this type of calibration is ensuring everything is aligned, and the line of force is as straight as possible. I like to say free from eccentric or side forces. The key to proper alignment is using the right adapters in the calibrating machine, from alignment plugs to top adapters.

Morehouse has a technical paper on recommended compression and tension adapters for force calibration that can be found on our website.

What is Tension Calibration?

When discussing tension calibration, we should think of something being stretched. I like to describe tension calibration as a pull.

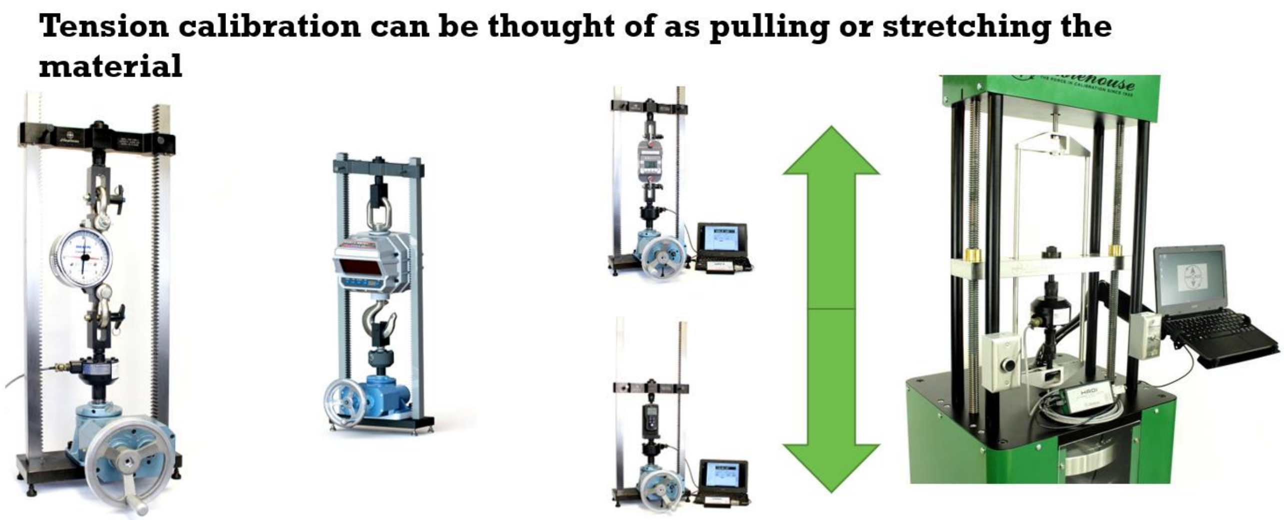


Figure 10: Tension Calibration Examples

Above are multiple examples of tension setups in calibrating machines. The machine on the left is the Morehouse benchtop calibrating machine. A dynamometer is fixed to a stationary beam, and force is generated by pulling on the load cell and the dynamometer. More examples are shown with different instruments, from crane scales to hand-held force gauges. The picture on the right shows a load cell fixtured for tension calibration in a Morehouse deadweight machine. The load cell is fixtured to the frame, and the weights are applied and hung, which stretches the material. The key to getting great results in tension calibration is also adapters.

The ISO 376 Annex gives excellent guidance on adapters that help keep the line of force pure. It states, "Loading fittings should be designed so that the line of force application is not distorted. As a rule, tensile force transducers should be fitted with two ball nuts, two ball cups, and, if necessary, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads."[2] Morehouse follows the ISO 376 standard for several of our products. We also design adapters to help technicians and end-users replicate and reproduce calibration results.

How a load cell measures compression and tension force

As force is exerted on a load cell, the material deflects. The deflection is typically measured by a strain gauge, which is placed on the material inside the load cell.

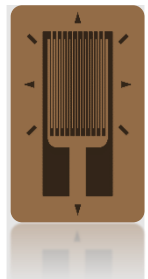


Figure 11: An Example of a Strain Gauge

When placed appropriately, the strain gauge will measure the change in resistance as force is applied. The ideal load cell only measures force in defined directions and ignores force components in all other directions. Approaching the ideal involves optimizing many design choices, including the mechanical structure, gauge pattern, gauge placement, and the number of gauges.

Sometimes, you may only have one strain gauge. Two can be common in cheap loadcells like bathroom scales. Four is the most common. More gauges are usually used to increase some aspects of performance. Sixty-four is the most we've ever heard of on one bridge.

Compression shortens the wire, causing a decrease in its resistance, while tension stretches the wire, causing resistance to increase. If we can imagine a column with strain gauges on it and we apply a compressive force, its diameter will increase, and when a tensile force is applied, its diameter decreases.

The proportional change in diameter is predicted by Poisson's ratio. 'Poission's ratio' is the ratio of transverse strain (change in diameter) to axial strain (change in length).

If a strain gauge is bonded to the column to measure this circumferential strain, the strain gauge's resistance changes directly in response to the applied force. The change in resistance of an axially oriented strain gauge is opposite to that of a circumferentially oriented strain gauge when force is applied.

When we measure the resistance of the gauge under load, the force can be computed. A meter or indicator displays the force measurement value when hooked to a load cell. A load cell may be calibrated at a company like Morehouse using deadweight primary standards known to be within 0.002 % of applied force. The machine's deadweights are adjusted for local gravity, air density, and material density to apply the force accurately. The weights are used to calibrate the load cell, which may be used to calibrate other instruments or calibrate and verify a testing machine.

Calibration versus Verification

Calibration and verification are not the same. This section describes the differences between calibration and verification.

What is Calibration?

Let me start by stating that there are several calibration definitions across multiple standards. My favorite definitions are below:

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Thus, we are comparing something that we know to some degree of certainty to something that may not be known or that needs to be checked at a time interval to ensure drift and other characteristics are controlled. Thus, in simple terms, calibration can be thought of as validation.

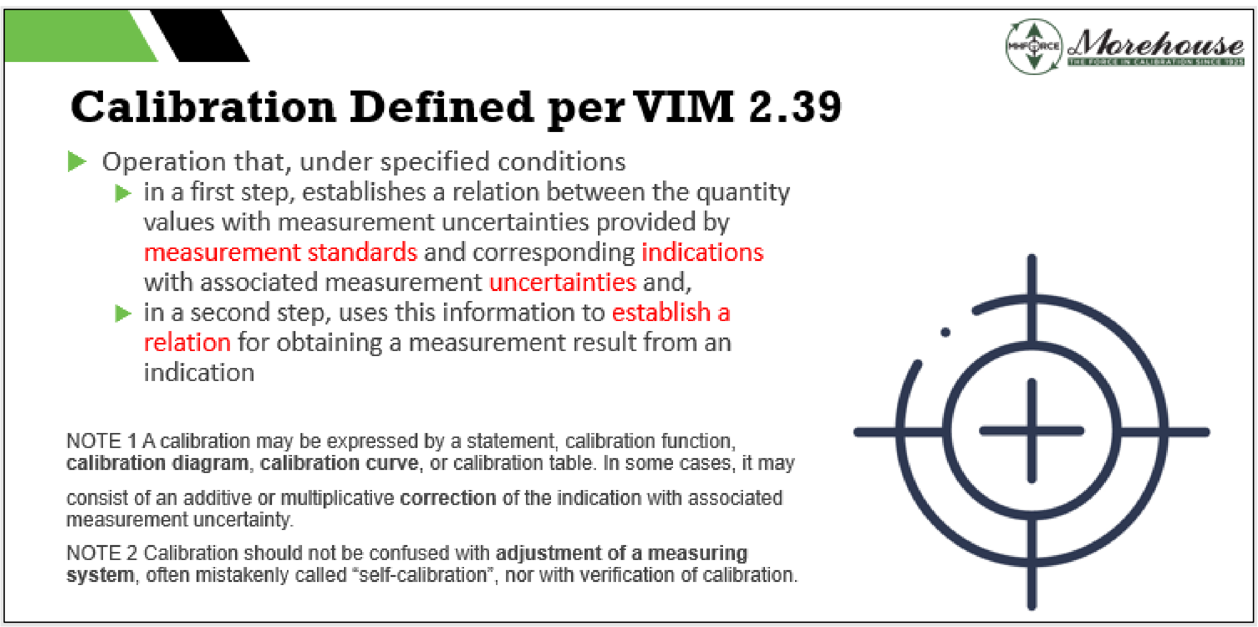


Figure 12: Calibration Definition

The definition from the International Vocabulary of Metrology (VIM) in section 2.39 is interesting because many assume calibration is also an adjustment. It is not. The VIM is clear in Note 2: "Calibration should not be confused with a measuring system, often mistakenly called "self-calibration," nor with verification of calibration." Think about it this way: when you send most instruments to a National Metrology Institute, such as NIST, they only report the device's value at specific points and the associated measurement uncertainties. Why? Because the end-user can take those values and use those values with the associated measurement uncertainties as a starting point to characterize whatever is being tested. Measurement uncertainty will be explained in the next section.

When an end-user uses a calibrated device, it is often under different conditions than when it was calibrated. For example, if Morehouse calibrates a device in one of our deadweight machines known to be better than 0.002 % of applied force, and the end-user later uses this device, the conditions will vary. It is almost certain that their use conditions do not exactly replicate the lab's calibration. For example, the temperature, rigidity of the machine, and hardness of adapters could vary, and their machine could introduce torsion, etc. These are a few of several conditions that can impact the results.

I want to explain that Morehouse calibrates the device and assigns a value that can be considered the expected performance of the device under the same conditions at which it was calibrated. The end-user then varies those conditions, which adds additional measurement uncertainty. Therefore, the end-user can use the calibration data as a starting point to evaluate their measurement uncertainty.

What is Verification?

The VIM in section 2.44 defines verification “as the provision of objective evidence that a given item fulfills specified requirements.” Then, the VIM goes on to list several additional examples and notes:

- Example 1: Confirmation that a given reference material as claimed is homogeneous for the quantity value and measurement procedure concerned, down to a measurement portion having a mass of 10 mg.
- Example 2: Confirmation that performance properties or legal requirements of a measuring system are achieved.
- Example 3: Confirmation that a target measurement uncertainty can be met.

Note 1: When applicable, measurement uncertainty should be taken into consideration.
Note 2: The item may be, e.g., a process, measurement procedure, material, compound, or measuring system.
Note 3: The specified requirements may be, e.g., that a manufacturer's specifications are met.
Note 4: Verification in legal metrology, as defined in VIML [53], and in conformity assessment in general, pertains to the examination and marking and/or issuing of a verification certificate for a measuring system.
Note 5: Verification should not be confused with calibration. Not every verification is a validation.
Note 6: In chemistry, verification of the identity of the entity involved or of activity requires a description of the structure or properties of that entity or activity.

For example, a 10,000-load cell, like the one shown below, is submitted to Morehouse and found to be within ± 5 lbf, per the customer's required tolerance of 0.05 % of full scale.

Figure 13: Morehouse Ultra-Precision Load Cell

In this scenario, verification is more of a conformity assessment and should not be confused with calibration. However, many commercial laboratories perform calibration by reporting the applied force and the device's corresponding measurement values for calibration. Then, they make a conformity assessment, a statement to the end-user that the device is either in or out of tolerance. They typically say a device passes calibration or fails calibration.

The critical detail here is that measurement uncertainties must be reported to ensure measurement traceability. **You should not perform a calibration with a statement of verification without reporting the measurement uncertainty. That uncertainty should be considered when making a statement of conformance to a specification.**

Therefore, these definitions and examples show that calibration and verification are different.

Measurement Uncertainty

What is Measurement Uncertainty?

What measurement uncertainty is not is just an error. Understanding the differences between these two terms is imperative, as they are often confused. Measurement error is often described as the difference between the measured value and the device's actual value, or artifact being measured (measured value minus a reference value). We often try to correct known errors by applying corrections from the calibration certificate. These corrections can be a curve, a diagram, a table, and all items found in note 1 of the calibration definition from the VIM.

Uncertainty, often referred to as 'doubt,' is the quantification of 'doubt' about the measurement result. The VIM in section 2.26 defines Uncertainty as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. The VIM goes into further detail with several notes about the components of measurement uncertainty, such as those arising from systematic effect, components associated with corrections, assigned quantity values of measurement standards, etc. Measurement Uncertainty compromises many components.

OIML G 19:2017 sums up the definition of Uncertainty as "the concept of measurement uncertainty can be described as a measure of how well the 'true' value of the measurand is believed to be known."

Note: A known measurement error should be reported together with an associated uncertainty.

One of the best guides to Uncertainty is JCGM 100:2008 Evaluation of measurement data — Guide to the expression of Uncertainty in measurement, free to download at https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6?version=1.12&t=1696944486074&download=true.

In general, when you calculate measurement uncertainties following the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) and ILAC (International Laboratory Accreditation Cooperation) P-14 as required by ISO/IEC 17025 guidelines for calibration labs, you will need to consider the following:

- Repeatability (Type A)
- Resolution
- Reproducibility
- Reference Standard Uncertainty
- Reference Standard Stability
- Environmental Factors

Morehouse has written several published documents on the topic of measurement uncertainty. We have created a spreadsheet tool to help everyone correctly calculate uncertainty for force following accreditation requirements and in line with the Guide to the expression of uncertainty in measurement. That tool can be downloaded here.

Why is Measurement Uncertainty Important?

A robust evaluation of measurement uncertainty helps support metrological traceability and measurement decision risk. It refers to the extent to which measurements can vary and provides an estimate of the confidence in a measurement result. Measurement Uncertainty is crucial for decision-making as it helps users understand the reliability of a measurement.

The uncertainty of the measurement must be reported on a certificate of calibrations if you are accredited to ISO/IEC 17025:2017, as well as several other standards. It is essential if your customer wants you to make a statement of conformance on whether the device or artifact is within the acceptance zone ("in tolerance"). It may need to be considered if you do a test and want to know if the device passes or fails. Measurement uncertainty is required to establish your measurement traceability, which is defined in the VIM as the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations contributing to the measurement uncertainty.

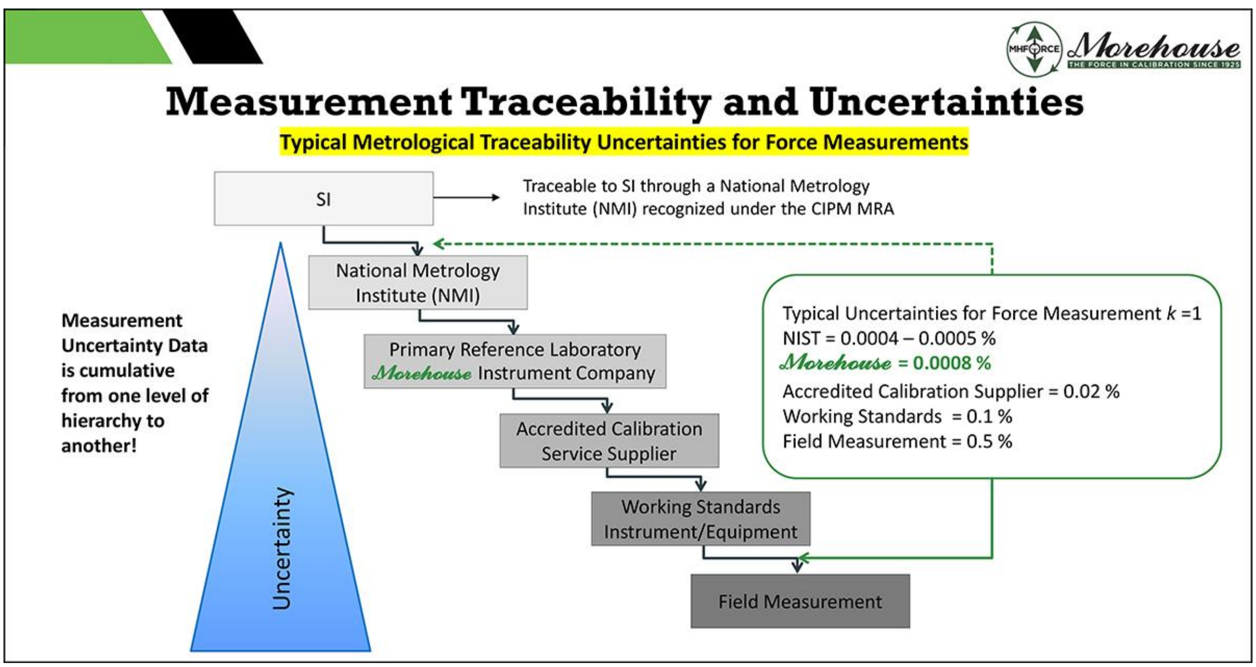


Figure 14: An Example of Measurement Traceability for Force

In simplistic terms, measurement uncertainty is crucial because you want to know that the laboratory calibrating your device or artifact can perform the calibration. If you need a device to be known to be within less than 0.02 %, you must use a calibration provider that gives you the best chance of achieving that result. If the calibration provider has a stated measurement uncertainty of 0.04 %, mathematically, they are not the right calibration lab to calibrate or verify your device or artifact.

Measurement uncertainty also keeps us honest. Suppose a laboratory claims traceability to SI through NIST; the more significant the uncertainty, the further away from NIST. The above picture shows this concept: the further away from SI units, the more significant the uncertainty.

Your Measurement Uncertainty is directly affected by the standards used to perform the calibration. Morehouse offers the lowest uncertainties for a commercial calibration laboratory. We work with customers to help lower their measurement risk. We have been successful in helping our customers make better measurements for over a century.

Morehouse has videos on measurement traceability, risk, and confidence. We have a 6-minute easy to understand video that ties everything together. [Measurement Confidence Video]

Load Cell Terminology

Non-linearity, Hysteresis, Non-Repeatability, Static Error Band, and Creep are common load cell terminology typically found on a load cell specification sheet. There are several more terms regarding the characteristics and performance of load cells. However, I chose these four because they are the most common specifications found on calibration certificates.

When broken out individually, these terms can help you select the suitable load cell for an application. Some of these terms may not be as important today as they were years ago because better meters that overcome inadequate specifications are available. One example is Non-Linearity. An indicator capable of multiple span points can significantly reduce the impact of a load cell's non-linear behavior.

The meanings of these terms are described in detail below.

Specifications	Model - Capacity (lbf / kN)					
	300-2K / 1-10	5K-10K / 20-50	25K-50K /100-250	60K / 300	100K / 500	200K / 900
Accuracy						
Static Error Band, % R.O.	±0.02	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05
Non-Linearity, % R.O.	±0.02	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05
Hysteresis, % R.O.	± 0.02	± 0.04	± 0.04	± 0.04	± 0.05	± 0.05
Non-Repeatability, % R.O.	± 0.005	± 0.005	± 0.005	± 0.005	± 0.005	± 0.005
Creep, % Rdg / 20 Min.	± 0.015	± 0.015	± 0.015	± 0.015	± 0.015	± 0.015
Off-Center Load Sensitivity, %/in	±0.1	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
Side Load Sensitivity, %	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
Zero Balance, % R.O.	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0

Figure 15: Morehouse Load Cell Specification Sheet

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

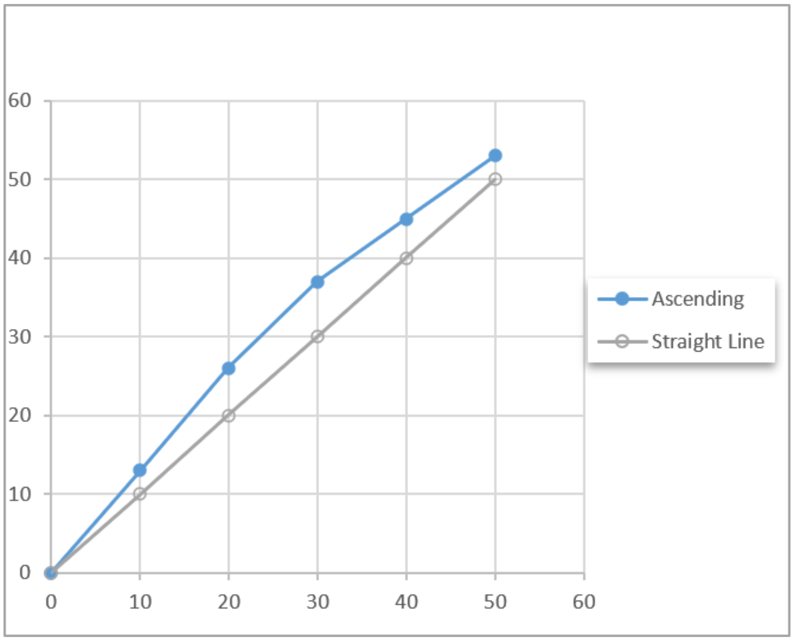


Figure 16: Non-Linearity Expressed Graphically

Non-linearity is one of the specifications that would be particularly important if the indicating device or meter used with the load cell only has a two-point span, such as capturing values at zero and capacity or close to capacity. The specification gives the end-user an idea of the anticipated error or deviation from the best fit straight line. However, suppose the end-user has an indicator capable of multiple span points and uses coefficients from an ISO 376 or ASTM E74 calibration. In that case, the non-linear behavior can be corrected, and the error significantly reduced.

One way to calculate Non-Linearity is to use the slope formula or manually perform the calibration by using the load cell output at full scale minus zero and dividing it by force applied at full scale and 0. For example, a load cell reads 0 at 0 and 2.00010 mV/V at 1000 lbf. The formula would be (2.00010-0)/ (1000-0) = 0.002. This formula gives you the slope of the line, assuming a straight-line relationship. Some manufacturers take a less conservative approach and use higher-order quadratic equations.

Plot the Non-Linearity baseline as shown below using the force applied * slope + Intercept or y = mx +b formula. If we look at the 50 lbf point, this becomes 50 * 0.0020001 +0 = 0.100005. Thus, at 50 lbf, the Non-Linearity baseline is 0.100005.

To find the Non-Linearity percentage, take the mV/V value at 50 lbf minus the calculated value and divide by the full-scale output multiplied by 100 to convert to a percentage. Thus, the numbers become ((0.10008-0.100005)/2.00010) *100) = 0.004 %.

Non-Linearity Potential Shortcomings

Non-linearity is a great way to visualize how much a measuring device deviates from an "ideal" device. However, all points may be perfectly linear, yet if the full-scale point is non-linear itself, the rest of the points will appear to be non-linear.

Some manufacturers use higher-order equations to improve their non-linearity specification. Therefore, it is important to ask them how they calculate Non-Linearity.

At Morehouse, we use the more conservative straight-line approach method.
Non-Linearity Calculations
Calculate Slope
$Slope = (0_{start(force)} - FullScale_{(force)}) / (0_{start(response)} - FullScale_{(response)})$

Calculate Intercept
$Intercept = FullScale_{(force)} - Slope \times FullScale_{(response)}$

Calculate Non-Linearity per Response
$Non\text{-}Linearity = (Point_{(force)} - (Slope \times Point_{(response)} + Intercept)) / FullScale_{(force)}$

For example, a load cell reads 0 at 0 lbf, 1.20003 at 600 lbf, and 2.00010 mV/V at 1000 lbf.

To calculate the Slope, the formula would be (0-1000)/ (0-2.00010) = 499.975001249937

To calculate the Intercept 1000 – (499.975001249937 * 2.00010) = 0.0

Non-Linearity = (600 – (499.975001249937*1.20002+0))/1000 = 0.000019999

This value is 0.0019999 % or 0.02 % using the 600 lbf (60 %) point.

Non-Linearity Calculations Ignoring Ending Zero though Running it through the formula						
Force Appied (lbf)	Run 1 Adjusted	Non-Linearity Base line	Non-Linearity (%FS)		Non-linearity Line	
0	0.00000	0	0.000		Slope=	0.0020001
50	0.10008	0.1000050	0.004		Intercept=	0
100	0.20001	0.2000100	0.000			
200	0.40002	0.4000200	0.000			
300	0.60001	0.6000300	0.001		Non-linearity=	0.004
400	0.80002	0.8000400	0.001		(%FS)	
500	1.00005	1.0000500	0.000			
600	1.20002	1.2000600	0.002			
700	1.40003	1.4000700	0.002			
800	1.60004	1.6000800	0.002			
900	1.80006	1.8000900	0.001			
1000	2.00010	2.0001000	0.000			
0	0.00000	0				

Figure 17: Non-Linearity Example

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 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.

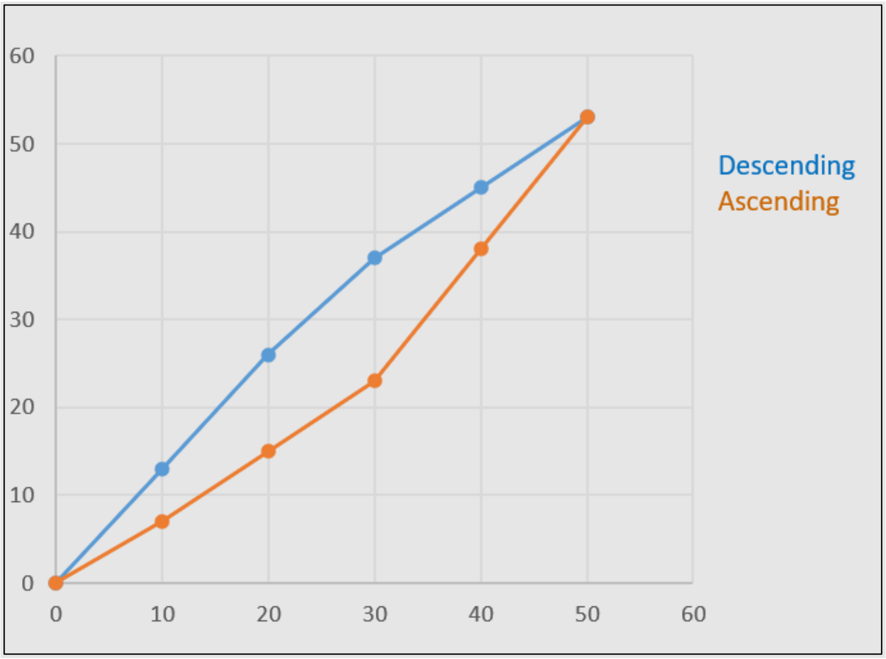


Figure 18: Hysteresis Example

Hysteresis is normally expressed in units of % full scale. It is normally calculated between 40 - 60 % of full scale. The graph above shows a typical Hysteresis curve where the descending measurements have a slightly higher output than the ascending curve.

If the end-user uses the load cell to make descending measurements, they may want to consider the effect of Hysteresis.

Hysteresis Potential Shortcomings

Errors from hysteresis can be high enough that if a load cell is used to make descending measurements, it must be calibrated with a descending range. The difference in output on an ascending curve versus a descending curve can be significant.

At Morehouse, our calibration lab sampled several load cells from five manufacturers, and the results were recorded. The differences between the ascending and descending points varied from 0.007 % (shear web type cell) to 0.120 % on a column type cell.

Calculate Hysteresis

$Hysteresis = | (Ascending_{(response)} - FullScale_{(response)}) / Descending_{(response)} |$

Non-Repeatability: The maximum difference between output readings for repeated loadings under identical and environmental conditions. Usually, this is expressed in units as a % of rated output (RO). Non-repeatability tells the user a lot about the performance of the load cell. It is important to note that non-repeatability does not tell the user about the load cell's reproducibility or how it will perform under different loading conditions (randomizing the loading conditions). At Morehouse, we have observed numerous load cells with good non-repeatability specifications that perform poorly when the loading conditions are randomized, or the load cell is rotated 120 degrees as required by ISO 376 and ASTM E74.

The calculation of non-repeatability is straightforward. First, compare each observed force point's output and run a difference between those points. The formula would look like this: Non-repeatability = ABS(Run1-Run2)/AVERAGE (Run1, Run2, Run3) *100. Do this for each combination or run, then take the maximum of the three calculations.

non-repeatability calclulations		
Run 1	Run 2	Run 3
4.0261	4.02576	4.02559
Difference b/w 1 & 2 (%FS)	Difference b/w 1 & 3 (%FS)	Difference b/w 2 & 3 (%FS)
0.0084	0.0127	0.0042
Non-Repeatability (%FS)=		0.013

Figure 19: Non-Repeatability Numbers

non-repeatability calclulations		
Run 1	Run 2	Run 3
4.0261	4.02576	4.02559
Difference b/w 1 & 2 (%FS)	Difference b/w 1 & 3 (%FS)	Difference b/w 2 & 3 (%FS)
=ABS(U4-V4)/AVERAGE($U$4:$W$4)*100	=ABS(U4-W4)/AVERAGE($U$4:$W$4)*100	=ABS(W4-V4)/AVERAGE($U$4:$W$4)*100
Non-Repeatability (%FS)=		=MAX(U9:W9)

Figure 20: Non-Repeatability Calculations

Static Error Band: is the band of maximum deviations of the ascending and descending calibration points centered on the best-fit straight line through zero output (0,0). It includes the effects of Non-Linearity, Hysteresis, and non-return to minimum load. SEB is usually expressed in units of % of full scale. Thus, a SEB of 0.02 % of FS would have a maximum error of 0.02 % of its full-scale capacity. SEB is a helpful tool in determining how accurate a load cell is.

SEB is calculated to find a line that results in the slightest maximum error. This line also needs to fit through the origin (0, 0), so only the slope needs to be calculated via $(y_1+y_2) / (x_1+x_2)$. The best approach is to iterate across every pair of percent force applied of full scale (**% FS**) and the zero adjusted responses.

For each pair, calculate the slope, use the slope to calculate the percent error for all % FS, and take the largest error as that slope's "absolute error" value. Repeat this for all possibilities, taking the slope that has the smallest absolute error value.

SEB Potential Shortcomings

If the load cell is used for ascending measurements and, occasionally, descending measurements are needed. The user may want to evaluate Non-Linearity and Hysteresis separately, as those two definitions may provide a more accurate depiction of the load cell's performance.

What needs to be avoided is a situation where a load cell is calibrated following a standard such as ASTM E74 or ISO 376 and additional uncertainty contributors for Non-Linearity and Hysteresis are added. ASTM E74 has a procedure and calculations that, when followed, use a method of least squares to fit a polynomial function to the data points.

The standard uses a specific term called the Lower Limit Factor (LLF), which is a statistical estimate of the error in forces computed from a force-measuring instrument's calibration equation when the instrument is calibrated following the ASTM E74 practice.

SEB Calculation

Excel Macro Snippet

```
'Iterate across every permutation of 2 points
For i = 0 To N - 1
  'Start at i + 1 to duplicating work, reducing iterations
  For j = i + 1 To N - 1
    'Prevent checking the same point and dividing by zero
    If i <> j And PercentFS(i) + PercentFS(j) <> 0 Then
      'tempSlope = (Vj + Vi) / (Rj + Ri)
      maxError = 0
      tempSlope = (Responses(j + 2, 1) + Responses(i + 2, 1)) / (PercentFS(j) + PercentFS(i))

      'Ensure we don't accidentally set the minimum error to 0 or divide by 0
      If tempSlope <> 0 Then
        For k = 0 To N - 1
          tempError = (Responses(k + 2, 1) - tempSlope * PercentFS(k)) / tempSlope

          'Take the largest error for this slope
          If Abs(tempError) > Abs(maxError) Then
            maxError = tempError
            slope = tempSlope
          End If
        Next k

        'Find the slope that provides the lowest maximum error
        If IsNull(minError) Or Abs(maxError) < Abs(minError) Then
          minError = maxError
          sebSlope = slope
        End If
      End If
    End If
  Next j
Next i
```

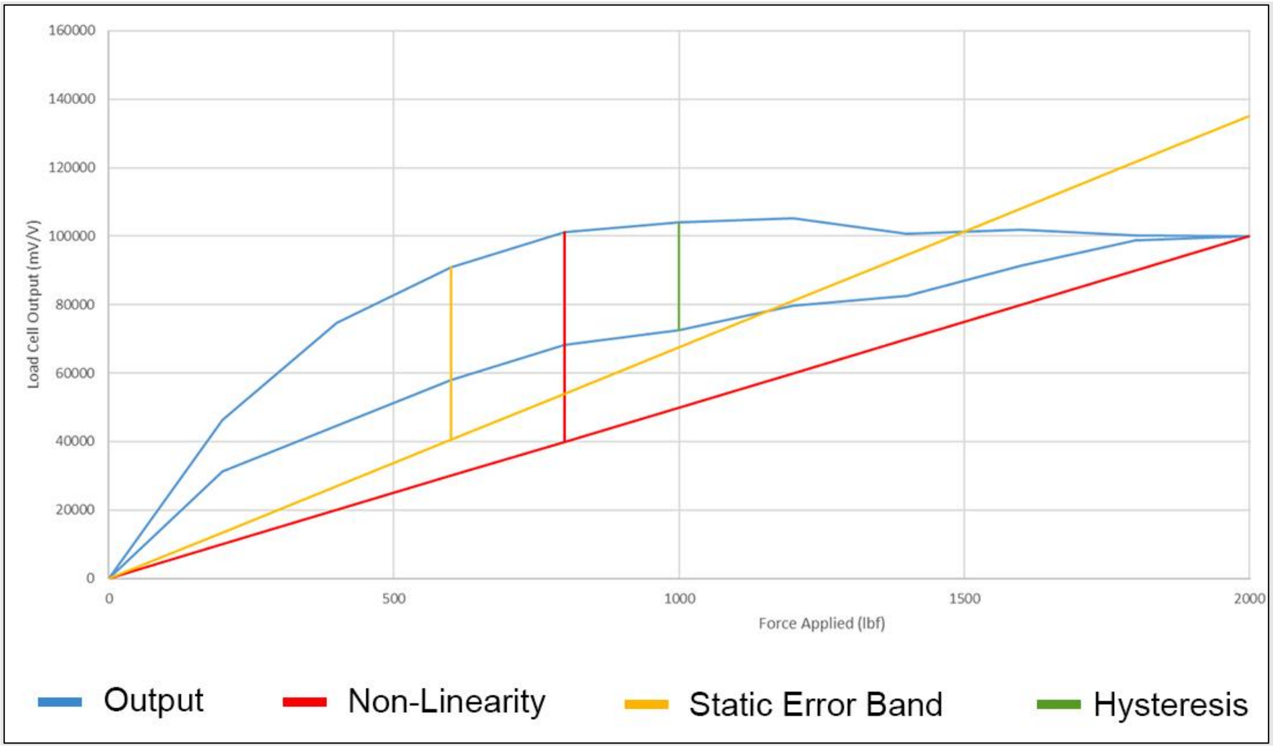


Figure 21: Static Error Band and Other Specifications Displayed Visually

Because of what it captures, Static Error Band might be the most exciting term. 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.

Earlier, I noted that the end-user might want to consider the effects of Hysteresis unless they use the load cell as described above because a Static Error Band would be the better specification. The end-user could likely ignore Non-Linearity and Hysteresis and focus on static error band and non-repeatability.

However, we find that many calibration laboratories primarily operate using ascending measurements and, on occasion, may have a request for descending data. When that is the case, the user may want to evaluate Non-Linearity and Hysteresis separately. When developing an uncertainty budget, use different budgets for each type of measurement, i.e., ascending and descending.

Creep

Creep: The change in load cell signal occurring with time while under load and with all environmental conditions remaining constant.

Load Cell Creep Return: The difference between the load cell signal immediately after removal of a load applied for a specific time interval, environmental conditions, and other variables remaining constant during the loaded interval and the load cell signal before the load application. Load Cell Creep Return is commonly expressed in units of % of applied load over a specified time interval. It is common for characterization to be measured with a constant load at or near capacity.

Creep Recovery: This is expressed as a percentage difference calculated by dividing the change in output at zero force following a creep test by the initial zero force output at the start of the creep test and then dividing by the output during the creep test.

Note: For many tests to determine the creep specifications, a constant temperature is maintained to eliminate the effects of thermal expansion. It is also important to note that for many load cells, creep gets better with time.

To learn more about load cell creep, check out our blog.

How Load Cells Work – Stress, Strain, and Elasticity Basics.

It is essential to understand the common types of load cells used in force measurement and choose your application's suitable load cell.

Strain

Most load cells are made with strain gauges, and unsurprisingly, their job is to measure strain. But what is strain? Simply stated, it defines how much a material stretches.

When we mount a strain gauge to a body, its length stretches or shrinks along with that body. It's common to denote that increase or decrease with the Greek letter Delta, D, as shown below.

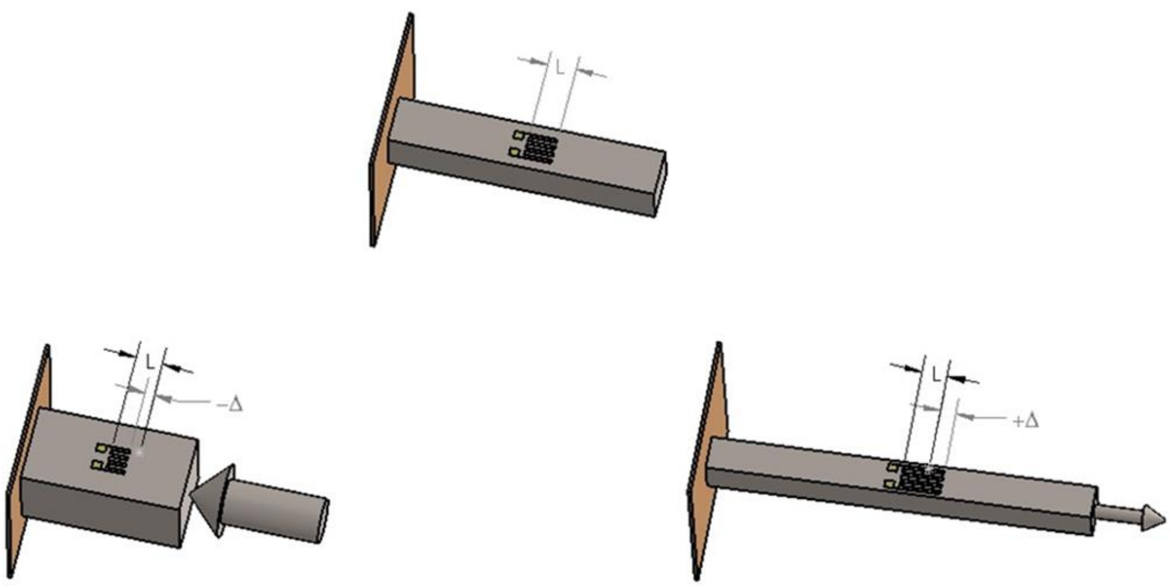


Figure 22 Examples of Compressive and Tension Strain.

The figure above shows D decreasing when the material is pushed on and increasing what the material is pulled on.

Typically, many load cells are wired so that a meter will read a negative value in compression and a positive value in tension.

Strain is then defined as the change in the length divided by the original length and is symbolized by the Greek letter ε (epsilon). Mathematically, you write the expression for strain as:

$$Strain\ (\varepsilon) = \frac{Change\ in\ length\ (\Delta)}{Original\ length}$$

The units of length usually cancel, and we call it a dimensionless unit. However, it is often denoted with units such as mm/mm or in/in to keep track that we are referring to strain.

It is interesting to note in the above figure that the overall length of the bar changes more than the strain gages. However, they both experience the same strain. Adding numbers to the figure above when the length changes 0.167 % we get:

Strain gage original length=0.060”	Strain gage increase in length=0.0001”	Strain=0.0001”/0.060” = 0.00167in/in
Bar original length = 3”	Bar increase in length= 0.005”	Strain=0.005”/3” = 0.00167 in/in
Bar original length = 3”	Bar decreases in length= 0.005”	Strain=-0.005”/3” = -0.00167 in/in

It’s also true that if we increase the length of the bar, it will stretch more, but the strain will be the same. This is true as long as the cross-section of the bar and the applied force remain the same. For example, if the bar started as 6” with the same force, then:

Bar original length = 6”	Bar increase in length= 0.010”	Strain= 0.010”/6” = 0.00167 in/in

Stress

External forces will obviously cause strains in a body. But instead of talking about forces directly, we introduce the related term of stress, denoted by the letter σ (sigma), which facilitates the study of materials.

Stress is defined as force per unit area and is typically measured in units of lb/in^2 (psi) or N/m^2 (Pa or Pascals). Stress is written mathematically:

$$\text{Stress}\ (\boldsymbol{\sigma}) = \frac{\boldsymbol{F}}{\boldsymbol{A}}$$

σ = Stress
F = Force Applied
A = Cross section area on the force is acting

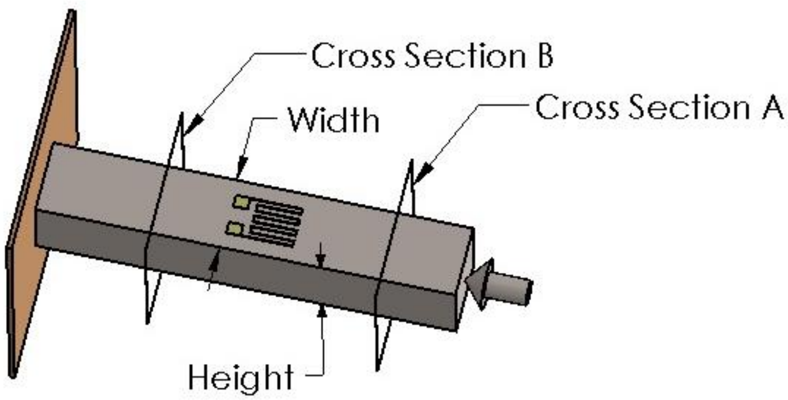


Figure 23 Calculating Cross Section Stress σA= σB

Given that the Height is 20 mm, the Width is 20 mm, and the compressive force is 100 Newton, we can calculate the stress at cross-section A.

σ =100N/(.02m*.02m) = 250,000 N/m^2 =250,000 Pascals (Pa) = 0.25 MPa

We note that the cross-section area shown above is the same for “A” and “B”. Therefore, the stress is also the same. But if the size of cross-section “B” is enlarged, the stress goes down in that area.

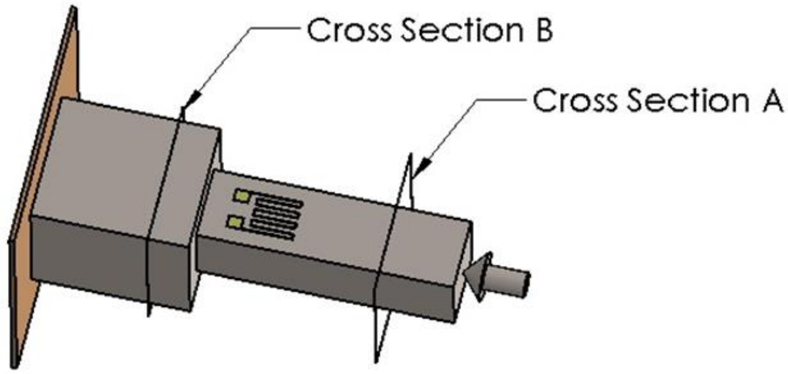


Figure 24 Calculating Cross Section Stress σA> σB

It's no coincidence that pressure is measured in the same units as stress. Whether you call something a stress, or a pressure can be just a matter of what reference frame you choose. It's common to say that pressures are forces acting on the external faces of a body. Stress is a force internal to the body.

Modulus of Elasticity

Having defined the terms of Stress and Strain, we now show they are related by a property called the Modulus of Elasticity. It is written mathematically:

$$\text{Modulus Of Elasticity (E)} = \frac{Stress\ (\sigma)}{Strain\ (\varepsilon)}$$

Since Strain is said to be dimensionless, the unit of E is the same as Stress. It's common to report values as GigaPascals (GPa) or 10^6 PSI

The Modulus of Elasticity for most materials is published by manufacturers. Here are some typical values:

Aluminum	$10 * 10^6$ PSI
Steel	$30 * 10^6$ PSI
Copper	$16 * 10^6$ PSI
Titanium	$16 * 10^6$ PSI
Brass	$14 * 10^6$ PSI

Upon rearranging, we see that if we know the force acting on a body and the Modulus of Elasticity, we can predict the stretching or shrinking of that body.

$$\text{Change in length } (\Delta) = \frac{Original\ length * Force}{Cross\ Section\ Area * E}$$

From this equation in the chart, we can observe that E is three times higher for steel than aluminum. This means that steel part will stretch 3X less than the same part made of Aluminum. We referred to strain as meaning "stretch". We can likewise think of E as the "stretchability" of a material.

The Stress-Strain Diagram

Engineers use the stress-strain diagram to quickly understand important aspects of material behavior. By plotting stress against strain, we can see how a material behaves as forces increase.

The graph below, typical for most engineering metals, is divided into elastic and plastic regions. Elasticity is the property of a material that allows it to return to its original shape and size after removing an applied force. In the plastic region, the forces are so high that the material is permanently deformed when the forces are removed. Anyone who has played with a paperclip will already have some intuition of this behavior.

In this graph, we introduce the term 'Yield Stress.' This is the amount of stress in a material where only a very small amount of plastic deformation occurs. We usually limit rated capacity to less than 1/3 the Yield Stress for a load cell to operate correctly.

We also note that the Modulus of Elasticity only applies in the elastic region. By definition, it is the slope (Rise/Run or Stress/Strain) of the straight curve in this region.

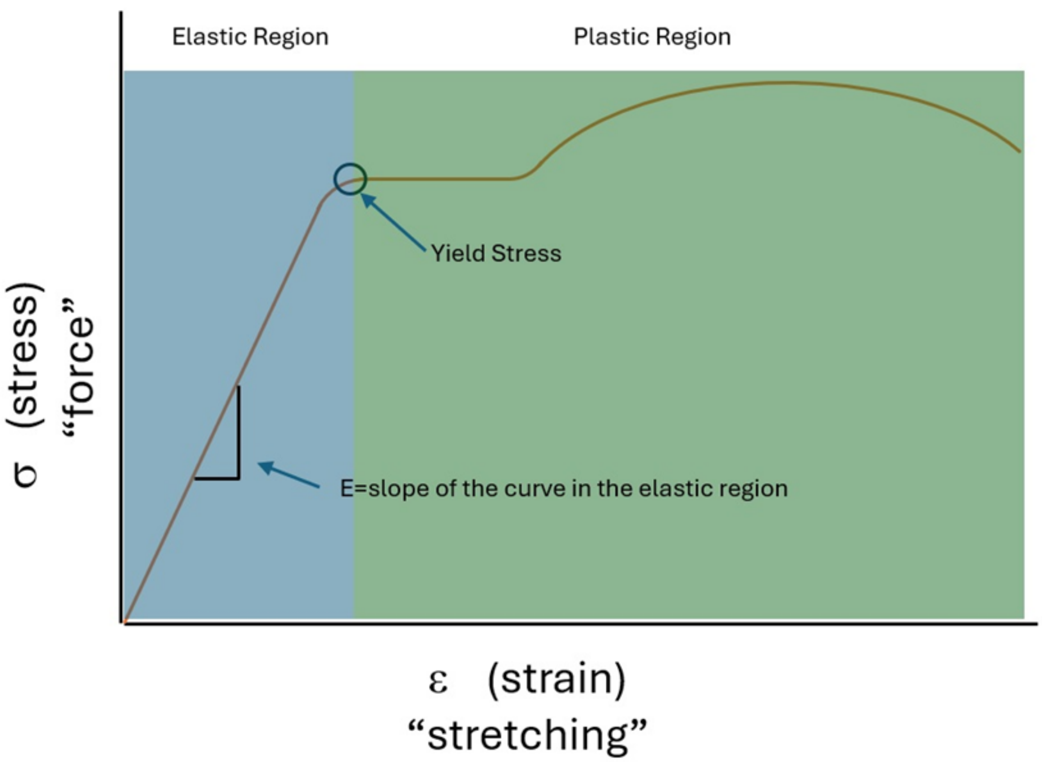


Figure 25 Graph showing the Stress-Strain Diagram (Young's Modulus)

Types of Load Cells

It is essential to understand the common types of load cells used in force measurement and choose your application's suitable load cell.

The four types of load cells typically used in force measurement are bending beam, shear beam, miniature, and column. We will describe the common types used as reference and field standards below. Many other load cells are shown in commercial applications, such as scales used at supermarket checkouts, weight-sensing devices, and weighing scales.

Figure 26: Types of Load Cells

S-beam (S-type)

The S-beam is a bending beam load cell typically used in weighing applications under 50 lbf. These load cells work by placing a weight or generating a force on the load cell's metal spring element, which causes elastic deformation. The strain gauges in the load cell measure the fractional change in the length of the deformation. There are generally four strain gauges mounted in the load cell.

Figure 27: S-beam Load Cell

Advantages

- In general, linearity will be enhanced by minimizing the deflection ratio at the rated load to the length of the sensing beam, thus minimizing the change in the element's shape.
- Ideal for measuring small forces (defined as under 50 lbf) when physical weights cannot be used.
- It is suited for scales or tension applications.

Disadvantages

- The load cell is susceptible to off-axis loading.
- Compression output will differ if the load cell is loaded through the threads versus flat against each base.
- Typically, it is not the right choice for force applications requiring calibration to the following standards: ASTM E74, ASTM E4, ISO 376, and ISO 7500.

Watch this video demonstrating the misalignment due to off-axis loading.

Shear Web

We believe that the shear web is a shear beam load cell ideal as a calibration reference standard for up to 100,000 lbf. Morehouse shear web load cells are typically the most accurate when installed on a tapered base with an integral threaded rod installed.

Figure 28: Morehouse Ultra-Precision Shear Web Load Cells

Advantages

- Typically, they have very low creep and are less sensitive to off-axis loading than the other load cells.
- Recommended choice for force applications from 100 lbf through 100,000 lbf.

Disadvantages

- After 100,000 lbf, the cell's weight makes it exceedingly difficult to use as a reference standard in the field. A 100,000 lbf shear web load cell weighs approximately 57 lb., and a 200,000 lbf shear web load cell weighs over 120 lb.
- Without the threaded adapter installed, as shown in the picture, errors from thread engagement can be significant (meaning 0.1 – 2 %). **Always use these load cells with the adapter installed, or if space is an issue and the adapter is removed, make sure the load cell is calibrated with whatever adapters are being used with it.**

Watch this video showing a Morehouse load cell with only 0.0022 % off-axis error. If this load cell is used without a base or an integral top adapter, there may be significant errors associated with various loading conditions.

Figure 29 Morehouse Shear Type Budget Load Cell

Morehouse Modified Budget Shear Web

Advantages

- Typically, they have very low creep and are less sensitive to off-axis loading than the other load cells.
- They are machined out of Stainless Steel and hold up well aesthetically.
- These load cells are a better choice if the top threaded adapter needs to be removed, as the errors are significantly less than the traditional shear web cells.

Disadvantages

- After 100,000 lbf, the cell's weight makes it exceedingly difficult to use as a reference standard in the field, as these cells are modified to have more material than a traditional shear web cell.
- Without the threaded adapter installed, as shown in the picture, errors from thread engagement can be 0.02 % or more.

Check out our blog to learn more about the differences between these two types of shear web load cells.

Button Load Cell

The button is a miniature load cell typically used in applications with limited space. It is a compact strain gauge-based sensor with a spherical radius often used in weighing applications.

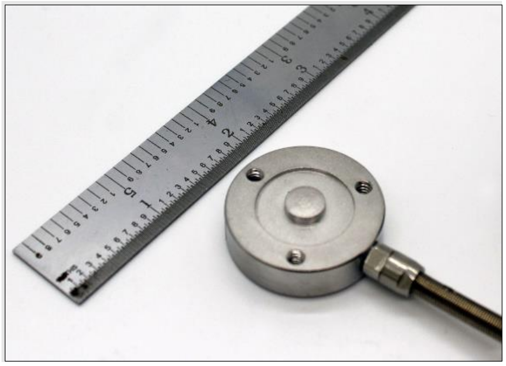


Figure 30: Button Load Cell

Advantages

- Suitable for applications where there is limited room to perform a test.

Disadvantages

- High sensitivity to off-axis or side loading. The load cell will produce high errors from any misalignment. For example, a 0.1 % misalignment can produce a significant cosine error. Some have errors anywhere from 1 % to 10 % of rated output.
- Do not repeat well in the rotation.

Figure 31: Button and Washer Load Cell Adapters

Morehouse has developed custom adapters for button, washer, and donut load cells that improve repeatability. We achieved a 525 % improvement in our testing using the above adapters. If your laboratory calibrates these load cells and observes the same repeatability problems, please contact Morehouse, as the above adapters will improve the calibration results.

Check out our website for more information on custom adapters for button, washer, and donut load cells that improve repeatability.

Single-Column or High-Stress Load Cells

The single column is a column load cell suitable for general testing. The spring element is intended for axial loading and typically has a minimum of four strain gauges, with two in the longitudinal direction. Two are oriented transversely to sense the Poisson strain. The Morehouse single-column load cell is economical and lightweight.

Figure 32: Morehouse Single Column Load Cell

Advantages

- Physical size and weight: It is common to have a 1,000,000 lbf column cell weighing less than 100 lb.

Disadvantages

- Reputation for inherent Non-Linearity. This deviation from linear behavior is commonly ascribed to the change in the column's cross-sectional area (due to Poisson's ratio), which occurs with deformation under load.
- Sensitivity to off-center loading can be high.
- Larger creep characteristics than other load cells often do not return to zero, as do other load cells. (ASTM Method A typically yields larger LLF)
- Different thread engagement can change the output.
- The design of this load cell requires a top adapter to be purchased with it. Varying the hardness of the top adapter will change the output.

Multi-Column Load Cells

The multi-column column load cell is suitable from 100,000 lbf through 1,000,000 plus lbf. In this design, the load is carried by four or more small columns, each with a complement of strain gauges. The corresponding columns' gauges are connected in a series in the appropriate bridge arms. The Morehouse multi-column 600K load cell weighs 27 lb. and has an accuracy of better than 0.02 % of full scale.

Figure 33: Morehouse Light Weight 600k (26 lb.) Multi-Column Load Cell

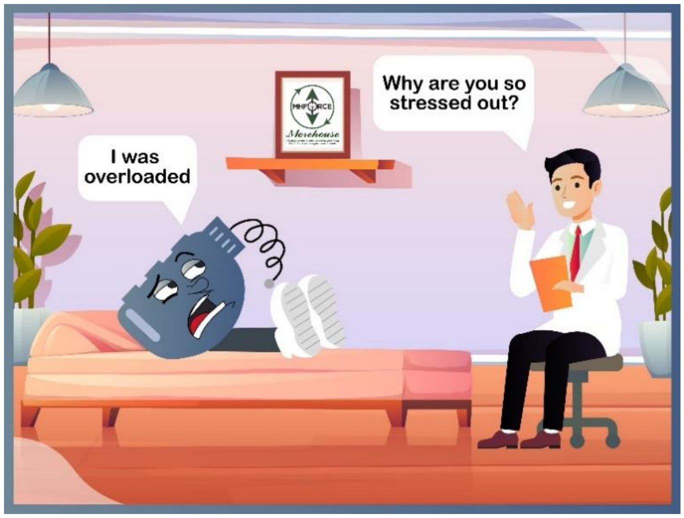
Advantages

- It can be more compact than single-column cells.
- Improved discrimination against the effects of off-axis load components.
- Typically, they have less creep and better zero returns than single-column cells.
- In many cases, a properly designed shear-web spring element can offer greater output, better linearity, lower hysteresis, and faster response.

Disadvantages

- The design of this load cell requires a top adapter to be purchased with it. Varying the hardness of the top adapter will change the output.

Several more types of load cells have various advantages and disadvantages. If the type of load cells you commonly use is not covered, contact us, and we will be happy to discuss the advantages and disadvantages based on our experience.



Load Cell Troubleshooting

Have you ever wasted hours troubleshooting a nonworking load cell to diagnose the problem? If you deal with load cells, you know how much of a time suck they can be when they are not working correctly. This section is designed to save you or your technicians valuable time by following an easy seven-step troubleshooting guide. The time saved can be beneficial to getting more calibrations done or getting the measurements correct by using the proper setup adapters and understanding how to replicate how the end-user uses the device.

7-Step Process for Troubleshooting a Load Cell

Morehouse technicians have seen many different load cell issues and have lots of experience identifying and fixing the problems. With this experience, we developed a 7 Step Process for Troubleshooting a Load Cell to shorten our calibration lead time (most calibrations are performed in less than 7-10 business days) and provide better customer service.

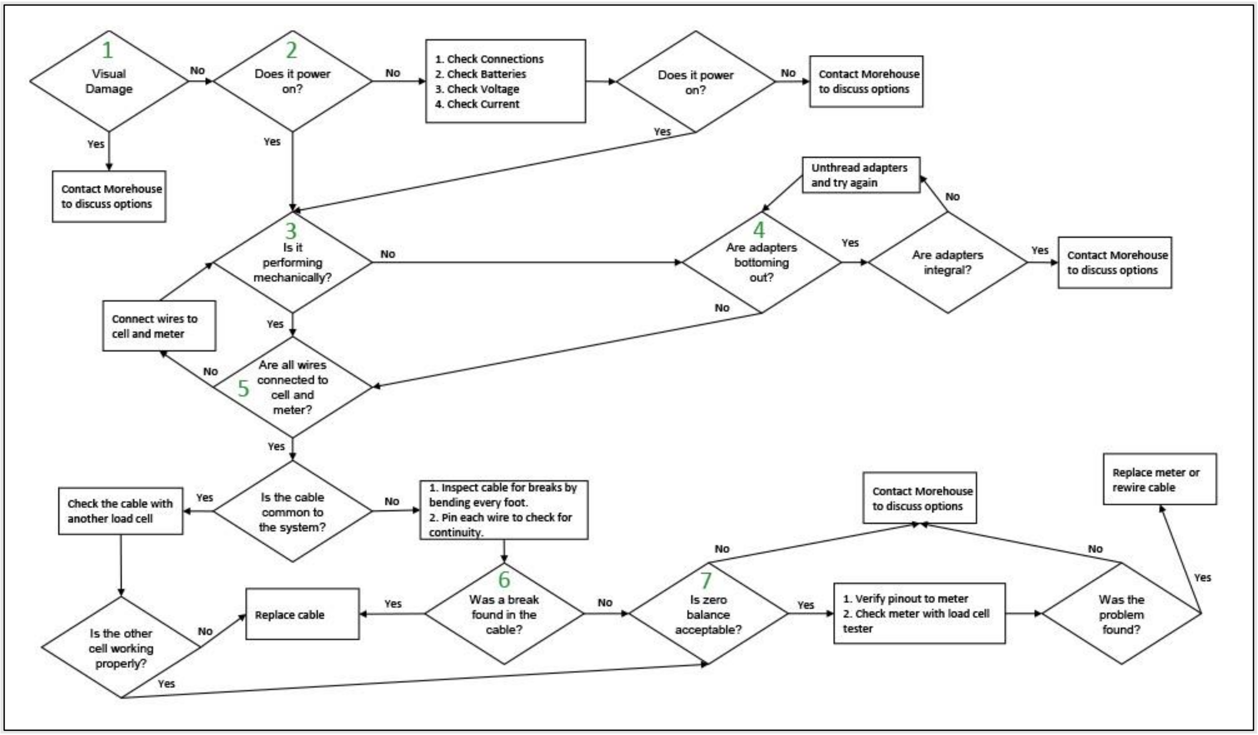


Figure 34: Load Cell Troubleshooting Process

This 7-step process outlined above can help you save countless hours trying to diagnose the problem with your load cell.

1. Visually inspect the load cell for noticeable damage. If it is damaged, contact Morehouse to discuss options.

Figure 35: Overloaded Load Cell

2. Power on the system. Make sure all connections are made and verify batteries are installed and

have enough voltage. Check the voltage and current on the power supply. If it still does not power on, then replace the meter. An inexpensive multimeter like the one pictured below can be used for **Steps 2, 6, and 7.**

Figure 36: Generic Multimeter

3. If everything appears to be working, the output does not make sense. Check for mechanical issues. For example, some load cells have internal stops that may cause the output to plateau. Do not disassemble the load cell, as it will void the manufacturer's warranty and calibration. The best example of this error is that the load cell is linear to 90 % capacity. Then, either the indicator stops reading or the output diminishes. The data will show poor linearity when using 100 % of the range and excellent linearity when only using the data set to 90 % of the range. Morehouse can likely fix this error and should be contacted for more information.
4. Ensure any adapters threaded into the transducer do not bottom out. If an adapter is bottoming out and integral, contact Morehouse to discuss options.
5. Ensure the leads (all wires) are correctly connected to the load cell and meter. If the cable is common to the system, check another load cell and verify that the other cell works correctly. If the other load cell is not working, contact Morehouse to discuss options.
6. Inspect the cable for breaks. With everything hooked up, test the cable, making a physical bend every foot. Pin each connection to check for the continuity of the cable.
7. Use a load cell tester or another meter to check the load cell's zero balance. You can check the bridge resistance with an ordinary multimeter if you do not have a load cell tester. A typical Morehouse shear web load cell pins (A & D) and (B & C) should read about 350 OHMS ± 3.5. If one set reads high and another low (ex. (A & D) reads 349 and (B & C) reads 354), then there is a good chance that the load cell was overloaded.

Note: Different load cells use different strain gauges and have different resistance values. It is essential to check with the manufacturer on what they should read and the tolerance.

Figure 37: Inside of an Overloaded Shear Web Load Cell Showing a Clear Break of the Web Element

Diagnose with a load cell tester.

A Morehouse load cell has saved us countless hours of testing and can be used to test for the following:

- Input and Output Resistance
- Resistance difference between sense and excitation leads.
- Signal Output
- Shield to Bridge
- Body to Bridge
- Shield to Body
- Linearity

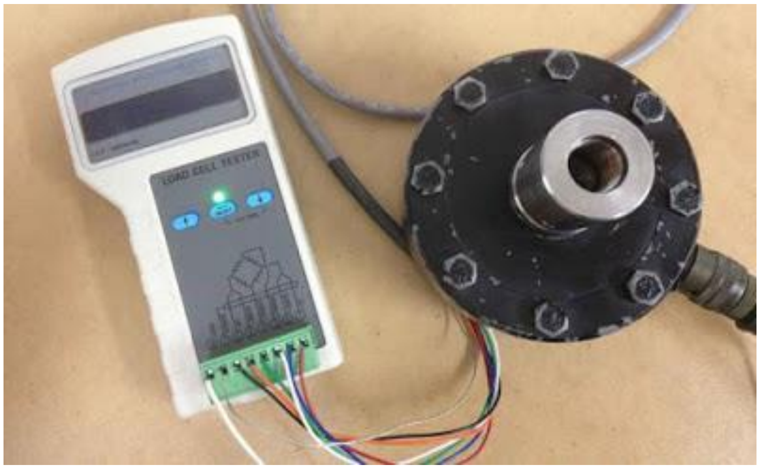


Figure 38: Morehouse Load Cell Tester

Watch this video showing how the load cell tester works.

Overloaded load cell

It is important to note that if a load cell has been overloaded, mechanical damage has been done that is not repairable. Overloading causes permanent deformation within the flexural element and gauges, which destroys the carefully balanced processing. While it is possible to electrically re-zero a load cell following overload, it is not recommended because this does nothing to restore the affected performance parameters or the degradation of the structural integrity.

Morehouse stocks common capacity load cells and most equipment is available in 1 week, with calibration performed using deadweight primary standards. Shorter lead times are available upon request, and Morehouse always aims to provide superior customer support. Visit mhforce.com/load-cells/ for more information on our wide selection of load cells.

Indicator Basics

Figure 39: Morehouse High Accuracy Digital Indicator (HADI)

When force is exerted on a load cell, the mechanical energy is converted into equivalent electrical signals. The load cell signal is converted to a visual or numeric value by a "digital indicator." When there is no load on the cell, the two signal lines are at equal voltage. As a load is applied to the cell, the voltage on one signal line increases slightly, and the voltage on the other line decreases very slightly.

The indicator reads the difference in voltage between the two signals that may be converted to engineering or force units. Several indicators are available, and they have different advantages and disadvantages. The decision on which indicator to use that meets your needs might be based on the best non-linearity and stability specifications.

Figure 40: Morehouse 4215 High Stability Indicator

Non-linearity and uncertainty specifications

The specification that most users look for in an indicator is Non-Linearity. The better the Non-Linearity is, the less the indicator will contribute to the system uncertainty.

Some indicators on the market may specify accuracies in the percentage of reading. Although these may include specifications such as 0.005 % of reading, they can cause negative impacts on the system's uncertainty. The problem is that the resolution or number of digits may be such that the specification will not be maintained. Morehouse has a 4215 High Stability Indicator pictured above with 0.002 % Non-Linearity specification. The Morehouse 4215 meter will display up to 5 decimals in mV/V, equating to a resolution of 200,000 to 400,000 counts on the most common load cells.

In other cases, the indicator may require adjustment at various span points to achieve non-linearity between span points that they are substituting for an overall accuracy specification. The purpose of multi-spanning the range in an indicator is to divide the sensor output range into smaller segments and reduce Non-Linearity errors. However, accuracy claims can be questionable. Ensure the accuracy specification includes stability over time, repeatability, non-linearity, temperature characteristics, and consideration of the resolution.

Non-linearity errors in a load system can be drastically reduced by:

- Employing the right calibration and measurement process
- Pairing a highly stable indicator to the load cell
- Having the system calibrated to highly accurate standards such as Primary Deadweight Standards
- Using ASTM E74 or ISO 376 calibration coefficients to convert load cell output values into force units.

Better linearity can be achieved using a Morehouse HADI or 4215 load cell indicator with the Morehouse calibration software, which is included with the indicator. The Morehouse 4215 Plus can use the software, or coefficients can be manually entered. For those not wanting to use a computer, the 4215 Plus is the recommended choice. The 4215 Plus, when comparing Non-Linearity, the HADI is better than 0.002 % of full scale, the 4215 H and 4215 Plus are better than 0.002 % of full scale, and the PSDS is better than 0.005 % of full scale.

Stability and drift

This characteristic is often more difficult to quantify on non-high-end multimeters. Some indicators will specify thermal drift, long-term stability of zero, and some actual stability per range. Often over $10,000, the indicators will fall into specifying drift at different intervals, such as 90 days (about three months) and one year. Most indicators under $2,500 will not specifically address 90 days or 1-year stability. Stability can be monitored and maintained by a load cell simulator. However, a user can live with the entire system drift of the load cell and indicator combined.

The $10,000 plus indicators from Agilent, Keysight, and Fluke win in this category, yet these are not portable and are often overkill for general application force systems. The Morehouse HADI, with long-term stability of zero at 0.0005 %/year at room temperature, is an excellent choice for around a fraction of the cost.

Resolution

Using the indicator as a field system, a stable resolution of greater than 50,000 counts over the load cell's output range will allow higher-order fits. It is also desirable for ASTM E74 calibrations because a higher order fit generally yields a Lower Limit Factor (LLF) and better Class AA and Class A loading ranges. The Morehouse HADI is an excellent indicator to pair with your reference standard to calibrate other load cells, as it can display 4.50000 mV/V stable to within 0.00001 mV/V on a good load cell. Either our 4215 HS or Plus is the next best choice as it is typically stable to within 0.00002 mV/V.

Number of span points

This assumes you require the actual display to read in engineering units and are not okay with 4.00001 mV/V representing 10,000.0 force units such as lbf or kN. If you want the indicator to read 10,000.0 when 10,000.00 is applied and do not want to use a computer for the physical display, then the Morehouse 4215 Plus or C705P, which stores coefficient files, is an excellent choice.

Figure 41: Morehouse C705P Indicator

The Morehouse C705P indicator comes standard with an up to 7-pt linearization option and the ability to use coefficients. We recommend using the coefficient function because as the system drifts, so will the readings.

Therefore, 10,000.0 today may equate to 10,000.9 in a year. If coefficients are used, we would report the values in mV/V and reprogram based on mV/V internally. The only downside is that the units must be toggled between mV/V and force units, as only one can be displayed simultaneously.

The Morehouse 4215 Plus can use calibration coefficients and display both mV/V and force units simultaneously, or the Morehouse 4215 and HADI with the software would also work if one wanted drift corrected during calibration.

Environmental conditions

Specifications such as temperature effect on zero and temperature effect on span indicate the environmental effects. The Morehouse HADI is excellent in this category, with a typical one ppm per degree Kelvin and a max of 2 ppm.

Four or six wire sensing

Cable resistance is a function of temperature and length. A 4-wire system will have additional errors from temperature changes and from using cables of different lengths. In most cases, changing a cable will require calibration, while a 6-wire system will run sense lines separate from excitation and eliminate the effects due to these variations. The Morehouse 4215 and HADI are both 6-wire systems.

Required load cell output.

Some indicators cannot handle load cell output above 2.5 mV/V, creating problems with 3 mV/V and 4 mV/V load cells. Morehouse indicators such as the PSDS, HADI, and 4215 handle load cells with output up to 4.5 mV/V.

Figure 42: Morehouse PSDS Indicator

Ease of use

This is a preference-based consideration. Some ease-of-use examples eliminate the need for a computer or power supply. Or not having to use load tables and merely pushing the spacebar for the computer to grab readings. If you want something simple that does not need a power cord, the PSDS is the winner. The HADI is the winner if you want a portable system that can run on laptop power and capture readings.

Figure 43: Morehouse G501F Indicator

If one can use a power cord and wants a bit more in terms of span points, less cost, and less portability, we have a G501F indicator that provides a simple solution for one compression and tension-type load cell.

Multiple span points can be programmed to get closer to the nominal value. This meter is a direct replacement and upgrade over several other inexpensive meters on the market.

Ruggedness

The Morehouse HADI, G501F, and PSDS are enclosed and more durable than the 4215. The PSDS, and G501F would be the hardest to break physically and the best choice for a very rugged environment where a computer cannot go.

The number of load cell channels required.

If you want to use several load cells on the system, the Morehouse 4215 HS or HADI can be used. If the requirement is to set each channel up to multiple span points, then the 4215 HS or the Morehouse/Admet Indicator would win.

If you had a compression or tension-only load cell or two, the PSDS is a sub $ 1000.00 indicator that can read TEDS (Transducer Electronics Datasheet) templates 33,40 and 41.

Excitation voltage

Some users may need to change the excitation voltage or have a specific requirement for a 10V DC excitation to be applied to the sensor. In this scenario, the Morehouse 4215 is the only choice.

Choosing the right indicator is often a matter of personal preferences. The HADI indicator comes first for several selection criteria, yet these may not be the criteria that matter for your individual needs. Choose the indicator that meets your needs and has the best non-linearity and stability specifications. If you need a rugged, battery-powered indicator with at least 50,000 counts of resolution, a PSD is an excellent choice. HADI may make the most sense if you need a stable system and can carry a laptop. Finally, if you need a system where you must have a live display, use a computer, and need a 10V excitation source, 4215 would be a great option.

This section covers the basics of selecting the right equipment and knowing the proper terminology; the next section will cover more advanced applications.

TEDS

Introduced in the early 2000s, TEDS IEEE chips promised to revolutionize load cell application standardization and efficiency.

However, TEDS for Load Cells never took off how they should have. There are multiple reasons, from the cost to implement, the increased calibration cost, incorrect implementation of the IEEE standard, and creation of proprietary and non-compliant standards such as "SigCal, " Signature Calibration," and "TEDs Enabled" that confused users.

This section explores the world of TEDS for load cells, uncovering the potential pros and cons, applications for TEDS for load cells, and considerations to help you decide whether TEDS is suitable for your organization.

Understanding TEDS for Load Cells:

Aligned with the IEEE 1451.4 standard, TEDS IEEE chips can offer a transformative approach to integrating load cells.

These chips are designed to embed essential information directly into load cells, providing a standardized data storage and retrieval method.

When looking for TEDS for load cells, one will want to look for "IEEE 1451.4 compliant". If not so labeled, the vendor should be contacted to verify compliance.

This is important because several manufacturers use terms like "TEDS Enabled" or "SigCal," which are not entirely or partially IEEE 1451.4 compliant versions.

TEDS Enabled, for example, only stores an identifier so the indicator can pull the S/N of the unit. Here, no calibration information is stored on the chip. Therefore, "TEDs enabled" load cells can neither talk to IEEE 1451.4 compliant meters nor other "TEDS enabled" meters except the one it was calibrated with.

IEEE 1451.4 TEDS is inherently a straightforward concept that can be fitted to new load cells or refitted to existing load cells. Implementation is via a simple memory chip. The chip is separate from the sensor bridge circuit, although wiring connections may be shared. People are confused and think TEDs will calibrate the load cell, yet it does not affect the bridge circuit. Instead, the memory chips store the information to allow the meter or DAQ to scale and linearize the output from the load cell.

Therefore, it eliminates the need to manually program the indicator from the front panel and often eliminates the need to read hundreds of pages of user manuals to set up the indicator.

Before exploring the templates' technical aspects, consider whether a TEDS for load cell system is the right choice for you.

Top Pros of TEDS for Load Cells:

1. Plug-and-Play Simplicity: Effortless setup due to automatic configuration, saving time and reducing errors.
2. Cost-Effective Efficiency: Standardized data format promotes interoperability and eliminates manual configuration efforts, minimizing operational costs.
3. Enhanced Accuracy and Reliability: Embedded sensor details and calibration data prevent manual entry errors and ensure accurate load cell readings.
4. Streamlined Data Management: Easier access and management of load cell information, including calibration data, for efficient data analysis.
5. Increased Versatility and Safety: Interoperability across platforms and protection against incorrect settings or connections improve overall system flexibility and safety.

Sounds great, doesn't it, though there are also cons, which can be expensive to maintain.

Top 5 Cons of TEDS for Load Cells:

1. Cost Implications: Integrating TEDS into load cells may involve additional costs, impacting organizations with existing load cell systems that require retrofitting. A chip can easily be embedded in the load cell or cable, though new indicators must be purchased. Typically, indicators with the ability to read and write TED templates are much more expensive.
2. Limited Adoption and Compatibility: Despite IEEE standardization, not all meters may comply with the TEDS IEEE 1451. Many meters list TEDS-enabled, which means they only store the ID, not the calibration data, potentially affecting seamless interoperability in mixed systems.
3. Complexity in Calibration: Integrating TEDS into load cells can introduce more calibration work for the calibration laboratory. For instance, load cells that are calibrated with a meter require an "As Received" calibration, then a separate calibration or run to obtain the raw values (likely mV/V), programming the TED chip, and then the "As Returned" verification. The cycle time is typically at least double for the calibration lab, which increases calibration costs.
4. Meter Calibration: If one wants to establish metrological traceability, one must either pay for all of their readouts (indicators) to be calibrated that can read the TEDS for load cell chips or purchase more equipment, such as a high-end load cell simulator to calibrate all their meters.
5. Data Security Concerns: TEDS IEEE chips raise concerns about embedded data security within load cells, necessitating measures to protect sensitive information.

TEDS for Load Cells can undoubtedly lead to better efficiency gains, and the lure of using multiple load cells and only needing one calibrated meter with TEDS is appealing.

Despite the additional calibration cost, buying IEEE 1451.4 TEDs equipment can reduce costs for most customers. It also lets customers calibrate their indicators in-house by purchasing a high-load cell accuracy simulator.

Templates and How TEDS stores information.

IEEE has published a great resource with the tables shown @ https://standards.ieee.org/wp-content/uploads/import/documents/tutorials/teds.pdf

Information stored on the IEEE 1451.4 standard memory chip is organized into four sections. The first two are required, and the last two are optional.

1)Basic Teds: Serial Number and other misc. information
2) Standard template: Stores the basic calibration data like output range, calibration date, force units, and excitation.

Template 33 for mV/V load cell (unamplified)
Template 31 for 4-20mA or 0-20mA
Template 30 for voltage amplified. i.e. 0-5V, .5 to 10.5V, etc.
3)Linearization templates (optional)

Template 40 provides linearization data piecewise (shown below on a graph as a 4 pt Span point option).

Template 41 provides linearization data via a curve fit polynomial. (Ideally suited for using calibration information from Morehouse ASTM E74 or ISO 376 certificates, as well as any Tension and Compression load cell)

The disadvantage of any of the above templates is the inability to characterize a load cell well in tension and compression.

The programmed mode (compression or tension) will be closer to nominal, and the other mode will likely have large deviations unless the load cell has perfect symmetry between modes (this is rare).

There are ways to install two different TEDS for load cell chips in one load cell. If that option is chosen, the operator typically must use a switch to change between the two different chips.

4) User TEDS: Additional memory space that can store miscellaneous information. The standard does not define this information. Therefore, if the load cell is to be used by multiple brands of indicators, it must not contain any necessary information.

Note: Compression and Tension points can be programmed, though it depends on the meter/DAQ's firmware's ability to make the proper interpretation and calculation.

It is highly recommended that any programming method be verified with the entire system and that the user understands how their meter interprets the data. A good validation method would be to send the system in with the meter and request a second calibration after the TEDS chip has been programmed.

Note: If the calibration is performed using ISO 376 or ASTM E74, the coefficients from the polynomial equation must be used.

Templates 33,40 & 41

Template 40 is nice as it offers more data points, though it has significant disadvantages compared with Template 41.

One of the more significant differences is calibration, assuming the end-user wants data reported in engineering units.

Any force-measuring system will drift over time and may require adjustments to bring the unit as close to nominal as possible. Templates 33 & 40 will likely create more calibration time and cost for the end-user to adjust their system constantly.

Template 41 may also create more time if a calibration standard like ASTM E74 or ISO 376 is not followed.

If the desire is to have force readings as close to nominal as possible for all templates, three calibrations would likely be needed to make that happen.

Template 33 or 40 is typically for calibration in one mode, Compression or Tension.

1. An "As Received" calibration in force units.
2. A separate calibration to obtain A/D or mV/V values to reprogram the TEDS for load cells chip.
3. An "As Returned" calibration will show the new values and the errors from the nominal.

Note: The price for this type of calibration is typically 1.5 times the cost of a regular calibration.

For Template 41, only one calibration would need to be performed and recorded in mV/V or A/D counts if a calibration standard like ASTM E74 or ISO 376 is not followed.

Template 41 criteria typically for only one calibration in one mode, Compression or Tension.

1. The load cell is always calibrated in mV/V without or without an indicator, or A/D counts with an indicator.
2. The calibration conforms to ASTM E74 or ISO 376 and generates coefficients.
3. The Teds for the load cell chip are programmed with coefficients.
4. The end-user must be okay with all mV/V or A/D counts calibration reports.

Note: If without the indicator, whatever indicator is used must be calibrated, and measurement uncertainties must be accounted for.

Also, the calibration required doubles if the end-user wants the data in engineering units programmed as close as possible to nominal, lbf, kgf, N.

Morehouse Products with TEDS

Figure 44 Morehouse PSDS meter can read TEDS templates 33,40 & 41.

We have a PSDS; the only option under $ 1000.00 we have seen that can read all three templates.

The manual for this device can be downloaded here.

From our manual on how the PSDS works:

All standard TEDS devices contain a basic 2-point calibration.
TEDS devices can also optionally hold multiple extended calibration tables: template ID=40 (multi-point calibration) or template ID=41 (polynomial calibration).
When you first connect a new TEDS device to the PSDS, a message will be displayed stating that a new TEDS device has been detected and that default settings have been used.
The first detected, valid calibration table from the TEDS device will be selected.
The user can select an alternative calibration table from the menu or Toolkit, and this selection will be remembered. The table will be re-selected next time the device is plugged in.

Figure 45 Morehouse 4215 Plus Does Not Come Standard with TEDS

Unlike the PSDS, the 4215 Plus does not come standard with the ability to read and write TED templates 33,40, & 41.

This upgrade can be added, though the lead time is typically longer.

The 4215 Plus comes standard with the ability to use polynomials internally, making it an excellent choice to reap the benefits of using coefficients to generate a polynomial curve.

Force Calibration System Accuracy

At Morehouse, we are frequently asked about accuracy, with questions such as "What is the accuracy of this system you offer for sale?"

At first glance, it should be an easy question to answer, and, indeed, we could give a glib answer of "Our system is accurate to 0.005 % of full scale." However, there are so many variables to consider that giving this throwaway answer sets the wrong expectations.

Morehouse recommends systems based on an understood requirement and where the end-user can control certain conditions. We must understand the application and know the customer's expectations. We can only provide a complete system with the right indicator and appropriate adapters when we know these parameters.

To further clarify, below is a detailed explanation based on these basic premises and ground rules:

1. The definition of Accuracy per VIM (International Vocabulary of Metrology).
2. You cannot have a more accurate system than the reference standard used to calibrate it.
3. Agreement on the calibration method for portability of the data.
4. Other manufacturers may overpromise and underdeliver.

1. The definition of Accuracy per the VIM

The current draft of the International Vocabulary of Metrology (VIM) defines *Measurement Accuracy* as "the closeness of agreement between a measured value and a reference value of a measurand."[9] The VIM then states that Accuracy can be interpreted as the combination of measurement trueness and measurement precision.

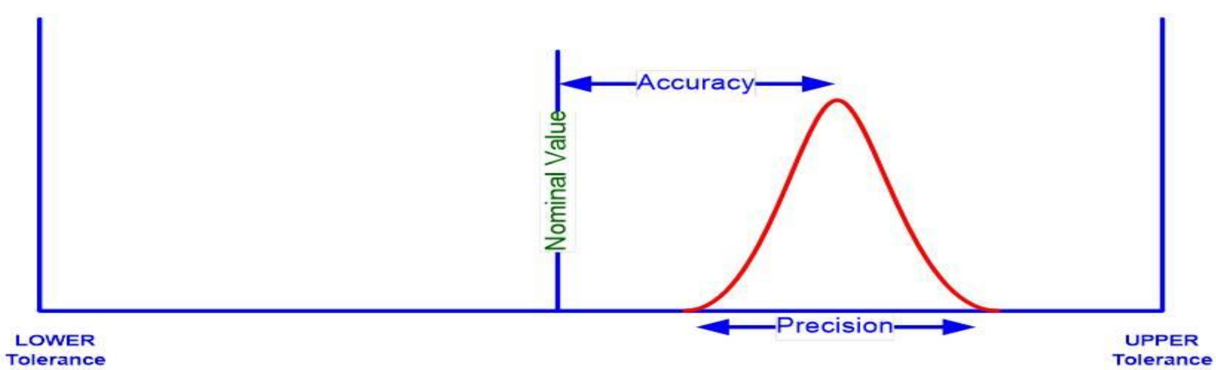


Figure 46: Measurement Accuracy Expressed Graphically

Accuracy is how close the system is to the nominal value (measurement trueness) and how well the system repeats (measurement precision). The above graph gives a graphical representation of this explanation. For example, suppose we had a 10,000 lbf load cell, and the accuracy specification was ± 0.05 % of full scale. In that case, we should expect the system to read 10,000 ± 5 lbf when used under the same calibration conditions, and that specification should be repeatable.

A better description of what is above would be to substitute the word "Accuracy" for "bias." Bias is a Type B contributor to measurement uncertainty, while precision is Type A.

Repeatability, or how well it repeats, is defined in the VIM as "it repeats when the same procedure, operators, system, operating conditions, location, and force machine are used."[1] This definition is what makes defining Accuracy difficult. Force is mechanical, and the interactions of different equipment and loading conditions can significantly affect the output and Accuracy of the force-measuring system. Therefore, we must understand the application, know the expectations, and provide the complete system with the appropriate indicators and adapters.

2. **You cannot have a more accurate system than the reference standard used to calibrate it.**

Common sense says that the reference standard **must** be more accurate and repeatable than the system used to calibrate. Many international standards document these calibration procedures and calculations, which subsequently allow the portability of test data, along with laboratory accreditation groups that keep everyone honest.

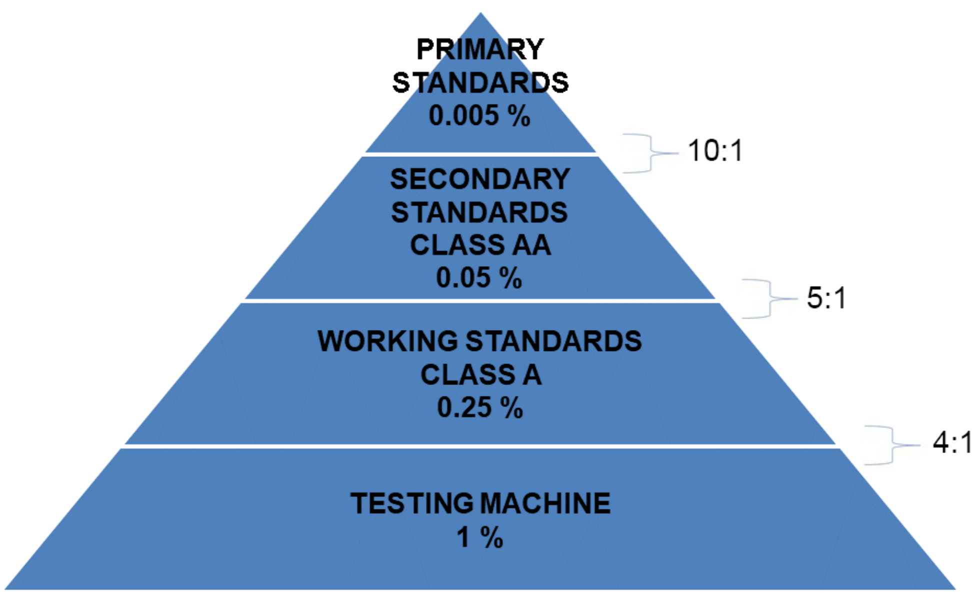


Figure 47: ASTM E74 Pyramid of Ratios

International calibration standards agree on the factors and levels of accuracy, which are depicted here. Any accredited calibration laboratory should have a scope, and their measurement capability should be listed using the above classifications. However, things are not always what they appear to be, and you need to know what to look for in these certs and promises.

For example, let us look at three labs:

1. The way it should be - using an actual calibration laboratory as an example.
2. Barely acceptable - using a hypothetical laboratory.
3. Disaster - using a hypothetical laboratory.

In these examples, we will demonstrate measurement risk using specific or bench-level risk scenarios regarding capability.

Here are three examples of what happens at various levels of Accuracy from Morehouse at 0.0016 %, Calibrations "R" Us at 0.04 %, and Malarky Calibration at 0.1 %.

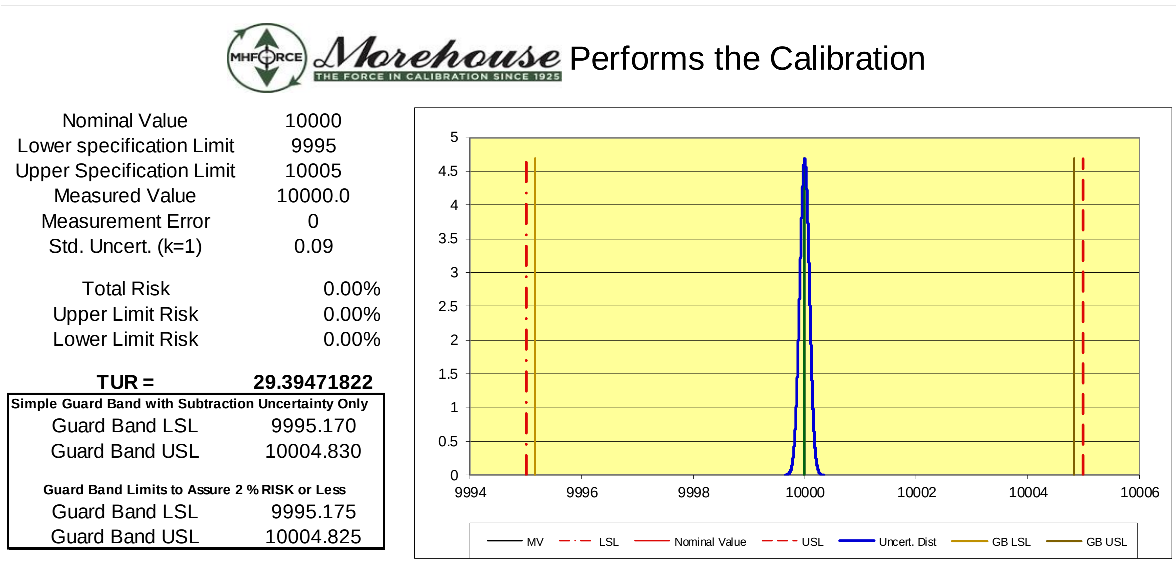


Figure 48: Morehouse Does the Calibration with Primary Standards

When a 10,000 lbf force-measuring system has a specification of ± 5 lbf or 0.05 % of full scale, applying accepted compliance decisions, Morehouse can "pass" the instrument if the reading is between 9,995.170 and 10,004.825. This is a significantly larger window to say an instrument is good compared to other calibration laboratories that use secondary standards. They use standards that are typically 10-20 times less accurate.

The second laboratory with the 0.04 % capability can only "pass" the instrument when it reads almost perfectly between 9,999.108 and 10,000.892.

Calibration "R" US Performs the Calibration

Nominal Value	10000
Lower specification Limit	9995
Upper Specification Limit	10005
Measured Value	10000.0
Measurement Error	0
Std. Uncert. (k=1)	2.00
Total Risk	1.24%
Upper Limit Risk	0.62%
Lower Limit Risk	0.62%
TUR =	**1.249869804**
Simple Guard Band with Subtraction Uncertainty Only	
Guard Band LSL	9999.000
Guard Band USL	10001.000
Guard Band Limits to Assure 2 % RISK or Less	
Guard Band LSL	9999.108
Guard Band USL	10000.892

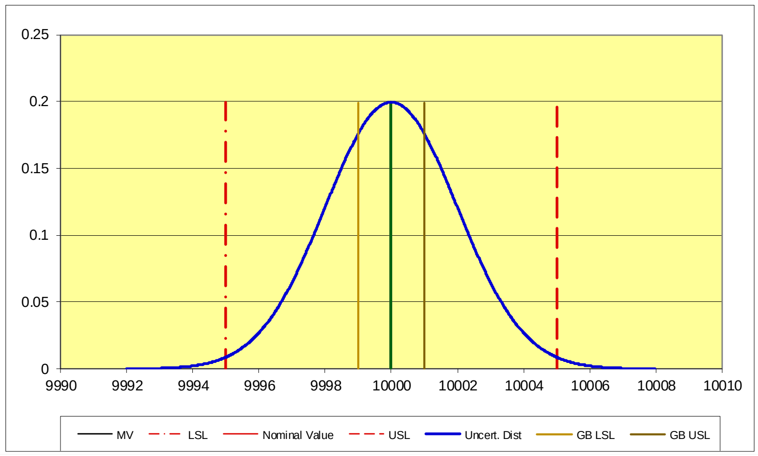


Figure 49: A Lab Using Load Cells as Standards Does the Calibration

Lastly, we have a disaster when a device is submitted to a laboratory that does not have the capability. They "calibrate" the device where the expectation is ± 5 lbf, yet the best they can do is ± 10 lbf. Their graph shows that 31.73 % of the curve will be outside the specification limit in the absolute best case. This means the customer must accept an absurd amount of risk. The risk to the end-user of this equipment is high, as is the likelihood of future lawsuits, mass recalls, enormous amounts of rework or scrap, and worse still, a seriously tarnished reputation for quality.

Malarky Calibration Performs the Calibration

Nominal Value	10000
Lower specification Limit	9995
Upper Specification Limit	10005
Measured Value	10000.0
Measurement Error	0
Std. Uncert. (k=1)	5.00
Total Risk	31.73%
Upper Limit Risk	15.87%
Lower Limit Risk	15.87%
TUR =	**0.499991666**
Simple Guard Band with Subtraction Uncertainty Only	
Guard Band LSL	10005.000
Guard Band USL	9995.000
Guard Band Limits to Assure 2 % RISK or Less	
Guard Band LSL	10005.269
Guard Band USL	9994.731

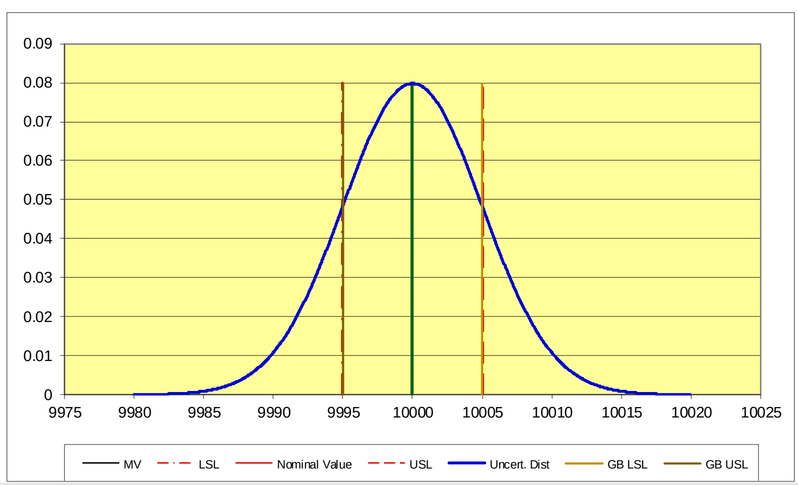


Figure 50: A Lab Using Load Cells as Standards Calibrated by Other Load Cells Does the Calibration

3. Agreement on the calibration method for the portability of the data

We will keep this simple by limiting our analysis to the two most common types of calibration:

a. Calibration following ASTM (American Society for Testing & Materials) E74.
b. The commercial type of calibration consists of a 5-to-10-point calibration, known as the non-ASTM method.

a. Morehouse Load Cells and Accuracy with ASTM E74 Calibration

The specifications of our Ultra-Precision Load Cell state that they are accurate to 0.005 % of full scale, meaning that the ASTM LLF (lower limit factor, which is the expected performance of the load cell) is better than 0.005 % of full scale. However, this is only one component of the much larger Calibration and Measurement Capability Uncertainty parameter (sometimes called CMC). When the load cell is under the same conditions that Morehouse used for calibration (same adapters, application with a machine that is just as plumb, level, square, rigid, has low torsion, and other repeatability conditions), it is expected to perform better than 0.005 % of full scale.

The expected performance on a 10,000 lbf load cell is better than 0.5 lbf (10,000 * 0.005 %). Therefore, at the time of calibration, the load cell's expected performance will be better than 0.005 % or 50 parts per million.

b. Morehouse Load Cells and Accuracy with Non-ASTM Calibration

We know from the accreditation requirements that when we test a good force-measuring system in our machine, it will repeat. We have done countless tests and incorporated these into our CMC uncertainty parameter. When we perform calibrations, we report the measurement uncertainty and consider it.

Thus, when we set the specification, it includes our measurement uncertainty at the time of calibration. That uncertainty captures the repeatability conditions well. The uncertainty is also quite low in almost all cases below 120,000 lbf of Force. The uncertainty is 0.002 % of applied Force or better because Morehouse Deadweight Primary Standards are the most accurate force machines.

4. **Other manufacturers may overpromise and underdeliver.**

Figure 51: Averages Hide the Extremes

Morehouse will not overpromise and underdeliver a solution. However, other manufacturers have different methods for testing their devices. Some are conservative, others not so much. Morehouse has been around long enough to hear and witness countless customer stories.
Often, it is too late because the end-user has bought a device and been promised an accuracy that no other calibration laboratory can meet. These over-promising suppliers do not understand metrology and consequently promote terrible, often impossible measurement practices.

Some notable examples include:

1. Averages are used to specify a tolerance. The above figure above shows a plane being weighed. Not all the values are within the target weight, but based on the average (30,000 lbf), all is good since the target has not been breached.
2. The simple, more economical way is easier than doing things correctly. It is easy to say you can do things, apply some force, and report results without knowing their use. This is an exploitation of the customer.
3. The resolution is equal to Accuracy. This is a large, complex issue concerning conformity assessment and uncertainty. We have many published guidance documents and whitepapers on Measurement Risk and TUR (Test Uncertainty Ratio) available for download from our website.

4. Using a specification of non-linearity for Accuracy. The problem is that this does not include critical factors such as the meter, reference standard, adapters, and everything that impacts the measurement results.
5. The location of the measurement must be considered when making a conformity assessment of a "pass" or a "fail."

Measurement Bias

What can happen when we use an accuracy specification and assume all the measurements are centered per the specification limits? Many people in the metrology community face this as many papers assume a centered process or measurement.

The last section dealt with accuracy and made assumptions about the process being centered.

When the measurement deviates from the true value, it is said to have bias. Measurement bias refers to systematic errors in a measurement or measurement process that consistently cause the measured values to deviate from the true value of the measured quantity.

Making a conformity assessment could mean the measured value might be anywhere within the specification. In cases of simple acceptance, the measured value might even be at the tolerance limit. Why does this matter? When a known bias is ignored —i.e., not corrected or not included in the Statement of Measurement Uncertainty on the Calibration Certificate—you may not fully achieve measurement traceability, and all subsequent measurements will be suspect.

The Location of the Measurement and Bias

Why do we care about the location of the Measurement if the device is within tolerance? If a device has a specification of 0.1 % of full scale and the calibrating laboratory reports a value within 0.1 %, the device is "Within Tolerance. " However, realize that determining tolerance depends on all parties agreeing — per a contract — on a decision rule for how measurement uncertainty should be handled.

It also depends on the uncertainty of the measurement and whether the lab performing the calibration followed the proper calculations in evaluating the Uncertainty of Measurement (UOM) when making a statement of conformity.

Nominal Value	**10000.0**
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	**10009.0**
Measurement Error	9.0
Std. Uncert. (k=1)	**0.085**
Total Risk	**0.00%**
Upper Limit Risk	0.000%
Lower Limit Risk	0.000%
TUR =	**58.78943644**
Cpk=	**5.999032319**
TAR=	**62.5**
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	**9990.170**
Guard Band USL	**10009.8299**
Percent of Spec	**98.30%**
Guard Band Limits for Risk of	**2.500%**
Guard Band LSL	**9990.167**
Guard Band USL	**10009.833**
Percent of Spec	**98.33%**

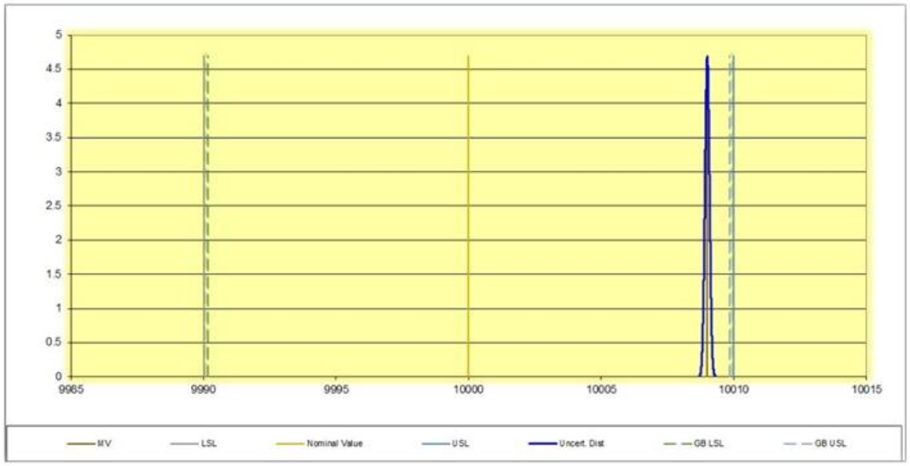


Figure 52: Graph Showing 10 009.0 as the Measured Value

Making a conformity assessment of "In Tolerance" is all about location, location, and location of the Measurement. It's also about the Uncertainty of the Measurement because anything other than a nominal measurement can significantly raise the risk associated with the Conditional Probability of False Accept (PFA).

The probability of a false acceptance is the likelihood of a lab calling a measurement "In Tolerance" when it is not. PFA is also commonly called consumer risk (β: Type II Error).

The measurement location we are referring to is how close the Measurement is to the nominal value. If the nominal value is 10 000.0 N and the instrument reads 10 009.0 N, the instrument bias is 9.0 N, as shown in the above figure. The bias is 0.09 % of the measured value or 90 % of the overall tolerance.

The higher the measurement bias from the nominal, the higher the Measurement Uncertainty of subsequent measurements unless the measurement bias is corrected. In the above, if the unit under test becomes the reference standard, and the measurement bias is not corrected, future measurements with this Reference Standard will introduce additional Measurement Risk that is not accounted for in the reported Measurement Uncertainty.

Note: NIST SOP 29 has additional information on bias and gives further examples of accounting for any measurement bias in an uncertainty budget.

Low-Risk Scenario

Nominal Value	10000.0
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	10009.0
Measurement Error	9.0
Std. Uncert. (k=1)	0.085
Total Risk	0.00%
Upper Limit Risk	0.000%
Lower Limit Risk	0.000%
TUR =	58.78943644
Cpk=	5.999032319
TAR=	62.5
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	9990.170
Guard Band USL	10009.8299
Percent of Spec	98.30%
Guard Band Limits for Risk of	2.500%
Guard Band LSL	9990.167
Guard Band USL	10009.833
Percent of Spec	98.33%

High-Risk Scenario

Nominal Value	10000.0
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	10009.0
Measurement Error	9.0
Std. Uncert. (k=1)	1.250
Total Risk	21.19%
Upper Limit Risk	21.192%
Lower Limit Risk	0.000%
TUR =	3.998933697
Cpk=	0.408061957
TAR=	4
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	9992.501
Guard Band USL	10007.4993
Percent of Spec	74.99%
Guard Band Limits for Risk of	2.500%
Guard Band LSL	9992.451
Guard Band USL	10007.549
Percent of Spec	75.49%

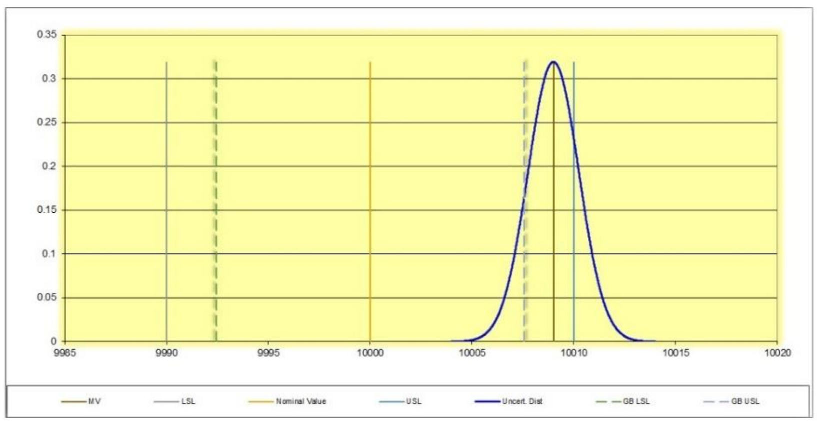


Figure 53: Graph Showing 10 009.0 as the Measured Value Comparing Two Different Calibration Providers

The above figure compares two suppliers using a discrete measurement point at the bench level, resulting in different calibration process uncertainty values. The bottom graph shows the higher risk level using a different supplier.

The new provider has a higher Measurement Uncertainty of 0.025 % than shown in the High-Risk Scenario graph, where the calibration provider had a 0.0016 % Measurement Uncertainty. Everything else has remained the same. However, the overall measurement risk is now 21.19 %.

The assumption is that the measurement bias is known (+ 9 N). Although the risk is 21.19 %, the bias can usually be corrected (adjusting the measuring system) or incorporated in a measurement model as a correction. Using the high-risk scenario, we will discuss what happens when bias is not corrected.

What happens when we do not correct the bias?

Let us look at the high-risk scenario. When 10 000.0 N of force ± 2.50 N was applied, the measured value was 10 009.0 N.

The right thing for the end-user to do is to load the device to 10 009.0 N to apply 10 000.0 N of force. Let us assume they do not do that and use this device to calibrate another 10,000 N instrument.

If we look at the minimum Measurement Uncertainty for the device that read 10 009.0, assuming the bias is corrected, the Measurement Uncertainty would have to be greater than that of the Measurement Uncertainty used for calibrating the device, which was ± 2.50 N.

The Measurement Uncertainty for this device would be ±2.5 N plus additional Measurement Uncertainty contributors for repeatability, reproducibility, resolution, environmental, stability between calibrations, and other error sources. Likely, our measurement uncertainty assuming stability of 0.02 % as the second highest contributor would become around 5.178 N.

Nominal Value	10000.0
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	9996.0
Measurement Error	-4.0
Std. Uncert. (k=1)	2.589
Total Risk	1.02%
Upper Limit Risk	0.000%
Lower Limit Risk	1.024%
TUR =	1.931223436
Cpk=	1.182403422
TAR=	3.99840064
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	9995.178
Guard Band USL	10004.8219
Percent of Spec	48.22%
Guard Band Limits for Risk of	2.500%
Guard Band LSL	9995.074
Guard Band USL	10004.926
Percent of Spec	49.26%

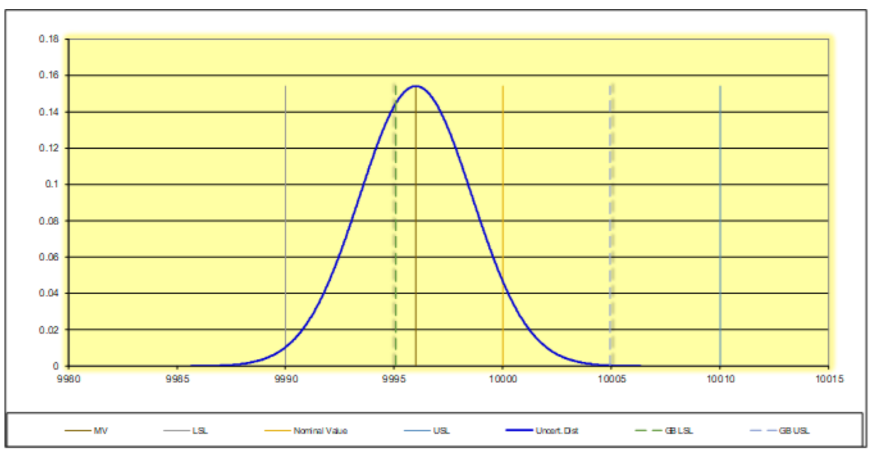


Figure 54: Graph Showing 9 996.0 as the Measured Value

Scenario 1: Bias is corrected by loading the reference standard to 10 009.0 N to apply 10 000.0 N.

The above figure shows a subsequent measurement being made with the calibrated device that read 10 009.0 N when 10 000.0 N ± 2.5 N was applied. This device is now used as a reference standard to calibrate other devices (UUT).

The graph represents correcting the reference standard for the + 9 N bias and using it to calibrate another device (UUT). The measured value of the Unit Under Test reads 9,996 N.

The reference standard is being loaded to 10 009.0 N to apply 10 000.0 N ± 5.178 N. The UUT reads 9996.0 with a Total Risk of 1.02 %.

Nominal Value	**10000.0**
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	**9987.0**
Measurement Error	-13.0
Std. Uncert. (k=1)	**2.589**
Total Risk	**87.67%**
Upper Limit Risk	0.000%
Lower Limit Risk	87.672%
TUR =	**1.931223436**
Cpk=	**-0.59120171**
TAR=	**3.99840064**
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	**9995.178**
Guard Band USL	**10004.8219**
Percent of Spec	**48.22%**
Guard Band Limits for Risk of	**2.500%**
Guard Band LSL	**9995.074**
Guard Band USL	**10004.926**
Percent of Spec	**49.26%**

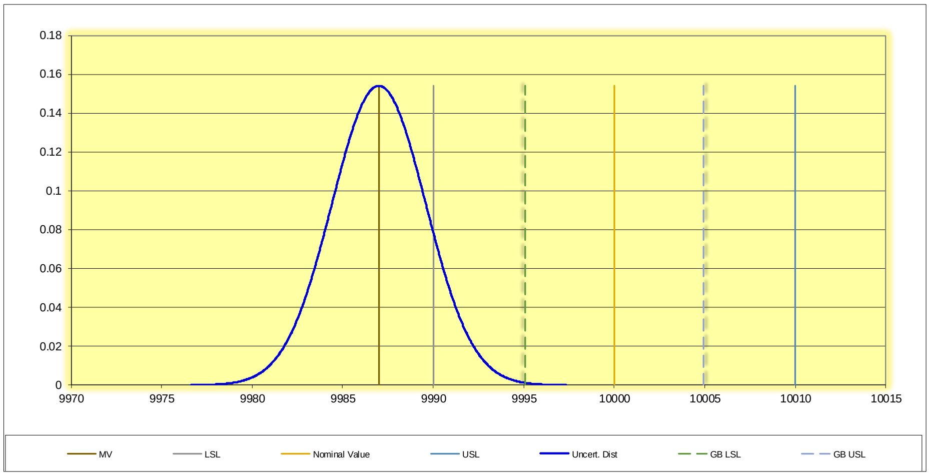


Figure 55: Graph Showing What Happens if we do not correct for the + 9 N Bias.

Scenario 2: The reference standard is not loaded to 10 009.0 N to apply 10 000.0 N. Instead, the device is loaded to 10 000.0 N, which means only 9 991.0 N is applied (10 000.0 – 9.0 = 9 991.0)

We show that we are not correcting this +9 N bias graphically by subtracting 9 N (9 996.0 – 9.0 = 9 987.0) from the measured value. The UUT reads 9 987.0 N, which could result in the lab failing the instrument and deciding to adjust the device within the acceptance limits (the measured value of this calibration is now off by 9 N and transferred to the UUT).

The result of not correcting for the +9 N bias is a failed instrument that has been adjusted using a reference standard with a high bias and a measurement risk above 87 %.

Bias Conclusion

Using the manufacturer's accuracy specification and not correcting for bias can further increase Measurement Risk. Not correcting for bias seems to be a problem many in the calibration deal with, and their unsuspecting customers are getting calibrations that carry too much overall Measurement Risk.

The risk of not correcting for this offset (Bias) should concern anyone making measurements. Furthermore, the habit of insisting on a 4:1 TUR assumes the measurement process is centered (measurement bias is corrected).

In all cases, paying attention to the location of the Measurement and calculating Measurement Risk is imperative to making accurate measurements. Anyone wanting more accurate measurements (measurements with less Measurement Uncertainty) should have a defined process to account for and correct bias.

They should also examine their calibration providers' practices in terms of how they handle and correct their measurement biases.

Figure 56: Morehouse 4215 Plus & C705P Meters Use Coefficients to Reduce Bias

Morehouse has many options with our force calibration systems that use coefficients generated during calibration. Our 4215 plus and C705P use coefficients programmed into the indicator to help correct and minimize measurement bias.

When the bias is not corrected, the risk of making a measurement that does not correctly account for bias can result in an underestimation of measurement uncertainty and, therefore, disagrees with the metrological traceability definition and undermines measurement confidence.

Load Cell Stability

Load cells combine metal, strain gauges, adhesive, and more. Like humans, every measuring instrument is subject to aging. Load cells age from mechanical stress or fatigue, and over time, this ensures that there will be some instability in the system.

Some common factors that impact load cell stability or system stability include:

- The meter used with the system - Like load cells, the electronic components can drift.
- The amount of usage of the load cell.
- The material and strain gauges used to make the cell.
- If the load cell has been loaded past capacity, how many times has it been loaded?
- Exposure to higher temperatures.
- Amount of creep in the Load Cell.
- Strain Hardening - This is why load cells get better with age until they do not.
- High cyclic applications that stability can degrade vary gradually with time.
- Manufacturing defects may show up vary gradually on some load cells.
- Variations in applying the strain gauges.
- Using different cables and connections than what was used during calibration.
- Adapters - generally, calibration adapters do not impact stability, though changing the hardness and types of adapters can impact the calibration results.

The list of factors that impact load cell stability can continue. There are thousands of variables that can cause a change in load cell stability. Having a documented process and purchasing load cells from reputable manufacturers is a start to controlling the load cell stability.

Not every source of load cell stability can be prevented. However, the impact of load cell stability can be detected and corrected by setting the appropriate calibration cycle, implementing statistical process controls, and following accepted good practice guidelines.

Load cell stability or drift is usually assumed to be the 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 stability can impact the following:

- Potentially consume your uncertainty budget.
- Cause the force measuring device to be out of tolerance.
- Cause all measurements between the last and 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 manufacturers. Most load cells are categorized as either general purpose or those calibrated by more stringent standards, such as ASTM E74 or ISO 376.

We will discuss both load cell types and their typical instability characteristics. In each case, we will start with the general uncertainty contributors, then progress to what we usually observe and recommend improvement.

The systems are each broken down into Good, Common, and Bad. Systems that fall into the good category are usually those by reputable manufacturers who understand load cells and indicating systems.

The Common category may consist of suboptimal combinations, such as an excellent load cell and an average indicator or an excellent indicator and an okay load cell. In the Bad category, one or both components are unsuitable for the end user's overall uncertainty needs.

Typically, general-purpose load cells are more inexpensive and paired with indicating systems contributing to drift or system stability. The requests we see on these systems are generally for a 10-pt. Calibration. The accuracy specifications are usually 0.05 % to 1 % of full scale.

General Purpose Load Cell Instability	
Good	0.025 % - 0.1 %
Common	> 0.1 % - 0.5 %
Bad	> 0.5 % - 5 %

Figure 57: Typical Instability Numbers for Various Load Cells

The long-term instability of the reference force transducer is determined either from previous calibrations or by estimations of similar systems until the actual values can be obtained. The figure above shows the instability Morehouse typically observes on general-purpose load cells.

Next, we will discuss calculating expanded uncertainty and how reference standard stability (or instability) affects overall expanded uncertainty.

Measurement Uncertainty Budget Worksheet									
Laboratory	General Purpose Load Cell								
Parameter	FORCE	Range	10K	Sub-Range					
Technician	HZ	Standards Used							
Date									
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	0.645497224	A	Normal	1.000	1	645.50E-3	416.67E-3	0.30%	173.6E-3
Reproducibility Between Techs	0.11785113	A	Normal	1.000	10	117.85E-3	13.89E-3	0.01%	19.3E-6
Repeatability of Best Existing Device	500.0000E-3	A	Normal	1.000	3	500.00E-3	250.00E-3	0.18%	20.8E-3
Non-Repeatability of Reference	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	0.96%	8.9E-3
Resolution of UUT	1.0000E+0	B	Resolution	3.464	200	288.68E-3	83.33E-3	0.06%	34.7E-6
Environmental Factors	300.0000E-3	B	Rectangular	1.732	200	173.21E-3	30.00E-3	0.02%	4.5E-6
Reference Standard Stability	20.0000E+0	B	Rectangular	1.732	200	11.55E+0	133.33E+0	95.90%	88.9E+0
Ref Standard Resolution	50.0000E-3	B	Resolution	3.464	200	14.43E-3	208.33E-6	0.00%	217.0E-12
Specified Tolerance or Non-Linearity	2.1000E+0	B	Rectangular	1.732	200	1.21E+0	1.47E+0	1.06%	10.8E-3
Hysteresis	2.3000E+0	B	Rectangular	1.732	200	1.33E+0	1.76E+0	1.27%	15.5E-3
Other Error Sources	1.0000E+0	B	Rectangular	1.7321E+0	200.0000E+0	577.35E-3	333.33E-3	0.24%	555.6E-6
Reference Standard Uncertainty	200.0000E-3	B	Expanded (95.45% k=2)	2.000		100.00E-3	10.00E-3	0.01%	
			Combined Uncertainty (u_c)=			11.79E+0	139.04E+0	100.00%	89.1E+0
			Effective Degrees of Freedom			216			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			23.24	0.23241%		
Per Point Example									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	10000.00	10001.00	10001.00	10000.00	10001.00	10000.75	0.5000	0.0020%	0.2
Repeatability of Best Existing Device			Average Standard Deviation of Runs			0.500000			

Figure 58: Expanded Uncertainty Budget with 0.2 % instability.

With general-purpose load cells, observing systems with accuracy specifications lower than the instability observed from one calibration to the next is common. If the accuracy requirement is for 0.1 % of full scale and the instability from one calibration to the next is 0.2 %, it becomes nearly impossible to claim 0.1 % accuracy as your tolerance.

The above figure shows the uncertainty of 0.2 % instability on a 10,000 lbf load cell. This accounts for approximately 95.90 % of the uncertainty contribution.

When accounting for reference standard stability in an uncertainty budget, stability can be treated as type A or B. Most calibration laboratories claim instability as a type B uncertainty contributor with a rectangular distribution. This means that instability of 0.2 % would be divided by a square root of 3 (or 1.732), about 0.115 %.

Now, let's think about that. A calibration laboratory claims 0.1 % accuracy on their scope, and their device's instability accounts for 115 % of their accuracy statement alone. This is a case of system stability accounting for more than 100 % allowable.

The solution to this problem is often simple. Either shorten the calibration frequency or purchase better equipment. This could mean upgrading the indicator, load cell, or both.

Next, let's assume the end-user decided it would be much less expensive to buy a better load cell than to shorten the calibration interval. A year after the purchase, the reference standard stability is observed to be 0.05 % or 5 lbf on a 10,000 lbf load cell.

Measurement Uncertainty Budget Worksheet									
Laboratory	General Purpose Load Cell								
Parameter	FORCE	Range	10K	Sub-Range					
Technician	HZ	Standards Used							
Date									
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	0.645497224	A	Normal	1.000	1	645.50E-3	416.67E-3	2.97%	173.6E-3
Reproducibility Between Techs	0.11785113	A	Normal	1.000	10	117.85E-3	13.89E-3	0.10%	19.3E-6
Repeatability of Best Existing Device	500.0000E-3	A	Normal	1.000	3	500.00E-3	250.00E-3	1.78%	20.8E-3
Non-Repeatability of Reference	2.0000E+0	B	Rectangular	1.732	200	1.15E+0	1.33E+0	9.50%	8.9E-3
Resolution of UUT	1.0000E+0	B	Resolution	3.464	200	288.68E-3	83.33E-3	0.59%	34.7E-6
Environmental Factors	300.0000E-3	B	Rectangular	1.732	200	173.21E-3	30.00E-3	0.21%	4.5E-6
Reference Standard Stability	5.0000E+0	B	Rectangular	1.732	200	2.89E+0	8.33E+0	59.37%	347.2E-3
Ref Standard Resolution	50.0000E-3	B	Resolution	3.464	200	14.43E-3	208.33E-6	0.00%	217.0E-12
Specified Tolerance or Non-Linearity	2.1000E+0	B	Rectangular	1.732	200	1.21E+0	1.47E+0	10.47%	10.8E-3
Hysteresis	2.3000E+0	B	Rectangular	1.732	200	1.33E+0	1.76E+0	12.56%	15.5E-3
Other Error Sources	1.0000E+0	B	Rectangular	1.7321E+0	200.0000E+0	577.35E-3	333.33E-3	2.37%	555.6E-6
Reference Standard Uncertainty	200.0000E-3	B	Expanded (95.45% k=2)	2.000		100.00E-3	10.00E-3	0.07%	
			Combined Uncertainty (u_c)=			3.75E+0	14.04E+0	100.00%	577.5E-3
			Effective Degrees of Freedom			341			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			7.37	0.07369%		
Per Point Example									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	10000.00	10001.00	10001.00	10000.00	10001.00	10000.75	0.5000	0.0020%	0.2

Figure 59: Expanded Uncertainty Budget with 0.05 % instability.

In this example, shown above, the reference standard stability (load cell stability) is still the most significant contribution to expanded uncertainty. However, the end-user can now claim 0.1 % of full scale and have room to maintain the accuracy from one calibration to the next. The instability can go as high as 0.077 %, and they could still be within the 0.1 % of full scale!

Note: Morehouse recommends our Calibration Grade Load Cells and a G501F or C705P Indicator for General Purpose Calibration.

Figure 60: Morehouse Calibration Grade Load Cells

The Morehouse calibration grade load cell with G501F indicator will typically maintain an accuracy of 0.1 % of full-scale year over year, with load cell stability accounting for about 0.05 % of overall accuracy. If an accuracy of 0.05 % or better is required, we recommend a different meter, the C705P, the Morehouse 4215 HS, or the 4215 Plus.

ASTM E74 Calibration Instability	
Good	0.005 % - 0.03 %
Common	> 0.03 % - 0.16 %
Bad	> 0.16 % - 0.3 %

Figure 61: Typical Instability Numbers for ASTM Load Cell Calibrations

Note: In this example, anything over 0.16 % of the applied force is bad because we are discussing ASTM calibrations, and section 11.2.1 has the requirements, and the stability requirements for a Class A device need to be better than 0.16 % of the applied force.

The assumption is that most end-users use force-measuring instruments for calibration following ASTM E4 and would like to comply with the ASTM E74 standard. That requires a calibration interval of two years; otherwise, the end-user is to ensure the device is calibrated at an interval that meets the criteria.

Through our experience, we have rarely observed bad load cells meeting the stability criteria if the calibration interval was shortened to one year. If stability is higher than 0.16 % and everything else remains constant (e.g., the cell has not been overloaded), the recommendation is to replace the load cell.

Let's compare two examples by comparing a reference standard stability of 0.16 % to a typical Morehouse HADI system with Ultra-Precision Class or a better load cell with 0.01 % stability.

Measurement Uncertainty Budget Worksheet									
Laboratory	ASTM E74 Load Cell System								
Parameter	FORCE	Range	10K	Sub-Range					
Technician	HZ	Standards Used							
Date									
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	0.032435888	A	Normal	1.000	1	32.44E-3	1.05E-3	0.00%	1.1E-6
Reproducibility Between Techs	0.006481823	A	Normal	1.000	10	6.48E-3	42.01E-6	0.00%	176.5E-12
Repeatability	577.3503E-3	A	Normal	1.000	3	577.35E-3	333.33E-3	0.39%	37.0E-3
ASTM LLF at 1 Standard Deviation	104.1667E-3	A	Normal	1.000	32	104.17E-3	10.85E-3	0.01%	3.7E-6
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.00%	3.5E-9
Environmental Factors	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	0.01%	281.3E-9
Reference Standard Stability	16.0000E+0	B	Rectangular	1.732	200	9.24E+0	85.33E+0	99.54%	36.4E+0
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.00%	11.5E-12
Other Error Sources	300.0000E-3	B	Rectangular	1.7321E+0	200.0000E+0	173.21E-3	30.00E-3	0.03%	4.5E-6
Reference Standard Uncertainty	200.0000E-3	B	Expanded (95.45% k=2)	2.000		100.00E-3	10.00E-3	0.01%	
			Combined Uncertainty (u_c)=			9.26E+0	85.73E+0	100.00%	36.4E+0
			Effective Degrees of Freedom			201			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			18.26	0.18257%		
Slope Regression Worksheet									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	10000.00	10001.00	10001.00	10000.00	10000.00	10000.5	0.5774	0.0020%	0.2
Repeatability (Of Error)			Average Standard Deviation of Runs			0.577350			

Figure 62: ASTM E74 Expanded Uncertainty with 0.16 % Load Cell Stability.

Measurement Uncertainty Budget Worksheet									
Laboratory	ASTM E74 Load Cell System								
Parameter	FORCE	Range	10K	Sub-Range					
Technician	HZ	Standards Used							
Date									
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Repeatability Between Techs	0.032435888	A	Normal	1.000	1	32.44E-3	1.05E-3	0.14%	1.1E-6
Reproducibility Between Techs	0.006481823	A	Normal	1.000	10	6.48E-3	42.01E-6	0.01%	176.5E-12
Repeatability	577.3503E-3	A	Normal	1.000	3	577.35E-3	333.33E-3	45.85%	37.0E-3
ASTM LLF at 1 Standard Deviation	104.1667E-3	A	Normal	1.000	32	104.17E-3	10.85E-3	1.49%	3.7E-6
Resolution of UUT	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.11%	3.5E-9
Environmental Factors	150.0000E-3	B	Rectangular	1.732	200	86.60E-3	7.50E-3	1.03%	281.3E-9
Reference Standard Stability	1.0000E+0	B	Rectangular	1.732	200	577.35E-3	333.33E-3	45.85%	555.6E-6
Ref Standard Resolution	24.0000E-3	B	Resolution	3.464	200	6.93E-3	48.00E-6	0.01%	11.5E-12
Other Error Sources	300.0000E-3	B	Rectangular	1.7321E+0	200.0000E+0	173.21E-3	30.00E-3	4.13%	4.5E-6
Reference Standard Uncertainty	200.0000E-3	B	Expanded (95.45% k=2)	2.000		100.00E-3	10.00E-3	1.38%	
			Combined Uncertainty (u_c)=			852.64E-3	726.99E-3	100.00%	37.6E-3
			Effective Degrees of Freedom			14			
			Coverage Factor (k) =			2.14			
			Expanded Uncertainty (U) K =			1.83	0.01829%		
Slope Regression Worksheet									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	10000.00	10001.00	10001.00	10000.00	10000.00	10000.5	0.5774	0.0020%	0.2
Repeatability (Of Error)			Average Standard Deviation of Runs			0.577350			

Figure 63: ASTM E74 Expanded Uncertainty with 0.01 % load cell stability.

The actual load cell in this test is a Morehouse Ultra Precision 10,000 lbf load cell with an ASTM lower limit factor (LLF) of 0.25 lbf. Assuming everything else remains the same, the Reference Standard Stability (load cell stability) is the largest contributor to uncertainty in both scenarios. Often, this isn't the case. Load cells with bad instability often have much higher LLFs than better load cells. A load cell with 0.16 % stability usually has an LLF worse than 2 lbf.

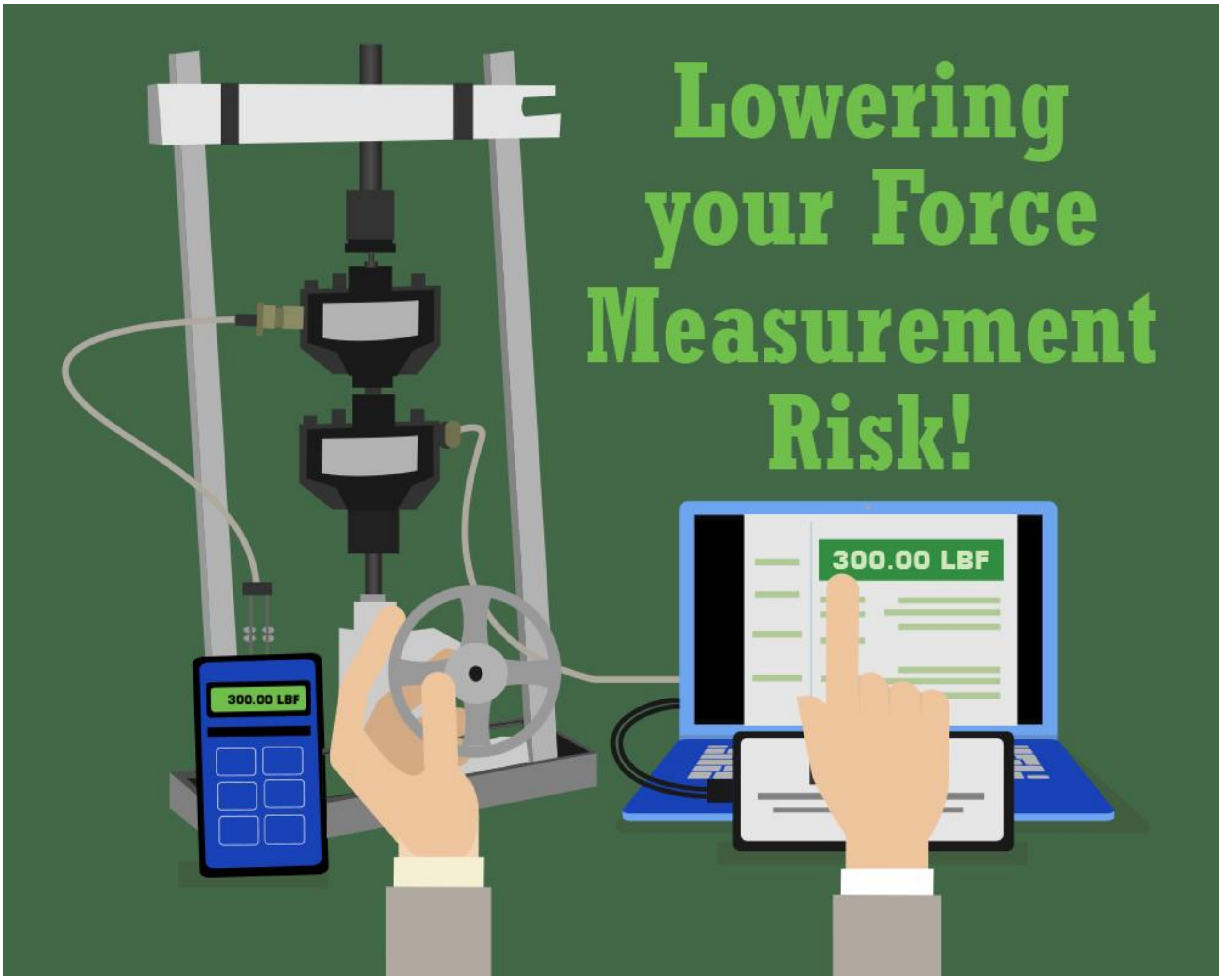
However, we aim to show the impact of stability on a load cell system and how it should impact your decisions when purchasing a load cell system. The system will probably not meet your accuracy requirements if stability is bad. In general, repeatability, reproducibility, and stability are the most important characteristics when evaluating a load cell system.

Adapters play a considerable role in actual results, and careful attention must be paid to purchasing the right adapters.

For ASTM E74 or ISO 376, Calibration Morehouse recommends our Precision Grade Load Cells and either a Morehouse HADI or Morehouse 4215 Plus.

Figure 64: Morehouse 4215 Plus

The Morehouse Ultra-Precision Load Cell with the 4215 Plus will typically maintain an ASTM Class A verified range of forces from 2 % of capacity (accuracy at the time of calibration of 0.005 %) or better year over year. Load Cell Stability accounts for 50 % or less of the overall uncertainty budget, usually below 0.02 % of applied force (0.01 % or better instability from year to year).



Advanced Force Measurement

My load cell calibration does not match what my calibration provider sent me!

Data not matching is something we all dread. For those who do sanity checks and follow good metrological practices, this is more of a common occurrence than it should be. Why? What was done at the time of calibration that is not being done now? What is happening that is drastically different?

Section 7 in the ISO/IEC 17025 deals with process requirements and contract review and can help us find the answer. The customer and calibration provider should be specific to this section's expectations. The bottom line is that the calibration lab should discuss what matters per the specifications. For example, we know the various mechanical and electrical interfaces matter if the instrument is a force-measuring device. At the time of calibration, these consist of the following:

- Selecting the right calibration method.
- The loading conditions.
- Use of adapters.
- Verification of the adjustments.
- Meters.

We will investigate each of these sources of error in greater detail.

Figure 65: Common Force Measurement Errors

Selecting the Right Calibration Method

The calibration method, such as compression, tension, ascending, descending, and the number of test points, is critical in using a force-measuring instrument. If the force-measuring instrument is to be used for compression (push) and tension (pull), it must be calibrated in both modes. After the basics are discussed, the question becomes whether calibration is required to a documented metrology standard such as ASTM E74 or ISO 376.

Most people understand that load cells are not symmetrical, and the differences between compression and tension calibration can be quite large. Many do not understand that a force-measuring device should only be used at the range in which it was calibrated.

An example is a 10,000 lbf load cell calibrated at 10 % force increments. The device has not been tested below 1,000 lbf and may not be accurate from 0.1 lbf through close to 1,000 lbf. The easiest solution is to discuss the requirements with your calibration provider because expecting a 10,000 lbf load cell to measure 20 lbf of force may not be realistic. However, using two load cells to measure from 20 lbf through 10,000 lbf is achievable.

Another common error is assuming that the force-measuring instrument can make descending or decremental measurements when only ascending or incremental calibration is performed. Ascending and descending calibration is typically required for low-cycle fatigue machines, nuclear requirements, and universities conducting research and development.

The final error we see is that the force-measuring device does not match the calibration results because the end-user uses mass weights for the verification and not weights adjusted for force. Force is force anywhere globally, and a force weight requires adjustment for material density, gravity where it is being used, and air buoyancy. Therefore, the errors can be quite high when using mass weights to perform force measurement, and the end-user may not think much of it.

Load Cells Used to Make Descending Measurements

Load cells used to make descending measurements must be calibrated in descending mode.

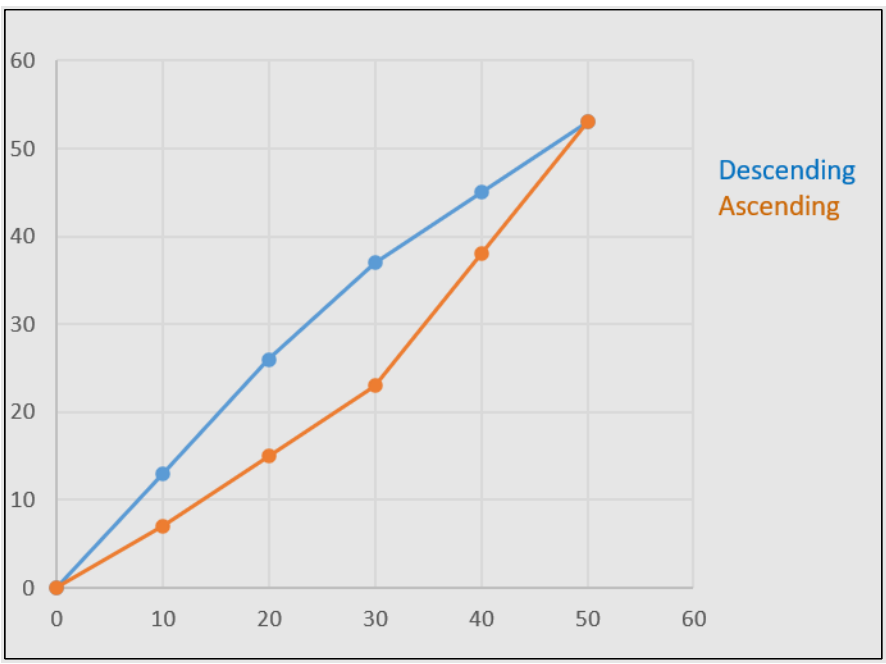


Figure 66: Descending Versus Ascending Calibration Curves

The difference in output on an ascending curve versus a descending curve can be significant. A particularly good 100K load cell had an output of -2.03040 on the ascending curve and -2.03126 on the descending curve. Using the ascending-only curve would result in an additional error of 0.042 %.
The common term to describe this result is Hysteresis.

We learned earlier that the definition of Hysteresis is the algebraic difference between the output at a given load descending from the maximum load and the output at the same load ascending from the minimum load.

Hysteresis is typically expressed as a % of full-scale output.

This section only looks at the percentage difference between the same force point, ascending versus descending. If someone used the ascending calibration curve to make descending measurements, the difference between the ascending and descending points would be a significant measurement error.

Load Cell Manufacturer (names removed)	1	2	3	4	5	5	3	4
Ascending Output 50 % Force Point	1.49906	1.20891	-2.0304	24990	-5.18046	-2.49899	-2.0886	-2.15449
Descending Output 50 % Force Point	1.49947	1.21022	-2.03126	25020	-5.18265	-2.50103	-2.08846	-2.15579
Difference	0.027%	0.108%	0.042%	0.120%	0.042%	0.082%	0.007%	0.060%

Figure 67: Five Different Load Cells and Corresponding Outputs Ascending Versus Descending Data

Load cells from five different manufacturers were sampled, and the results are recorded above. The numbers varied from 0.007 % (shear web type cell) to 0.120 %. On average, the difference was approximately 0.06 %.

Six of the seven tests were performed using deadweight primary standards, which are accurate within 0.0016 % of the applied force.

The conclusion from these tests is clear: If a load cell calibrates both ascending and descending forces, it must be calibrated in both modes.

If a load cell is calibrated following the ASTM E74 standard and a combined curve is used, the end-user could use the load cell anywhere in the verified range of forces. The downside to this method is that the combined curve will produce a Lower Limit Factor (LLF) larger than using separate curves.

However, the larger LLF will include any point within the verified range of forces for ascending and descending forces. Suppose the end-user cannot always load the reference standard to capacity and wants a smaller LLF. In that case, the load cell tested with several hysteresis loops for every capacity they wish to calibrate.

ASTM E74 states: For any force-measuring instrument, the errors observed at corresponding forces taken first by increasing the force to any given test force and then by decreasing the force to that test force may not agree. Force-measuring instruments are usually used under increasing forces, but if a force-measuring instrument is to be used under decreasing force, it shall be calibrated under decreasing forces as well as under increasing force. Use the procedures for calibration and analysis of data given in Sections 7 and 8 except where otherwise noted. When a force-measuring instrument is calibrated with increasing and decreasing forces, the same force values should be applied for the increasing and decreasing directions of force application. However, separate calibration equations should be developed.[3]

ASTM E74 further clarifies, "For any testing machine, the errors observed at corresponding forces taken first by increasing the force to any given test force and then by decreasing the force to that test force may not agree. Testing machines are usually used under increasing forces, but if a testing machine is to be used under decreasing forces, it should be calibrated under decreasing forces as well as under increasing forces."[4]

Compression Data for 23 °C ± 0.3 °C -- Force Units of lbf

Applied Force (lbf)	Predicted Response	Response Run 1	Response Run 2	Response Run 3
20000	0.035789	0.035795	0.035789	0.035789
30000	0.053648	0.053637	0.053635	0.053638
50000	0.089367	0.089376	0.089376	0.089373
100000	0.178669	0.178691	0.178691	0.178688
200000	0.357293	0.357274	0.357276	0.357274
300000	0.535944	0.535936	0.535932	0.535931
400000	0.714623	0.714620	0.714615	0.714617
500000	0.893329	0.893346	0.893338	0.893337
600000	1.072062	1.072059	1.072051	1.072057
700000	1.250822	1.250836	1.250825	1.250825
800000	1.429609	1.429627	1.429615	1.429623
900000	1.608423	1.608424	1.608412	1.608420
1000000	1.787265	1.787263	1.787250	1.787260

The coefficients of the following equation were fitted to the calibration data using the method of least squares. The units for force (lbf) and response are the same as shown in the table above.

Response = A + B(force) + C(force)^2

where A = 7.14099E-05
B = 1.78584E-06
C = 1.35715E-15

Standard deviation = 0.000012 response units

This standard deviation was computed according to ASTM E74-18 from the differences between the calibration data and the fitted equation given above.

The following values, as defined in ASTM E74-18, were determined from the calibration data:
Lower Limit Factor = 16 lbf
Class A Loading Range = 20000 lbf to 1000000 lbf
Class AA Loading Range = 32611 lbf to 1000000 lbf

Compression Data for 23 °C ± 0.3 °C -- Force Units of lbf

Applied Force (lbf)	Predicted Response	Response Run 1	Response Run 2	Response Run 3
1000000	1.787273	1.787270	1.787260	1.787267
900000	1.608377	1.608392	1.608373	1.608383
800000	1.429522	1.429537	1.429528	1.429534
700000	1.250706	1.250708	1.250701	1.250704
600000	1.071930	1.071920	1.071915	1.071918
500000	0.893193	0.893204	0.893199	0.893201
400000	0.714497	0.714499	0.714494	0.714496
300000	0.535841	0.535834	0.535832	0.535833
200000	0.357224	0.357235	0.357220	0.357220
100000	0.178648	0.178659	0.178657	0.178658
50000	0.089374	0.089369	0.089369	0.089369

The coefficients of the following equation were fitted to the calibration data using the method of least squares. The units for force (lbf) and response are the same as shown in the table above.

Response = A + B(force) + C(force)^2

where A = 1.11083E-04
B = 1.78517E-06
C = 1.99527E-15

Standard deviation = 0.000009 response units

This standard deviation was computed according to ASTM E74-18 from the differences between th calibration data and the fitted equation given above.

The following values, as defined in ASTM E74-18, were determined from the calibration data:
Lower Limit Factor = 12 lbf
Class A Loading Range = 50000 lbf to 1000000 lbf
Class AA Loading Range = 50000 lbf to 1000000 lbf

Figure 68: Pages from NIST Calibration Report for Morehouse 1,000,000 lbf Reference lbf Load Cell

ASTM E74 Versus ISO 376

Morehouse has been performing ASTM E74 and ISO 376 calibrations for decades. We have followed the ASTM E74 standard since its likely introduction in 1947 and have performed ISO 376 calibrations since early 2000. Before early 2000, ISO-376 was a DIN standard that later became EN-10002-3 and ISO 376 in the 1990s. Therefore, we had always assumed that the world 'force measurement community' knew the standards were completely different and could not be interchanged. However, we have learned that some laboratories provide field calibrations by intermixing and using an ASTM E74 calibration to certify a tensile machine to ISO 7500. Several organizations worldwide are unaware that the standards have vastly different criteria requirements.

If ISO 7500 is the requirement, then calibration needs to be performed following ISO 376 on the force-proving instruments used to certify the tensile machine. If ASTM E74 is the requirement, then the elastic force-measuring instrument must be calibrated following the ASTM E74 standard. The differences have already begun to emerge with the subtle use of terminology.

ASTM E74 is titled "Standard Practices for Calibration and Verification for Force-Measuring Instruments."

ISO 376:2011 Metallic materials is titled "Calibration of force-proving instruments used for the verification of uniaxial testing machines."

Here are some of the fundamental differences:

Selection of Forces

ASTM E74

- Requires at least 30 force points to be selected and typically three runs of data, each with a force point taken at about a 10 % interval.
- If the Class A or Class AA verified range of forces is anticipated to be less than the first non-zero force point, then a point equal to at least 400 times the resolution for Class A or 2000 times the resolution for Class AA needs to be added to the calibration forces selected.

ISO 376

- Requires at least eight force points throughout the range and at least four separate runs of data with a creep test when the force-measuring instrument is used for incremental loading only.
- If the force-proving instrument is used for incremental and decremental loading, then two extra runs of data are taken to make a total of 6 runs.
- ISO 376 does not allow the first test point to be less than 2 % of the measuring range. It has classifications that state the first point cannot be less than 4,000 times the resolution for Class 00, 2,000 times the resolution for Class 0.5, 1,000 times the resolution for Class 1, and 500 times the resolution for Class 2.

Creep Tests

- ASTM E74 requires a creep test if the data is analyzed with Method A, which allows the trailing zero to be ignored.
- ISO 376 requires a creep test if only incremental loads are applied.

More information on the creep tests is found in each of the standards.

Time requirements for application of forces

- ASTM E74 does not reference a specific set time; a force should be applied before the point is taken.

- ISO 376 states, "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." [5]

Note: The thought is that the force does not need to be held for 30 seconds. Rather, the target force should be approached slowly and not be exceeded. At around 30 seconds from the start of the change from one force point to the next force point, the reading can be taken.

Determination of deflection

- ASTM E74 allows for Method A, which involves ignoring the trailing zero, and Method B, which involves using an acceptable method such as average zero or zero interpolation.
- ISO 376 defines deflection as the difference between a reading under force and a reading without force.

Curve Fitting

- ASTM E74 uses the observed data and fits the data to a curve. A second-degree equation is used most of the time, and ASTM E74 allows up to a 5th-degree equation, assuming the device's resolution is over 50,000 counts and an F test is passed per Annex A1.
- ISO 376 allows the use of curves up to a third degree only.

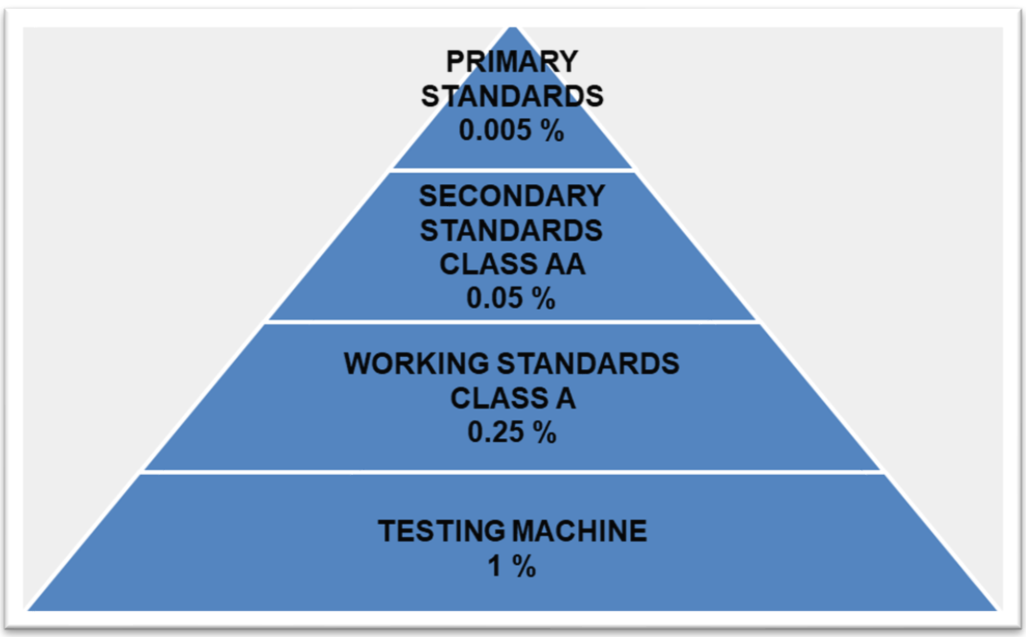


Figure 69: ASTM E74 Test Accuracy Ratio Pyramid

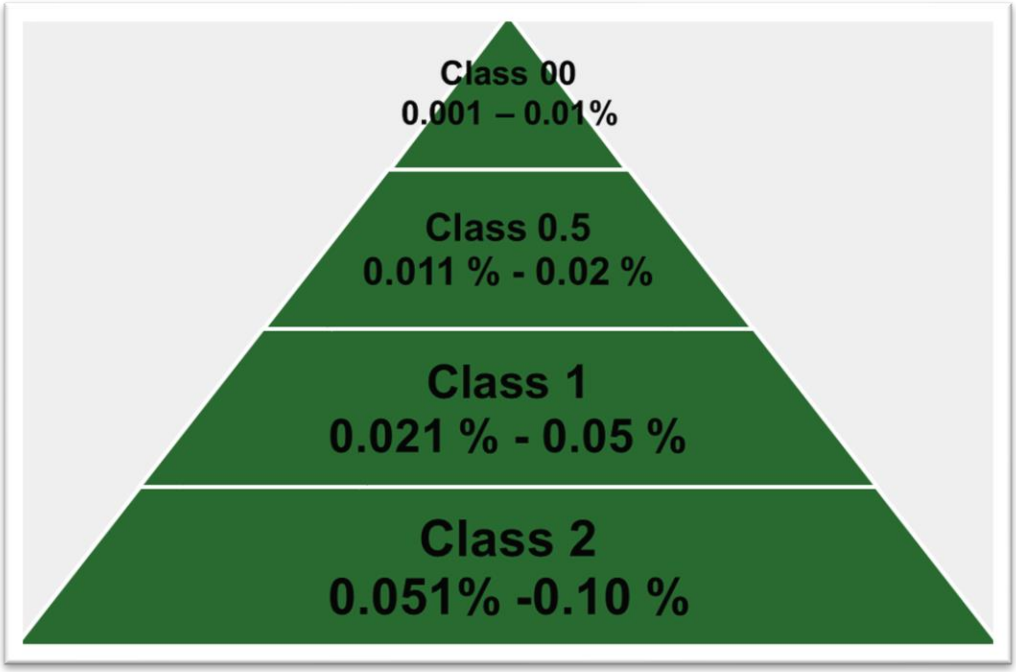


Figure 70: ISO 376 Expanded Uncertainty of Applied Calibration Force

Calculation and Analysis of Data

This section may be the most dramatic regarding differences.

ASTM E74 uses the observed data to calculate a standard deviation from the difference in the individual values observed in the calibrationand the corresponding values taken from the calibration equation.

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

Figure 71: Formula in ASTM E74 to Calculated the Pooled Standard Deviation

The equation uses the differences and divides them by a more conservative number by subtracting the number of deflection values minus the degree of polynomial fit minus one. This value is then converted to the proper force unit and multiplied by 2.4. The multiplied value is called the Lower Limit Factor, or LLF.

LLF, or Lower Limit Factor, 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 ASTM E74 standard practice for calibration and verification for force-measuring instruments.

LLF is calculated as 2.4 times the standard deviation. If the calculated LLF is less than the instrument resolution, the LLF is defined as equal to the resolution (Section 8.5 of the ASTM E74-18 Standard). It is expressed in force units, using the average ratio of force to deflection from the calibration data.

The LLF is then used to calculate the useable or verified forces range.

A verified range of forces is defined based on specific criteria. If the device was calibrated using deadweight primary standards and intended to calibrate other force-measuring instruments, then a Class AA verified range of forces could be assigned. The lowest point in the Class AA verified range of forces is calculated by multiplying 2000 times the LLF. If the LLF is 1 lbf, the first point in the verified range of forces will be 1 x 2000 or 2000 if we divide 1/2000, 0.0005, converted to a percentage of 0.05 %.

If the force-measuring device were calibrated using another force-measuring device with a Class AA verified range of forces, then only a Class A verified range of forces could be assigned by substituting 2,000 for 400 as the multiplier.

The lowest point in the Class A verified range of forces is calculated by multiplying 400 times the LLF. If the LLF is 1 lbf, the first point in the verified range of forces will be 1 x 400 or 400 if we divide 1/400, 0.0025, converted to a percentage of 0.25 %.

ASTM E74 works on the concept that the deadweight primary standards are at least ten times more accurate than the secondary standards with a Class AA verified range of forces. The Class AA standards are five times more accurate than the Class A standards, and the Class A standards are four times more accurate than a one percent testing machine.

ISO 376 uses the observed values to ensure that specific characteristics of the force-proving instrument are met and rates the device's performance based on its characteristics. ISO 376 uses four runs of data, a creep test, or six runs of data to characterize the force-proving instrument and the associated relative error. ISO 376 takes the highest error percentage per point for each parameter and assigns a class based on the highest error shown in the table/figure below.

Force-proving instruments where only increasing data used (four runs of data) are tested for reproducibility, repeatability, resolution, interpolation, zero, and creep. Force-proving instruments were increasing and decreasing data is used (six runs of data) are tested for reproducibility, repeatability, resolution, interpolation, zero, and reversibility. The expanded uncertainty of the applied calibration force must also be less than the table allows.

If a force-proving instrument has a relative error % for one of the parameters more than what is required for Class 00 but meets the criteria for all other parameters, then the best classification for the device is limited by class for the highest error.

ISO 376 classifies everything per point and then breaks down the classification per verified range of forces. Suppose the relative error of reversibility is Class 1, yet all other criteria meet Class 00. In that case, the device is rated as a Class 1 device if the expanded uncertainty of the applied calibration force also meets the criteria. ISO 376 does very well because it accounts for the uncertainty of the applied calibration force within the standard. As shown in the figure above, a force-proving device cannot have an uncertainty of less than the reference used for calibration.

ASTM E74 addresses this point in the appendix and not in the main body of the standard. ASTM E74 currently allows for a Lower Limit Factor that can be less than the uncertainty of the reference standard. EURAMET cg-4 (European Association of National Metrology Institutes) features a useful write-up.

Table 2 — Characteristics of force-proving instruments

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 72: Table 2 from ISO 376 Standard for Classification of Force-Proving Instruments

EURAMET cg-4 states, "ASTM E74 includes a mandatory method for calculating a value of uncertainty, which it defines as "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. This calculation of uncertainty only includes contributions due to reproducibility and deviation from the interpolation equation, although the value is increased to equal the resolution if the original value is calculated to be lower, and the uncertainty of the calibration force applied is also specified to be within certain limits. The method results in an uncertainty value in units of force, which is applicable across the range of calibration forces and is used to determine the lower force limits for the two standard verified range of forces (2,000 times the uncertainty for Class AA and 400 times the uncertainty for Class A). The uncertainty calculated by this method ignores some of the components included in Section 6.1 and, as such, is likely to result in different and probably lower values. The use of only the calculated uncertainty value associated with the calibration when developing an uncertainty budget for the subsequent use of the force-measuring instrument should be avoided – the contributions due to the other uncertainty components present during the calibration should also be included."[6]

Read the EURAMET cg-4 v 2.0 for more information on Uncertainty of Force Measurements and learn more about the difference between the ASTM E74 and ISO 376 standards.

Recalibration dates

- ASTM E74-18, Section 11 deals with recalibration intervals. To simplify things, if the force-measuring device demonstrates 0.032 % or better over the Class AA range or 0.16 % over the Class A range, then a two-year calibration interval can be assigned. Section 11 explains that if this criterion is not demonstrated, the end devices not meeting the stability criteria of 11.2.1 Section shall be recalibrated at intervals that ensure the stability criteria are not exceeded during the recalibration interval.[7]

- ISO 376 allows for the maximum validity of the calibration certificate not to exceed 26 months (about 2 years).[8]

Reporting Criteria

ASTM E74 requires:[9]

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

- Statement that the calibration has been performed in accordance with Practice E74. It is recommended that the calibration be performed in accordance with the latest published issue of Practice E74.
- Manufacturer and identifying serial numbers of the instrument calibrated
- Name of the laboratory performing the calibration
- Date of the calibration
- Type of reference standard used in the calibration with a statement of the limiting errors or uncertainty
- Temperature at which the calibration was referenced
- Listing of the calibration forces applied and the corresponding deflections, including the initial and return zero forces and measured deflections.
- Treatment of zero in determining deflections 8.1(a) or (b), and if method (b) is elected if zero was determined by the average or interpolated method
- List of the coefficients for any fitted calibration equation and the deviations of the experimental data from the fitted curve
- Force-measuring instrument resolution, the measurement uncertainty associated with the calibration results, and the verified range of forces or verified ranges of forces
- The result of the creep recovery test, when performed
- The excitation voltage and waveform used for calibration when known
- Statement that the lower force limit expressed in this report applies only when the calibration equation is used to determine the force

ISO 376 requires:[10]

- The identity of all elements of the force-proving instrument and loading fittings and of the calibration machine
- The mode of force application (tension/compression)
- That the instrument is in accordance with the requirements of preliminary tests

- The class and the range (or forces) of validity and the loading direction (incremental-only or incremental/decremental
- The date and results of the calibration and, when required, the interpolation equation
- The temperature at which the calibration was performed
- The uncertainty of the calibration results (one method of determining the uncertainty is given in Annex C)
- Details of the creep measurement, if performed

Miscellaneous Items

Both ASTM E74 and ISO 376 have non-mandatory appendixes. The ASTM E74 appendix does not address adapters, which can be a significant error source.

ISO Annex A 4 discusses loading fittings. Loading fittings should be designed in such a way that the line of force application is not distorted. As a rule, tensile force transducers (shown in the figure below) should be fitted with two ball nuts, two ball cups, and, if necessary, two intermediate rings, while compressive force transducers should be fitted with one or two compression pads.

In addition, the ISO 376 appendix deals with bearing pad tests, which are highly recommended for verifying that there is no interaction between the force transducer of an instrument used in compression and its support on the calibration machine. Morehouse can perform bearing pad tests if requested.

Figure 73: Morehouse Quick Change Tension Adapter Value Meets ISO 376 Standard Annex A.4 Requirements

Figure 74: Drawing of Morehouse Load Cell with ISO 376 Compression Adapter

ASTM E74 Versus ISO 376 Summary

ASTM E74 is different from ISO 376. One cannot effectively use an ASTM E74 calibration to certify to ISO 7500, and one cannot effectively use an ISO 376 calibration to certify to ASTM E74. However, it is possible to use some of the ISO 376 data for analysis with ASTM E74. This practice assumes that the minimum number of test points is met. In addition to differences between the standards covered here, several others exist.

Morehouse recommends that anyone performing force calibrations to ASTM E74, or ISO 376 should purchase the standards. Morehouse can calibrate to ISO 376, ASTM E74, or both standards. Suppose you need calibration in accordance with either standard? In that case, it is essential to look at the scope of accreditation and verify that your calibration provider has the capability mentioned on their scope, as shown below.

Morehouse Calibrating Machines simplify force calibration by reducing rework, errors from misalignment, and problematic setups. The operator can replicate how the force instruments are used for ASTM E4 and ISO 7500 calibrations by using different setups for tension and compression and proper adapters recommended by several standards, including ISO 376.

Parameter/Equipment	Range	CMC[2, 3] (±)	Comments
Force –			
Dead Weight Primary Standards Tension and Compression	(0.1 to 10) lbf [(0.44 to 44) N]	0.0025 %	Force Calibration including ASTM E74 Class A and AA, ISO 376 Class 00, 0.5, 1 and 2
	(10 to 100) lbf [(44 to 444) N]	0.0016 %	
	(100 to 12 0000) lbf [(444 to 53 378) N]	0.0016 %	Forces can be applied incrementally and decrementally thus permitting the determination of hysteresis errors.
	(12 000 to 120 000) lbf [(53 378 to 533 786) N]	0.0016 %	

Figure 75: Sample from Morehouse Scope Showing ASTM and ISO 376 Capability

ASTM E74 and Accuracy Statements

The current ASTM E74-18 standard is *Standard Practice for Calibration and Verification for Force-Measuring Instruments*. At Morehouse, we support the best practices outlined in the ASTM E74 standard to represent the expected performance of a load cell or other force-measuring instrument. What may be a bit of an industry disconnect is that some companies receive a full ASTM E74 calibration report only to ignore a sizable portion of the report. The confusion comes when someone is used to entering an accuracy on the receiving report for the force-measuring instrument, and there is not one to be found on the ASTM E74 calibration certificate.

When reporting measurement error, we have observed numerous users taking the liberty of standing behind common misconceptions that a measurement is as accurate from which it came, or they adopt a fallback position of saying the calibration of the force-measuring instrument needs to be four times more accurate than the force-measuring instrument being calibrated. When these types of questions are raised, we typically observe best practices falling short of the actual intent of the ASTM E74 standard.

A key indication of best practices not being followed is when someone asks about an accuracy statement in the report or does not find one and goes back to the instrument's specification sheet. The specification sheet is useless when relating to ASTM E74 calibration. The ASTM E74 calibration report typically encompasses the "lion's share" of the overall measurement uncertainty, which is missed if only the specification sheet is used.

The specification sheet will be helpful in figuring out uncertainty contributors, such as environmental conditions relating to operating at various temperatures. It helps evaluate errors due to misalignment or how well the device may return to a zero condition. The specification sheet is also helpful in evaluating how good the force-measuring instrument may be. Specifically, non-repeatability often shows how well the force-measuring instrument may repeat without being placed under different conditions.

The major flaw is that the specification sheet does not give the end-user much of their needs. It does not tell the user the actual expected performance of the device. A force standard such as the ASTM E74 excels at providing the end-user with meaningful data. It tests the reproducibility characteristics of the force-measuring device.

The standard guides one on how to perform these tests, such as randomizing force application conditions. This randomization, as simple as rotating and repositioning the instrument, often yields the actual expected performance of the load cell or other force-measuring instrument.

ASTM E74 Compression Calibration Data 3rd-Order Fit - Method B						
Force Applied lbf	Measured Output Run 1 - 0° mV/V	Measured Output Run 2 - 120° mV/V	Measured Output Run 3 - 240° mV/V	Fitted Curve mV/V	Expanded Uncertainty lbf	Force Standard Used
1000	0.04350	0.04353	0.04354	0.04354	2.059688	M-4644
2000	0.08704	0.08702	0.08704	0.08702	2.059749	M-4644
6000	0.26090	0.26088	0.26100	0.26092	2.060297	M-4644
12000	0.52170	0.52170	0.52172	0.52172	2.061995	M-4644
18000	0.78243	0.78244	0.78241	0.78245	2.064800	M-4644
24000	1.04309	1.04317	1.04308	1.04310	2.068711	M-4644
30000	1.30365	1.30370	1.30363	1.30365	2.073731	M-4644
36000	1.56409	1.56414	1.56409	1.56409	2.079846	M-4644
42000	1.82441	1.82446	1.82441	1.82443	2.087050	M-4644
48000	2.08459	2.08466	2.08461	2.08464	2.095329	M-4644
54000	2.34462	2.34479	2.34469	2.34471	2.104671	M-4644
60000	2.60459	2.60476	2.60464	2.60465	2.115061	M-4644
				Lower Limit Factor: **2.425 lbf**		
				Standard Deviation: **0.00004 mV/V**		
				Resolution: **0.23009 lbf**		

Figure 76: Data from an ASTM E74 calibration.

The expected performance from the ASTM E74 calibration is determined by performing a series of measurements and calculations per the standard. A standard deviation is calculated using the difference between the individual values observed in the calibration and the corresponding values taken from a regression-type equation. The standard deviation is then multiplied by a coverage factor of 2.4 to determine the LLF. This term is dubbed the Lower Limit Factor (LLF). The LLF is then used to calculate the verified range of forces. This is where certain Marketing specifications can assign accuracy.

A good example is marketing materials for Morehouse load cells. For our Ultra-Precision Load Cells, we specify that the load cells are accurate to 0.005 % of full scale. We are saying that the ASTM LLF, the expected performance of the load cell, is better than 0.005 % of full scale. However, this is only one component of the much larger Calibration and Measurement Capability Uncertainty Parameter, called CMC.

Under the same conditions that Morehouse used for calibration, the device is expected to perform better than 0.005 % of full scale. The expected performance on a 10,000 lbf load cell should be better than 0.5 lbf (10,000 * 0.005 %). So, we are saying that at the time of calibration, the load cell's expected performance will be better than 0.005 % or 50 parts per million.

If we continue to follow the ASTM E74 standard, the calculated LLF will be used to determine the usable range of the device. If you are not using the load cell for ASTM E74, E18, E10, E4, or other standards referencing ASTM E74, then this verified range of forces may not hold much value.

ASTM E74 Load Cell Selection Guide

Figure 77: Morehouse Precision Load Cell

Many people get confused with load cell specifications and what they mean. What does it mean when a company says the load cell is accurate to 0.01 % of full scale? If calibrated using the ASTM E74 standard, the meaning differs from a pure accuracy specification. The ASTM E74 calibration offers greater robustness compared to a basic single-run commercial calibration or one where acceptance limits are adjusted based on measurement uncertainty, with a subsequent pass/fail conformity assessment.

We designed an easy-to-follow ASTM E74 Load Cell Selection Guide to assist everyone in comprehending load cell specifications in line with the ASTM E74 standard. For example, when we specify that a load cell is better than 0.01 % of full scale, we say the load cell will have an ASTM Class A verified range of forces (usable range per ASTM E74) of better than 4 % through 100 %.

Download the ASTM Load Cell Selection spreadsheet here.

	Precision 0.01 % of full scale	
	ASTM llf = 0.1 lbf	
	lbf	% of capacity
ASTM CLASS A VERIFIED RANGE OF FORCES	40.0	0.250%
	100.0	0.100%
	200.0	0.050%
	300.0	0.033%
	400.0	0.025%
	500.0	0.020%
	600.0	0.017%
	700.0	0.014%
	800.0	0.013%
	900.0	0.011%
	1000.0	0.010%
ASTM Class AA 200 lbf		

Figure 78: Precision Load Cell Accuracy Chart

The above figure breaks down the ASTM E74 criteria. On a 1,000 lbf load cell, the ASTM E74 LLF (how well the load cell performs when conditions are varied following the standard) will be better than 0.1 lbf. The Class A loading range will be 400 x 0.1 (ASTM E74 LLF) or 40 lbf. If calibrating a testing machine that is accurate to 1 %, the first force point is exactly 4:1, or 4 times better than what is being verified to ASTM E4. The 40 lbf point is known to be within 0.25 % of the applied Force (0.1/40 = 0.25 %).

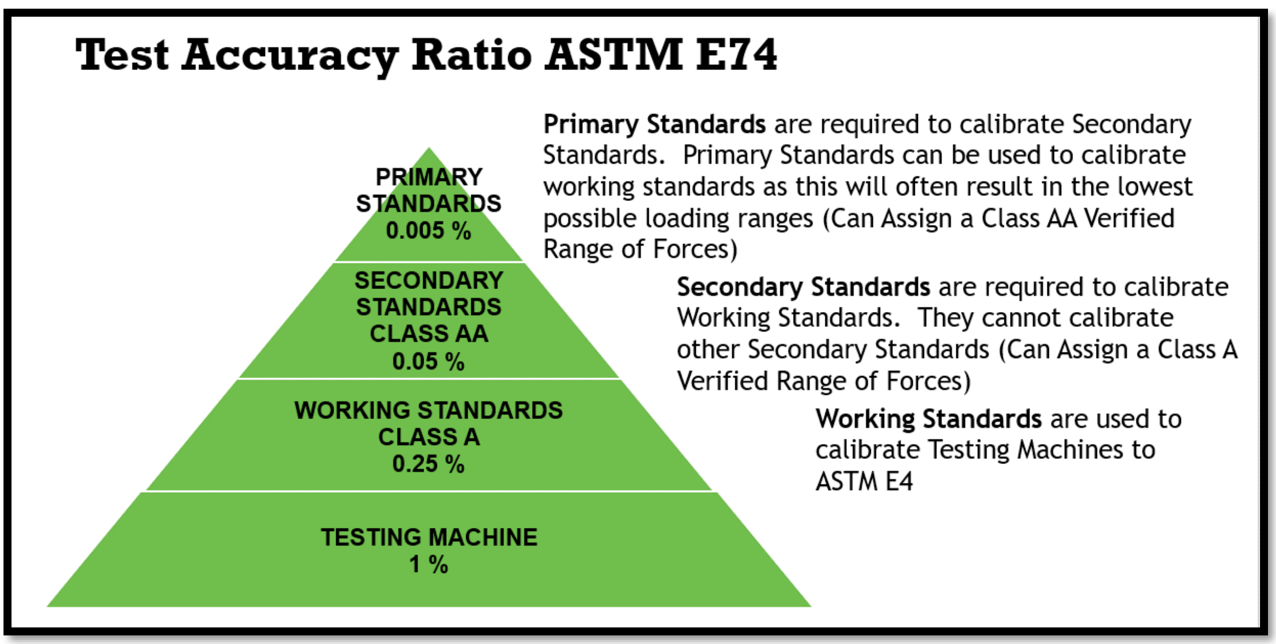


Figure 79: ASTM E74 Test Accuracy Ratio Pyramid

This correlates well with the above figure, which shows the different accuracy ratios. Working standards need to be better than 4:1 when compared to the accuracy of the testing machine. Secondary standards calibrated by primary standards must be better than 0.05 % of applied Force. These standards are assigned a Class AA verified range of forces. In our example above, if deadweight primary standards calibrated the load cell, a class AA verified range of Force would be calculated by multiplying 0.1 lbf by 2000. The result would be an ASTM Class AA verified range of Force of 200 through 1,000 lbf. At the 200 lbf test point, the device is known to be within 0.05 % of the applied Force (0.1/200 = 0.05 %).

Company	
Instrument Type	Load Cell
Capacity	1000.00
Force Units	lbf

Morehouse Load Cells	
Ultra	**0.005%**
Precision	**0.010%**
Calibration	**0.020%**
Custom	0.025%

Figure 80: Morehouse Spreadsheet Inputs

Our easy-to-use spreadsheet calculates everything based on the load cell capacity and units that are entered. Anything in Orange would be filled in.

The table incorporates a Custom field where individuals can make assumptions about the specifications to determine the usable range.

ASTM E74 Load Cell Selection

	Ultra 0.005 % of full scale			Precision 0.01 % of full scale			Calibration 0.02 % of full scale			Custom 0.025 % of full scale	
	ASTM lIf = 0.05 lbf			ASTM lIf = 0.1 lbf			ASTM lIf = 0.2 lbf			ASTM lIf = 0.2 lbf	
	lbf	% of capacity		lbf	% of capacity		0.0005	% of capacity		0.001	% of capacity
ASTM CLASS A VERIFIED RANGE OF FORCES	20.0	0.250%	ASTM CLASS A VERIFIED RANGE OF FORCES	40.0	0.250%	ASTM CLASS A VERIFIED RANGE OF FORCES	80.0	0.250%	ASTM CLASS A VERIFIED RANGE OF FORCES	100.0	0.250%
	100.0	0.050%		100.0	0.100%		100.0	0.200%		100.0	0.250%
	200.0	0.025%		200.0	0.050%		200.0	0.100%		200.0	0.125%
	300.0	0.017%		300.0	0.033%		300.0	0.067%		300.0	0.083%
	400.0	0.013%		400.0	0.025%		400.0	0.050%		400.0	0.063%
	500.0	0.010%		500.0	0.020%		500.0	0.040%		500.0	0.050%
	600.0	0.008%		600.0	0.017%		600.0	0.033%		600.0	0.042%
	700.0	0.007%		700.0	0.014%		700.0	0.029%		700.0	0.036%
	800.0	0.006%		800.0	0.013%		800.0	0.025%		800.0	0.031%
	900.0	0.006%		900.0	0.011%		900.0	0.022%		900.0	0.028%
	1000.0	0.005%		1000.0	0.010%		1000.0	0.020%		1000.0	0.025%
ASTM Class AA 100 lbf			ASTM Class AA 200 lbf			ASTM Class AA 400 lbf			ASTM Class AA 500 lbf		
Class AA Verified range of forces for calibration of a testing or tensile machine means every force point needs to be better than 0.5 % of the applied force											
Class A Verified range of forces for calibration of a testing or tensile machine means every force point needs to be better than 0.25 % of the applied force											

Figure 81: Table of Each Type of Morehouse Load Cell

Once everything is entered, the table will calculate everything. If someone wanted a Class AA verified range of forces better than 10 % of the load cells capacity (0.05 %), a Morehouse Ultra-Precision Load Cell would need to be purchased. These load cells can be used as low as 2 % and sometimes 1 % of capacity to verify testing machines to ASTM E4. Everything is shown in the table so the end-user can make the most informed decision about which load cells meet the appropriate specifications.

In most cases, Morehouse Precision Load Cells will yield the best performance-to-price ratio as they are often usable below 4 %. Thus, the end-user can calibrate a broader range and carry much less equipment than if they purchased a load cell that was only accurate to 0.025 % of full scale.

The other point to make here is that the calibration supplier must have the capability to calibrate the equipment to ensure accuracy. If the requirement is 0.01 % of full scale, can a supplier with a Measurement Uncertainty of 0.025 % calibrate a load cell to 0.01 % of full scale? Simple math, right, yet many load cell manufacturers do not have equipment with measurement uncertainties better than their specifications.

Therefore, it's not feasible to acquire a load cell from them and anticipate maintaining a 0.01 % of full-scale accuracy when their scope of accreditation indicates a higher measurement uncertainty.

Part of any risk mitigation strategy should consider the following:

- Selecting a calibration supplier that offers the smallest measurement uncertainty (Look at the scope of accreditation for your supplier and verify their measurement uncertainty is lower than your requirements)
- Utilizing the appropriate reference standards (ASTM E74 selection guide should help)
- Improving reliability by managing calibration intervals (follow ASTM guidelines of a 1-year initial calibration interval on new equipment and then increase if specifications are met)
- Monitoring of standards using control charts (Morehouse has a 5-in-1 Force Verification System to help.)
- Continual improvement of the calibration processes (We all want to improve continually by

investing in employee education, equipment, and learning as much as possible)

How to Choose the Best Reference Standard Load Cell

What is the best load cell I can use as a reference standard? This question appears straightforward, yet it takes a series of questions to answer once we examine the issue. The most common answer is, "Well… that depends on your expectations."

If your primary concern is performance alone, disregarding price and ergonomics, the response differs significantly compared to when considering the best value. To provide a comprehensive answer to this question, we will delve into some fundamentals related to the choice of a load cell as a reference standard. Key considerations include price, actual performance attributes, specifications, ergonomic considerations, and overall value.

Once you have chosen the best load cell, if you have a calibration with significant uncertainties, a substandard meter, or the wrong adapters, the load cell performance will be inferior. Thus, we will consider the uncertainty of the laboratory performing the calibration and some meter and adapter options to support the reference standard load cell.

Reference Standard Setup

To start, let’s look at an example of a reference standard load cell in a Morehouse [Universal Calibrating Machine]().

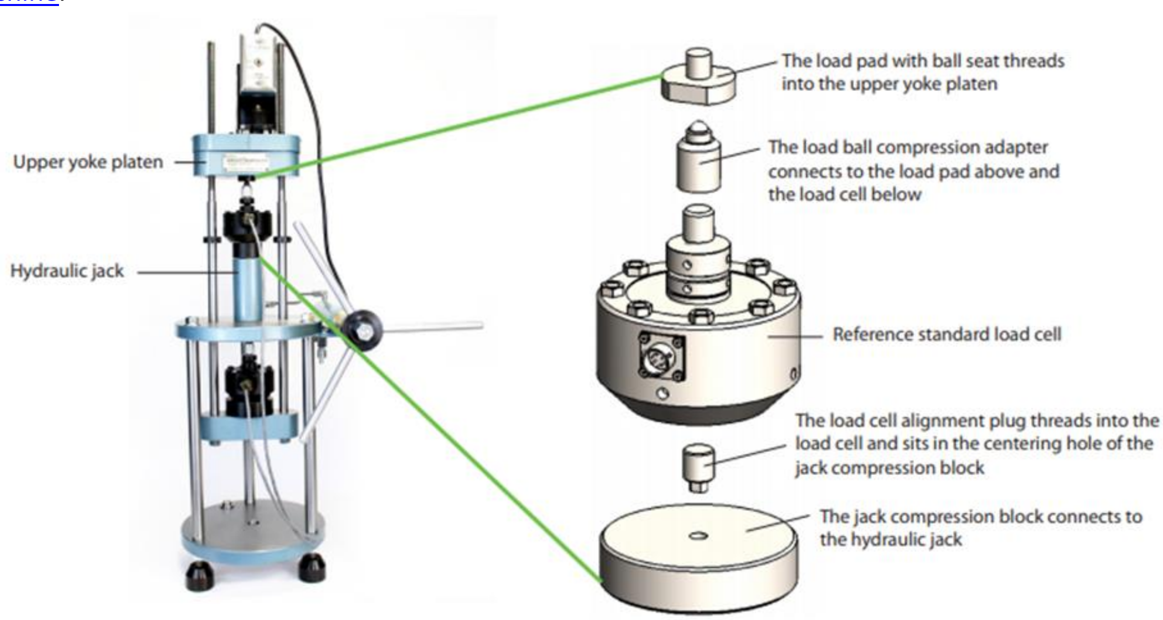


Figure 82 Morehouse UCM Showing Adapters to Mount a Reference Standard Load Cell in Compression

The reference load cell is mounted in compression, and the breakout picture shows the adapters used to mount the reference standard. These adapters facilitate keeping the line of force pure by centering the load cell in the machine. The adapters undergo machining and occasional heat treatment, utilizing connections such as ball adapters and spherical joints. These ball adapters improve the performance characteristics of the load cells. Initial testing with and without the load ball compression adapter increased reproducibility by 30 – 40 %.

At Morehouse, we calibrate the load cell using the ball adapter shown. The above shows a load cell with a load ball compression adapter being set up for calibration. The expectation for anyone making force measurements should be to replicate use. Not doing so can produce significant errors. These errors can range from 0.01 % to 5 %, depending on the device.

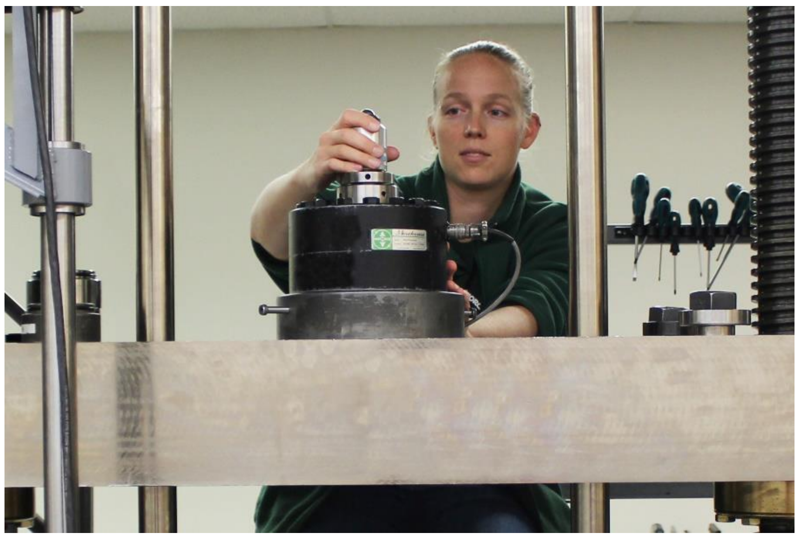


Figure 83 Load Cell Calibration in a Morehouse Deadweight Machine

Calibration with Low Uncertainties

When you think of a great reference standard load cell, you must consider the uncertainty of the laboratory performing the calibration. This is important because the uncertainty of your new reference standard load cell cannot be less than that of the laboratory performing the calibration.

For comparison purposes, contemplate calibration at both Morehouse and NIST. At Morehouse, most of our calibrations are performed using deadweight machines known to be within 0.002 % (k = 2) of applied force. If we use transfer machines, the uncertainty rises to 0.01 % or better of applied force. NIST has the lowest uncertainties because they have deadweight calibrations up to 1,000,000 lbf with uncertainties as low as 0.0008 % (k = 2). On average, the price is four times higher than Morehouse at 0.002 % (k = 2).

Is there a vast difference between these numbers? Not really, when you look at the overall uncertainty of the reference standard load cell and factor in resolution, repeatability, stability, and environmental influences. If you want the lowest measurement uncertainty value possible, go with NIST or buy a deadweight machine from Morehouse.

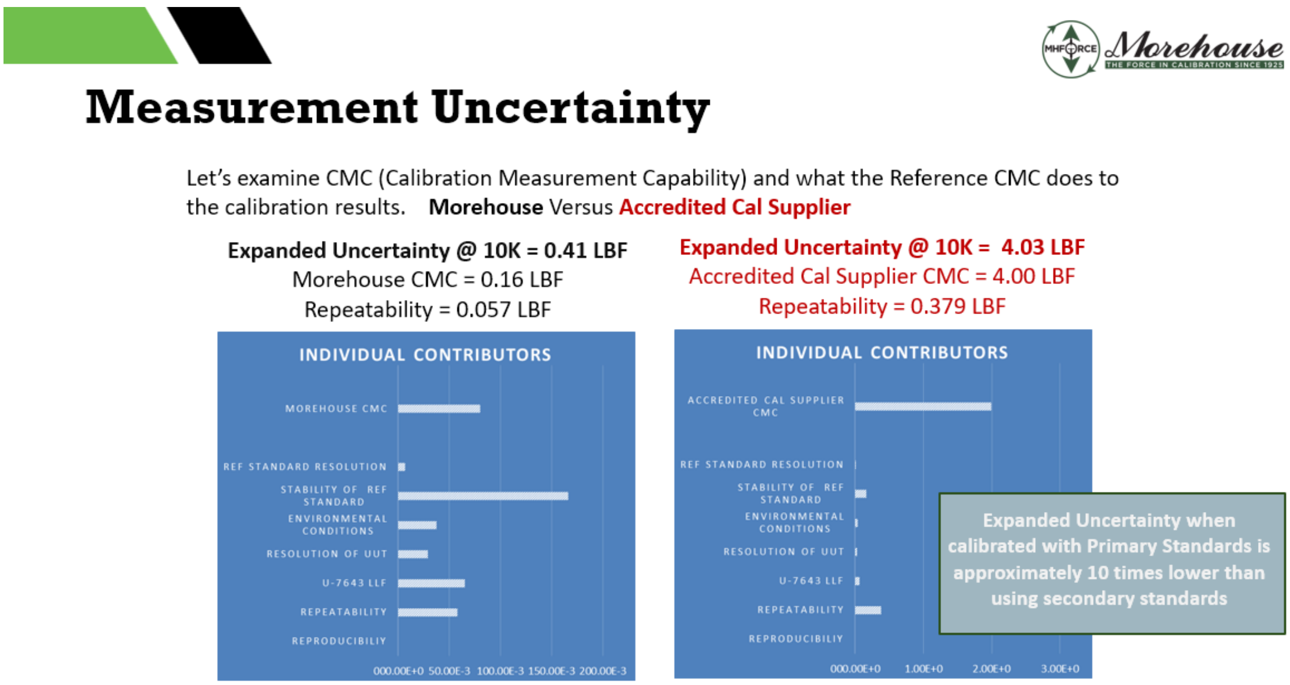


Figure 84 Measurement Uncertainty Analysis Comparing Calibration by Primary Standards Versus Secondary Standards.

Let us compare 0.002 % to 0.01 % or 0.04 % using transfer standards (non-deadweight), such as a load cell in a dynamic calibrating machine. There will be a significant difference because you have changed the starting uncertainty of the measurement by a factor of 10 – 25 times that of starting with deadweight.

The provided figure illustrates an analysis displaying the Expanded Uncertainty on a 10,000 lbf load cell when calibrated at Morehouse compared to an Accredited Calibration Supplier. During calibration by Morehouse, the Expanded Uncertainty is 0.41 lbf, whereas when the Accredited Calibration supplier conducts the calibration, the figure increases to 4.03 lbf. The overall difference in Expanded Uncertainty is significant.

No matter what load cell system you purchase, it will be limited by those much more significant uncertainties.

Therefore, the suggested starting point is to insist on a deadweight calibration. Consider NIST if the price is not an issue.

Price Considerations

If the price doesn't matter much, a deadweight machine might be in your future. Price is always an important consideration. If someone says they want the best reference standard load cell, they may hear, "Can you wait a year to have a specialty load cell made?" We did that for our 4.4 MN (1,000,000 lbf) load cell.

The price of the load cell and meter over a decade ago eclipsed $150,000. Each year, NIST performs a calibration for approximately $30,000, and we get a report back with an ASTM Lower Limit Factor between 11 – 16 lbf. This allows us to use one reference standard to calibrate other load cells from approximately 32,000 lbf to 1,000,000 lbf without changing standards. We pair this custom load cell with a $60,000 HBM DMP40 meter, which is nearing obsolescence and will soon be replaced by the HBM DMP-41.

Test No.: 684.07/O-0000001609-20 Page 5 of 7
Calibration Date: October 5, 2020

GTM Load Cell No. 50751, ASCENDING DATA, SECOND-ORDER FIT
Capacity 1000000 lbf Compression, Calibrated to 4448222 N
HBM DMP40 Indicator No. 093520044

Compression Data for 23 °C ± 0.3 °C -- Force Units of lbf

Applied Force (lbf)	Predicted Response	Response Run 1	Response Run 2	Response Run 3
20000	0.035789	0.035795	0.035789	0.035789
30000	0.053648	0.053637	0.053635	0.053638
50000	0.089367	0.089376	0.089376	0.089373
100000	0.178669	0.178691	0.178691	0.178688
200000	0.357293	0.357274	0.357276	0.357274
300000	0.535944	0.535936	0.535932	0.535931
400000	0.714623	0.714620	0.714615	0.714617
500000	0.893329	0.893346	0.893338	0.893337
600000	1.072062	1.072059	1.072051	1.072057
700000	1.250822	1.250836	1.250825	1.250825
800000	1.429609	1.429627	1.429615	1.429623
900000	1.608423	1.608424	1.608412	1.608420
1000000	1.787265	1.787263	1.787250	1.787260

The coefficients of the following equation were fitted to the calibration data using the method of least squares. The units for force (lbf) and response are the same as shown in the table above.

$$\text{Response} = A + B(\text{force}) + C(\text{force})^2$$

where A = 7.14099E-05
B = 1.78584E-06
C = 1.35715E-15

Standard deviation = 0.000012 response units

This standard deviation was computed according to ASTM E74-18 from the differences between the calibration data and the fitted equation given above.

The following values, as defined in ASTM E74-18, were determined from the calibration data:
Lower Limit Factor = 16 lbf
Class A Loading Range = 20000 lbf to 1000000 lbf
Class AA Loading Range = 32611 lbf to 1000000 lbf

Figure 85 Calibration from NIST of Morehouse/GTM Cell with HBM DMP40

Compare the $160,000 plus load cell with a Morehouse load cell and 4215 indicator. In the report below, the ASTM Lower Limit Factor is double that of the GTM/Morehouse Custom with HBM indicator. The price is roughly 1/10 of the highest-performing load cell plus the $30,000 calibration.

Test No.: 684/288900-16
Calibration Date: August 22, 2016

Page 5 of 7

Morehouse Load Cell No. 58853
Capacity 1000000 lbf Compression, Calibrated to 3558577 N
Morehouse M4215A Indicator No. 61172

Compression Data for 23 °C ± 0.3 °C -- Force Units of lbf

Applied Force (lbf)	Predicted Response	Response Run 1	Response Run 2	Response Run 3
10000	0.03172	0.03175	0.03178	0.03177
20000	0.06357	0.06352	0.06354	0.06355
50000	0.15911	0.15909	0.15907	0.15911
100000	0.31830	0.31828	0.31832	0.31832
200000	0.63650	0.63650	0.63648	0.63648
300000	0.95443	0.95441	0.95443	0.95447
400000	1.27206	1.27204	1.27206	1.27209
450000	1.43076	1.43074	1.43078	1.43080
500000	1.58937	1.58932	1.58939	1.58940
600000	1.90633	1.90628	1.90634	1.90632
700000	2.22291	2.22287	2.22296	2.22291
800000	2.53908	2.53903	2.53920	2.53903

The coefficients of the following equation were fitted to the calibration data using the method of least squares. The units for force (lbf) and response are the same as shown in the table above.

$$\text{Response} = A + B(\text{force}) + C(\text{force})^2 + D(\text{force})^3$$

where
A = -1.34346E-04
B = 3.18545E-06
C = -1.05308E-14
D = -4.69606E-21

Standard deviation = 0.00004 response units

This standard deviation was computed according to ASTM E74-13a from the differences between the calibration data and the fitted equation given above.

The following values, as defined in ASTM E74-13a, were determined from the calibration data:
Lower Limit Factor = 31 lbf
Class A Loading Range = 12226 lbf to 800000 lbf
Class AA Loading Range = 61131 lbf to 800000 lbf

Figure 86 Calibration from NIST of Morehouse 1,000,000 lbf load cell with 4215.

The initial equipment price is 1/10 of the other system, and the performance is excellent, although it is not as good as the system, costing ten times more. Most labs would love the numbers that the Morehouse system with the 4215 indicator is capable of. For comparison, the approximate price of a 1,000,000 lbf deadweight machine is $10,000,000, and a 1,000 lbf deadweight machine is around 1/100 of that cost. However, we are not showing the full details yet. Looking at the performance characteristics sheds more light on how good the system is.

Actual Performance Characteristics

When we look at load cells, we need to consider how reproducible the results are and how stable the system is between calibration intervals. We should also look at creep characteristics, zero return, how well the load cell is temperature compensated and non-repeatability.

Many people get caught up in the wrong things. They look at non-linearity, SEB, and other specifications. It may not matter if the calibration follows a standard such as ISO 376 or ASTM E74; these specifications are irrelevant. These standards use higher-order curve fitting routines and rely on polynomial equations.

Some may fail to consider how good the load cell is between calibrations. You can have great calibration numbers yet find the load cell and meter have more significant drift than expected. This can increase the overall uncertainty by two to ten times the initial calibration numbers.

What you want to know is the expected performance of the load cell. ASTM E74 and ISO 376 are standards that do an excellent job of giving us the right expectations. The better these load cells perform when following these standards, the better we can expect the load cells to perform.

Morehouse lists how we guarantee our load cells perform to these standards because these characteristics tell you how good the load cell is. They are not made up of numbers. They guarantee the reproducibility of the measurement when used in a similar environment.

Figure 87 Performance Characteristics that Matter.

Some simple things are often overlooked. For example, there are some very high-end load cells on the market. The performance looks fantastic until you calibrate them. Are the load cells bad? No! They are not bad; they are difficult to calibrate.

Numerous manufacturers make fantastic load cells that do not calibrate well. They are less rigid, making them super sensitive to any fluctuation. When you start with the best calibration (deadweight), the weights tend to swing, the machines are never perfectly level, and everything deflects.

These load cells pick up all of that in the measurement and do not calibrate well because of it.
Some high-level industries that own their deadweight frames have purchased these super-sensitive load cells and found that they cannot get repeatable numbers because they are too sensitive. At Morehouse, we do not typically recommend one of these load cells. Our Ultra-Precision load cell is rigid enough to calibrate very well. If we made a better load cell, it would be more sensitive and pick up all the calibration noise, for lack of a better term. That brings us to overall value.

Morehouse Instrument Company
1742 Sixth Ave.
York, PA 17403-2675
(717) 843-0081

Value

What is the best value? Is it the super-duper load cell that picks up all the calibration noise? Is it a precision class load cell? A thorough needs assessment of nice-to-haves versus actual needs will lead you to the right choice.

Our Ultra-Precision load cell is an excellent choice if the goal is the largest loading range with the smallest uncertainty. However, a 500 kN (112,000 lbf) load cell weighs around 26 kgs (57 lb.). HBM makes some fantastic load cells, which are also heavy and tend to have a higher price tag.

Sometimes, the HBM load cell may be the better load cell. One case would be if the requirements are for a combined loading range using incremental (ascending) and decremental (descending) loading.

The Shear web load cell is the best design for many compression and tension applications. Other manufacturers make this style of load cell, and many would be great if they had a tapered base and integral adapter.

Value-wise, the best value might be our Precision class load cells. They are almost half the price of the Ultra-Precision cell, and the specifications, which do not tell the entire picture, are not half as good. What is guaranteed is an ASTM E74 Class A lower limit better than 4 %. The load cells often calibrate much better than that.

Even if cost remains a consideration, our Budget class load cells continue to utilize the shear web design, albeit at a lower expense due to specific design modifications. Importantly, their performance is uncompromised and only marginally less than that of the Precision load cell.

Pairing your load cell with the right meter is essential to maintaining performance. Suppose you pair a Morehouse Ultra-Precision load cell or HBM TOPT-Transfer load cell with a commercial off-the-shelf lower-performance meter. The load cell will not benefit you because the meter severely limits performance characteristics.

We are often asked, "What is the best meter I can use with my load cell?" The answer is an HBM DMP-41, which costs about $60,000. For many, this is way too expensive. A more economical solution is the Morehouse 4215, which is about $3,000.

The calibration report from NIST displays a Morehouse 1,000,000 lbf load cell employing a 4215 indicator. The 4215 indicator has approximately 400,000 counts, in contrast to the 2,500,000 counts on the HBM DMP 41.

However, buying the best load cell and meter usually requires lifting and mounting the load cell into a machine. If the calibration laboratory does not have the proper lifting mechanisms, a 26 kg (57lb) lift, or heavier on shear web load cells over 50 kN, may not make sense.

Ergonomic Issues

If weight is an issue, you can get other style load cells with similar performance characteristics. However, there is usually a trade-off in the expected performance. For example, consider our lightweight compression-only multi-column load cell. The load cell is unsuitable for tension applications, and the performance is like a precision load cell with an ASTM Class A loading range of better than 4 % of capacity. The Ultra-Precision is twice as good yet weighs about five times more than this load cell.

Figure 88 Morehouse Load Cell Lightweight Compression-Only Multi-Column Load cell

The bottom line is that there will always be a trade-off between ultimate performance and what is generally accepted to meet all the criteria.

At Morehouse, we educate our customers and provide tools to help them make a decision that makes the most sense.

I take great pride in our knowledgeable team at Morehouse, who will work with you to find the best load cell to use as a reference standard for your application. If we do not make that load cell, we can source it, assemble a complete system, including transportation cases, and provide the best calibration level next to NIST.

You might have narrowed down your decision on choosing the right load cell, and now you might be curious about the range of use that makes the most sense to obtain and maintain the measurement uncertainty you want.

How Low Can My Load Cell Go?

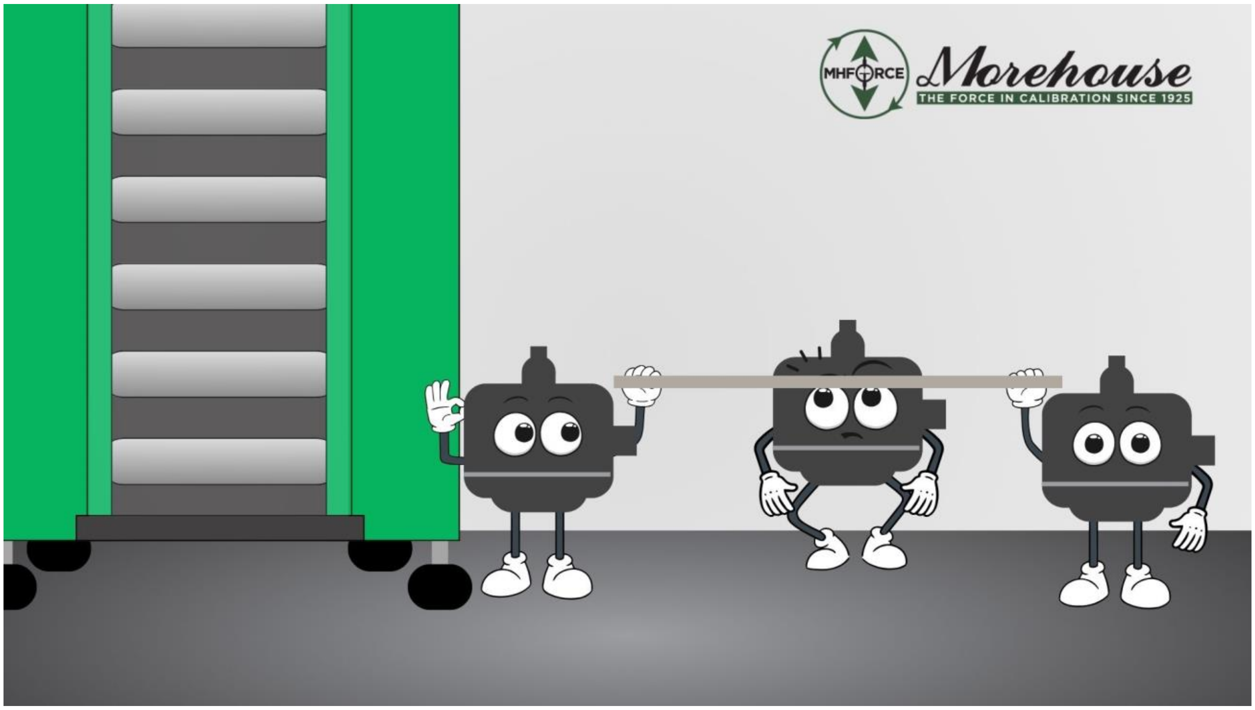


Figure 89 How Low Can My Load Cell Go

Numerous factors can affect the performance of load cells. Some factors include the design of the load cell, the readout used with the load cell, environmental conditions, cable length (if only a four-wire cable is used), overloading, adapters, stability, alignment, and the test method.

There are enough load cell intricacies that impact measurement uncertainties to write a book strictly on the subject that you are currently reading.

Management often wants to spend the least on equipment and push equipment such as load cells to their lowest operational level.

Who can blame them as who would not want less equipment with better performance?

Using equipment such as load cells below 5 – 10 % of their capacity or lower, such as 2 %, is a frequent practice that demands attention as it can significantly impact measurement uncertainty.

This section examines the impact on measurement uncertainty of using a load cell as low as 2 % of its rated capacity, compliance with ISO 376 and ASTM E74 lowest force point criteria, and how to uphold the reliability necessary to maintain a specific calibration interval. What holds for these standards can apply to any load cell.

The Top 3 Considerations for How Low Can My Load Cell Go?

Many customers ask, "How low can my load cell go?" We understand the potential benefits of using a load cell from 2 % to 100 % of its capacity.

Benefits like the lower your load cell can go to measure forces, the less equipment one would need to carry, and the fewer setups one would need to make; sometimes, fewer calibration costs would occur, and who would not want any of these things?

So, how low can your load cell go?

Like the Limbo, everything has a threshold beyond which going lower becomes improbable.

In this section, we hope to provide some things to consider regarding measurement uncertainty when you ask how low my load cell can go.

We assume that one has communicated clearly with their calibration provider how they use the load cell so that the calibration lab can best replicate use. That means whatever readout is being used, adapters, cables, and standards or procedures being followed are sent in and communicated to the calibration laboratory.

How low can my load cell go?

#1. What is the impact on measurement uncertainty for using a load cell as low as 2 % of its rated capacity? The most significant contributions to MU (Measurement Uncertainty) would be the resolution, stability of the instrument, ASTM LLF (Lower Limit Factor) if applicable, and the reference standard uncertainty used to perform the calibration.

Resolution is the smallest change in the measured quantity that causes a detectable change in the corresponding indication.

Calculating Resolution – Resolution is found by taking the output of the load cell / by the indicated reading at capacity, and then that number is multiplied by the readability.

Case # 1 in mV/V At 25,000, a load cell typically has an output of 2 – 4 mV/V. Most meters will read up to the 5^{th} decimal place. Thus, 25,000 / 4.00000 = 6250, which we multiply by the readability of 0.00001 = 0.0625.

Case # 2 In force units, a 25,000-load cell may count by 1; there would be 25,000/25,000 = 1, then multiply by 1 = 1.

Comparing Case # 1 at the 2 % force pt, our MU (Measurement Uncertainty) is 0.47 or 0.094 %, and in Case # 2, 0.74 or 0.149 % by only changing the reference resolution from 0.0625 to 1.

More on the complete MU budget later.

Reference Standard Stability – Typically, this is defined as the change from one calibration to the next. Morehouse wrote a paper on load cell reliability that goes into much more detail about the reliability of load cells. https://mhforce.com/wp-content/uploads/2023/09/Morehouse-Load-Cell-Reliability-1.pdf.

The conclusion was that selecting the load cell and meter is pivotal If one wants to maintain an overall reliability of 95 % with 95 % confidence of 0.05 % or better.

In our sampling, we did not look at data below 10 % of a load cell capacity as the population data showed the very best systems to have a 95 % confidence that the process was at least 89.33 % reliable at 10 % of capacity, the numbers would have been much worse below that number.

For our example, we will assume you chose an exceptionally good load cell, like a shear web type with a base and threaded adapter installed, paired with a higher-end meter like the 4215 HS. Typical stability might be around 0.1 % at 1 % capacity and 0.05 % at 2 %.

ASTM LLF, or Lower Limit Factor, 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 ASTM E74 standard practice for calibration and verification for force-measuring instruments.
The ASTM LLF quantifies the Reproducibility Condition of the calibrated device by following the ASTM E74 standard.

For our example, the **ASTM LLF is 0.209**.

The Reference Standard Uncertainty – This is the uncertainty of the reference standard used to calibrate the load cell.

Note: If the calibration was not done following ASTM E74, one might use the load cell specifications or values from the calibration certificate, including non-linearity, repeatability, and, if making descending measurements, hysteresis.

Case # 1. Primary Standards (Deadweights) are used to calibrate the load cell within 0.0016 %.
In Case # 1, our MU cannot be less than the standard used to calibrate the device.
Thus, our load cell cannot be less than 0.0016 % of the applied force.

Case # 2. Secondary Standards (those calibrated by deadweight) are used to calibrate the load cell. The typical number for a secondary standard varies between 0.02 – 0.05; we will use 0.035 % for comparison.
In Case # 2, our MU cannot be less than the standard used to calibrate the device.
Thus, our load cell cannot be less than 0.035 % of the applied force.

Note: The deadweight primary standard gives one the best possible calibration on How Low Can My Load Cell Goes.

The following Measurement Uncertainty Budgets only include information available to Morehouse and are incomplete as environmental conditions during use, repeatability studies, repeatability and reproducibility between operators, resolution of the best existing device, and other error sources are not included.

These examples represent close to the absolute best one could achieve, and their Overall Measurement Uncertainty would be much higher with more contributions to MU than shown here.

Measurement Uncertainty Budget Worksheet								
Laboratory	Morehouse							
Parameter	FORCE	Range	25000	Sub-Range	2 % Force Point			
Technician	HZ	Standards Used	SAMPLE LOAD CELL FOR HOW LOW CAN MY LOAD CELL GO					
Date	12.28.2023							
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
ASTM E74 LLF	87.0833E-3	A	Normal	1.000	32	87.08E-3	7.58E-3	13.85%
Environmental Conditions	7.5000E-3	B	Rectangular	1.732	200	4.33E-3	18.75E-6	0.03%
Stability of Ref Standard	375.0000E-3	B	Rectangular	1.732	200	216.51E-3	46.88E-3	85.58%
Ref Standard Resolution	58.0000E-3	B	Resolution	3.464	200	16.74E-3	280.33E-6	0.51%
Morehouse CMC (Ref Lab)	8.0000E-3	B	Expanded (95.45% k=2)	2.000		4.00E-3	16.00E-6	0.03%
			Combined Uncertainty (u_c)=			234.04E-3	54.77E-3	100.00%
			Effective Degrees of Freedom			234		
			Coverage Factor (k), Confidence Interval =		95.45%	2.01		
			Expanded Uncertainty (U) K =			0.47	0.09412%	

Figure 90 How Low Can My Load Cell Go 2 % of Capacity Incomplete MU Budget.

When we look at the overall measurement uncertainty of the 2 % force point at the time of calibration, the dominant contribution is the stability of the reference standard in this example.

We typically will see either the ASTM LLF or the reference standard stability as a dominant contributor to the overall measurement uncertainty.

Occasionally, one will set the resolution too coarse, and that will become dominant.

Measurement Uncertainty Budget Worksheet								
Laboratory	Morehouse							
Parameter	FORCE	Range	25000	Sub-Range	1 % Force Point			
Technician	HZ	Standards Used	SAMPLE LOAD CELL FOR HOW LOW CAN MY LOAD CELL GO					
Date	12.28.2023							
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution
ASTM E74 LLF	87.0833E-3	A	Normal	1.000	32	87.08E-3	7.58E-3	26.42%
Resolution of UUT	000.0000E+0	B	Resolution	3.464	200	000.00E+0	000.00E+0	0.00%
Environmental Conditions	3.7500E-3	B	Rectangular	1.732	200	2.17E-3	4.69E-6	0.02%
Stability of Ref Standard	250.0000E-3	B	Rectangular	1.732	200	144.34E-3	20.83E-3	72.58%
Ref Standard Resolution	58.0000E-3	B	Resolution	3.464	200	16.74E-3	280.33E-6	0.98%
Morehouse CMC (Ref Lab)	4.0000E-3	B	Expanded (95.45% k=2)	2.000	200	2.00E-3	4.00E-6	0.01%
			Combined Uncertainty (u_c)=			169.43E-3	28.71E-3	100.00%
			Effective Degrees of Freedom			207		
			Coverage Factor (k), Confidence Interval =		95.45%	2.01		
			Expanded Uncertainty (U) K =			0.34	0.13637%	

Figure 91 How Low Can My Load Cell Go 1 % of Capacity Incomplete MU Budget.

When we look at the overall measurement uncertainty of the 1 % force point at the time of calibration, the dominant contribution is the stability of the reference standard in this example.

Note: We use some best-case scenarios for stability and the ASTM LLF.

On how low my load cell will go, the comparison between a 2 % and 1 % force point percentage-wise shows that at the 1 % force point, the overall MU is 0.136 % versus 0.094 % at the 2 % point.

If the ASTM LLF factor was dominant, there are options such as having the load cell calibrated using its normal range and then calibrating a separate low range.

The ASTM LLF is often lower at a low-range calibration than at normal calibration.
The stability, resolution, and reference standard uncertainty typically remain constant; thus, only specific load cells can be used with multiple ranges.

In some cases, a second range from 1 % -10 % of capacity might work, some 2 % -20 % of capacity might work, and in others, a second range would have minimum benefit, if any.

To know what may work, contact your calibration provider to review the calibration history or history of like systems.

How Low Can My Load Cell Go?

#2 ISO 376 and ASTM E74 lowest force point criteria.

Using a load cell below 2 % of its capacity is not recommended. ASTM E74 and ISO 376 have different criteria for establishing the first usable force point.

ASTM Sections referencing the lowest possible applied force.

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

ASTM E74 Note 8 states, "It is recommended that the lower force limit be not less than 2 % (^{1}/50) of the capacity of the force-measuring instrument."[3]

ISO 376 section 7.3 requires the minimum force to be greater than or equal to 2 %.

7.3 Minimum force

Taking into consideration the accuracy with which the deflection of the instrument can be read during calibration or during its subsequent use for verifying machines, the minimum force applied to a force-proving instrument shall comply with the two following conditions:

a) the minimum force shall be greater than or equal to:

— 4 000 × r for class 00;

— 2 000 × r for class 0,5;

— 1 000 × r for class 1;

— 500 × r for class 2.

b) the minimum force shall be greater than or equal to 0,02 F_f.

Figure 92 How Low Can My Load Cell Go ISO 376 Requirements [5]

How low can my load cell go?

#3 ASTM E74 on Calibration Due Dates

One of the main reasons we would advise against using a load cell below 5 % or 2 % is found in section 11.2.1 of the ASTM E74 standard, which states, "Force-measuring instruments shall demonstrate changes in the calibration values over the range of use during the recalibration interval of less than 0.032 % of reading for force-measuring instruments and systems used over the Class AA verified range of forces and less than 0.16 % of reading for those instruments and systems used over the Class A verified range of forces.". [3]

Notice we are not considering 1 % as the likelihood of meeting the criteria is low.

Some load cells may meet the criteria, though almost any shift in output would cause the instrument not to meet the criteria outlined in section 11.2.1, and the result would be the user no longer being able to have a calibration interval of two years, which would increase downtime and calibration costs.

How Low Can My Load Cell Go? Conclusion.

The question "How low can my load cell go?" involves intricate considerations. To maintain a low measurement uncertainty and reliability, one needs to maintain a specific calibration interval.

The assessment of measurement uncertainty, including factors such as resolution, reference standard stability, ASTM LLF or other specifications, when applicable, and the uncertainty of the calibration standard, is vital for understanding the limitations and precision of a load cell at lower force levels.

Moreover, adherence to industry standards, such as ASTM E74 and ISO 376, provides clear guidelines and recommendations on the minimum force points for load cell usage.

The implications of calibration due dates, as outlined in ASTM E74, further emphasize the practical challenges associated with using load cells at extremely low force levels.

Meeting calibration criteria becomes critical for maintaining calibration intervals and avoiding increased downtime and calibration costs.

Like people doing the Limbo, each load cell is different.

Some will be able to go lower than others, and some will fail early.

If you buy great equipment, the chances of maintaining a usable range of 2 % or better with a Measurement uncertainty of under 0.1 % of applied is possible, though not typical.

The decision on how low a load cell can go should be a careful balance between the application's specific requirements, adherence to the appropriate standard, and the practical constraints imposed by calibration considerations.

Force Versus Mass

Figure 93: Morehouse Tensiometer

Using mass weights to calibrate force devices can result in a significant measurement error if one assumes the nominal mass value is equal to the same nominal force value.

When metrologists discuss measurement errors, we typically discuss the difference between the nominal value and the reading observed on the instrument when the nominal value is applied. If 10,000 lbf is applied to a force-measuring device, and the readout displays 10,002 lbf, the device has a 2 lbf *bias*; logically, if we load the same force-measuring device to 10,002 lbf, we will have applied 10,000 lbf.

Measurement errors can have many different causes. Some are easy to find, and others might be more elusive. In discussions with many professionals in the weighing industry, we have found that some labs use mass weights to calibrate devices that are generally calibrated using force. These devices could include dynamometers, crane scales, handheld force gauges, and many other devices, resulting in significant measurement errors.

Let us quickly review the difference between mass and force. Mass, under almost every terrestrial circumstance, is the measure of matter in an object. However, measuring force considers additional factors:

air density, material density, and gravity. The effect of gravity can produce significant errors when comparing mass and force measurements.

Mass calibration usually results in a calibration certificate specifying the weight's conventional mass. If you went anywhere in the country with that mass, the conventional mass number on the certificate would be correct. There is no need for any gravity corrections because the local gravity is different between where the mass was calibrated and where it is being used. The mass (the amount of what it is) does not change with location. A legal for trade scale is calibrated using conventional mass value to indicate the conventional mass.

Since mass doesn’t change, what is going on when mass is used for force? A force is produced by gravity pulling down on the mass. The force varies with location because gravity varies throughout the world. While gravity is pulling down on the mass, another force is pushing up on the mass. The air around the mass causes the mass to float slightly. F=mg is the formula for force.

Gravity is not constant over the surface of the Earth. The most extreme difference is 0.53 % between the poles and the equator (983.2 cm/s2 at the former compared to 978.0 cm/s2 at the latter). A force-measuring device calibrated in one location using mass weights and then deployed somewhere else will produce different physical elements, and the resulting measurement errors can be significant.

A force or torque measuring device calibrated in one location using mass weights and then deployed somewhere else will produce different physical elements at all but two places in the United States, and the resulting measurement errors can be significant.

The effect of gravity can produce significant errors when comparing mass and force measurements unless used in two places in the United States. Standard gravity (9.80665 m/s2) happens at two places in the US. There is sea level on the 45th parallel (one place in Maine and one place in Oregon). If you are not at sea level on the 45th parallel, then the gravity you are experiencing is probably not standard gravity.

At these two places, local gravity equals standard gravity. When local gravity equals standard gravity, 1 lb. of mass equals 1 lbf. If you aren't at one of those locations, then 1 lb. of mass doesn't equal 1 lbf. This is why the ASTM E74 formula for force uses g/9.80665. It is to correct the force indication (lbf) so that if the force device were ever used at a location with standard gravity, the 1 lb. of mass would equal 1 lbf.

Correcting for the difference in force and mass measurements is possible. When adjusting a device for force measurements, the device will measure force without additional error for gravity correction, air density correction, etc.

Luckily, NOAA's website has a tool for predicting local gravity anywhere on Earth (ngs.noaa.gov). At Morehouse in York, Pennsylvania, the gravitational constant is 9.801158 m/s2. If we compare that to the gravity of Houston, TX (9.79298 m/s2), we find the difference is -0.00084 ((9.79298 m/s2 - 9.801158 m/s2) / 9.79298 m/s2); as a percentage, that is -0.084%.

So, if a lab in Houston calibrated a force-measuring device with mass weights for use at Morehouse, we could expect anything we weigh to be heavier by 0.084%. Not correcting values can have many consequences. If we were shipping steel by tonnage, we would ship less steel, reducing costs and upsetting our customers. If a steel supplier in Houston uses a scale calibrated in York with mass weights without correction, they will ship more steel per ton.

Note that dynamometers, crane scales, tension links, handheld force gauges, and similar devices are not always "Legal for Trade Scales." They can be used as force-measuring devices because their displayed value can be adjusted based on a known force. If a known mass is used on-site, there is an insignificant gravitational measurement error, and the device can be used as a low-accuracy mass comparator. Many of these instruments are used for measuring loads of 1 ton through 300 tons, so having the mass weights necessary to calibrate on-site is usually impractical. Therefore, calibrating using force may be the only practical method to certify the device.

In the tender request phase, it's crucial to determine if the lab possesses the desired capabilities and whether the device should undergo calibration using force or mass.

Figure 94: Morehouse 2,000 lbf Portable Calibrating Machine

Another typical example of these measurement errors occurs with scales (a mass measurement device). If 1,000 lb. mass is used to calibrate a scale at Morehouse and shipped to Denver, CO, it would have to be calibrated again or corrected by formula to obtain the proper mass. Just comparing the gravity in York (9.801158 m/s2) and Denver (9.79620 m/s2), we find a difference of about 0.05 %. This means that 1,000 lb. applied would read as 999.5 lb. without correction. If the scale's accuracy were 0.01 %, then the device would be at least five times greater than the accuracy specification.

Morehouse manufactures force-calibrating machines with varying degrees of mobility, including highly convenient 1-ton capacity Portable Calibrating Machines (pictured above) and our Benchtop Calibrating Machine (5-ton capacity). These machines can calibrate in mass, using a correction formula, or in force.

Unless otherwise specified, Morehouse calibrates in pounds-force. The equation to convert mass to force is:

Force = M x g / 9.80665 (1 – d/ D)

Where:

m = true mass of the weight (not to be confused with conventional mass)

g = local acceleration due to gravity, m/s2

d = air density (approximately 0.0012 g/cm3)

D = density of the weight in the same units as d (approximately 8.0 g/cm3)

Note: 9.80665 = the factor converting SI units of force into the customary units of force. For SI units, this factor is not used.

For our application, these values become ((mass * 9.801158 m/s2)/9.80665 m/s2) * (1 –(0.001185/7.8334)

Force = mass x 0.999288781

or

mass = Force x 1.000711725

When Morehouse converts to mass up to 120,000 lbf, the applied force is multiplied by 1.000712003.The difference in the percentage of using mass instead of force at Morehouse is 0.071 %. The 1.000712003 includes corrections for air density as well as gravity.

Enter Information in the Orange Cells			
Company Name	Calibrations R Us		
Date	4/20/2022		
Instrument Type	Load Cell		
Instrument Serial Number	U-7643		
Meter Serial Number	MY25245		
Force Units	lbf		
Location	New Jersey		
Mode Type	Tension		
Morehouse Ratio (Mass/Force)	**1.000711725**		
Gravity at Morehouse (m/s^2)	**9.801158**		
MH Air Density (g/cm^3)	**0.001185**		
MH Material Density (g/cm^3)	**7.8334**		
Gravity at Your Location (m/s^2)	9.792980		
Average Air Density at Your Location (g/cm^3)	0.001225	**0.001225**	Density of air at normal pressure (1 atm) & temperature (68F)
Material Density of Your Weights (g/cm^3)	8.000000	8	Stainless Steel Average Density for selected material
Optional Class Wt Error %	0.01%		

Force to Mass						
MH Force	MH Mass	Mass Req'd at Customer Site	Customer Mass Weight	Force Applied by Customer Weight	Gravity Error	Total Error Diff
250.0	250.1779	250.3873	250.00	249.61	-0.084%	0.1647%
500.0	500.3559	500.7746	500.00	499.23	-0.084%	0.1647%
1000.0	1000.7117	1001.5493	1000.00	998.45	-0.084%	0.1647%
1500.0	1501.0676	1502.3239	1500.00	1497.68	-0.084%	0.1647%
2000.0	2001.4234	2003.0985	2000.00	1996.91	-0.084%	0.1647%
2500.0	2501.7793	2503.8732	2500.00	2496.13	-0.084%	0.1647%
3000.0	3002.1352	3004.6478	3000.00	2995.36	-0.084%	0.1647%
Note: This sheet is to calculate potential differences from force to Mass. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.						

Figure 95: Morehouse Force to Mass Spreadsheet

Morehouse has a spreadsheet to help with these conversions from force to mass and mass to force. The spreadsheet will allow load cells to be converted from force to mass and provide formulas to correct mass weights properly for force.

> Download the force-to-mass spreadsheet that can also be used to convert mass to force [here.]

The sheet presents all the information in a summary force to mass table. The total error contains an additional error source from the mass weights class. It is added to the overall difference to be on the conservative side.

When converting mass weights to force, the weights are likely to be strange, not nominal values. If this is an issue, we recommend purchasing weights or equipment capable of generating Forces correctly. Morehouse can supply such equipment. An uncertainty analysis must be performed if the decision is made to convert the mass weights to force.

Mass to Force						
Mass lb	Force Desired lbf	Actual Force lbf	Actual Mass Required	Difference in lbf	Gravity Error	Additional UNC
250.0	250.0	249.61	250.39	0.39	-0.310%	0.01001%
500.0	500.0	499.23	500.77	0.77	-0.310%	0.01001%
1000.0	1000.0	998.45	1001.55	1.55	-0.310%	0.01001%
1500.0	1500.0	1497.68	1502.32	2.32	-0.310%	0.01001%
2000.0	2000.0	1996.91	2003.10	3.09	-0.310%	0.01001%
2500.0	2500.0	2496.13	2503.87	3.87	-0.310%	0.01001%
3000.0	3000.0	2995.36	3004.65	4.64	-0.310%	0.01001%
Note: This sheet is to calculate potential differences from Force to Mass. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.						

Figure 96: Morehouse Mass to Force Tab

The above figure shows the significant errors that are often unaccounted for by using mass weights for a force application. Examples include using mass weights with a torque arm, using mass weights to calibrate a load cell, force gauge, crane scale, or any application requiring force. This is a real example of a 0.155 % error between York, PA, and West Berlin, New Jersey, from assuming mass weights can be used for force.

Note: The uncertainty budget many labs claim is only a fraction of the total error.

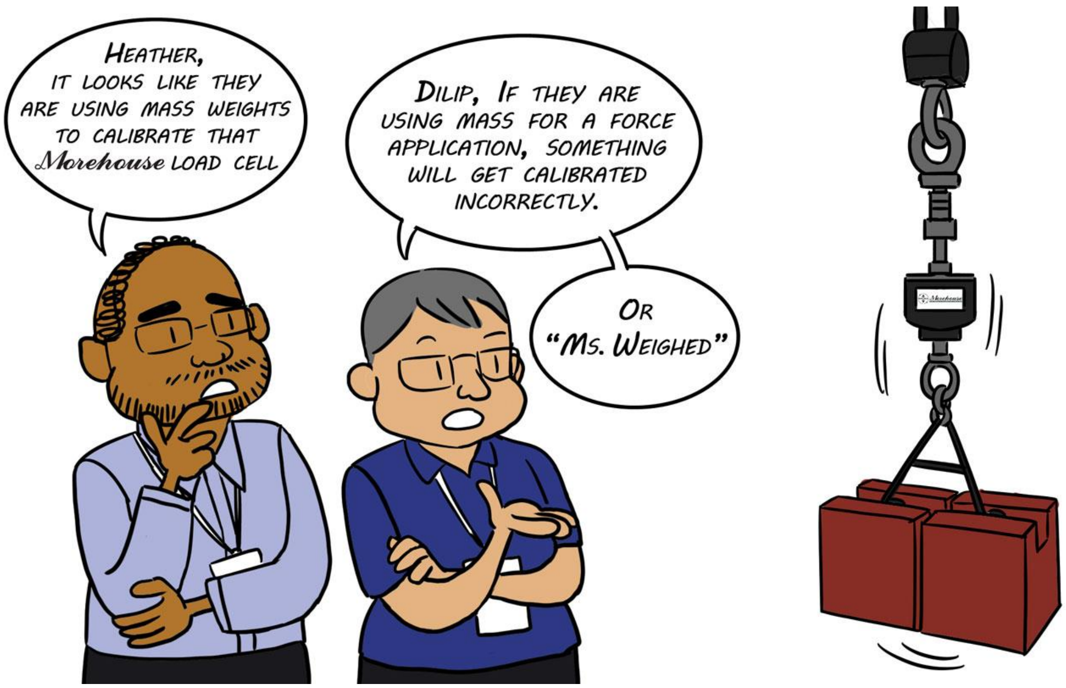


Figure 97: Cartoon Showing a Load Cell being Miss Weighed.

Mass to Force Calculation Example:

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

(Force Equation)

m = true mass of the weight (not to be confused with conventional mass) enter the weight value.
We will start with 1 kg, which is **1000.002259 g or 1.000002259 kg.**

g = local acceleration due to gravity, m/s2 **9.801158 m/s^2**.

d = air density (approximately 0.0012 g/cm3) **0.001225 g/cm^3**

D = density of the weight in the same units as d (approximately 8.0 g/cm3) **7.95g.cm^3**

For the 1 kg weight
Force = (**1.000002259 * 9.801158) / 9.80665 = 0.9994422296**
(1 – (0.001225 / 7.95)) = 1 - 0.00015409 = 0.999845912
0.9994422296*0.999845912 = 0.999288227 kgf.

Thus, when adjusted for force, our 1 kg class 2 weight equals **0.999288227 kgf or 999.28822749 gf.** We continue to apply this formula to all weights to convert our set to force at the location of use.

Note: If our location changed, so would the gravity value and, likely, the air density value.

Air Density	0.001225
Material Density	7.95

Standard Weight	True Mass Gram	Gravity at Location	Material Density	Air Density	Force gf	Force kgf
500	500.000937	9.801158	7.95	0.001225	499.64392138	0.499643921
300	300.000466	9.801158	7.95	0.001225	299.78625670	0.299786257
200	200.000372	9.801158	7.95	0.001225	199.85756575	0.199857566
100	100.000239	9.801158	7.95	0.001225	99.92883584	0.099928836
50	50.000074	9.801158	7.95	0.001225	49.96437245	0.049964372
30	30.000054	9.801158	7.95	0.001225	29.97863306	0.029978633
20	20.000057	9.801158	7.95	0.001225	19.98577636	0.019985776
10	10.000022	9.801158	7.95	0.001225	9.99288169	0.009992882
5	5.000019	9.801158	7.95	0.001225	4.99644884	0.004996449
3	3.000025	9.801158	7.95	0.001225	2.99788289	0.002997883
2	2.000018	9.801158	7.95	0.001225	1.99858993	0.001998590
1	1.000019	9.801158	7.95	0.001225	0.99930496	0.000999305
5000	5000.010069	9.801158	7.95	0.001225	4996.43991231	4.996439912
3000	3000.007098	9.801158	7.95	0.001225	2997.86500323	2.997865003
2000	2000.004282	9.801158	7.95	0.001225	1998.57621914	1.998576219
1000	1000.002259	9.801158	7.95	0.001225	999.28822749	0.999288227

Figure 98 True Mass from a calibration certificate converted to kgf.

Note: If we wanted closer to a nominal 1 kgf, we would add our 1 g or 0.000999305 kgf weight to our 0.999288227 kgf weight to get 1.000287532 kgf.

We would use this method for the remaining weights to find combinations to apply the needed force. For 10 kgf, we might use a 5 kg, 3kg, 2 kg, 10g, which would convert to 10.002905477 kgf.

This guidance follows the conversion formula. Additional uncertainties need to be accounted for when using this formula. These include uncertainty due to material density, air density, local gravity, standard contributors for the reference standard, resolution of the unit under test, stability of the reference, environment, repeatability, and more.

Aircraft and Truck Scale Calibration

Aircraft and truck scales come in all different shapes and sizes and typically serve one purpose: to approximate the weight of an aircraft or truck. Why might that be important? It is about knowing the aircraft's center of gravity (CG). The center of gravity will influence stability and performance. Different airplanes have specified limits for longitudinal and lateral limits. If the airplane does not meet these requirements, it will not fly properly.

If it is not operating properly, the results could be a bad landing, handling problems, exceeding the needed runway length for takeoff, or an all-out crash. Weighing is essential not only with the aircraft empty but also with cargo and fuel. The airplane can have a good CG on takeoff, and the decreased fuel can cause an imbalance during the flight. Knowing the weight is also important because the aircraft's structural strength limits the maximum weight that the aircraft can safely carry.

For trucks, it is a matter of safety and profitability. Safety is the biggest concern for most because an overweight truck could cause severe structural damage over time or immediate damage to bridges and overpasses. Being overweight, which can lead to increased profitability for the company transporting the products, can also interfere with the driver's ability to maneuver quickly, control the truck going uphill or downhill, and stop. It can result in loss of balance or busted or blown-out tires due to the pressure of the excess weight, which leads to severe accidents. The exact limit of how heavy a truck varies by state laws and the type and number of axles on the truck. Federal law dictates trucks must weigh below 80,000 lb.

Since it is essential to know the weight, it is also important to look at how we can improve the calibration of these scales.

Figure 99 Morehouse Aircraft and Truck Scale Calibrator

1. We can control the equipment we purchase for calibration. Plumb, level, square, and rigid equipment should be used to achieve proper calibration. The above Figure is a Morehouse Aircraft and Truck Scale Calibrator. This new machine was designed to minimize the bending of the top beam and load-bearing table, which had occurred in older Morehouse models and occurs in several non-Morehouse products.

   The plates are designed to be square and level, using custom machining processes and ground to maintain a level surface. If there is an increase in bending or uneven surfaces, the strain elements in the scale will vary. These errors could easily be from two to ten times the tolerance.

   Also, the right equipment is stable and has enough resolution to not significantly impact the overall uncertainty. Deadweight machines would be the best, yet they are not the most cost-effective and are not built to support large scales. Therefore, several load cell transfer standards calibrated by deadweight and used in a machine with fine control will allow the operator to achieve the desired force point.

The Morehouse machine has the capability to maintain forces easily within a ± 0.05 lbf margin. However, this precision may be restricted if the appropriate combination of load cell and indicator is not utilized. On a 10,000 lbf load cell, used with a Morehouse HADI, the resolution of the load cell system would be 0.025 lbf. The hydraulics and control will vary and can typically be held to 4-8 counts, so the control will vary between 0.01 and 0.02 lbf. A skilled operator can typically control the machine to within four counts or 0.01 lbf on a 10,000 lbf load cell. Our Automation upgrade can easily hold the machine to ± 0.01 lbf on a 10,000 lbf load cell. Stability could be influenced by the adapters and the Unit Under Test (UUT).

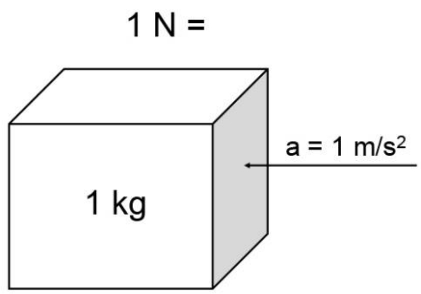


Figure 100 Force Units

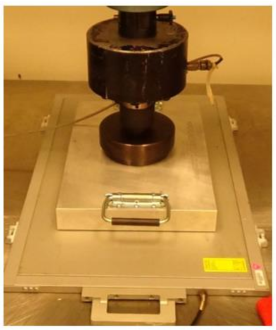
2. We can use the proper units for calibration. We highly recommend calibrating any scale in force units. The scales would be calibrated in lbf, N, or kgf at the calibration site. Force is mass times acceleration, and calibration in lbf, N would be constant over the planet's surface. If someone calibrated in mass, lb., or kg and used the scale in a different location, they would have gravity, material, and air density errors.

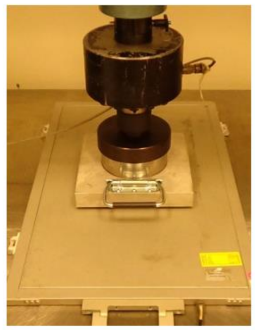
   A recap from the last section: Mass, under almost every terrestrial circumstance, is the measure of matter in an object. Measuring force considers additional factors: air density, material density, and gravity. The effect of gravity can produce significant errors when comparing mass and force measurements. Gravity is not constant over the surface of the earth. The most extreme difference is 0.53 % between the poles and the equator (983.2 cm/s^2 at the former compared to 978.0 cm/s^2 at the latter).

   A force-measuring device calibrated in one location using mass weights and deployed somewhere else will produce different strains on the physical element. The resulting measurement errors can be significant. Correcting the difference in force and mass measurements is possible. When a device is adjusted for force measurements, the device will measure force without additional error for gravity correction, air density correction, etc.

Aircraft and Truck Scale Adapters

Morehouse has tested truck and aircraft scales and there can be a large difference in output from using different size plates





Force Applied lbf	Scale Reading w/ Large pad	Scale Reading w/ Small pad	Diff in lbf	%
0	0	0		
4000	3950	3980	-30	-0.759
8000	7980	8030	-50	-0.627
12000	11990	12020	-30	-0.250
16000	15980	16090	-110	-0.688
20000	19980	20140	-160	-0.801
24000	23990	24210	-220	-0.917
28000	27990	28270	-280	-1.000
32000	31990	32350	-360	-1.125
36000	35990	36460	-470	-1.306
40000	40010	meter saturated		

Figure 101 Difference in Adapters

3. We can control the adapters to simulate the tires' footprint. Aircraft and truck scale calibration often requires special adapters to simulate a tire contact area with the scale. Scales come in a variety of sizes and have specific tolerances. The problem is that not many calibration laboratories use the right adapters. Not using the proper adapters can result in significant measurement errors.

   When an adapter differs from the tire footprint on the scale, we have found substantial errors. The above figure shows the calibration of a scale with a tolerance of 0.1 % of full scale using two different size adapters. The adapter on the left better simulates the tire of a truck; the adapter on the right simulates that of an airplane. The difference between the adapters is over 1.3 % on a 0.1 % device. It quickly becomes apparent that this scale, like several others, will not be within the specification if different-size tires that vary from the footprint of the adapter used during calibration are used.

   Therefore, all scales must be calibrated with the appropriate adapters to simulate the application best.

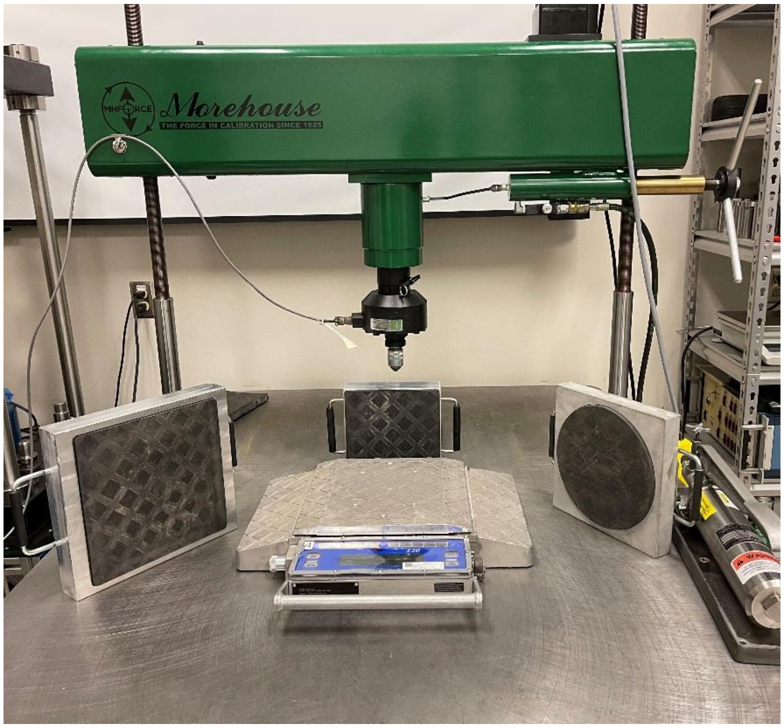


Figure 102 A Truck Scale Tested with 3 Different Size Adapters

Example: The above figure shows various adapters Morehouse can make. Our lab decided to test three different adapters that closely matched the recommended footprint of 8 x 8 on the same scale and report the results. All the adapters made by Morehouse are shown from left to right as a 10 x 10-inch pad, an 8 x 8-inch pad (recommended by the manufacturer), and a 9" round pad Morehouse designed to replicate a tire footprint closely.

The Morehouse website contains additional information about aircraft and truck scale calibration, including adapters, replicating the tire footprint, and measurement accuracy.

FORCE APPLIED	10 X 10 PAD READINGS	8 X 8 PAD READINGS	9" ROUND PAD READINGS	Maximum Difference	% Maximum
2000	2000	2000	2000	0	0.00%
4000	4040	3990	4000	50	1.25%
6000	6090	5990	5990	100	1.67%
8000	8130	7990	8000	140	1.75%
10000	10170	10000	10010	170	1.70%
12000	12190	12010	12000	190	1.58%
14000	14210	14010	14000	210	1.50%
16000	16230	16010	15990	240	1.50%
18000	18230	18010	17980	250	1.39%
20000	CAP	20000	19980	N/A	N/A

Figure 103 Data from Using the Blocks Pictured Above

The test was performed, and the output was recorded above. Any point in green is within the manufacturer’s specification of 1 % of the applied load. We met the manufacturer's specification when using the recommended size adapter because we used an adapter designed to match the tire footprint. The numbers above show a noticeable difference outside the allowable tolerance when using a 12 x 12 block (actual rubber footprint 10 x 10) in red. This further supports the idea that scale calibration should be done with the proper size adapter.

The Morehouse Aircraft Scale Calibrator was designed to be the best option for calibrating aircraft and truck scales of various sizes and capacities up to 60,000 lbf. The scale is designed to be plumb, level, rigid, and square. The transfer of force is typically facilitated through a load cell, and adapters are custom-made to duplicate the footprint of the tires of the airplane or truck that the scale will be used to weigh.

The errors associated with using improper equipment, units, or adapters can make achieving the tolerance impossible. If you need to certify an instrument within a tolerance of 0.1 % of applied force, you may need to use several standards over the entire measurement range. There will be a significant risk if the measurement's uncertainty is less than the tolerance required. Most legal metrology, ASTM E617-23, and OIML R111 require uncertainties to be less than 1/3 of the tolerance. Hence, the recommendation for several load cells.

Measurement uncertainty often includes the reference standard uncertainty, the reference and UUT resolution, environmental conditions, reproducibility, repeatability, stability, and other error sources. If the machine has uneven surfaces or bending, reproducibility and repeatability will vary greatly. Typically, one can maintain a CMC uncertainty component of about 0.02 % to 0.04 % from 20 % of the rated capacity of the load cell in a Morehouse frame.

If a 60,000 lbf load cell can achieve 0.025 % at 12,000 lbf, and a 10,000 lbf load cell can achieve 0.025 % at 2,000 lbf, then we could assume that we are meeting the 1/3 requirement on a 0.1 % device using two load cells from 2,000 lbf through 60,000 lbf. If we wanted to do smaller scales, we might add a 2,000 lbf load cell and expand our loading range to 400 lbf through 60,000 lbf while maintaining a better than 0.03 % CMC uncertainty component.

If you need to get the most accurate measurement out of your scale and minimize risk, then the Morehouse scale press with 2-3 load cell standards and the proper adapters to simulate what is being weighed will meet your calibration needs.

The calibrator is crafted to uphold the high accuracy necessary for accurate scale certification. It is versatile and can be applied to various truck and aircraft scales as well as aircraft weighing kits.

Calibrating these scales correctly is essential to your safety or those you may know.

Tension Link Calibration

Tension Link Calibration requires advanced knowledge of the calibration process to pass an instrument. There will be additional errors if there is any variation in the adapters used for calibration. Here at Morehouse, we have done testing using different pin sizes and adapters. Forged pins, for example, can differ by small amounts in diameter from pin to pin.

Depending on the Scale manufacturer, we have seen differences of up to 1.7 % between different sets of pins, as shown in our chapter on adapters. If your instrument has an accuracy of 0.1 %, your error could be 17 times greater by substituting pins.

We think three things need to be followed regarding tension link calibration and keeping them in tolerance from calibration to actual use. The top 3 things to follow are:

- Use the appropriate pin size.
- If the pins have irregular sizing, label the top and bottom pins and note the position.
- Use the appropriate equipment and adapters.

Use the Appropriate Pin Size

Figure 104: Figure Showing Pin Size Diagram

In general, the pin diameter and the clevis hole size must be a close fit, and for safety, always use the manufacturer's recommended pin diameter. Pins smaller than recommended can cause failure.

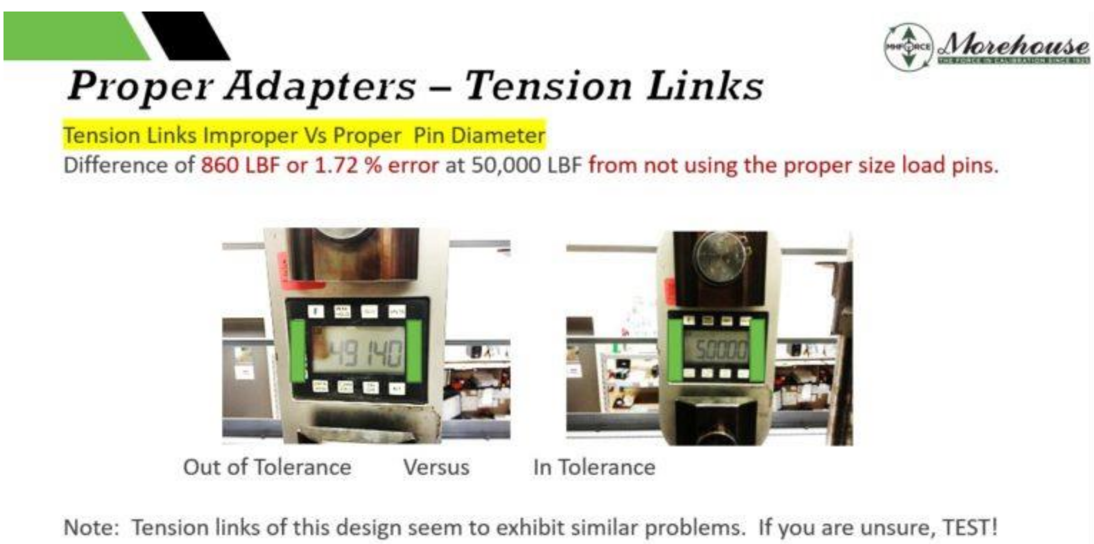


Figure 105: Showing Large Pin Size Error

The above picture shows a test Morehouse performed using two different size pins: A 50 mm pin, which yielded a result of 50,000 lbf when 50,000 lbf was applied, and a 1.75 " inch pin, which yielded a result of 49,140 lbf when 50,000 lbf was applied. The results were significant as the manufacturer accuracy of this Tension Link is 0.1 % of full scale.

It is an understatement to say that tension link calibration requires the same pin size used in the field during calibration. Not using the appropriate pin size will lead to significant measurement errors.

If The Pins Have Irregular Sizing, Label the Top and Bottom Pins and Note the Position

We use the correct pins with the unit, although our pins vary slightly in diameter. However, this does not produce significant errors, as **not using the proper pin size** can be enough to cause the instrument to fail during calibration.

Figure 106: Pins labeled A and B are shown above, and each corner has been labeled.

	PIN A		PIN B	
	Q1 to Q3	Q2 to Q4	Q1 to Q3	Q2 to Q4
Diameter	2.0005	2.0045	2.0060	2.0030

Figure 107: Shackle pins were measured using these coordinates.

A maximum variation of 0.0055 isn't much. This could easily happen with repeated loadings, as most pins are cast and will wear over time. The main issue is when the wear starts to happen, maintaining calibration becomes more difficult.

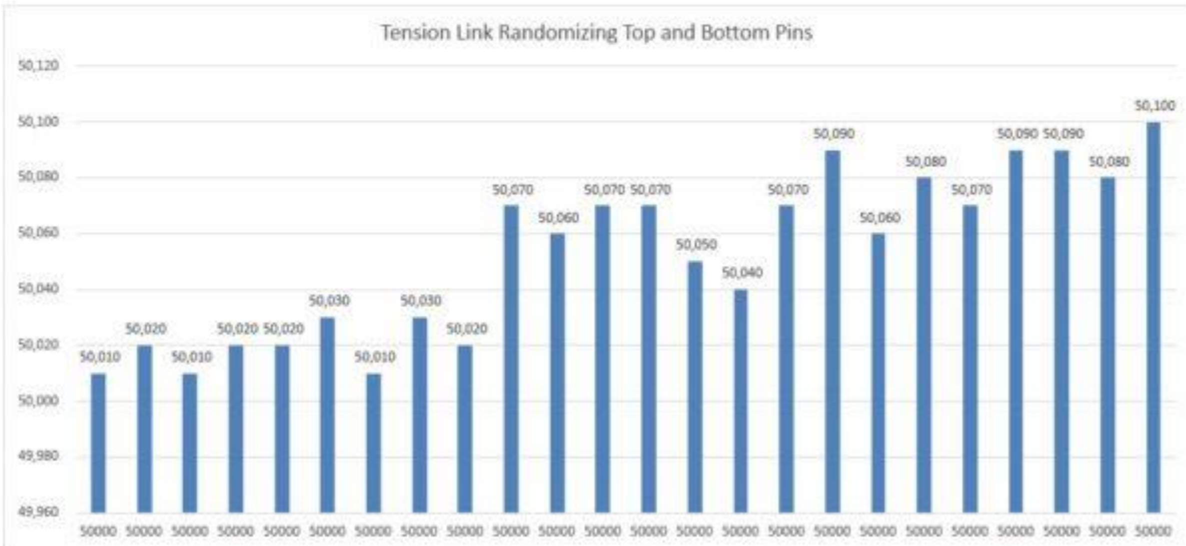


Figure 108: Tension Link Randomizing Top and Bottom Pins

The above graph shows what happens when we do not label the pins and use A and B at random positions. Some measurements are within the specification, and others are not.

Pin B (2.0030 to 2.0060)	Pin A (2.0005 to 2.0045)
50,070	50,010
50,050	50,020
50,040	50,010
50,070	50,020
50,090	50,020
50,060	50,030
50,080	50,010
50,070	50,030
50,090	50,020
50,090	50,070
50,080	50,060
50,100	50,070
17.81640375	22.74696117
Out of 24 tests 13 did not meet spec ± 50	

Figure 109: 24 Tests on the Same Instrument and 13 Failed

Thirteen out of the 24 samples did not meet the specification. This further supports that labeling the top and bottom pins is the best practice and should be required for tension link calibration. If your pins are worn, we can help find replacements. We have several solutions if your customers are not sending their pins, or you can standardize your process with machined pins.

Use the Appropriate Equipment and Adapters

We discuss Tension Link Calibration Adapters, including an appropriately sized Clevis set to use the customer-supplied pin, load with the shackle, and adapters to ensure the forces are centered. The adapters pictured below are designed with several spherical radiuses to limit misalignment.

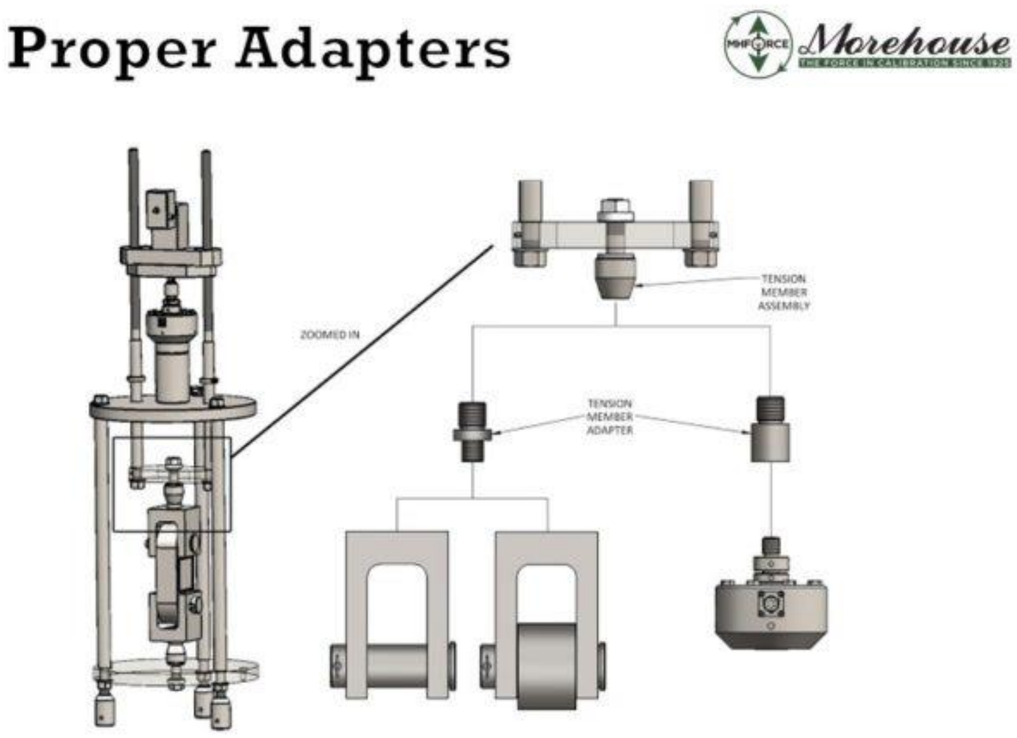


Figure 110: Morehouse UCM with Tension Member Adapters

The Morehouse Clevis assembly for tension adapters is used to calibrate dynamometers, load links, tension rods, crane scales, or other weighing devices. The assemblies can be used with Morehouse Quick Change Tension Members to minimize errors by improving tension alignment. The Clevis assemblies are Patented (No. 11,078,052).

The Morehouse website has more information on Morehouse Quick Change Tension Members, and our YouTube channel has an easy-to-follow whiteboard video on Tension Link Calibration.

Tension Link Calibration Safety Notes

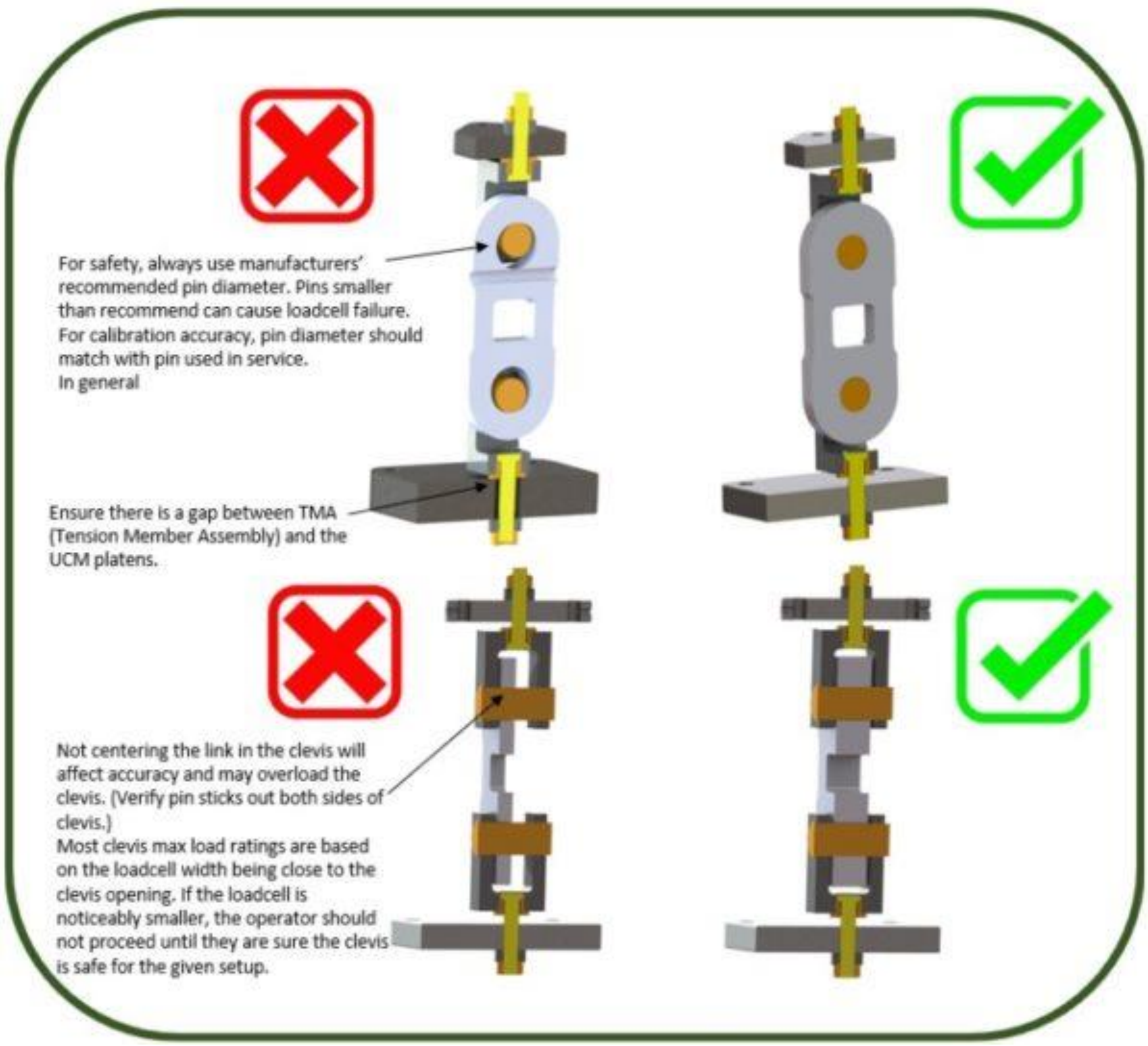


Figure 111: Tension Link Calibration Safety Notes

1) Ensure the clevis pin is fully inserted. If the design includes safety pins, ensure they are installed before loading.

2) Some tension link load cells are designed with a noncylindrical hole or large chamfers. This effectively reduces the contact area on the pin and decreases its maximum load capacity.

3) Never use fixtures that don't have traceability to their load ratings. Always remember load ratings must be reduced if the setup does not match the original design intent.

Cable Tensiometer Calibration

What is a Cable Tensiometer?

Figure 112: Digital Cable Tensiometer in the Morehouse PCM-2MD-T1 Cable Tensiometer Calibrator.

Cable tensiometers are devices used to measure the tension or force in cables, wires, and ropes. They are commonly employed in engineering, construction, and industrial applications to ensure the proper tension of cables to prevent overloading or under-tensioning, which can impact safety and performance. These devices typically feature a load sensor or gauge that provides real-time tension readings.

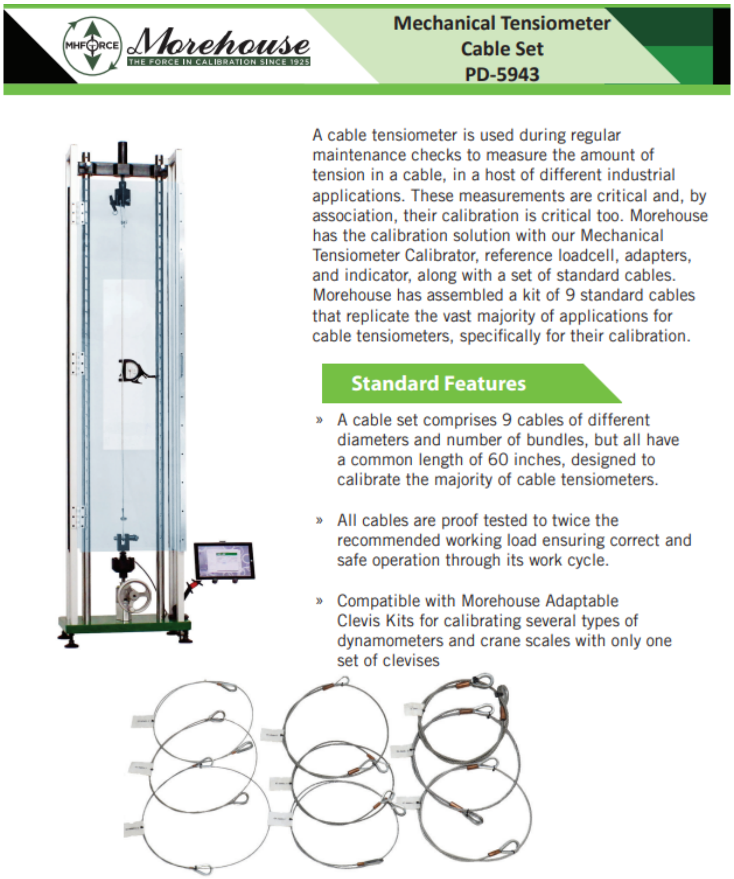


Figure 113: Morehouse Tensiometer Calibrator.

Calibrating a cable tensiometer involves knowing the right requirements, having the right equipment, and the right processes.

How to Calibrate Cable Tensiometers: The Right Requirements

What is needed to accomplish this task? Does cable tensiometer calibration affect the type and length of cable used?

Several variables can influence the readings of the cable tensiometer. The standard variables are.

1. The Length of the Cable.
2. The Method Used for Calibration.
3. The Type of Cable GAC versus SSAC.

To ensure meaningful data, one must determine the appropriate test method that best replicates how your customers use the equipment.

Are they clamping a tensioned cable or adjusting the tension based on the calibration chart?

How to Calibrate Cable Tensiometers: The Right Equipment

Figure 114: Henry Zumbrun is using a Morehouse Cable Tensiometer Machine (PCM-2MD-T1).

In the above image, Henry Zumbrun uses a Morehouse Cable Tensiometer Machine (PCM-2MD-T1) and a 500 lbf Morehouse load cell reference standard that was calibrated using the ASTM E74 standard using deadweight primary standards known to be better than 0.002 % of applied force.

Note: The Expanded Measurement Uncertainty for the Morehouse Cable Tensiometer typically falls between 0.02 % and 0.04 % of applied forces.

The right equipment may also consist of cables of at least 3 feet or greater free from defects. That means the cable should lie flat and not have any bends or kinks. Some systems use cables that are 18 – 24 inches, and these shorter cables can lead to different results.

Some of these systems even use torsion cells meant to calibrate torque wrenches. Torque equipment used to calculate the force on a cable typically utilizes shorter cables and is likely not the right equipment. This approach is complicated by the calculation of force from a torsion cell and introduces measurement uncertainty and error components that are extremely difficult to quantify and often quite large.

For calibrating any cable tensiometer, it is essential to read the manufacturer's recommendations, which often include cable lengths and types.

The Morehouse system incorporates several key features to ensure accurate and reliable tensiometer calibration:

- Minimized Strain: A load cell positioned at the base eliminates the influence of any extra strain caused by hanging and clamping the tensiometer.
- Precise Frame: The machine's frame is meticulously designed to be plumb, level, square, and rigid, minimizing torsion and offering exceptional control during calibration.
- Versatile Calibration: The Morehouse system allows for two calibration methods: clamping and adjusting the tension, pre-loading the cable to a specific value, and clamping. It can accommodate cables up to 5 feet long and generate tension forces as high as 2,000 pounds-force (lbf).

This combination of features includes minimizing strain, utilizing a precise frame, and offering versatile calibration methods to calibrate tensiometers. One may want to investigate frames with versatile calibration options when evaluating the right equipment.

How to Calibrate Cable Tensiometers: The Right Processes

For cable tensiometers, this might be as follows:

Apply the reference force: Attach the reference standard to the tested cable or wire and apply the known tension or force. Then, clamp the device to the cable, adjust the force to the desired reading, unclamp it, and clamp it again. This method would be equivalent to one fixed point, such as the hanging weight method. There is another method of clamping after a known force is applied. Depending on the cable size, these methods produce a significant difference.

Compare readings: Read the tension measurement on the cable tensiometer while the reference load is applied. Compare this reading to the known reference standard value.
Repeat as needed: Take as many measurements as deemed necessary; in our testing, we usually take six measurements at each test point to have confidence in the repeatability numbers.

Record calibration data: Document the calibration process, including the reference standard used, the measured values, and any adjustments made.

Note: It's essential to follow the manufacturer's guidelines and recommendations for calibration specific to your cable tensiometer model, as the process can vary between devices.

Cable Tensiometer Known Error Sources

The Length of the Cable
The length of the cable can be a significant error source. This error source makes sense because a shorter cable will be more rigid. Therefore, lower readings will show the most differences between the cable lengths.

In some of our testing, we compared cables made from the same material using the same tensiometer, and the same calibration method. This calibration method employs a "clamp and adjust" technique. It involves applying a force close to the desired reading, clamping the cable, and then fine-tuning the force back to the intended value before recording the measurement.

Testing of 3/16" Cables			
Test Point	3 Ft Cable	5 Ft Cable	% Difference
50	63	50	20.42%
250	270	254	5.44%
500	528	519	3.35%

Test Point	3 Ft Cable	5 Ft Cable	% Difference
50	64	52	20.31%
250	275	262	5.93%
500	528	516	2.33%

Figure 115: Comparing 3 and 5' cable lengths on 3/16" GAC cables.

The overall results for "clamp and adjust" technique using different digital tensiometers show a similar trend that makes sense. The higher the tested value, the lower the percentage difference between cables.

We can draw an analogy between cables and springs. When subjected to the same force, a longer cable, like a spring with double the length, will experience greater stretching. Consequently, compared to a shorter cable stretched by the same amount, a longer cable may exhibit a smaller relative increase in tension.

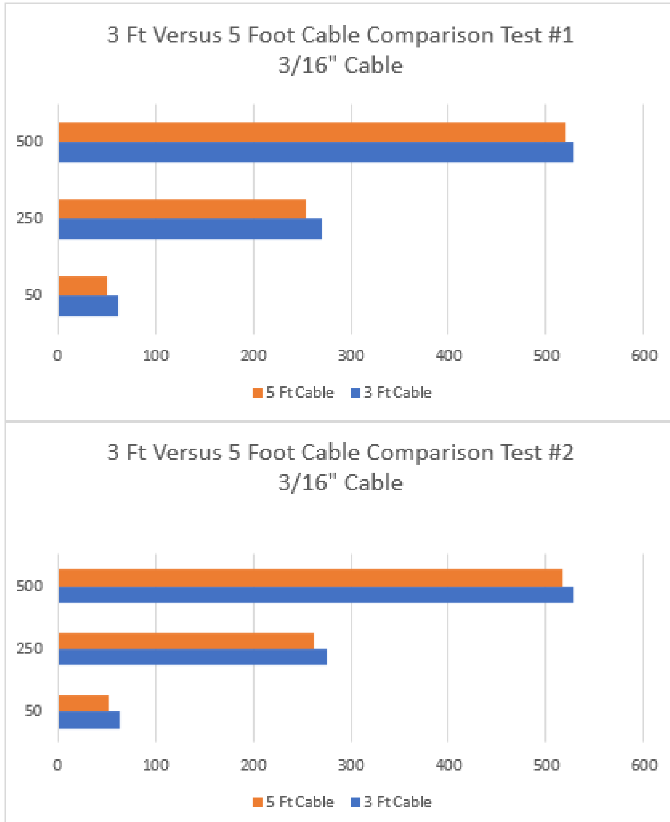


Figure 116: Comparing Different Length Cables.

Think about a rubber band and how a thinner or longer one will stretch more than its thicker or shorter counterpart. A cable acts the same. Steel is much less stretchy, so the length changes are much less.

Additionally, we are only varying the cable length from what is generally considered a minimum cable length to a longer cable length. Those who use cables from 18 inches to 24 inches in length will likely observe higher differences compared with 60-inch cables, depending on the thickness of the cable.

The formula for deflection of a uniform cross-section in tension summarizes that force (F), length (L), width (area, A), and material (modulus of elasticity, E) are all related to deflection (e):

$$e = \frac{F \cdot L}{A \cdot E}$$

Rearranging gives:

$$\frac{F}{e} = \frac{A \cdot E}{L}$$

F/e is the spring rate, which is the amount of force (e.g., lbf.) per displacement (e.g., in). So 50lbf/in means if you apply 100 lbf., it will stretch 2 inches. Thinking about the cable, we can see that increasing area increases the spring rate, increasing material stiffness (modulus of elasticity) increases the spring rate, and increasing length decreases the spring rate. A lower spring rate means less change in force (tension) when applying the tensiometer.

The Machine and Method Used for Calibration

There are two common calibration machines used to calibrate cable tensiometers:

- Deadweight calibration with one fixed point: The hanging deadweight avoids introducing additional tension, as clamping the cable does not affect the measured force.
- Machine calibration with two fixed points: Clamping the cable in this method shortens the distance between two fixed points, introducing additional tension.

Calibration Using Deadweight.

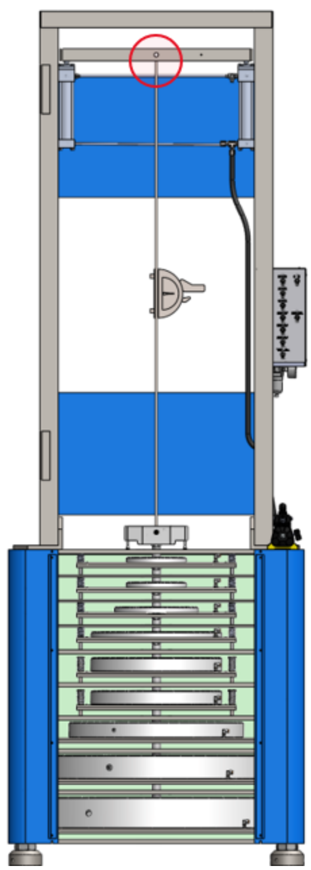


Figure 117: Morehouse 774000 Tensiometer Deadweight Calibrator with 1 fixed point.

The Morehouse 774000 Tensiometer Deadweight Calibrator revolutionized calibration processes. A fixed point (shown in the red circle) eliminates the need to secure cables to beams and manually hang weights.

This design prioritizes safety and simplifies the calibration technician's work. The operator secures the cable and selects desired weights up to 2000 lbf.

The design allows the weights to hang in the air, so we call this a machine with one fixed point, as clamping the cable will not create any additional force.

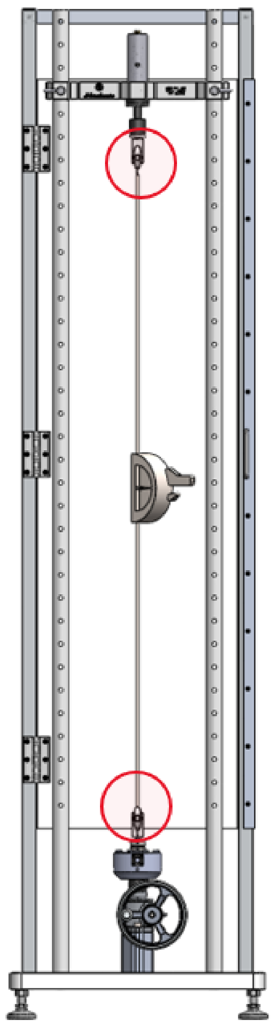


Figure 118: The Morehouse Cable Tensiometer Machine (PCM-2MD-T1) with two fixed points.

The Morehouse Cable Tensiometer Machine (PCM-2MD-T1), with two fixed points (shown in the red circles), also eliminates the need to secure cables to beams and manually hang weights. However, this machine uses two fixed points to apply tension to the cable, meaning that when we use a tensiometer to clamp the cable, we create additional tension. It is the way the cable tensiometers work. They have a system that clamps the cable and thus tries to shorten the length between the two fixed points.

Using the Morehouse PCM-2MD-T1, we can evaluate two different methods. One of the methods simulates that close to that of deadweight.

Method 1 Clamp the tensiometer and adjust the force. This method is when the force is applied close to the desired reading, the cable is clamped, and then the force on the cable is adjusted back to the nominal value. In this case, we might load to 460 lbf, clamp the cable, get a reading of 495 lbf, and adjust the force value to 500 lbf. Since we clamp and then adjust to the force value, the results are like using deadweight as we have manually compensated for the increased tension of the tensiometer by decreasing the distance between the two fixed points.

Method 2 Clamp tensiometer. This method is when the force is applied at the desired reading, the cable is clamped, and the value is read. In this scenario, the applied force might be 500 lbf, and when clamped, the value might jump to 528 lbf.

Replicating Real-World Use:

While the calibration process typically involves securing the tensiometer and applying a known tension first, the cable loading method (Method 2) better represents real-world usage.

In this method, the force is applied to the desired level, the cable is clamped, and then the reading is taken. This captures not only the actual cable tension yet also the slight internal tension introduced by the tensiometer during measurement, which is present in actual field usage.

Applied	Method 1	Method 2	Diff	% Difference
50	49	63	14	22.22%
250	255	270	15	5.56%
500	510	528	18	3.41%

Figure 119: Comparing 3/16" cables using different methods.

To ensure consistency, both calibration methods were tested using the same setup: a single cable, load cell, and Morehouse reference machine (Figure 7).

Comparing these two methods using five-foot long 3/16-inch cables yielded a significant difference. The largest difference was at the lower test points.

In principle, this makes sense as we shorten the distance between the two cables by grabbing it with the tensiometer. That is a fixed distance that is repeatable; thus, the difference is close to a constant one.

Clamping the tensiometer shortens the effective length of the cable. This modification in effective length influences the increase in tension and forces read, which directly relates to the overall "spring rate" of the system.

Note: Our tests used a digital tensiometer, which does not introduce as much internal tension as some analog tensiometers.

The Type of the Cable GAC versus SSAC

Figure 120: Two 3/32" Cables. The one on the left is a GAC, and the other an SSAC.

GAC cable is short for Galvanized Aircraft Cable, while SSAC is Stainless Steel Aircraft Cable.

Figure 121: Two Digital Cable Tensiometers.

For the comparison tests, we used two 3/32" cables and two tensiometers with the following specifications below.

Model #	Range	Performance Specification
CT12A – 3/32	30 - 400 lb.	± 4 Lbs. 30-100 lb. ± 8 Lbs. 101-400 lb.

Figure 122: Performance Specifications for the CT12AA Digital Tensiometer.

The Data

Overall, the units performed very well. The standard deviation from test multiple points was typically 1 lb. or better. The variation between six repeated measurements varied from 1 to 3 lb. per point. The repeatability data varied from a minimum of 0.41 to a maximum of 1.03 lb.

GAC 3/32" 5' Cable with Barfield CT12A S/N 564						
Applied Force	Instrument Readings					
50	48	47	48	48	47	48
200	193	192	192	191	193	191
300	283	284	284	283	283	285

SSAC 3/32" 5' Cable with Barfield CT12A S/N 564						
Applied Force	Instrument Readings					
50	49	49	49	49	48	48
200	198	197	197	199	196	197
300	293	293	293	295	294	294

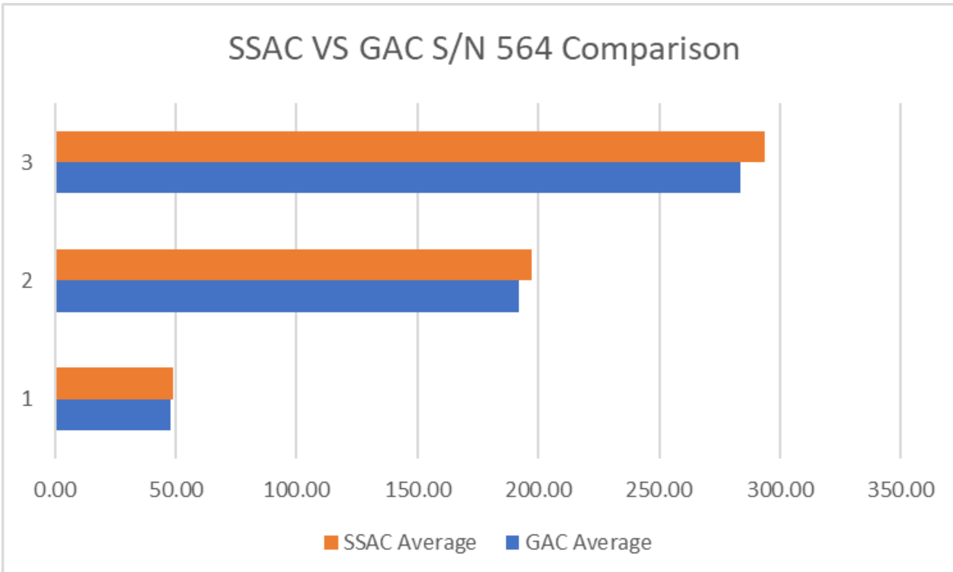
Figure 123: Data Comparison Between the Two Types of Cables S/N 564.

GAC 3/32" 5' Cable with Barfield CT12A S/N 544						
Applied Force	Instrument Readings					
50	48	48	48	48	48	49
200	196	195	194	195	195	195
400	396	397	395	394	395	395

SSAC 3/32" 5' Cable Barfield CT12A S/N 544						
Applied Force	Instrument Readings					
50	50	50	50	50	50	49
200	202	202	203	204	204	204
400	405	407	406	405	407	405

Figure 124: Data Comparison Between the Two Types of Cables S/N 544.

Comparing the different cable types SSAC versus GAC

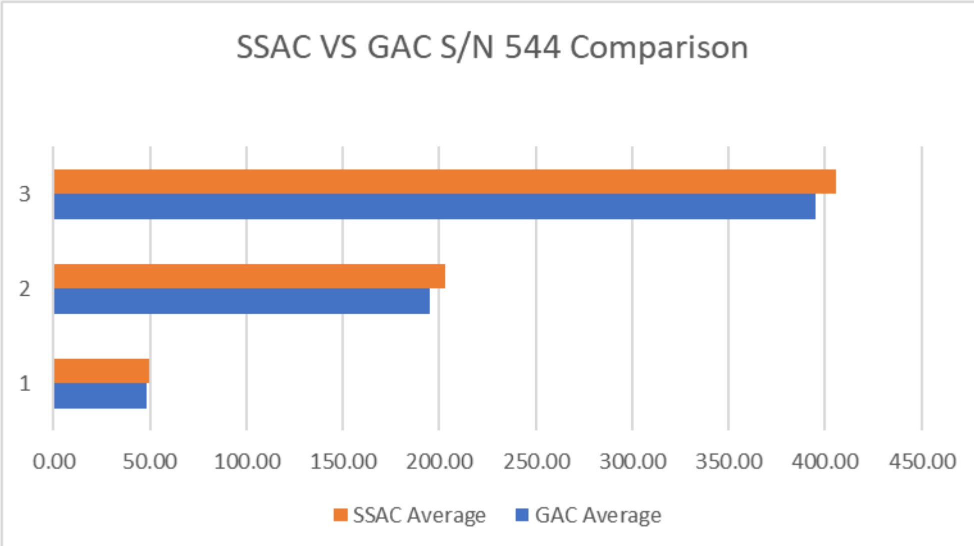


Applied Force	GAC Average	SSAC Average	Difference in lb	% Difference
50	47.67	48.67	1.00	2.08%
200	192.00	197.33	5.33	2.74%
300	283.67	293.67	10.00	3.46%

Figure 125: Comparison Data using S/N 564 Tensiometer Graphed.

We compared the GAC and SSAC on two different cable tensiometers. The highlighted cell in the above figure from the comparison using S/N 564 shows the measurement in which the unit does not meet the specifications of ± 8 lb. from 100-300 lb. This might result in a failed calibration and adjustment when the tensiometer is within the specifications.

Note: When considering measurement uncertainty, the expanded measurement uncertainty at a confidence interval of 95 % is around ± 0.5 lb., which would decrease the acceptance limits to ± 7.5 lb.



Applied Force	GAC Average	SSAC Average	Difference in lb	% Difference
50	48.17	49.83	1.67	3.40%
200	195.00	203.17	8.17	4.10%
400	395.33	405.83	10.50	2.62%

Figure 126: Comparison Data using S/N 544 Tensiometer Graphed.

The tension readings between 3/32" SSAC and 3/32" GAC cables vary. The end-user needs to assess if their specific tensiometer meets their testing requirements for both cable types, considering the observed variations and their associated risks.

The manual for the tensiometers confirms this by mentioning that SSAC needs a different calibration than GAC.

If the measurement is at the tolerance limit, there would be a 50 % risk, and the unit is either good or bad. If the specification were from 30 – 100 lb. to be within ± 4 lb. & from 101 -400 ± 8, then S/N 544 would fail using a GAC cable, while S/N 564 would pass.

How to Calibrate Cable Tensiometers Conclusion

Calibrating cable tensiometers involves using the right equipment, such as a calibrated load cell and appropriately sized cables and following specific processes to ensure accurate tension measurements for various cable types.

However, a crucial question remains: which calibration method best reflects the actual end-use conditions for the equipment? Are calibration laboratories actively engaging with their clients to determine the method that best replicates how the equipment is used?

Replicating Equipment Use

At Morehouse, we occasionally get calls from customers or potential customers asking why they get results that are different from what we achieved during calibration. In the case of an existing customer, we often learn information we did not have before. For example, the equipment they used to generate the force is not plumb, level, square, rigid, or low torsion. Another common issue is that someone checks the calibration with mass weights, which can be vastly different from weights adjusted for force.

When we get calls from potential customers, we typically find the common theme is that many calibration providers do not replicate actual use when they calibrate equipment.

This section will examine common error sources and how calibration setups in the Morehouse deadweight and calibrating machines best replicate field use. Specifically, we will review field use in performing calibrations following ISO 7500 and ASTM E4. Several other examples and loading conditions that can impact calibration results are covered in the next section.

Common Error Sources in Force Calibration

Figure 127 Compression/Tension Machine that Does Not Replicate Field Use

The force-measuring instrument's end-user must ensure that the calibration laboratory replicates how the instrument will be used. As shown in the above figure, specific calibrating machines that perform tension and compression in the same setup do not replicate use.

Many calibration laboratories can replicate use if they use the customer's adapters and independent setups for compression and tension. However, this takes more time and raises costs, so it is done infrequently.

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 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 the adapter than what was used for calibration.
- Using a different size adapter 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.
- An excitation voltage different from the voltage used at the calibration time is used.
- 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, or 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 the realized value from the deadweight calibration.

> Morehouse has several articles, videos, webinars, and other training courses, including on-site courses focusing on these error sources and correcting them.

The primary focus of this chapter is to use different setups for compression and tension when calibrating to ASTM E74 or ISO 376. Independent setups are required for almost all calibrations done to calibrate the testing machine following ASTM E4 or ISO 7500 requirements.

Replicating Field Use is Best Practice: Calibration using Different Setups for Compression and Tension.

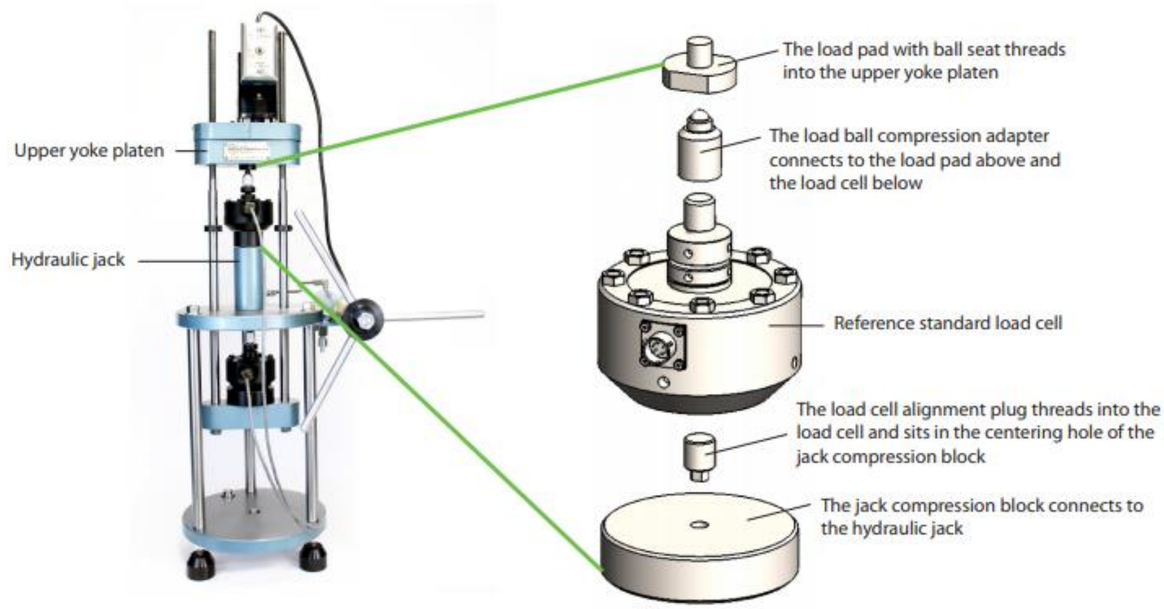


Figure 128 Morehouse Universal Calibrating Machine with a Compression Setup for the Unit Under Test

At Morehouse, customers often ask questions such as, “Why should we use your machine?” This is a fair question to answer. One reason is cost. The machine ranks among the most versatile and cost-effective solutions to calibrate all force instruments. However, the most important answer is that our Morehouse machines allow the end-user to replicate best how the equipment is used in the field. For example, the end-user can have different setups for tension and compression and use the proper adapters, as recommended by several published standards.

Figure 129 Morehouse Universal Calibrating Machine with a Unit Under Test in Tension using ISO 376 Compliant Tension Adapters

What Replicates Field Use is Often Best Practice

Different setups need to be made with different adapters for tension than compression to replicate field use. The two Morehouse Universal Calibrating Machine figures above show different setups for compression and tension. These drastically differ from the figure Compression/Tension Machine, which does not replicate field use, where compression and tension are done using the same setup.

Knowing the importance of replicating field use, the committee that drafts the ISO 376 standard has written specific guidance on adapters. The ISO 376 recommended adapters do not include a recommendation for an adapter capable of being used for both compression and tension calibration.

Tensile force transducers should be fitted with two ball nuts, two ball cups

Figure 130 Morehouse Tension Adapters Designed Using Recommendations from ISO 376 [10]

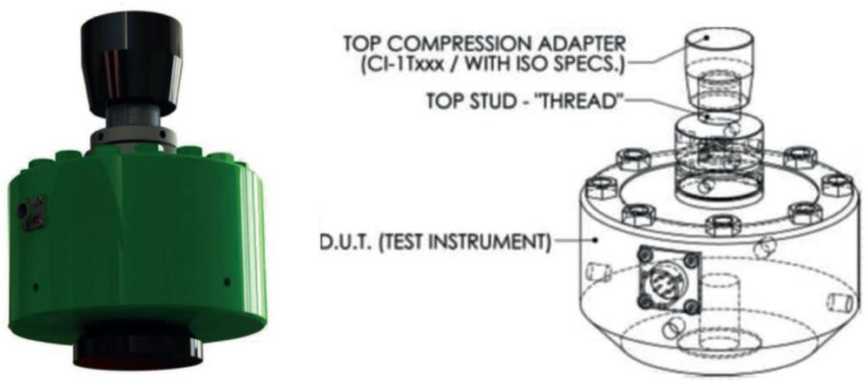


Figure 131 Morehouse Compression Adapters Designed Using Recommendations from ISO 376

Some testing machines calibrated to ISO 7500 or ASTM E4 are calibrated in compression and tension.

The technician will use different setups for each mode. Most will use calibration adapters as recommended in ISO 376 section A 4.1, which states, “Loading fittings should be designed in such a way that the line of force application is not distorted. As a rule, tensile force transducers should be fitted with two ball nuts, two ball cups, and, if necessary, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads.”[11]

Figure 132 Tension Rods Comparing the “Right” Surface Finish Versus a “Rough” Finish

The parts must be finished with the correct surface finishes to function as intended.

Reproducibility Study Rough Versus Smooth Finish							
Smooth Finish				**Rough Finish**			
0	120	180	Max % Error	0	120	180	Max % Error
10001.8	10001.8	10001.5	0.003%	10016.9	10009.2	10004.7	0.122%

Figure 133 Load Cell Performance Using Smooth and Rough Finishes

The above figure shows an error over 100 times expected using a rough surface finish. When this happens, the parts might not find the center and produce some side load. The data above shows an S-Beam type load cell sensitive to off-axis loading caused by the rough finish. A different load cell may show minimum error depending on how well they are compensated.

Figure 134 Tinius Olsen Universal Testing Machine

Replicating field use should give the end-user confidence in their measurements. With a Morehouse Universal Calibrating Machine, the user is forced to change setups for compression and tension, thus reducing common errors that other machines allow. These errors include using adapters that are different from those used during calibration and loading through the bottom threads in compression.

Other machines performing tension and compression in the same setup may not wait to apply the force for at least 30 seconds, as specified in the Time/loading profile in ISO 7500-1 and ISO 376. For these reasons, most NMI force standard machines have separate areas for compression and tension setups. There is a debate on static versus dynamic calibration. However, dynamic calibration is not supported per the standard.

Dynamic force is different than static, and a dynamic machine should not be used for calibration following ISO 376. Per ISO 376 Section C.2.11, "This International Standard concerns only static force measurement. If the force-proving instrument is used under dynamic conditions, additional contributions should be considered. For example, the frequency responses of the force transducer and indicator and the interaction with the mechanical structure, can strongly influence the measurement results. This requires a detailed analysis of dynamic measurement, which is not part of this International Standard."[12]

Morehouse wants to educate its customers and provide them with tools to help the industry. Part of this is providing the appropriate equipment and adapters to replicate field use. We ask customers how the equipment is used so that we have the best chance of providing reproducible results.

Our calibrating machines are designed to allow the end-user to replicate most field use cases best. To best replicate field use for calibration performed following ASTM E74 or ISO 7500, during calibration, the minimum should be performed:

- The calibration laboratory should not perform compression and tension calibration in the same setup. This is a common practice because it is much quicker.
- They should use the customer's top blocks and separate compression setups.
- In compression, the calibration laboratory should require a baseplate to load against.
- For tension calibration, if the end-user is calibrating per ISO 7500, they should use adapters recommended per the ISO Annex, which would be different than what is shown above.
- During contract review, they should verify how the end-user uses the device.

5 Must-Have Characteristics of Great Force Equipment

Equipment used to measure force will be made to minimize off-center loading, bending, and torsion. To minimize off-center loading force, machines need to be:

1. Plumb
2. Level
3. Square
4. Rigid
5. Free of Torsion

All machines shown are designed with these five things in mind. Equipment used to measure force must replicate how most instruments are used in the field.

Figure 135: A Morehouse Primary Standard Automated Deadweight Machine

Plumb - Exactly vertical or true

Morehouse has a 1,000 lbf automated deadweight machine that is plumb. In this machine, the weights hang in a vertical direction, and if they are out of plumb, they will introduce misalignment through the vertical line of force.

Figure 136: An Example of Level Using a Morehouse Automated UCM

Level - A device for establishing a horizontal line or plane through a bubble in a liquid that shows the adjustment to the horizontal by the movement to the center of a slightly bowed glass tube.
On the Morehouse 30,000 lbf Automated UCM, the upper and lower platen are ground flat, and the adjustable feet allow the end-user to obtain a level condition. If the level is not achieved, errors from misalignment will happen.

Figure 137: An Example of Square Using a Morehouse BCM

Square - for Force Machines, this is about having four right angles.
The Morehouse 10,000 lbf Benchtop Machine. The adjustable beam and bottom base form the four right angles. This reduces the chance of misalignment. The bottom screw is aligned to the top beam to keep the line of force as plumb as possible.

Figure 138: An Example of Rigid Using a Morehouse USC-60K Scale Press

Rigid – not flexible. If the loading surface starts to bend, all sorts of alignment errors can happen, impacting the results.

Morehouse USC-60K With Reference Load and Morehouse 4215 Indicator – the top and bottom plates are reinforced to keep the machine from bending.

Figure 139: An Example of Low Torsion Using a Morehouse Portable Calibrating Machine

Torsion – the action of twisting or the state of being twisted. Being free of torsion implies minimal twisting when forces are applied.

Morehouse PCM-2K With Reference Load Cell. This machine has special bearings to keep things from twisting. Before putting in the bearings, the measurement errors were higher than 0.1 %; when we added the bearings, the errors became less than 0.02 %, which is better than most transfer standard-type machines.

Want to see a simple video explaining what makes a great force machine? Our YouTube Channel has an Easy-to-Follow White Board Video on What makes a great force machine.

Loading Conditions Impact on Calibration Results

Compression S-Beam Example

The loading conditions of an instrument can be responsible for substantial additional errors. Using a force-measuring device means dealing with material deformation and gauges to measure this deformation. The performance characteristics or specifications are typically excellent when everything is designed correctly. However, these specifications apply under ideal loading conditions and are not necessarily what the end-user might experience with their equipment.

This section covers the various loading conditions. Several examples are included from force-measuring devices that Morehouse has tested over the years. While not every force-measuring device is covered, most of these examples apply to similar instruments. The bottom line is that various loading conditions can be tested on your devices, and the lab calibrating your devices should be asking the right questions to replicate use.

Instrument Reading Thread Loading Loose Both Ends Output in mV/V	Instrument Reading Thread Loading Tight Both Ends Output in mV/V	Instrument Reading Thread Loaded on Top / Flat Base Output in mV/V	Instrument Reading Flat on Flat Output in mV/V
1.50136	1.50241	1.50182	1.50721
3.00381	3.00581	3.00459	3.01326

Maximum Difference mV/V	Maximum Difference lbf	Maximum % Difference	Smallest % Diffference
0.00585	4.618066191	0.369%	0.029%
0.00945	7.459953077	0.298%	0.025%

Figure 140: S-Beam Load Cell with Different Loading Adapters and Output from Changes in Loading Conditions

Many load cells are sensitive to even the slightest bit of side load, and many have relatively large errors if loaded differently from how they were calibrated. We use an S-beam load cell in this example, yet these tests can be conducted with almost any load cell. The results will vary from minimal error to a larger-than-expected error.

The figure above shows the output of the S-beam load cell using different adapters and loading conditions. These conditions are loading through both top and bottom threads, which is preferred if symmetry error is a concern. Symmetry error is the difference in output between the maximum force in compression and the maximum force in tension.

When loaded through the threads in both modes, the symmetry of the S-beam load cell is often incredibly good. The second loading condition is tight against the top and bottom thread. Based on discussions with our customers, top and bottom thread loading may be the least common loading application in the Morehouse force laboratory.

The most common requests we receive for S-beam load cells are for them to be loaded flat against the base in compression using some spherical top or ball adapter. We use an alignment plug to center on the base and use a threaded adapter with a ball to achieve the best alignment possible. The Morehouse Alignment Plug helps both the repeatability and reproducibility conditions of the load cell in our frame.

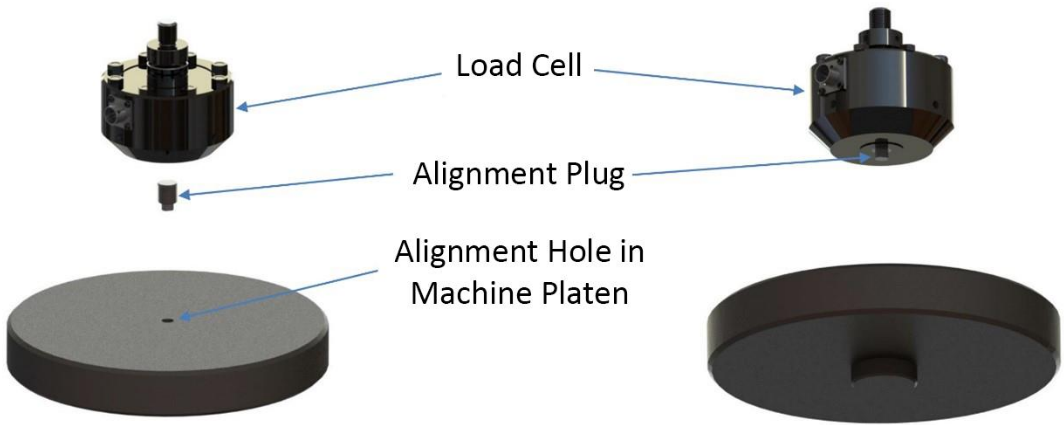


Figure 141: Morehouse Alignment Plug

Knowing that the S-beam load cells are so sensitive to any off-center loading, we highly recommend using machines built to be rigid, level, plumb, and square, like the Morehouse machines we build and use in our calibration laboratory. The S-beam load cell on the far right shows a flat-on-flat loading. This is not recommended because the load cell's output will vary significantly depending on where the force is transferred through the material. The area that interfaces with the top and bottom of the load cells will change the deflection.

The worst error occurs when comparing the far left and far right pictures. The error is between loading the load cell through the threads and loading it flat on flat. This error had a maximum difference of 0.369%. In general, the slightest error between the loading conditions, such as loading through the threads versus loading flat on the bottom and through the threads on top, had an error of almost 0.03 %.

Thus, the calibration laboratory and the end-user must communicate how the S-beam load cell is used. Communication about loading conditions should be part of the contract review. However, most companies fail to ask these questions, and most do not have this as part of the contract review. They aremore concerned with accreditation and decision rules than severely impacting the results.

Different Compression Adapters

Figure 142: Morehouse Calibration Grade Load Cell That Can Achieve Better 0.02 % of Full-Scale Accuracy

When load cells have an integral adapter installed, calibration results are typically superior to those without a threaded adapter installed, and errors are minimized. There are three very distinct benefits to installing an integral top adapter.

1. The load cell's output is more repeatable. When forces are applied to the load cell, the values obtained during calibration should repeat within the expected performance of the load cell. Additional error sources from the different hardness of the material, misalignment, and temperature still apply.

2. The technician can concentrate on alignment and other sources of error rather than being concerned about what adapters will yield a reproducible measurement. Those who do not lock an adapter into place will need to ensure the thread engagement and fit are the same as the lab that calibrated the device. The threaded adapter should not be removed because it will make the calibration void. These adapters are locked in at approximately 140 % of the rated capacity. Removal of the adapter can damage the load cell if sufficient torque is applied, and getting the adapter to the same position it was in before removal is highly improbable.

3. The load cell will repeat better when rotated per ASTM E74. When a load cell is calibrated following ASTM E74, the load cell is positioned at orientations of 0 degrees, 120 degrees, and 240 degrees. Installing a threaded adapter improves the reproducibility of the load cell. We observed an ASTM LLF of 0.32 lbf with a threaded adapter installed versus 0.553 lbf without the adapter installed when we tested this on the same load cell. The load cell with the threaded adaptor installed had a 42 % improvement in reproducibility.

Comparing the integral adapter with a load cell without an adapter installed is quite dramatic. The additional errors can be much higher when the non-threaded adapter is installed. There are threemain disadvantages of not installing the adapter.

Figure 143: Morehouse Calibration Grade Load Cell Without Integral Threaded Adapter

1. The load cell output can vary depending on the engagement of the adapter; we have performed many tests to prove this concept. In some cases, the errors for loading through the threads alone have exceeded 2.0 % of the applied force.

2. Shoulder loading is essential to minimize the thread depth error. When loading against the shoulder, we found an error of about 0.01 % by varying different adapters on a standard 10,000 lbf shear web cell. Different load cells react differently, and shoulder loading does not guarantee repeatability within 0.01 %. On a 3,000 lbf aluminum load cell, we found that various adapters could change the output by as much as 1.16 %. The best recommendation to limit this error source is to send your adapters to the lab to perform the calibration and have them shoulder-load the load cell.

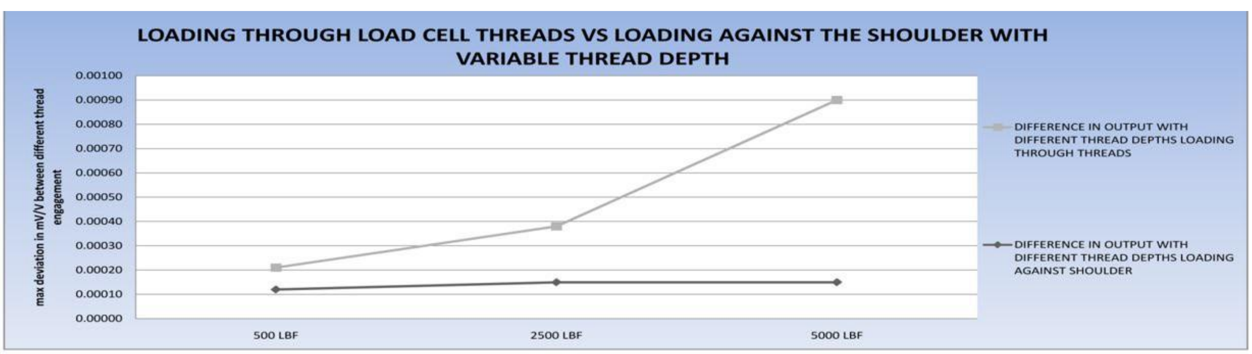


Figure 144: Graph Showing the Errors of Using Adapters with Different Thread Depths

3. The Reproducibility is not as good without a threaded adapter installed. The calibration data below shows the reproducibility data and the effect on the ASTM LLF; without the threaded adapter installed, the ASTM LLF was 0.553 lbf, and with the threaded adapter installed, the ASTM LLF was 0.32 lbf.

Applied Load	Deflection Values Per ASTM Method 8.1B Interpolated Zero			Deviation From Fitted Curve			Values From Fitted Curve
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	
LBF	mV/V	mV/V	mV/V	mV/V	mV/V	mV/V	mV/V
200	-0.08188	-0.08188	-0.08194	0.00005	0.00005	-0.00001	-0.08193
1000	-0.40943	-0.40937	-0.40939	-0.00004	0.00002	0.00000	-0.40939
2000	-0.81895	-0.81883	-0.81886	-0.00012	0.00000	-0.00003	-0.81883
3000	-1.22852	-1.22835	-1.22834	-0.00013	0.00004	0.00005	-1.22839
4000	-1.63822	-1.63799	-1.63796	-0.00014	0.00009	0.00012	-1.63808
5000	-2.04802	-2.04773	-2.04781	-0.00013	0.00016	0.00008	-2.04789
6000	-2.45795	-2.45774	-2.45780	-0.00013	0.00008	0.00002	-2.45782
7000	-2.86803	-2.86779	-2.86783	-0.00016	0.00008	0.00004	-2.86787
8000	-3.27821	-3.27796	-3.27796	-0.00017	0.00008	0.00008	-3.27804
9000	-3.68843	-3.68824	-3.68830	-0.00009	0.00010	0.00004	-3.68834
10000	-4.09885	-4.09868	-4.09879	-0.00009	0.00008	-0.00003	-4.09876

Calibration without a threaded adapter installed

The following polynomial equation, described in ASTM E74-13 has been fitted to the force and deflection values obtained in the calibration using the method of least squares.

response = A0 + A1(load) + A2(load)^2

Where: **A0** -7.34063885E-5
A1 -4.09256729E-4
A2 -6.1200166E-11

load = B0 + B1(response) + B2(response)^2

Where: **B0** -1.76786061E-1
B1 -2.44344720E+3
B2 -8.88747232E-1

The following values as defined in ASTM E74-13 were determined from the calibration data.
Lower Limit Factor, LLF 0.553 LBF

COMPRESSION CALIBRATION DATA 2ND-ORDER FIT

FORCE APPLIED LBF	MEASURED OUTPUT RUN 1 mV/V	MEASURED OUTPUT RUN 2 mV/V	MEASURED OUTPUT RUN 3 mV/V	FITTED CURVE mV/V	EXPANDED UNCERTAINTY LBF	FORCE STANDARD USED
200	-0.08192	-0.08191	-0.08194	-0.08190	0.01198	M-4644
1000	-0.40960	-0.40953	-0.40958	-0.40955	0.01973	M-4644
2000	-0.81922	-0.81916	-0.81920	-0.81919	0.03402	M-4644
3000	-1.22891	-1.22884	-1.22890	-1.22893	0.04937	M-4644
4000	-1.63880	-1.63865	-1.63871	-1.63876	0.06503	M-4644
5000	-2.04873	-2.04860	-2.04864	-2.04868	0.08083	M-4644
6000	-2.45874	-2.45869	-2.45874	-2.45870	0.09669	M-4644
7000	-2.86886	-2.86881	-2.86891	-2.86881	0.11260	M-4644
8000	-3.27909	-3.27902	-3.27911	-3.27902	0.12850	M-4644
9000	-3.68934	-3.68925	-3.68935	-3.68931	0.14450	M-4644
10000	-4.09969	-4.09959	-4.09968	-4.09971	0.16040	M-4644

The expanded uncertainty is the aggregate uncertainty of the Morehouse measurement process and the resolution of the unit under test. It is stated with a coverage factor of k=2, such that the coverage probability corresponds to approximately 95%.

POLYNOMIAL EQUATIONS

The following polynomial equation, described in ASTM E74-13a, has been fitted to the force and measured output values observed at calibration using the method of least squares

Response (mV/V) = $A_0 + A_1F + A_2F^2$
where: F = Force (LBF)
A_0 = -2.645837E-07
A_1 = -4.095030E-04
A_2 = -4.674799E-11

Force (LBF) = $B_0 + B_1R + B_2R^2$
where: R = Response (mV/V)
B_0 = 5.007991E-04
B_1 = -2.441981E+03
B_2 = -6.783889E-01

DATA ANALYSIS

STANDARD DEVIATION mV/V	RESOLUTION LBF	LOWER LIMIT FACTOR LBF
0.0000555	0.02	0.32

Figure 145: Comparison Calibration Data Showing a 42 % Improvement in the ASTM E74 LLF When a Threaded Adapter is Installed

Overall, the performance of the Morehouse Ultra Precision and Precision Shear web load cells is maximized when the threaded adapter is locked into place, reducing bending strains that can cause damage to the load cell. From years of performance testing, the Morehouse shear web load cells demonstrate excellent repeatability, reproducibility, and stability when the calibration adapter and jam nut are locked in and not tampered with.

Want to see a simple video on why an integral adapter should be installed in the shear web load cell? Check out our YouTube video here.

Thread Loading Through the Bottom Threads

This test was done to show the potential difference in output by loading a shear web load cell against the base of the load cell versus loading through the bottom threads. The test instrument used was a Morehouse Ultra-Precision Load Cell and a Morehouse 4215 indicator.

A Morehouse 120,000 lbf deadweight machine S/N M-7471 applied the force to the load cell. The weights in this machine were calibrated directly by NIST and are accurate to 0.0015 % of applied force. An ASTM E74 calibration was performed on the load cell, and the uncertainty of the load cell was determined to be 0.798 lbf. The load cell was kept at the same orientation for this test, and only the bottom adapters were changed.

FORCE APPLIED LBF	LOAD CELL OUTPUT LOADED AGAINST BOTTOM BASE	LOAD CELL OUTPUT LOADED AGAINST BOTTOM THREADS
1000	999.0	999.0
2000	1998.0	1998.0
5000	4996.0	4996.5
7000	6995.0	6995.5
10000	9994.5	9995.0
12000	11994.0	11995.0
15000	14993.5	14995.0
17000	16993.5	16995.0
20000	19994.0	19996.0
22000	21994.0	21996.5
25000	24994.0	24997.0

Figure 146: Data Showing a 0.012 % Difference by Varying the Loading Conditions

It is important to remember that not all calibration laboratories provide the same type of calibration service. There may be a noticeable difference in output for load cells calibrated in compression. The output depends on various parameters, such as the calibration fixtures used at the time of calibration, the alignment of the UUT (unit under test), the hardness of the top adaptor used, etc.

Some labs have a standard practice of loading flat against the base, while other labs may load the cell through the threads. You, the end-user, must know if your load cell was calibrated against a flat base or through the bottom threads. It could make a difference!

At Morehouse, our standard procedure is to load a cell flat against the base, as seen in the picture on the top left. We know other labs whose standard procedure is to load the cell through the bottom threads. There is a difference for shear web load cells; we can put a number on the potential difference between these two calibration methods.

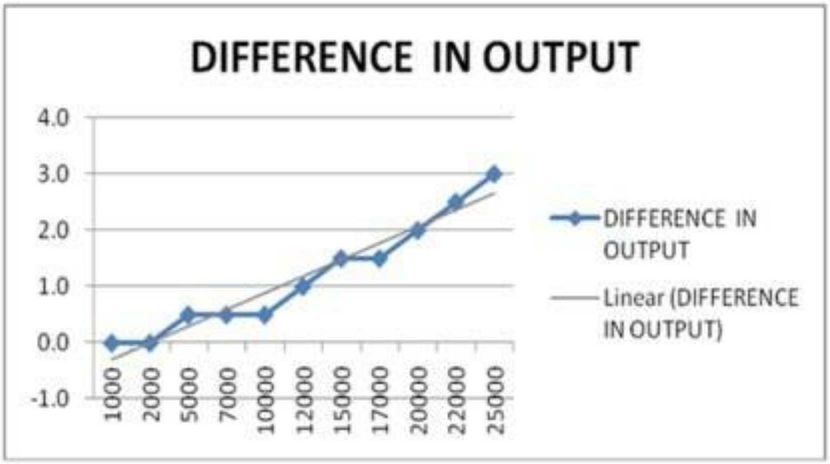


Figure 147: Graph Showing a 0.012 % by Varying the Loading Conditions

We took a standard Morehouse shear web load cell for the test above and calibrated it using our deadweight force machine. We can realize the unit of force with this machine to about 0.0016 % or better (our scope of accreditation lists 0.0016 % for our CMC uncertainty parameter). The results above show a difference of about 0.012 % in output at full scale, which is about four times larger than the initially reported uncertainty.

Top Block Hardness and Flatness

A best practice is to send whatever adapters you use with the force-measuring instrument forcalibration. It is improbable that the laboratory performing the calibration will match the exact hardness of your adapters. However, not all load cells react the same way when adapters are varied. If a top block is replaced, we recommend checking or calibrating the force-measuring equipment to ensure any additional errors are accounted for.

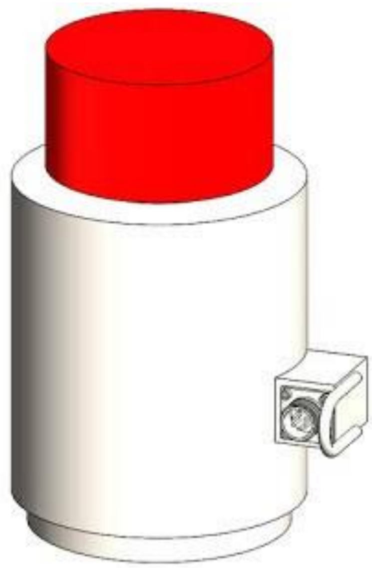


Figure 148: Multi-Column Load Cell

Using a top adapter with a different hardness value may affect the strain level in the load cell column or web and result in different measurement outputs. For example, we have observed errors of up to 0.5 % from varying the material on top compression pads.

We highly recommend the end-user send us the top adapter they use with the load cell and even load cell bases. If either adapter is not ground flat, additional errors could result. We have conducted several tests and have found repeatability errors to be about three times higher when the compression pads or load cell base are not flat. Morehouse is a proud US manufacturer with a complete machine shop, and we can grind top adapters for a nominal fee.

Two real-world examples:

1. A customer brought in a 1,000,000 lbf load cell for calibration. The load cell's output was recorded as 1,500 lbf higher than the previous calibration for a 1,000,000 lbf applied force, and we were unsure if this was a stability issue or an adaptor issue.

   We called the customer and were informed that a new top-loading block was supplied with the load cell for the current calibration. They sent the original top-loading block when we informed them about the error. Testing with the original block resulted in an output of 1,000,180 lbf when loaded to 1,000,000 lbf.

   Using the new adapter, we figured out the measurement error between the different top blocks (adapters). The Expanded Uncertainty would have increased from 269 lbf with the original top adapter to 1,490 lbf with the newly fabricated adaptor. The individual contribution to the overall measurement uncertainty was dominant.

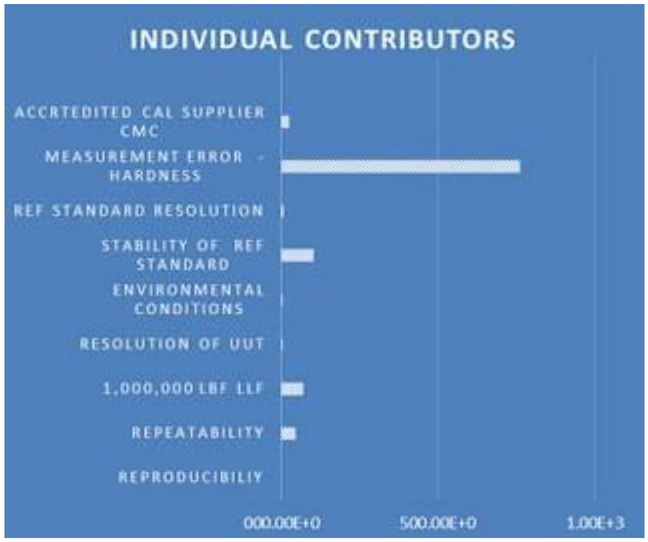
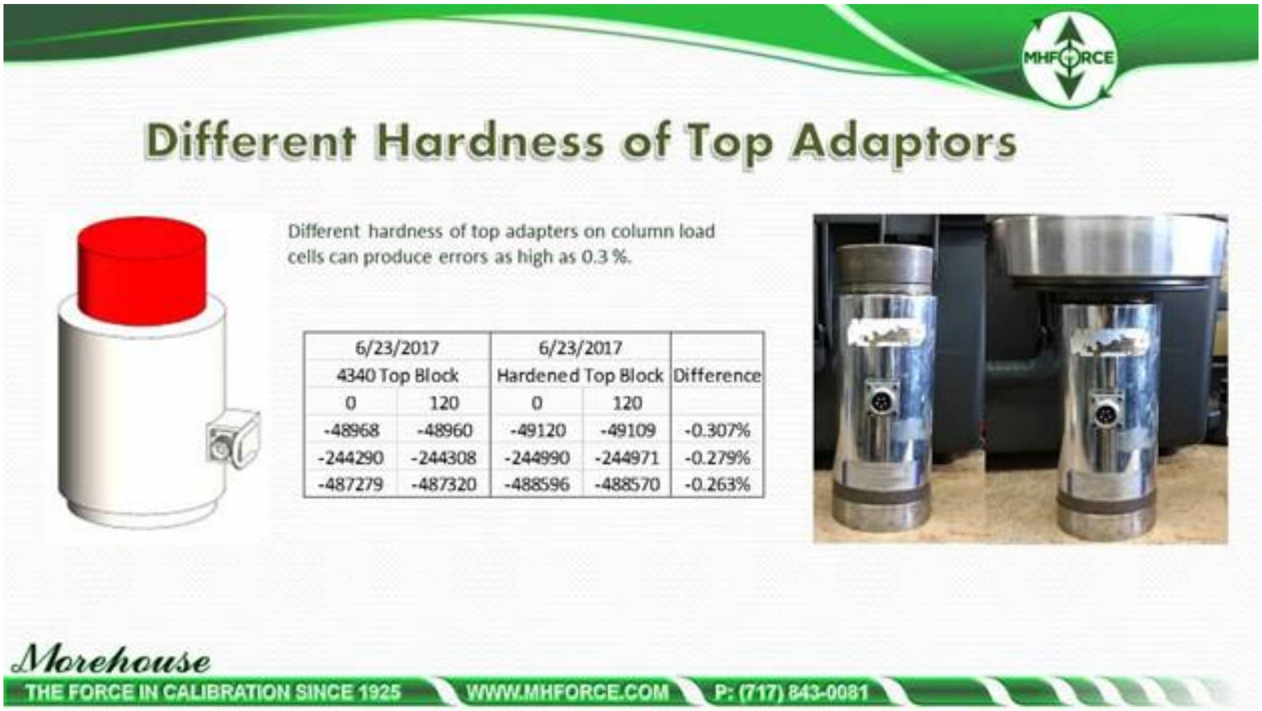


Figure 149: Individual Uncertainty Contributors

2. A customer sent in a single-column load cell and asked Morehouse to calibrate the load cell with our adapters. Since we wanted to make the correct measurements, we contacted the customer to ask for their blocks and advised that the output could change by not using their adapters. The customer instructed us to use our adapters, and since we are customer-focused, we performed the calibration.

   The tests showed a significant variation from the previous calibration, with the actual error percentage higher than expected. We notified the customer about this red flag in the tests. Understandably, a calibration interval decrease from two years was unacceptable for the customer. Therefore, they agreed to send us their top and bottom compression plates. We repeated the calibration several times on different days and with different variations of blocks. The test results clearly showed that the hardness of the platen material impacted the output of the single-column load cell.



6/23/2017		6/23/2017		
4340 Top Block		Hardened Top Block		Difference
0	120	0	120	
-48968	-48960	-49120	-49109	-0.307%
-244290	-244308	-244990	-244971	-0.279%
-487279	-487320	-488596	-488570	-0.263%

Figure 150: Different Hardness of Top Adapters

There are two factors to consider regarding hardness and flatness.

1. Materials with different hardness experience different amounts of lateral deflection under the same amount of load. Therefore, the varying hardness causes different amounts of stress between the block and the load cell. The figure below shows a 2 % strain difference between using two steel types. The error gets much worse if the material is significantly softer. Softer material might cause more load to be transferred through the outside surfaces, not the center.

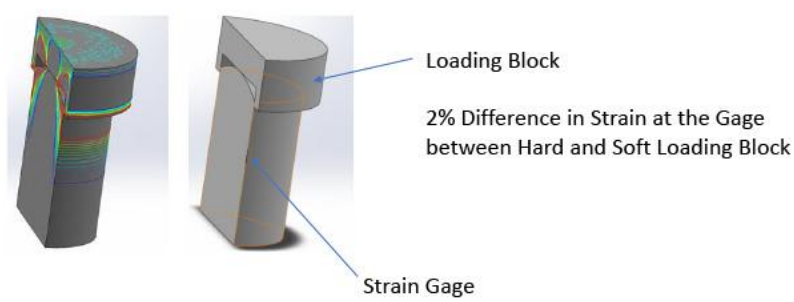


Figure 151: Effect of Loading Block on Column Type Load Cell

2. The block's flatness and smoothness are essential because they will change the contact position on the load cell. The assumption is that the load cell has a radius of R17 and is designed to be loaded precisely at the center of the spherical section. However, an unbalanced or non-flat block can shift the contact point off-center. As the stress analysis above shows, a small shift will change the stress distribution. Therefore, the key to an accurate calibration is using the same adapters used in the

field calibration. These adapters should be manufactured so they do not produce off-axis loads.

Not all load cells react the same way when the top adapter is varied. For example, on a Morehouse shear web load cell, the difference in using different top adapters is likely to be less than 0.003 %. We ran a similar test using materials of different hardness. The data for that test is below.

FORCE APPLIED	FITTED CURVE HARD BLOCK	FITTED CURVE SOFT BLOCK	Difference
10000	-0.40489	-0.4049	-0.002%
20000	-0.80979	-0.8098	-0.001%
30000	-1.21476	-1.21476	0.000%
40000	-1.61983	-1.61983	0.000%
50000	-2.02501	-2.02501	0.000%
60000	-2.43031	-2.4303	0.000%
70000	-2.83569	-2.83568	0.000%
80000	-3.24113	-3.24111	-0.001%
90000	-3.64657	-3.64655	-0.001%
100000	-4.05196	-4.05192	-0.001%

Figure 152: Load Cell Stress Analysis Example

We ran tests with three different adapters and hardness profiles, which yielded a maximum difference of about 0.002 %. We tested on shear web load cells with integral adapters installed and varied the adapters with around a 0.005 % difference. These were adapters that were threaded onto the load cell. For simplicity, the above table only shows the difference in deflection of the calibration curves using a similar adapter and varying hardness.

Figure 153: Morehouse 200 lbf through 600,000 lbf Concrete test Kit with the Proper Adapters to Ensure Reproducible Results and Limit Measurement Error

Different load cells will react differently to the hardness of the adapters. The Morehouse shear web-type load cell performed the best in this test case, with an additional error of less than 0.002 %. The top adapter tends to be the most critical component and can change the output of a force-measuring device by amounts of 0.5 % or more.

These two examples on column-type load cells show real-world examples where the overall expanded uncertainty was dramatically more significant than expected. In both examples, the customer expected the load cell's performance to be better than 0.025 % at capacity. The errors were five to ten times larger than what the customer expected. There could have been failures if these force-measuring devices had been used for calibration. These failures in testing may have resulted in bad products being passed as good and failures that could have impacted people's lives and safety.

In keeping with our purpose of creating safer work by helping companies improve their force and torque measurements, we urge anyone making force measurements to pay close attention to the adapters they use and to send those adapters in at the time of calibration.

If your adapters are not flat or you need to purchase a top adapter for your load cells, our team can help you start making better and more consistent measurements today. Pairing a top adapter with a load cell can improve stability and extend calibration dates. Less frequent calibrations equal more overall cost savings and a safer world.

Flat Base

Figure 154: Multi-Column 300K Load Cell with a Non-Ground Base

Installing a non-flat base on a multi-column cell can cause an error. The actual test results we observed on a multi-column cell are shown below. We received the load cell and tested it with the attached non-ground base. We set up the load cell in our 2,250,000 lbf force machine and exercised it 3-4 times, as the standard procedure requires, and then took three runs of data. We rotated the load cell 120 degrees between each run; the first set of results used the non-flat base supplied. Once complete, we removed the non-flat base, stoned the bottom of the load cell to ensure it was as flat as possible, and ran the same test.

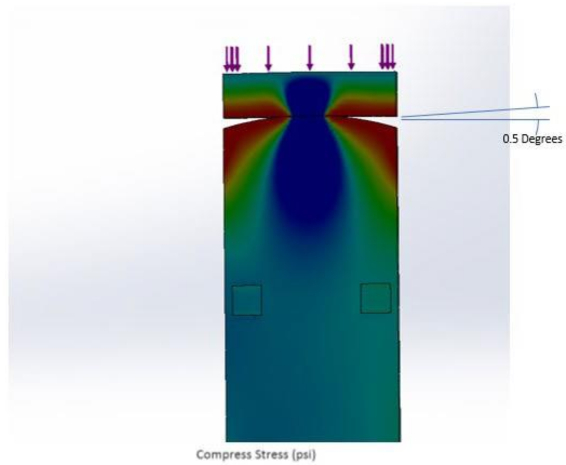
	Non Flat Base	Flat Base
	Maximum Error	Maximum Error
Force Applied	In Rotation	In Rotation
	LBF	LBF
30000	12	4
150000	136	24
300000	342	68
	% error	% error
30000	0.040%	0.013%
150000	0.091%	0.016%
300000	0.114%	0.023%

Figure 155: Shows Five Times the Measurement Error with a Non-Flat Base

A non-flat base produced a more significant variation in output when the load cell was rotated; this error was five times that of a ground base. Therefore, if you use a load cell with a non-ground base or use compression pads that are supposed to be flat, you should verify flatness before use. Top compression pads and load cell bases can usually be machined, stoned, or ground flat. A flat base or ground compression pad will produce better measurement results.

Radius versus Flat Surface

Radius Against Flat with 0.5 degree angle on bottom



	Gage 1	Gage 2	Gage Average	% difference
Radius against ideal load surface	54809	50152	52480.5	0
Radius against load surface 1/2 degree from level	54808	50152	52480	-0.001
Flat against load surface 1/2 degree from level	63656	42574	53115	1.21

Figure 156: Stress Analysis with Radius Surface 0.5 Degree from Level

Most compression force-measuring instruments are intentionally designed with a radius that helps concentrate the stresses to the appropriate columns or elements where the instrument is gaged. If a load cell is universal, meaning it is designed for both compression and tension calibration, it is recommended to practice machine the compression adapter to have a radius. The reason for this is demonstrated in the stress distribution image above, which clearly shows that the gage average and % difference on a spherical is significantly decreased than a flat on flat. The radius yields more repeatable and reproducible results.

Flat against flat with 0.5 degree misalignment

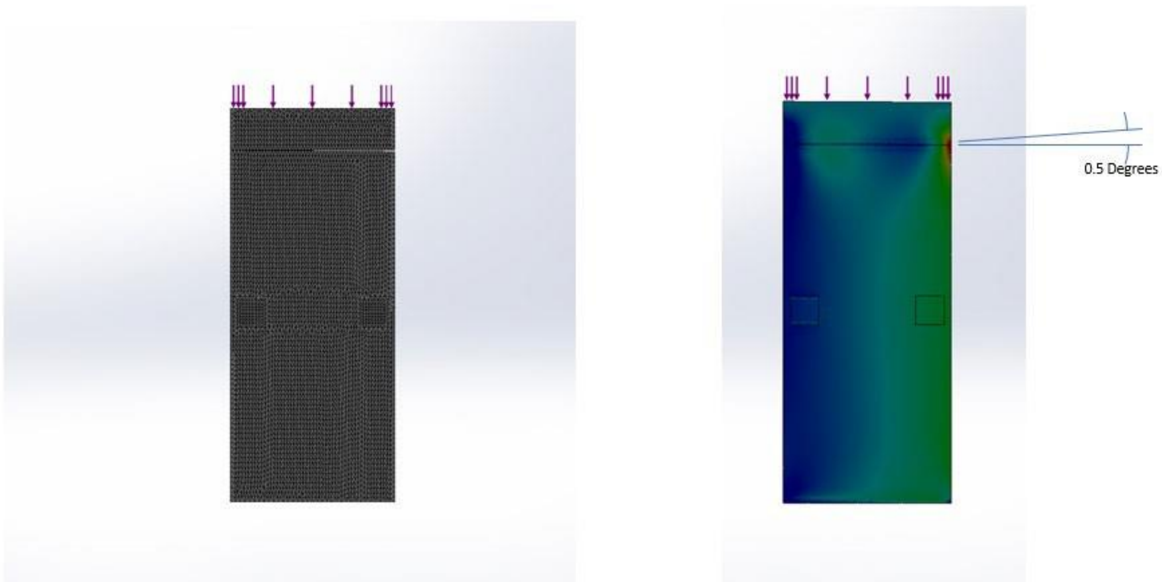


Figure 157: Stress Analysis with Flat Surface 0.5 Degree from Level

With flat-on-flat loading and designs, the transfer of force can often be distorted, and the compressive stress between gauges is often high with any misalignment. The cause is likely from force-measuring equipment that is not plumb, level, square, rigid, or low torsion. Any irregularities in the setup can be transferred to the force-measuring instrument, resulting in differences in deflection and the corresponding output. It is safe to say that flat-on-flat loading can result in the force-measuring instruments being less repeatable, and their output will vary more in different machines.

Overshooting a Test Point

Various calibration laboratories are using hydraulic, screw, and other force calibration machines where it is difficult not to overshoot a test point. By overshooting a test point, we are referring to loading past the desired point and then letting the creep in the hydraulic system naturally decrease the force point, overshooting the force point to 2543 lbf when the test point is 2500 lbf, and waiting several seconds until the reference standard reads 2500 lbf.

Anyone who has operated these hydraulic machines knows that overshooting a point will and can happen. Some automated force systems may overshoot the test point by up to 20 % of the desired force.

Morehouse decided to test the effects of overshooting a load cell in one of our deadweight frames with a measurement process uncertainty of better than 0.0026 % under controlled conditions. Before we get those results, we want to be clear on some things.

1. One should always approach the desired test point and not overshoot the test point when incrementally increasing the force. One should not undershoot the test point if performing a descending calibration.

2. The data presented is using a Morehouse 5,000 lbf Shear Web Type Precision Grade Load Cell. We cannot assume that all load cells act the same way. We suspect the shear web type of load cells will all act similarly. A Column, Multi-Column, S-beam, Button, or other load cells may act differently.

3. Anyone using a Morehouse Universal Calibrating Machine with a Morehouse Auxiliary Screw Pump can control the application of force. If they overshoot the test point, it should be less than 4 % of the desired test point. In practice, we find that most users overshoot by less than 2 % of the desired test point if they do overshoot it.

4. One can observe the overshooting of a force point on several non-Morehouse automated calibrating machines by watching the control and comparing the values against the calibration certificate. If the setpoint is 5,000 lbf the mV/V associated with 5,000 lbf is -4.18295, and the machine loads to -4.88490, one would know the machine overshot the test point by 14.4 %.

Note: The Morehouse Automated UCM can be set not to overshoot test points by more than 0.001 % of capacity in some conditions, there would be some additional overshoot, which we have observed to be less than 0.005 %. It took years of development by our engineering team to get the precision control to a point where overshooting a test point error can be controlled to very low numbers.

Figure 158: 6,600 lbf Morehouse Deadweight Machine with a 4215 meter and Morehouse Precision Load Cell

The Test Plan and Results

We took a Morehouse 5,000 lbf Precision load cell with a 4215 indicator and applied forces in our deadweight frame. We exercised the load cell three times before testing. Our test plan consisted of taking readings at 2500 lbf and 5000 lbf.

We then applied 2500 lbf and 5000 lbf and took three sets of readings.
We averaged these three sets of readings and called this the expected output of the load cell at each test

point. We then applied an additional 100 lbf to each test point and recorded the results.

So, we loaded the load cell to 2600 lbf, removed 100 lbf, and recorded the reading at 2500 lbf. The loading sequence presented in the table below was as follows:

0, 2600, 2500 take a reading, 5100, 5000 take a reading, 0.

0, 2700, 2500 take a reading, 5200, 5000 take a reading, 0.

0, 2800, 2500 take a reading, 5300, 5000 take a reading, 0.

0, 3000, 2500 take a reading, 5500, 5000 take a reading, 0.

	No overshoot Average	% Overshoot	% Difference
2500	-2.09028	0%	0
5000	-4.18260	0%	0
	100 LBF overshoot	% Overshoot	
2500	-2.09031	4%	0.0014%
5000	-4.18259	2%	-0.0002%
	200 LBF overshoot		
2500	-2.09032	8%	0.0019%
5000	-4.1827	4%	0.0024%
	300 LBF overshoot		
2500	-2.09034	12%	0.0029%
5000	-4.18275	6%	0.0036%
	500 LBF overshoot		
2500	-2.09047	20%	0.0091%
5000	-4.1828	10%	0.0048%

Figure 159: Observed Values

Next, we calculated the repeatability error and the expanded uncertainty. We thought this might be important as we needed to quantify the error from repeating the exact three measurements without overshooting the test point. We did this by taking the maximum deviation from the average.

Repeatability Data										
	Run 1	Run 2	Run 3	Run 1 Diff	Run 2 Diff	Run # Diff	Average	Max Error	Repeatability Error %	Expanded Uncertainty %
2500	-2.09026	-2.09028	-2.0903	-0.00002	0.00000	0.00002	-2.09028	-0.00002	0.0010%	0.0026%
5000	-4.18261	-4.18256	-4.18263	0.00001	-0.00004	0.00003	-4.1826	-0.00004	0.0010%	0.0026%

Figure 160: Repeatability Data

We then used the repeatability error as we expected the load cell to repeat within this number and subtracted it from the % difference of the average readings minus the observed value when returning to the force point. In summary:

Diff from expected % = (the value observed after returning to the test point – the no overshoot average) / the value observed after returning to the test point)) x 100

Overshoot Error Estimate= (Diff from Expected %) – (Repeatability Error %)

The expanded uncertainty was calculated by multiplying the standard uncertainty by a coverage factor of 2. The appropriate coverage factor for 95 % confidence should be used in an actual uncertainty budget, yet we used k = 2 to get us close to 95 %. The coverage factor of k = 2 corresponds to 95.45 %. For 95 %, one would use k = 1.96, assuming unlimited degrees of freedom (covered more in the Measurement Uncertainty section).

$$u = \sqrt{\left(\frac{CMC}{k}\right)^2 + \left(\frac{Res}{3.464}\right)^2 + \left(\frac{Rep}{1}\right)^2}$$

Figure 161: Standard Uncertainty Formula.

Force Applied	% Overshoot	Output	Diff from expected %	Repeatability Error %	Overshoot Error Estimate
2500	0%	-2.09028	0	0.0010%	
2500	4%	-2.09031	0.0014%	0.0010%	0.0005%
2500	8%	-2.09032	0.0019%	0.0010%	0.0010%
2500	12%	-2.09034	0.0029%	0.0010%	0.0019%
2500	20%	-2.09047	0.0091%	0.0010%	0.0081%

Figure 162: 2500 lbf Results.

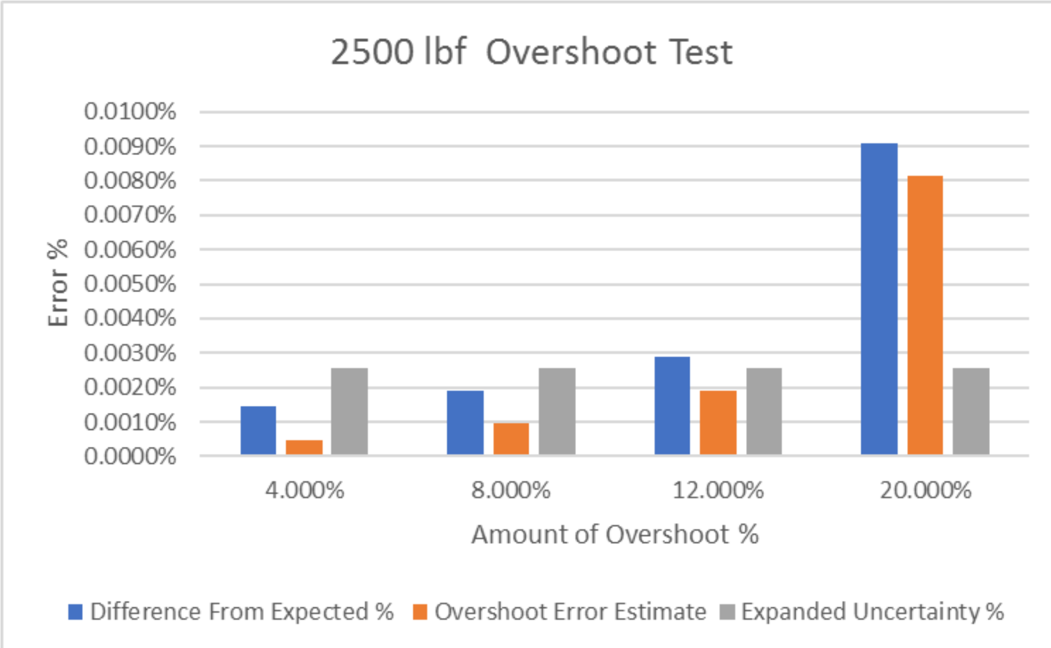


Figure 163: 2500 lbf Overshoot Additional Error Graph.

Force Applied	% Overshoot	Output	Diff from expected %	Repeatability Error %	Overshoot Error Estimate
5000	0%	-4.18260	0	0.0010%	
5000	2%	-4.18259	0.0002%	0.0010%	-0.0007%
5000	4%	-4.1827	0.0024%	0.0010%	0.0014%
5000	6%	-4.18275	0.0036%	0.0010%	0.0026%
5000	10%	-4.1828	0.0048%	0.0010%	0.0038%

Figure 164: 5000 lbf Results.

Conclusion:

% Overshoot	Difference From Expected %	Overshoot Error Estimate	Expanded Uncertainty %	Combined Uncertainty	Difference
2.000%	0.0002%	0.0007%	0.0026%	0.0029%	0.0004%
4.000%	0.0024%	0.0014%	0.0026%	0.0038%	0.0013%
6.000%	0.0036%	0.0026%	0.0026%	0.0058%	0.0033%
10.000%	0.0048%	0.0038%	0.0026%	0.0081%	0.0055%

Figure 165: Uncertainty Analysis.

Looking at the data conservatively, overshooting a test point by under 4 % would not introduce a significant source of error since most Uncertainty budgets for secondary standards are between 0.02 % and 0.05 % of applied force, and the maximum overshoot error estimate observed at a 2 % overshoot was 0.0007 %. We estimate this additional error to be less than 0.0004 % or 4 ppm. However, overshooting a test point by over 4 % may produce error sources that should be considered, and overshooting a test point by 6 % or more will produce a significant source of error for most force calibration laboratories using secondary standards.

Note: We are defining a significant error source as an error source that would impact the overall uncertainty budget. Best wishes on your future calibrations, and hoping your setups allow you to control the forces and not overshoot by more than 2 % of the desired test points.

Adapter Considerations

Several force measurement errors can result from using adapters that are different from the force-measuring instrument that was calibrated with since the basic premise is that mechanical measurements are being made. Therefore, most adapters used at a laboratory level are manufactured to keep the line of force-free from eccentric error and apply the same stresses from the adapter interface to the force-measuring instrument that was done at calibration.

Figure 166: Morehouse Ultra-Precision Shear Web Load Cell Showing Eccentric Forces

Not using the proper adapters to calibrate load cells, truck scales, aircraft scales, tension links, dynamometers, and other force-measuring devices can produce significant measurement errors and pose serious safety concerns. For example, different adapters can change the force-measuring instrument's stress distribution and produce errors ranging from minimal to an output difference more significant than the allowable tolerance.

There could be substantial errors if the calibration laboratory did not use the appropriate adapters, or your laboratory did not use similar adapters. For example, we have observed errors as high as 2 % of the full-scale output from varying loading conditions and adapters. Not all force-measuring instruments are created equal, and replicating use is essential to providing proper force measurements for all equipment.

Other important considerations are safety and improperly machined adapters, which may not allow a distortion-free load path.

Why is it critical to reduce misalignment errors? Pictured below is a test showing the spherical adapter without an alignment plug. The error observed is 0.752 % on S-beam load cells with less than 1/8" misalignment.

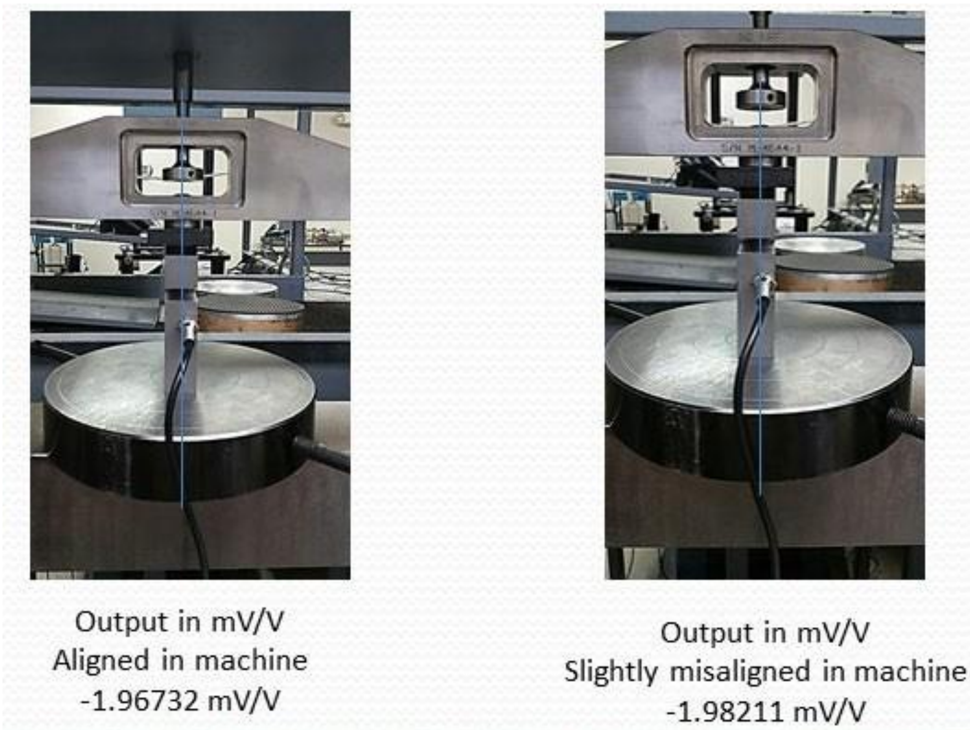


Figure 167: S-beam load cell with slight misalignment producing a 0.752 % error.

When the load cell was aligned and appropriately calibrated, the Expanded Uncertainty was calculated at about 10 lbf; when the load cell was misaligned, the Expanded Uncertainty was approximately 90 lbf, which is significant in a 10,000 lbf S-beam load cell. Thus, if the technician misaligned the load cell in a testing machine, they might adjust a machine that is actually "in tolerance," a recall may result from this simple error. Alignment plugs and base plates with alignment holes can drastically reduce misalignment errors.

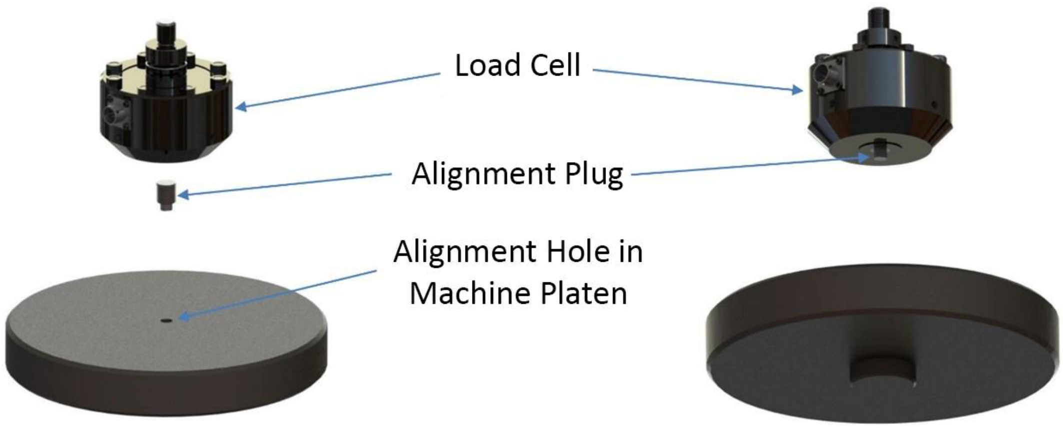


Figure 168: Morehouse Alignment Plug.

Figure 169: Proper Way to Thread an Alignment Plug: Thread is Past Flush and Into the Load Cell.

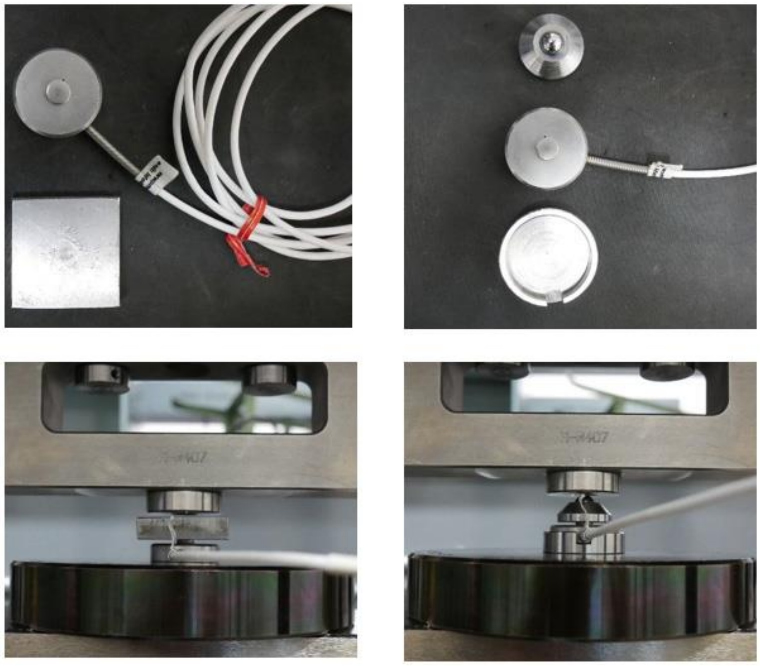
When using alignment plugs that thread into your load cells' bottom, ensure they are threaded flush to the load cell's bottom. Once flush, thread the adapter an extra turn into the cell. Ensure none of the threads are exposed below the load cell base. If one or more threads are exposed, the load will be generated through the cell's internal threads, not its base. The thread loading can result in an additional calibration error of about 0.012 % on shear web load cells and often damage the alignment plug. On other types of load cells, the errors may be larger.

Figure 170: Improper Way to Thread an Alignment Plug: Thread is Not Engaged Enough into the Load Cell.

Figure 171: Morehouse Button and Washer Load Cell Adapters.

The number one complaint with button and washer load cells is how to get them to repeat between rotations. These load cells are notoriously sensitive in rotation, and any misalignment will produce significant errors. The sensitivity to off-axis or sideloading conditions is relatively high. High enough that 0.1 % of misalignment is going to produce a relatively large cosine error. The error can sometimes be as large as 10 % of the rated output. We typically find this error between one and two percent in our well-aligned deadweight machines.

The button and washer load cell adapters above improve alignment and yield better calibration results. Usually, the results are better by a factor of 5 when using the above adapters than when a technician tries to center, as shown in the figure below. The picture on the left shows a typical setup where it is nearly impossible to get the readings to agree within 0.5 % when repositioning the button load cell. The picture on the right shows adapters that help improve alignment and yield much better results.



Standard Setup versus Morehouse Adapters in Morehouse Deadweight

Manually Aligned	Data	Aligned with Adapter.	Data
0 degree	2011	0 degree	2008
120 degree	1997	120 degree	2006
240 degree	2018	240 degree	2010
Average	2008.66667	Average	2008
Standard Deviation	10.6926766	Standard Deviation	2
Max Deviation	21	Max Deviation	4
% Error	1.045%	% Error	0.199%

Figure 172: Typical Button Load Cell Calibration Versus One with Morehouse Adapters.

The figure shows a 525 % improvement in rotation using the proper alignment adapters. The reproducibility error went from 1.045 % to 0.199 %. Most button load cell systems cannot achieve over 0.25 % of full scale, even with the proper adapters. We have seen some specifications where the end-user expects 0.1 % of full scale or better. However, 1 % of full scale is nearly impossible without proper adapters.

Proper testing involves putting the unit back into the machine and demonstrating agreement between the tests. As demonstrated with the Morehouse adapters, reproducibility of better than 0.25 % is possible, yet the button load cell must not be damaged or have wear patterns to achieve these results. Those cells with wear patterns will have much more significant errors, yet these adapters will not turn a worn button load cell with a 5-10 % error into a cell with an error better than 0.5 % of full scale.

Generally, we see improvements of 2 to 10 times better when using the proper adapters. These adapter sets can also accommodate alignment plugs to align the calibration setup with the calibration machine, such as a deadweight system, hydraulic Universal Calibrating Machines (UCM), or Portable Calibrating Machines (PCM).

Figure 173: Tension Members with two Ball Nuts and Two Ball Cups.

The ISO 376 standard says, "Loading fittings should be designed in such a way that the line of force application is not distorted. As a rule, tensile force transducers should be fitted with two ball nuts, two ball cups, and, if necessary, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads".[13]

Tension Clevis Adapters for Tension Links, Crane Scales, and Dynamometers

If a calibration lab uses a different pin from the manufacturer's recommendations, there will be a larger-than-expected bias. However, most manufacturers will agree on the following:

- Using correctly sized pins is critical.
- Do not use pins that are worn or bent.
- If the links are damaged, highly used, or worn, decrease the time between calibrations.
- The same size and style of shackle and pin used during operation should be used for calibration.

We loaded a tension link in our Morehouse deadweight machine to demonstrate the pin size error with an accuracy of better than 0.002 % of applied force and loaded it to 50,000 lbf with two different load pin sizes. When loaded with a smaller pin of 1.85 inches, the device read 49,140 compared to a 2-inch pin reading 50,000 lbf.

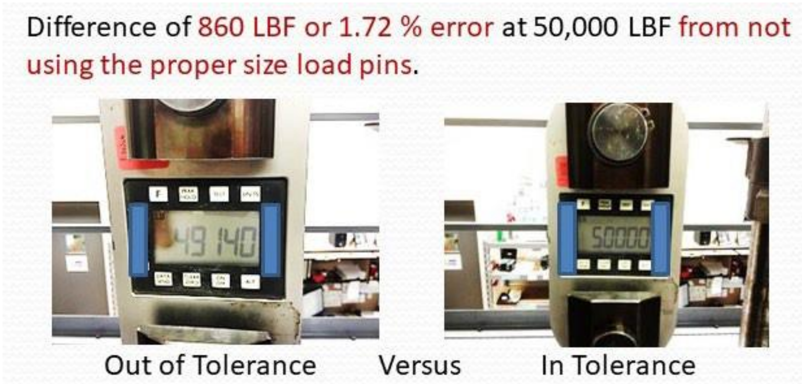


Figure 174: Tension Link Difference in Output with Pin Size.

Knowing these issues, Morehouse has designed clevis assemblies with our Quick-Change TensionAdapters. 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 using identical clevises. This simplifies the logistics of having the proper adapter, improves cycle time, and standardizes the calibration process.

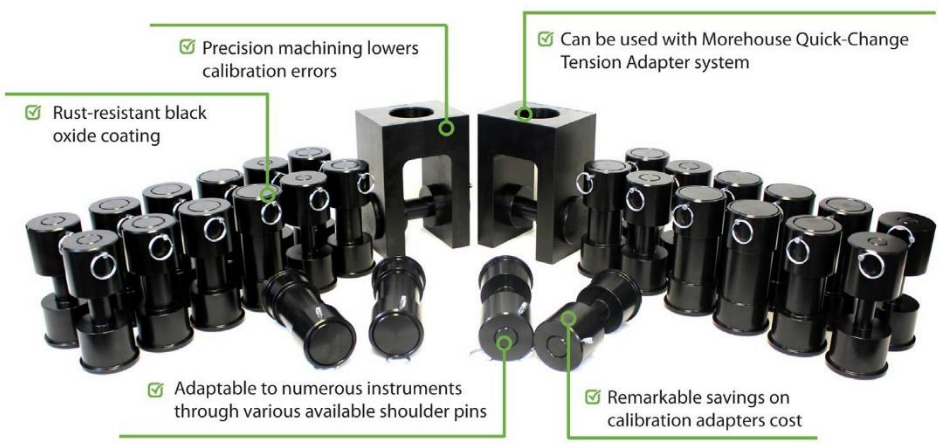


Figure 175: Morehouse Clevis Kits.

Read more about our Quick-Change Tension Adapters and Clevis Assemblies that simplify tension calibration.

Verification through Shunt Calibration

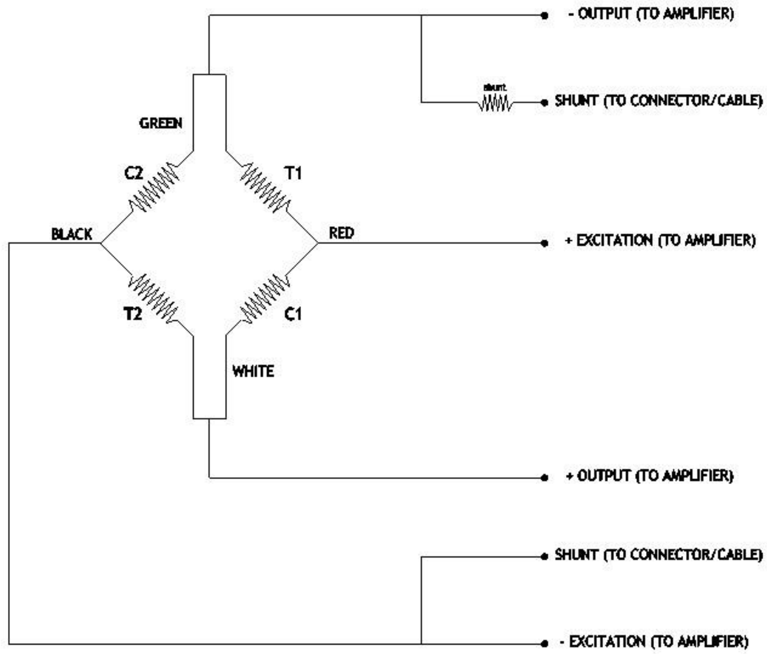


Figure 176: Load Cell Bridge with a Shunt Calibration.

Shunt calibration is a cost-effective means to confirm that the load cell and indicator system are not experiencing significant drift or potential damage. Shunt calibration involves introducing a known electrical resistance (shunt resistor) parallel to the load cell, allowing for modifications to the output signal.
The shunt resistor simulates a specific load condition, and the indicator system should display a corresponding reading. This reading can be compared to the expected output based on the known resistance of the shunt resistor.

This practice uses a known resistor across the load cell bridge (ex. 30k Ohm) and monitors the system. Shunt calibration involves simulating the input of strain by using a resistance value. It is accomplished by shunting or connecting in parallel (shunted) across the load cell terminals.
If a discrepancy is noted, it strongly suggests that the system should be compared to a recognized standard, and calibration may be required.
The main benefit is that it is a quick check to ensure the meter and load cell are stable to some degree of uncertainty. Usually, a single shunt value suffices for stability verification. However, employing a shunt calibration for positive and negative values can offer extra reassurance, especially in systems susceptible to tampering, ensuring that nothing on the meter's side has changed.

Here's a basic overview of how load cell shunt calibration works:

1. Normal Operation: In a properly functioning load cell, the electrical resistance across its terminals changes proportionally to the applied force or load. This change in resistance corresponds to a change in the electrical signal output.

2. Introduction of Shunt Resistor: To perform a shunt calibration, a known electrical resistance (shunt resistor) is connected in parallel with the load cell. This effectively creates an alternative current path for the electrical signal.

3. Modification of Output: By adjusting the value of the shunt resistor or the load resistor, the overall resistance in the circuit changes. This modification causes the load cell to respond as if a specific load were applied, even if no physical load is present. The electrical signal output of the load cell is then modified to match the expected response.

4. Comparison and Verification: The output signal is compared to the expected value based on the known resistance introduced by the shunt resistor. Any discrepancies between the expected and actual readings are used to verify the load cell's output, ensuring accurate and calibrated measurements.

Note: The end-user should perform this at some defined frequency. When it gets to the calibration laboratory, it is likely too late to spot differences. There may have been six months to whatever period between calibrations, which defeats the purpose of using the shunt.

5. Validation: After the shunt calibration, one can verify that the output matches the expected values. If it does not, there is likely a problem with the load cell, assuming other load cells check out.

A shunt calibration is an inexpensive check to decrease overall risk by spotting trends before too much time has elapsed. It's important to emphasize that a proper procedure should be established to utilize shunt calibration correctly. Consistently pressing tare on the meter before employing shunt calibration can significantly reduce the effectiveness of detecting a load cell overload.

A Shunt Calibration Example:

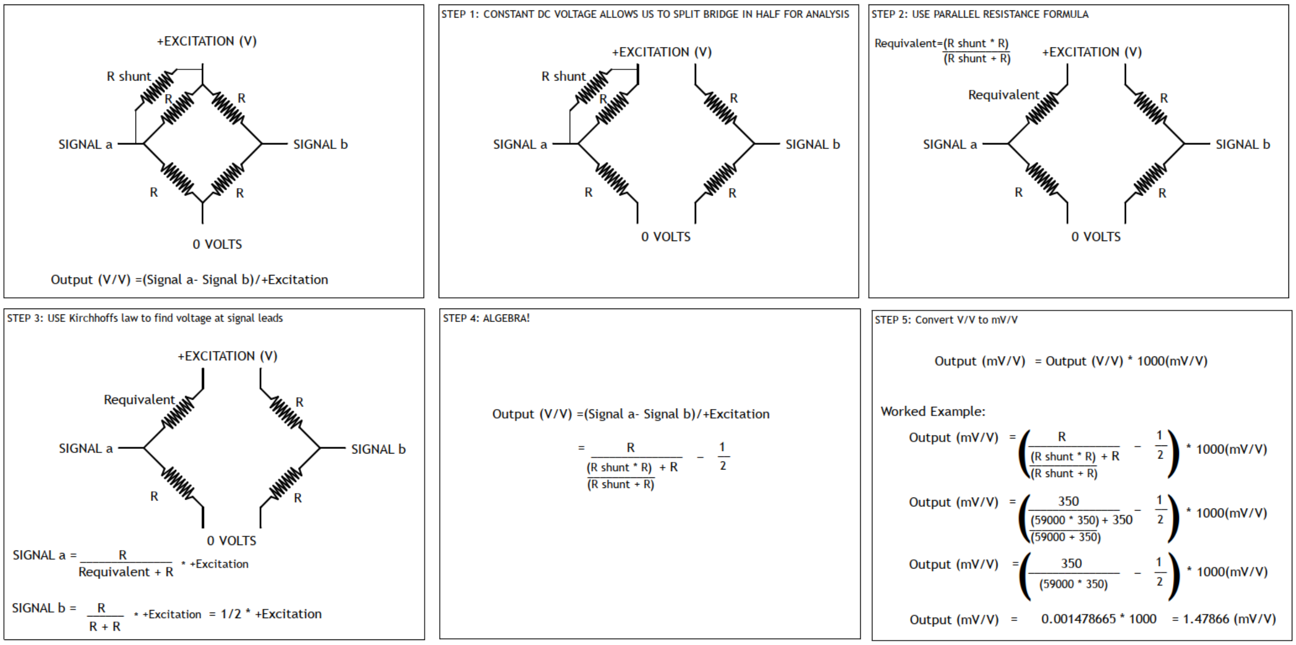


Figure 177: A Worked Example to Calculate Approximate mV/V output.

In the above example, a 59K shunt is used across a 350 OHM bridge load cell, and the expected output is 1.47866 mV/V. Of course, there will likely be a slight difference in the actual value as the cable length will have additional resistance.

The recommendation is to find the resistor value that will allow you to perform a simple check to ensure the system functions properly. Meters like the Morehouse 4215, have the built-in capability to perform shunt calibration.

Verification of the Adjustments

How does the calibration laboratory verify that the adjustments are made correctly? Do they apply a series of forces to test the results, or do they apply a correction equation and assume things are okay? For example, Morehouse continuously adjusts the force-measuring instrument and issues an "As Returned" calibration report. In contrast, others use alternate methods such as a shunt calibration or program the offset or corrections into the meter and assume it is good.

If they are programming a correction factor, there should be some testing method to verify it was done correctly. Using a load cell simulator or applying the force again to the instrument and verifying the results would work. If the calibration report has coefficients, one could verify the coefficients visually and double-check against the calibration report.

Rotational Tests

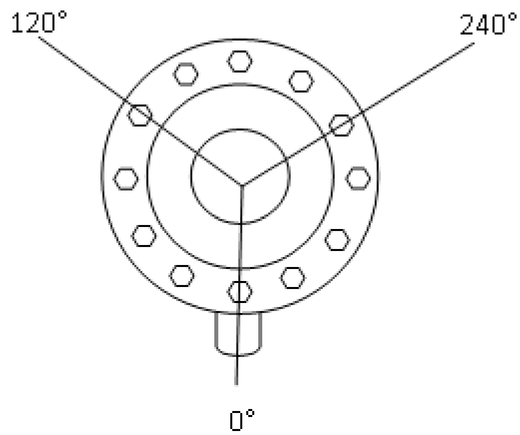


Figure 178: Diagram of Different Positional Tests at 120 Degrees Rotation.

Additional tests are needed to gauge the performance characteristics of a force-measuring device. One is a rotational test, which can help determine if the load cell is reproducible when loaded in different positions. The key to getting numbers that agree is to ensure that you use a good load cell with the proper adapters and that the machine where the load cell is tested meets the criteria below.

The right equipment for force will be made to minimize off-center loading, bending, and torsion and be:

1. Plumb – vertical or true.
2. Level – a device for establishing a horizontal line or plane by means of a bubble in a liquid that shows the adjustment to the horizontal by the movement to the center of a slightly bowed glass tube.
3. Square – for force machines, this is about having four right angles.
4. Rigid – not flexible. If the loading surface starts to bend, alignment errors can happen, impacting the results.
5. Free of torsion-free of being twisted when forces are applied. Torsion is the action of twisting or the state of being twisted.

If measurements are at various points, a calculation could be made to show how well the load cell repeats when rotated. This can be done in MS Excel by comparing each observed force point's output and running a difference between those points; the formula would look something like this:

*Non repeatability = ABS(Run1-Run2)/AVERAGE (Run1, Run2, Run3) *100   or using the data below*
*Non repeatability=ABS (4.0261- 4.02576)/AVERAGE (4.0261,4.02576,4.02559) *100.*

This must be performed for each combination (as shown below), and the maximum of the three calculations must be taken.

Run 1	Run 2	Run 3
4.0261	4.02576	4.02559
Difference b/w 1 & 2 (%FS)	Difference b/w 1 & 3 (%FS)	Difference b/w 2 & 3 (%FS)
0.0084	0.0127	0.0042

Figure 179: Sample Method to Determine the Maximum Difference from Rotational Tests.

By performing rotational tests on the right force equipment, we are starting to characterize the reproducibility condition of the measurement.

Reproducibility Condition of The Measurement

Most people in the metrology community will agree that a calibration laboratory's ability to reproduce measurement results belongs in an uncertainty budget. Several accreditation bodies require Reproducibility to be at least considered part of a calibration laboratory's Calibration and Measurement Capability (CMC). The questions on Reproducibility are, “Does it only apply to my equipment?” or “Should it be required for the calibration process as well?” We believe that, especially with force-measuring devices, the answer to both questions is Yes!

Is it acceptable for labs to calibrate items where the calibration method does not test for Reproducibility? The reproducibility of equipment is part of two very well-recognized force standards:

- ISO 376 Metallic materials - Calibration of force-proving instruments used for the verification of uniaxial testing machines.
- ASTM E74-18 Standard Practices for Calibration and Verification for Force-Measuring Instruments.

The ASTM E74 standard applies the term LLF (lower limit factor), a Type A uncertainty calculation that quantifies the equipment's reproducibility by calculating a pooled standard deviation from a range of 10-11 force points.

These deviations are found by applying a series of forces and rotating the instrument by varying degrees, such as 0,120, 240 (most common), or 0,60,300 in the deadweight machine or calibration frame. If the force-measuring device is susceptible to or the force machine has bending torsion or unparallel surfaces, then large deviations may occur when the device is rotated.

ASTM E74 and ISO 376 have rotational tests to capture the device's Reproducibility when calibrated. This is an excellent first step. Next, to calculate the CMC, the lab should obtain repeatability and Reproducibility of the process with different operators, machines, and locations. Various publications describe what Reproducibility is. There are also several examples of how short-term repeatability and Reproducibility can be calculated.

Reproducibility Definitions

Reproducibility 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 [14]

NOTE 1 The different measuring systems may use different measurement procedures.

NOTE 2 A specification should give the conditions changed and unchanged, to the extent practical.

Reproducibility, n—precision under reproducibility conditions. [15]

Reproducibility conditions, n—conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment. [16]

Reproducibility limit (R), n—the value below which the absolute difference between two test results obtained under reproducibility conditions may be expected to occur with a probability of approximately 0.95 (95 %). [17]

Reproducibility standard deviation (sR), n—the standard deviation of test results obtained under reproducibility conditions. [18]

Reproducibility: The closeness of the agreement between the results of measurements of the value of an attribute carried out under different measurement conditions. The differences may include the principle of measurement, method of measurement, observer, measuring instrument(s), reference standard, location, conditions of use, and time. [19]

Then, under error sources lists.

- Operator Bias (Reproducibility) - Error due to quasi-persistent bias in operator perception and/or technique. [20]

Reproducibility: This is traditionally referred to as the "between appraisers" variability. Reproducibility is typically defined as the variation in the average of the measurements made by different appraisers using the same measuring instrument when measuring the identical characteristic on the same part. This is often true for manual instruments influenced by the skill of the operator. It is not true, however, for measurement processes (i.e., automated systems) where the operator is not a major source of variation. For this reason, Reproducibility is referred to as the average variation between systems or between-conditions of measurement. [21]

The ASTM definition goes further to include not only different appraisers but also different gauges, labs, and environments (temperature, humidity), as well as including repeatability in the calculation of Reproducibility.

To better understand the effect of measurement system error on product decisions, consider the case where all the variability in multiple readings of a single part is due to the gage repeatability and

Reproducibility. The measurement process is in statistical control and has zero bias.

Between-appraisers (operators): the average difference between appraisers A, B, C, etc., caused by training, technique, skill, and experience. This is the recommended study for product and process qualification and a manual measuring instrument.[22]

Gage R&R is an estimate of the combined variation of repeatability and Reproducibility. Stated another way, GRR is the variance equal to the sum of within-system and between-system variances.

Guidelines for Determining Repeatability and Reproducibility, The Variable Gage Study can be performed using a number of differing techniques.[23]

Reproducibility Methods

Three acceptable methods are:

- Range method
- Average and Range method (including the Control Chart method)
- ANOVA (Analysis of Variances) method Except for the Range method, the study data design is similar for each of these methods.

The ANOVA method is preferred because it measures the operator-to-part interaction gauge error. The Range method and the Average and Range method do not include this variation. Therefore, we shall continue to focus on the ANOVA method and show how the calculations are performed.

The references to different operators, laboratories, and equipment in the definitions above underscore the importance of achieving consistent and comparable results. If the lab has only one location, we can remove different laboratories.

Some parameters, such as force measurement, where one lab rarely has two machines of the same size, rely on capturing the measurement process's reproducibility by comparing operators. The ideal solution is to set up SPC (Statistical Process Controls) procedures to obtain long-term Reproducibility. However, using ANOVA and other methods can capture a process's Reproducibility in the short term, which is accepted.

Repeatability and Reproducibility Worksheet						
	Technician 1	Technician 2	Technician 3	Technician 4	Technician 5	Technician 6
1	2.000000	2.000000				
2	2.000000	2.000000				
3	2.000000	2.000000				
4	2.000000	2.000000				
5	1.999990	2.000000				
6	2.000000	1.999980				
7						
8						
9						
10						
Std. Dev.	4.08248E-06	8.16497E-06				
Average	1.999998333	1.999996667				
Variance	1.66667E-11	6.66667E-11				
Repeatability	6.455E-6	F_{calc}	200.000E-3	Between Groups MS		8.33E-12
Reproducibility	1.179E-6	F_{crit}	4.9646	Within Groups MS		41.67E-12
$df_{Numerator}$	1	P-Value	If $F_{calc} > F_{crit}$, there is significance of Reproducibility data			
$df_{Denominator}$	10	664.25E-3	Reproducibility is less than Repeatability			

Figure 180: Morehouse Repeatability and Reproducibility Sheet Found in Our Free CMC Download Tool.

ANOVA will test for repeatability as well as Reproducibility between operators. Repeatability and Reproducibility between technicians should be performed:

- Whenever there is a change in personnel.
- The first time a budget is established.
- When new equipment is purchased.
- Whenever there is a change that may alter the measurement process (for example, upgrading a force-measuring system or load cells to ones provided by Morehouse, as shown below, which may drastically improve repeatability and reproducibility between operators),

The example below uses two technicians recording readings on the same equipment at the same measurement point. Repeatability between technicians can be found by taking the square root of the averages of the variances of the technicians' readings.

Reproducibility between technicians is found by taking the standard deviation of the averages of readings for each technician. The ANOVA analysis in Microsoft Excel is a valuable tool that can perform the same calculation with little manipulation. Below is an example of single-factor ANOVA. This is found in the data analysis section of Excel.

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Technician 1	6	11.99999	1.999998333	1.67E-11		
Technician 2	6	11.99998	1.999996667	6.67E-11		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.333E-12	1	8.33333E-12	0.2	0.664251472	4.9646027
Within Groups	4.167E-10	10	4.16667E-11			
Total	4.25E-10	11				

Figure 181: ANOVA Excel Example.

The results in each of these cases indicate that Reproducibility may be insignificant because the *F* value calculated is less than *F critical*. The *F* value is found by dividing two mean squares, and it will determine whether the test is statistically significant. A large F value means that variation among groups is greater than you would expect by chance or there is a significant difference between operators. In the example above, the P-value, or probability value, is 0.664251, which means there is a 66.4251 % chance that the operators will produce the same results. We can use the above ANOVA analysis to obtain Reproducibility and repeatability.

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Technician 1	6	11.99999	1.999998333	1.67E-11		
Technician 2	6	11.99998	1.999996667	6.67E-11		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.333E-12	1	8.33333E-12	0.2	0.664251472	4.9646027
Within Groups	4.167E-10	10	4.16667E-11			
Total	4.25E-10	11				
Reproducibility	1.179E-6		SQRT of Between Groups MS / SQRT Count			
Repeatability	6.455E-6		SQRT of Within Groups MS			

Figure 182: How to Calculate Reproducibility and Repeatability from the ANOVA Excel Example.

Reproducibility is found by taking the square root of the between-group's mean squared value and dividing that by the square root of the count (number of observed values per Technician 1).

Repeatability is found by taking the square root of the mean squared value of the within groups.

There is a significant issue with the parameter of force and torque measurements because the Reproducibility of the equipment is often not captured using these methods unless the reference standards are repositioned in machines. Often, they are not.

Therefore, there may be additional error sources for the Reproducibility of the reference standards, such as load cells. Suppose the reference load cell is calibrated following the ASTM E74 or ISO 376 standard. This issue becomes moot because both standards capture reproducible conditions at the time of calibration.

However, suppose the end-user alters the calibration by not using the right equation, uses different adapters other than what was used for calibration, or makes physical changes to the load cell. In that case, the system should be calibrated again. Companies not using these calibration standards will have additional error sources that may be difficult to quantify. We recommend that companies use legal metrological standards to calibrate their equipment and not rely on 5 to 10-point calibrations, often called commercial calibration, for their force-measuring devices.

The end-user should then test their equipment and the additional error from the interactions of bending, torsion, and uneven surfaces by comparing two force-measuring devices against each other. Both devices should have been calibrated by primary standards (deadweights).

If deadweights calibrate two standards, then comparing one standard with another will show any additional measurement errors in the machine, such as not being truly plumb, level, square, rigid, and free from torsion.

This error is called a dissemination error, and hardly any labs do this. It is a major problem with calibration laboratories making force measurements as these errors can be large.

Repeatability Condition of Measurement

The VIM defines repeatability condition of measurement as “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.” [24]

If you receive a force-measuring instrument back from calibration and the results do not agree, one of the first tests is to look at that instrument's repeatability in the machine. Force machines that are plumb, level, square, rigid, and have low torsion will lead to very repeatable measurements; if any one of these things is out of line, or the force-measuring instrument or system has additional problems, then they will be found and highlighted by repeating a series of measurements.

If a force is applied to an instrument three times without disturbing it, and the instrument does not repeat, then the next logical step is to consider that the source of the problem is the equipment or instrument. If other force-measuring devices repeat very well in a similar setup, it is likely that some part of the force-measuring equipment has gone bad or is malfunctioning. The error could be the indicator, cable, or instrument.

How to Correct for Tare Weight when Using Load Cells or Proving Rings

A common question we get asked is, "If I have a tare weight, how do I correct it?"
All instruments have different characteristics that may or may not require correction for the tare weight.

What is Tare Weight?

The tare weight is a "pre-load" on the reference standard. It is attributable to the weight of the moveable yoke, test instrument, bearing plate(s), load ball(s), and adapter fittings.

To answer this question, we will cover tare correction for the following instruments:

1. Load Cells
2. Proving Rings

Tare Weight Correction for a Load Cell

Load cells come in different shapes and sizes. Some load cells can withstand an overload of up to 150 % or more of rated capacity without damaging the load cell, and others only 110 %. When evaluating an additional error due to tare, one must compare the same force point with a tare load versus without.

In our lab, we tested several load cells with variable results. We tested our shear web load cells by taring out up to 10 % of the rated capacity and then loading to 110 % versus loading the load cell to 100 %. That means on a 10,000 lbf load cell, we applied 1,000 lbf, hit tare on a meter, and then applied an additional 10,000 lbf and compared the results against loading the load cell to 100 %.

We typically find that results will vary depending on the type of load cell and the amount of tare load. The repeatability does not change much. Yet, reproducibility does exist because we created a new variable by applying an additional 10 %, which introduces more stress onto the material. This creates more deflection, in which the strain gauges measure the fractional change in length in the load cell.

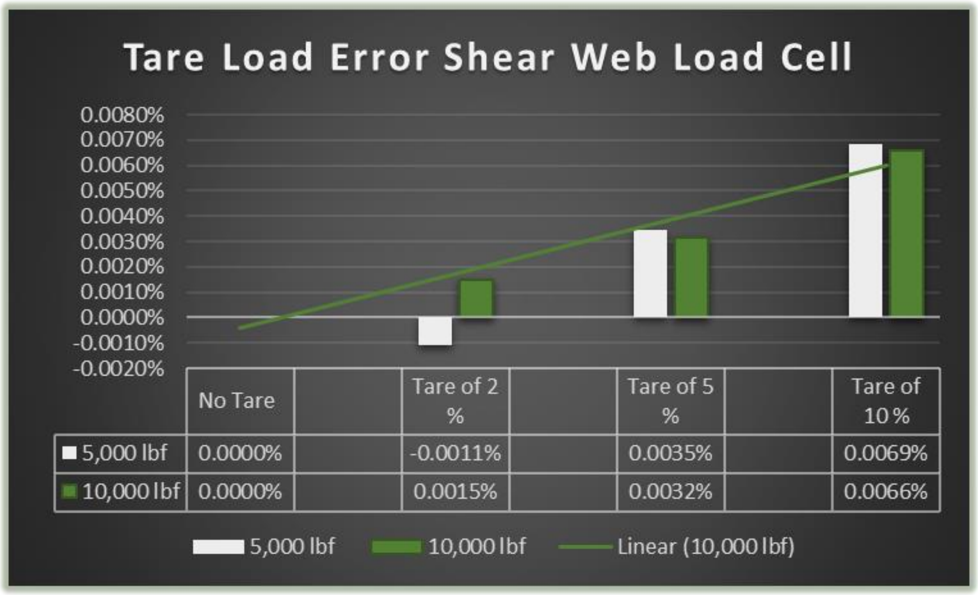


Figure 183: Load Cell Tare Load % Error Graph.

In cases where the “pre-load” is over 5 % of the capacity of the load cell, ignoring the tare load effect may introduce a significant error in the calibration. The error introduced can be determined by comparing two calculations.

First, calculate the load applied to the test instrument by treating the deflection of the calibration standard with the tare load applied as the “no-load” reading.

Next, calculate by considering the tare load. The tare load can be ascertained by weighing the items (yoke, test instrument, etc.) on a suitable platform scale. However, it may be more convenient to determine the tare load using a reference standard. The tare weight must be raised off the load cell, and the indicator should be zeroed. Then, the weight can be lowered, and the weight can be calculated.

Comparing the results of these two calculations will readily show the error introduced. Once the weight is calculated, the user can test to determine an additional error.

Example: A 10,000 lbf load cell with a 200 lbf tare weight

The user zeroes the load cell and applies the tare weight. The weight observed is 200 lbf. The indicator now reads 200 lbf. If one wants to apply 10,000 lbf, they need to apply 10,200 lbf, or they can hit tare and load to 10,000 lbf. The load cell will have a 10,200 lbf force applied regardless.

The best way to estimate the error is to calibrate the 10,000 lbf load cell to 10,200 lbf. Then, compare the calculated deflection values at 10,200 lbf and deflection values at 200 lbf, and compare that against the calculated value at 10,000 lbf (see example below). The difference would be insignificant if the instrument fits the calibration curve well.

Force	No Tare	Tare 2 %	Error
5000	-2.06036	-2.06034	-0.001%
10000	-4.12286	-4.12292	0.001%

Figure 184: Load Cell Tare 2 % Readings.

This example uses a Morehouse Ultra-Precision Load Cell. We have observed errors from 0.000 – 0.0025 % from various samples. Part of the issue in testing these low errors is that the repeatability and reproducibility errors of the load cell can be as high as ± 0.002 %. The resolution of the load itself could be 0.00050 % (50 % of the error at 5,000 lbf) and 0.00025 % (25 % of the error at 10,000 lbf). Therefore, we consider this error insignificant because many claim their measurement uncertainty is between 0.02 % - 0.05 % of applied force.

Example: A 10,000 lbf load cell with a 500 lbf tare weight

The user uses the zero or net button on the indicator and applies the tare weight. The weight observed is 500 lbf. The indicator now reads 500 lbf. If one wants to apply 10,000 lbf, they need to apply 10,500 lbf, or they can hit the tare and load to 10,000 lbf. The load cell will have a 10,500 lbf force applied regardless.

The best way to estimate the error is to calibrate the 10,000 lbf load cell to 10,500 lbf. Then, compare the calculated deflection values at 10,500 lbf and deflection values at 500 lbf, and compare that against the calculated value at 10,000 lbf (see example below). The difference will be insignificant if the instrument fits the calibration curve well.

Force	No Tare	Tare 5 %	Error
5000	-2.06036	-2.06043	0.003%
10000	-4.12286	-4.12299	0.003%

Figure 185: Load Cell Tare 5 % Readings.

This example uses a Morehouse Ultra-Precision Load Cell. We have observed errors from 0.003 – 0.006 % in various samples. We consider this error significant because many claim their Measurement Uncertainty to be between 0.02 % - 0.05 % of applied force. Steps might be taken to correct the error, or one might consider purchasing an additional load frame with less tare weight.

Example: A 10,000 lbf load cell with a 1,000 lbf tare weight (10 % of capacity)

The user uses the zero or net button on the indicator and applies the tare weight. The weight observed is 1,000 lbf. The indicator now reads 1,000 lbf. If one wants to apply 10,000 lbf, they need to apply 11,000 lbf, or they can hit tare and load to 10,000 lbf. The load cell will have an 11,000 lbf force applied to it.

The best way to estimate the error is to calibrate the 10,000 lbf load cell to 11,000 lbf. Then, compare the calculated deflection values at 11,000 lbf and deflection values at 1,000 lbf, and compare that against the calculated value at 10,000 lbf (see example below). The difference will be insignificant if the instrument fits the calibration curve well.

Force	No Tare	Tare 10 %	Error
5000	-2.06036	-2.06050	0.007%
10000	-4.12286	-4.12313	0.007%

Figure 186: Load Cell Tare 10 % Readings.

This example uses a Morehouse Ultra-Precision Load Cell. We have observed errors from 0.005 – 0.012 % from various samples.

Note: We consider this error significant because many claim their Measurement Uncertainty to be between 0.02 % - 0.1 % of applied force. Steps should be taken to correct the error or purchase an additional load frame with less tare weight.

Tare Weight Correction for a Proving Ring

Unlike several load cells, proving rings do require a correction for tare. This is due to the inherent non-linearity of the rings. For analog proving rings, the position of the dial on the micrometer can be an additional error source.

Tare Load Correction Formula for a Proving Ring

Below is an example of a formula used to correct tare loads. The tare load correction formula corrects for tare and is applied to the value of the applied load from the fitted curve data provided with your calibration report.
The tare load correction formula is represented as follows: TCF = ((2 * A2) * L * T)) – A0

Where:
A2 = The value of the A2 constant found on the ring calibration report
L = The force value applied
T = The force value of the tare applied
A0 = The value of the constant found on the ring calibration report

Calibration Report Data:
A2 = 0.2648421E-05
L = 3,000.00
T= 299.70 Lbf
A0 = 0.1673432E+00

TCF = (2*0.2648421E-05*3000*299.70)-0.1673432E+00
TCF = 4.595 div
3,000 LBF = +1002.050 div. From table
1006.645 div. Correction for tare

Accounting for Tare Weight Errors Summary

A tare weight of less than 2 % is likely insignificant regarding the overall measurement uncertainty.

When the tare weight exceeds more than 2 % of the rated capacity of a load cell or proving ring, we urge more testing to capture error sources.

If the tare weight exceeds 5 %, we recommend calibrating the device to 105 to 110 % of the rated capacity to account for any of these errors. Correction formulas must be used for proving rings to obtain the correct deflection values.

Indicators for Force Calibration Equipment

Selecting an indicator for your load cell calibration system can impact the measurement results. This section covers the following:

- Setting up an indicator via span points.
- Four-wire versus six-wire.
- Shunt calibration.
- Matching the excitation and waveform is important if separate measurement traceability is required.

The best practice is to pair an indicator with a load cell and calibrate them as a system.

Understanding mV/V and how it relates to load cells.

Most bridge-based sensors typically specify a rated output Sensitivity (RO), shown in the figure below. This Rated Output is found under Electrical specifications. It is usually stated in mV/V, where mV/V is the output voltage ratio to the excitation voltage required for the sensor to work.

Specifications	Model - Capacity (lbf / kN)				
	300-2K / 1-10	5K-10K / 20-50	25K-50K / 100-250	60K / 300	100K / 500
Accuracy					
Static Error Band, % R.O.	± 0.02	± 0.03	± 0.04	± 0.04	± 0.04
Non-Linearity, % R.O.	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03
Hysteresis, % R.O.	± 0.02	± 0.04	± 0.04	± 0.04	± 0.04
Non-Repeatability, % R.O.	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01
Creep, % Rdg / 20 Min.	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03
Off-Center Load Sensitivity, %/in	± 0.10	± 0.10	± 0.10	± 0.10	± 0.10
Side Load Sensitivity, %	± 0.10	± 0.10	± 0.10	± 0.10	± 0.10
Zero Balance, % R.O.	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0
Temperature					
Range, Compensated, °F	+15 to +115	+15 to +115	+15 to +115	+15 to +115	+15 to +115
Range, Operating, °F	-65 to +200	-65 to +200	-65 to +200	-65 to +200	-65 to +200
Sensitivity Effect, % Rdg / 100°F	0.08	0.08	0.08	0.08	0.08
Zero Effect, % R.O. / 100°F	0.08	0.08	0.08	0.08	0.08
Electrical					
Recommended Excitation, VDC	10	10	10	10	10
Input Resistance, Ω	350 +40/-3.5	350 +40/-3.5	350 +40/-3.5	350 +40/-3.5	350 +40/-3.5
Output Resistance, Ω	350 ± 3.5	350 ± 3.5	350 ± 3.5	350 ± 3.5	350 ± 3.5
Sensitivity (R.O.), mV/V, Nominal	2	4	4	4	4
Insulation Bridge/Case, MegΩ	5000 @ 50 VDC	5000 @ 50 VDC	5000 @ 50 VDC	5000 @ 50 VDC	5000 @ 50 VDC
Mechanical					
Safe Overload, % R.O.	150	150	150	150	150
Weight, lbs	1.0	2.9	9.1	11.2	23.5
Weight w/Base, lbs	2.5	6.5	21.5	26	52.5
Flexure Material	Aluminum	Steel	Steel	Steel	Steel

Figure 187: Morehouse Precision Shear Web Load Cell Specification Sheet with Rated Output Circled.

Most load cells are strain gauge-based sensors that provide a voltage output proportional to the excitation voltage. Many feature four strain gauges in a Wheatstone bridge configuration. When force is applied, the indicator measures the relative change in resistance. A digital indicator converts This load cell signal to a visual or numeric value.

When there is no load on the cell, the two signal lines are at equal voltage. As a load is applied to the cell, the voltage on one signal line increases very slightly,and the voltage on the other signal line decreases very slightly; the indicator reads the difference in voltage between these two signals.

Recording these readings in mV/V is often the most accurate method for measurement. Many indicators on the market can handle metric ratio measurements, measure the input in mV, and divide that measurement by the actual voltage being supplied. For example, if you have an mV measurement of 40.1235 mV and an excitation measurement of 9.9998 V, the display in mV/V would be 4.01243 mV/V.

Indicators that do not handle ratio-metric measurements have some internal counts that get programmed at the time of calibration. These indicators still read the change in resistance, but they require programming or points to be entered that correspond to force values.

Programming a load cell system via span points

Most indicators will allow the end-user to span or capture data points. Several indicators offer many ways of programming points; most will use some linear equation to display the non-programmed points along the curve or line.

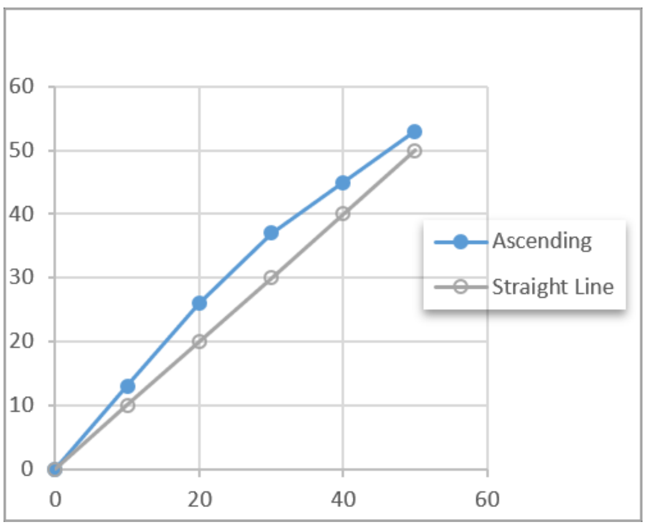


Figure 188: Load Cell Curve Versus a Straight Line.

When drawing a straight line between two points, you need to know the slope of the line to predict other points along the line. The common formula is y = mx + b, where m designates the slope of the line, and b is the y-intercept. When programming a load cell, the main issue with this approach is that the indicator and load cell will have some deviations from the straight line.

Non-linearity, found on the load cell specification sheet above, indicates how much deviation there is. It is 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 expressed in units of % of full scale. It is usually calculated between 40 - 60 % of the full scale.

Of course, factors such as stability, thermal effects, creep recovery, and return, and the loading conditions when the points are captured will influence each point's bias.

Programming an indicator via span points will follow a linear approach; some will have a 2-pt span, some 5-pts, and some even more. This method may include a straight line through all the points or several segmented lines. In all cases, there will be additional bias created by this method because the force-measuring system will always have some non-linear behavior.

Note: The segmented line approach with multiple span points will typically help linearize the system and have fewer errors than using two span points. However, do not assume multiple span points mean multiple segmented lines.

		Indicator with 2-pt adjustments		
Applied Force lbf	Actual Readings (mV/V)	Programmed Points	Calculated Values 2 pt span	Error
200	0.08279		199.6	0.4
1000	0.41415	0.41415	998.6	1.4
2000	0.82851		1997.6	2.4
3000	1.24302		2997.0	3.0
4000	1.65767		3996.8	3.2
5000	2.07242		4996.8	3.2
6000	2.48726		5997.0	3.0
7000	2.90216		6997.4	2.6
8000	3.31709		7997.8	2.2
9000	3.73203		8998.3	1.7
10000	4.14696	4.14696	9998.7	1.3

Figure 189: Programming an Indicator with a 2-pt Span Calibration.

The figure above exemplifies a Morehouse Calibration Shear Web Load Cell with a Non-Linearity specification of better than 0.05 % of full scale. In this example, the actual non-linearity is about 0.031 %. Using mV/V values and 0.032 % when using calculated values, it is well below the specification. However, the device cannot claim to be accurate to 0.032 % as this is a short-term accuracy achieved under ideal conditions.

Often, an end-user will see the results above, claim the system is accurate to a number such as 0.05 %, and believe they will maintain it. However, the end-user must account for additional error sources such as stability/drift, reference standard uncertainty that was used to perform the calibration, resolution of the force-measuring device,repeatability and reproducibility of the system, the difference in loading conditions between the reference lab and how the system is being used, environmental conditions, and the difference in adapters. All of these can drastically increase the overall accuracy specification.

As a rule, accuracy is influenced by how the system is used, the frequency of calibration, the non-linearity of both the load cell and indicator and thermal characteristics. In addition, the reference lab achieves short-term and does not include the system's stability or adapters, often the most significant error sources.

Several manufacturers claim specifications that use higher-order math equations for Non-Linearity to achieve unrealistic specifications, especially when programming an indicator with these values. At Morehouse, we find button or washer-type load cells to have specifications that are difficult to meet.

The figure above shows an example of a 2-pt span calibration. Values are programmed at 1,000 and 10,000 lbf. These values can often be entered into the indicator or captured during setup with the force-measuring system under load. In the above example, you can see the instrument's bias or error. Instrument bias is the average of replicate indications minus a reference quantity value. [25]

When discussing bias, we discuss the difference between the calculated and applied force values. In the example above, the worst error is 3.2 lbf, around 0.08 % of the applied force when 4,000 lbf is applied.

Many indicators do not allow the end-user to enter anything other than span points, and they do not allow using a polynomial equation with coefficients. Exceptions like the Morehouse C705P and 4215-Plus allow one to use points (data or span points) from the calibration data or coefficients.
Many of those indicators that do not allow a polynomial equation with coefficients to be used have USB, IEEE, RS232, or other interfaces that enable computers to read and communicate with the indicator. When software can communicate with an indicator, there may still be a way to use the polynomial equation using the coefficients for real-time response, converting the response to force to comply with ASTM E74 and ISO 376 requirements. ASTM E74 and ISO 376 require calibration to calculate higher-order polynomials, so the least squares method is often used.

Calculating Coefficients Used in Polynomial Equations

A polynomial equation is fitted to the calibration data using the least squares method to predict deflection values. The term "least squares" is used because it is the smallest sum of squares of errors. This method will contain a formula that is a bit more complex than a straight line, as most force-measuring devices will not be linear. A straight-line fit would be the best if a device were almost perfectly linear. The formula often uses higher-order polynomial equations to minimize errors and best replicate the line. The ASTM E74 standard details these equations and avoids overfitting and round-off errors if insufficient precision exists. The figure below shows a plot from the actual readings in mV/V and fits to a 3rd-order equation.

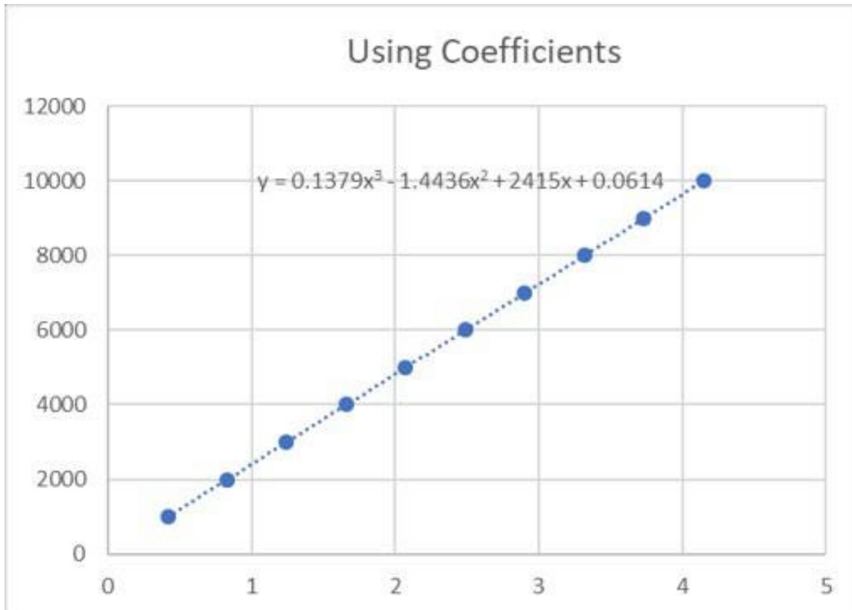


Figure 190: Graph of a 3rd Order Least Squares Fit.

Instead of using the equation for a straight line (y=mx+b), we have two formulas to solve for both force and response. These are:

Response (mV/V) = $A_0 + A_1(\text{Force}) + A_2(\text{Force})^2 + A_3(\text{Force})^{3,}$ and
Force (lbf) = $B_0 + B_1(\text{Response}) + B_2(\text{Response})_2 + B_3(\text{Response})^3$

When substituting these values with that in the equation shown on the line above, we are solving for Force when we know the Response; we would use $B_0 = 0.0614$, $B_1 = 2415$, $B_2 = -1.4436$, $B_3 = 0.17379$, so the formula becomes:

Force(lbf) = $0.0614 + 2415(\text{Response}) + -1.4436(\text{Response})^2 + 0.1379\,(\text{Response})^3$.

These are often called coefficients and are labeled as A0, A1, etc., and B0, B1, etc.; A0 or BO would determine the point at which the equation crosses the Y-intercept, while the other coefficients determine the curve.

Many force standards allow curve fitting of a 3rd degree and limit the maximum degree fit to a 5th degree. The most recognized legal metrology standards for using coefficients are ASTM E74, primarily used in North America, and ISO 376, which is used throughout most of Europe and the rest of the world.

When the equation in the graph above is used on the actual readings, the values calculated using the coefficients are very close to the applied force values. Thus, the bias, or measurement error, is around 0.1 lbf, far less than the 3.2 lbf error shown using a 2-pt span calibration.

Using Coefficient Conversion			
Calculated Values polynomial	Error	Diff in Errors	% difference
199.9	0.1	0.25	189%
999.9	0.1	-0.11	116%
1999.9	0.1	2.26	1846%
2999.9	0.1	2.82	2109%
3999.9	0.1	3.06	2413%
4999.9	0.1	3.05	2180%
5999.9	0.1	2.83	2060%
6999.9	0.1	2.47	1856%
7999.9	0.1	2.02	1446%
8999.9	0.1	1.56	1055%
9999.9	0.1	1.12	776%

Figure 191: Bias or Measurement Error When Using Coefficients.

The overall difference in the errors between these two methods is high. The figure below best summarizes these errors. One process produces an almost exact match, which is 0.001 % of full scale, while the other is 0.032 %. The worst point, at 4,000 lbf, has a difference of 3.06 lbf, or a 2413 % difference between errors. Using coefficients often requires additional software and a computer, whereas the 2-pt adjustment will not.

		Indicator with 2-pt adjustments			Using Coefficient Conversion			
Applied Force lbf	Actual Readings (mV/V)	Programmed Points	Calculated Values 2 pt span	Error	Calculated Values polynomial	Error	Diff in Errors	% difference
200	0.08279		199.6	0.4	199.9	0.1	0.25	189%
1000	0.41415	0.41415	1000.0	0.0	999.9	0.1	-0.11	116%
2000	0.82851		1997.6	2.4	1999.9	0.1	2.26	1846%
3000	1.24302		2997.0	3.0	2999.9	0.1	2.82	2109%
4000	1.65767		3996.8	3.2	3999.9	0.1	3.06	2413%
5000	2.07242		4996.8	3.2	4999.9	0.1	3.05	2180%
6000	2.48726		5997.0	3.0	5999.9	0.1	2.83	2060%
7000	2.90216		6997.4	2.6	6999.9	0.1	2.47	1856%
8000	3.31709		7997.8	2.2	7999.9	0.1	2.02	1446%
9000	3.73203		8998.3	1.7	8999.9	0.1	1.56	1055%
10000	4.14696	4.14696	9998.7	1.3	9999.9	0.1	1.12	776%

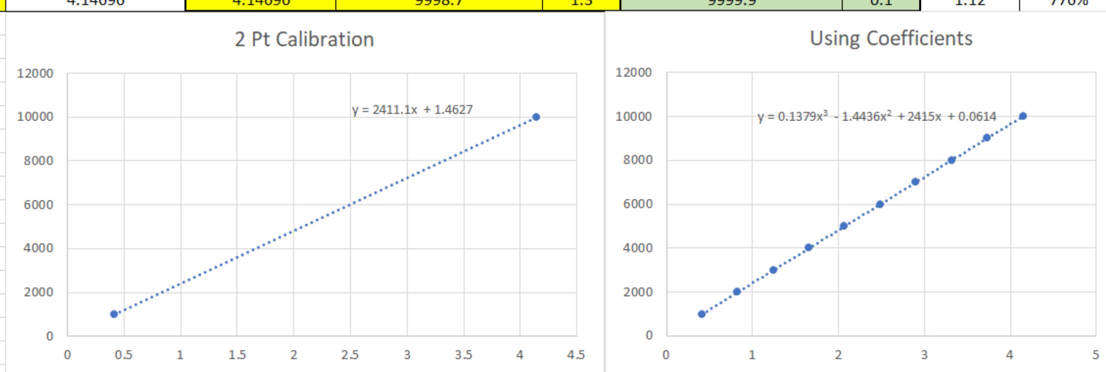


Figure 192: Difference Between 2-pt Span and Coefficients on the Same Load Cell.

Calculating Coefficients

CERTIFICATE OF CALIBRATION

AS RECEIVED / AS RETURNED

CALIBRATION & ISSUE DATE: 10/05/2020
Page: 3 of 4
REPORT NO.: U-SAMPLE(ASC)J0520

MOREHOUSE LOAD CELL MODEL: ULTRA PRECISION SERIAL NO.: U-SAMPLE(ASC)
CALIBRATED TO: 5000 lbf COMPRESSION ASCENDING

With Indicator:
MOREHOUSE MODEL: 4215 SERIAL NO.: SAMPLE

COMPRESSION CALIBRATION DATA 3RD-ORDER FIT

FORCE APPLIED lbf	MEASURED OUTPUT RUN 1 - 0° mV/V	MEASURED OUTPUT RUN 2 - 120° mV/V	MEASURED OUTPUT RUN 3 - 240° mV/V	FITTED CURVE mV/V	EXPANDED UNCERTAINTY lbf	FORCE STANDARD USED
100	-0.08264	-0.08265	-0.08268	-0.08267	0.0072	M-4644
500	-0.41328	-0.41331	-0.41333	-0.41329	0.0110	M-4644
1000	-0.82664	-0.82667	-0.82666	-0.82665	0.0170	M-4644
1500	-1.24008	-1.24007	-1.24012	-1.24010	0.0250	M-4644
2000	-1.65361	-1.65362	-1.65364	-1.65363	0.0330	M-4644
2500	-2.06722	-2.06727	-2.06729	-2.06725	0.0410	M-4644
3000	-2.48092	-2.48096	-2.48097	-2.48095	0.0490	M-4644
3500	-2.89473	-2.89467	-2.89472	-2.89472	0.0560	M-4644
4000	-3.30851	-3.30857	-3.30859	-3.30856	0.0640	M-4644
4500	-3.72245	-3.72249	-3.72250	-3.72245	0.0720	M-4644
5000	-4.13634	-4.13641	-4.13644	-4.13641	0.0800	M-4644

The Expanded Uncertainty is the aggregate uncertainty of the Morehouse measurement process, which includes the uncertainty of the reference standards used for calibration and the resolution of the unit under test. It is stated with a coverage factor of k=2, such that the confidence interval corresponds to approximately 95 %.

POLYNOMIAL EQUATIONS

The following polynomial equation, described in ASTM E74-18, has been fitted to the force and measured output values observed at calibration using the method of least squares

Response (mV/V) = $A_0 + A_1F + A_2F^2 + A_3F^3$
where: F = Force (lbf)
A_0 = -2.702818E-05
A_1 = -8.264230E-04
A_2 = -2.034020E-10
A_3 = 6.526291E-15

Force (lbf) = $B_0 + B_1R + B_2R^2 + B_3R^3$
where: R = Response (mV/V)
B_0 = -3.265079E-02
B_1 = -1.210034E+03
B_2 = -3.599920E-01
B_3 = -1.405484E-02

STANDARD DEVIATION mV/V	RESOLUTION lbf	LOWER LIMIT FACTOR lbf
0.0000301	0.0121	0.0874

Note: The lower limit factor applies only when the calibration equation is used to determine the force.

Figure 193: Morehouse Calibration Report with Two Sets of Coefficients.

The certificate shows two different polynomial equations.

Equation 1: Response (mV/V) = $A_0 + A_1F + A_2F^2 + A_3F^3$ where F = Force (lbf). It solves for Response when the Force is known.

When following the ASTM E74 standard, we get A coefficients. Calibration laboratories often use the A set of coefficients to read the reference standards and then record a reading on the unit under test (UUT). First, they load to a specific value determined by the equation. Then, they record the UUT reading. This calibration method is referred to as "Set to Force." Hence, in the above example, if they wanted to apply 5,000 lbf of Force, they would load the reference standard to -4.13641 mV/V.

Using the least squares method to generate the polynomial equation requires multiple runs of forces versus observed responses.

Supporting multiple runs may require using the ***TOCOL*** function to stack the responses vertically on top of each other. Likewise, the forces may need to be stacked vertically as well.
=LINEST(TOCOL(Run1$_{(responses)}$, Run2$_{(responses)}$, Run3$_{(responses)}$), TOCOL(Forces, Forces, Forces)^{1,2,3,4})

If not using Excel, equations exist online to aid in calculating the coefficients by other means.
Note: The coefficients may differ using different methods, such as rounding and zero reduction. We typically only care that the coefficients return the same result when the force is applied within the instrument resolution. If the zero reduction and rounding are the same, the values from the fitted curve should match.

Equation 2: Force (lbf) = $B_0 + B_1R + B_2R^2 + B_3R^3$ where R = Response (mV/V). It solves for Force when the Response is known.

This second equation is often used when the technician, field engineer, or end-user calibrates to the ASTM E4 or ISO 7500 standards. First, they load the UUT to a specific value. Then, they record what the reference reads when the UUT is loaded to a force value. Hence, they would load the UUT to 5,000 lbf and record the mV/V value of the reference. This calibration method is referred to as "Follow the Force."

Figure 194: Morehouse 4215 Plus Indicator.

However, the mV/V value must be converted to determine whether the measurements differ. An indicator like the 4215 Plus can store and use calibration coefficients to solve for Force. This is a good option when additional software is a concern.

Figure 195: Morehouse 4215 Plus Polynomial Screen to Enter B Coefficients.

There are ways in Excel to plot the Force versus Response using functions such as using this Excel formula =LINEST(Force, Response^{1,2,3}) where one would select the force values in this formula and Response values.

That formula would produce a set of coefficients to solve for force when the response is known. One would use =LINEST(Response,Force^{1,2,3}) to solve for a response when force is known. In this example, the 1,2,3 would yield a 3rd-order polynomial that could be entered into the Morehouse 4215 Plus and enable a much more exact conversion than using span points.

If you wanted to use a 4th degree equation, you would add =LINEST(Response,Force^{1,2,3,4}).
In addition, it is highly unlikely that the coefficients generated will match those of the calibration report. The reason they likely will not match is because of rounding, the zero-reduction method, version of Excel.

When Morehouse performs automated calibrations, we often record more digits than what is on the certificate. These numbers are eventually rounded to the significant figure, typically 0.00001 mV/V. Thus, the coefficients will not match. Our calculations may also be more exact than the functions in Excel.

Excel B Coeff		Morehouse B Coeff		% Differences
B0	4.7470569E-01	B0	4.7470555E-01	-0.000 030%
B1	-1.2115957E+04	B1	-1.2115957E+04	0.000 000%
B2	-3.7986597E+00	B2	-3.7986597E+00	-0.000 002%
B3	-7.1550926E-01	B3	-7.1550921E-01	-0.000 007%
B4	-2.5623835E-01	B4	-2.5623834E-01	-0.000 003%

Figure 196: Comparing the Same Data Set, Excel Versus Custom Code.

That is okay, as anyone wanting to verify their results may set the criteria that you have an agreement if the values you calculate match within ± 0.00001 mV/V assuming you are reading to ± 0.00001 mV/V. Typically, if the values differ by the resolution or less than the resolution of the instrument, rounding is likely the reason.

Morehouse has a coefficient generator that uses two different methods. One uses a more exact VB code, which means the spreadsheet contains Macros. The Excel spreadsheet can be downloaded here.

Calibration Differences

Most of our customers expect us to "tweak" their units sent in for calibration, which attempts to minimize the bias. However, tweaking may not be good practice. W. Edwards Deming has said, "If you can't describe what you are doing as a process, you don't know what you're doing."

Any force-measuring system will drift over time, and adjusting the values or processes tends to make it more out of control. Additionally, spotting trends, an ISO/IEC 17025 requirement becomes more challenging. "The laboratory shall have a procedure for monitoring the validity of results. The resulting data shall be recorded in such a way that trends are detectable and, where practicable, statistical techniques shall be applied to review the results."[26]

When coefficients are used, the reference laboratory reads the Actual Reading mV/V values at the time of each calibration. Establishing the baseline or monitoring the results is much easier based on rarely adjusted units.

Adjustments may be necessary if an indicator malfunctions or if a simulator is used to standardize and then calibrate the indicator. Yet, this introduces another potential error related to the electrical system. This issue becomes irrelevant if the indicator and load cell are paired and remain together as a unified system.

Note: If a meter is used independently of the load cell calibration, then simulation alone is not enough to establish metrological traceability. The meter must be calibrated, and the associated measurement uncertainties need to be accounted for.

We recommend keeping your load cells and indicators paired from one calibration to the next. When the reference laboratory reads and reports in mV/V using the least-squares method, your "As Received" calibration becomes the same as the "As Returned," and you are given a new set of coefficients to use. The mV/V values are recorded and can be monitored, and the new coefficients will account for any drift that has happened and bring the force-measuring system back to having a much lower bias than the span calibration.

Check out our video [4215 Plus Indicator Lowers Measurement Errors]() for further explanation.

Figure 197: Morehouse Portable Calibrating Machine with Calibration Software.

Converting an mV/V load cell signal into Engineering Units instead of Using Multiple SpanPoints

Morehouse software complies with ISO 376, ASTM E74, and E2428 requirements and eliminates the need to use load tables, Excel reports, and other interpolation methods to ensure compliance with these standards. NCSLI RP-12 states, "The uncertainty in the value or bias always increases with time since calibration."[27] When the drift occurs, the indicator needs to be reprogrammed.

Since most quality systems require an "As Received" calibration, the indicator must be reprogrammed, and an "As Returned" calibration is performed—the actual level of work results in calibration costs that are much higher than they need to be.

Morehouse developed our HADI and 4215 indicator systems with software to avoid excess costs. The coefficients used in the software are based on mV/V values, and the "As Received" and "As Returned" calibrations are the same. So, the end-user only needs to update the coefficients in the software.

The software allows for conversion from mV/V to lbf, kgf, kN, and N, reducing the overall cost for the customer while meeting the quality requirements in ISO/IEC 17025:2017. Suppose additional software is a concern or problematic. In that case, we have a 4215 plus model that can store and use calibration coefficients that have a minimal error compared with traditional methods such as spanning multiple points.

Using mV/V Calibration Data and Entering Those Values into the Meter

COMPRESSION CALIBRATION DATA 3RD-ORDER FIT

FORCE APPLIED lbf	MEASURED OUTPUT RUN 1 - 0° mV/V	MEASURED OUTPUT RUN 2 - 120° mV/V	MEASURED OUTPUT RUN 3 - 240° mV/V	FITTED CURVE mV/V	EXPANDED UNCERTAINTY lbf	FORCE STANDARD USED
100	-0.08336	-0.08337	-0.08342	-0.08339	0.0072	M-4644
500	-0.41671	-0.41674	-0.41678	-0.41674	0.0120	M-4644
1000	-0.83352	-0.83354	-0.83359	-0.83355	0.0210	M-4644
1500	-1.25046	-1.25046	-1.25050	-1.25046	0.0310	M-4644
2000	-1.66745	-1.66745	-1.66750	-1.66748	0.0410	M-4644
2500	-2.08457	-2.08456	-2.08460	-2.08458	0.0500	M-4644
3000	-2.50176	-2.50175	-2.50180	-2.50176	0.0600	M-4644
3500	-2.91902	-2.91901	-2.91905	-2.91901	0.0700	M-4644
4000	-3.33629	-3.33627	-3.33631	-3.33631	0.0800	M-4644
4500	-3.75365	-3.75364	-3.75367	-3.75365	0.0900	M-4644
5000	-4.17103	-4.17101	-4.17103	-4.17102	0.1000	M-4644

The Expanded Uncertainty is the aggregate uncertainty of the Morehouse measurement process, which includes the uncertainty of the reference standards used for calibration and the resolution of the unit under test. It is stated with a coverage factor of *k*=2, such that the confidence interval corresponds to approximately 95 %.

POLYNOMIAL EQUATIONS

The following polynomial equation, described in ASTM E74-18, has been fitted to the force and measured output values observed at calibration using the method of least squares

Response (mV/V) = $A_0 + A_1F + A_2F^2 + A_3F^3$
where: F = Force (lbf)
A_0 = -5.868913E-05
A_1 = -8.332379E-04
A_2 = -2.666242E-10
A_3 = 1.513019E-14

Force (lbf) = $B_0 + B_1R + B_2R^2 + B_3R^3$
where: R = Response (mV/V)
B_0 = -7.030104E-02
B_1 = -1.200137E+03
B_2 = -4.599537E-01
B_3 = -3.135373E-02

STANDARD DEVIATION mV/V	RESOLUTION lbf	LOWER LIMIT FACTOR lbf
0.0000246	0.0120	0.0708

Figure 198 Calibration Report for a 5,000 lbf load cell.

B Coefficients Additional Error				
mV/V	Predicted	Read on Meter LB S/N 12140	Difference	%
-0.03999	47.92	47.92	0.00	0.000%
-0.07998	95.91	95.91	0.00	0.000%
-0.19995	239.88	239.88	0.00	0.000%
-0.39991	479.80	479.80	0.00	0.000%
-0.79979	959.51	959.51	0.00	0.000%
-1.19970	1439.13	1439.13	0.00	0.000%
-1.59962	1918.64	1918.64	0.00	0.000%
-1.99952	2398.04	2398.04	0.00	0.000%
-2.39942	2877.35	2877.34	0.01	0.000%
-3.19927	3835.81	3835.81	0.00	0.000%
-3.99901	4793.94	4793.94	0.00	0.000%
-4.39888	5272.96	5272.95	0.01	0.000%

Figure 199 5,000 lbf Morehouse Load Cell B Coefficient Error.

We tested various scenarios using the formula for B coefficients embedded into a 4215 Plus meter. We have developed an algorithm for the meter to display force values using the B coefficients in the above figure. When tested, the error from predicted was almost zero, as there were some slight rounding errors, as shown above. We know some people in the industry take the calibration reports and then enter mV/V into the meter. Thus, we followed the same steps using a 5-pt and 2-pt calibration.

5 PT mV/V SPAN CALIBRATION				
mV/V	Predicted Force Values	Read on Meter LB S/N 12140	Difference	%
-0.03999	47.92	47.95	-0.03	-0.058%
-0.07998	95.91	95.91	0.00	0.004%
-0.19995	239.88	239.75	0.13	0.054%
-0.39991	479.80	479.54	0.26	0.055%
-0.79979	959.51	959.05	0.46	0.048%
-1.19970	1439.13	1438.59	0.54	0.037%
-1.59962	1918.64	1918.14	0.50	0.026%
-1.99952	2398.04	2397.51	0.53	0.022%
-2.39942	2877.35	2876.86	0.49	0.017%
-3.19927	3835.81	3835.33	0.48	0.013%
-3.99901	4793.94	4793.46	0.48	0.010%
-4.39888	5272.96	5272.52	0.44	0.008%
Programmed @ 1,2,3,4,5K				

Figure 200 5-PT mV/V Values Entered into the 4215 Meter.

When we entered values programmed at 20 % increments and the corresponding mV/V values, the error on a device one expects to be better than 0.07 lbf (the ASTM LLF) is much higher at almost all test points. So, the main issue is that if the end-user assumes they can do this and maintain the same uncertainty, they are mistaken.

2 PT mV/V SPAN CALIBRATION				
mV/V	Predicted Force Values	Read on Meter LB S/N 12140	Difference	%
-0.03999	47.92	47.93	-0.01	-0.016%
-0.07998	95.91	95.87	0.04	0.046%
-0.19995	239.88	239.68	0.20	0.083%
-0.39991	479.80	479.38	0.42	0.089%
-0.79979	959.51	958.74	0.77	0.080%
-1.19970	1439.13	1438.12	1.01	0.070%
-1.59962	1918.64	1917.51	1.13	0.059%
-1.99952	2398.04	2396.88	1.16	0.048%
-2.39942	2877.35	2876.25	1.10	0.038%
-3.19927	3835.81	3835.06	0.75	0.020%
-3.99901	4793.94	4793.81	0.13	0.003%
-4.39888	5272.96	5273.14	-0.18	-0.003%
Programmed @ 0, 5000				

Figure 201 2-PT mV/V Values Entered into the 4215 Meter.

The errors change quite when one elects to use just a 2-pt span. We discussed this earlier, though here is another example where the values are better the closer one gets to capacity and deviate quite a bit throughout the range. Thus, I would argue that a 5-pt calibration is superior, though still significantly flawed compared with the coefficients in the formula for the calibration report.

Suppose the end goal is the best accuracy available. In that case, the recommendation will be a 4215 or HADI indicator, an ASTM E74 calibration, and software to convert mV/V values to Engineering units or a meter allowing input coefficients. In these systems, we specify the accuracy from 0.005 % to 0.025 % of full scale. These do not include drift effects, usually better than 0.02 % on these systems. For other systems with a 5 or 10-point calibration, a meter is used to span the readings.

We typically do not get better than 0.1 % of full scale if the calibration frequency is one year, and we have had several systems that can maintain 0.05 % of full scale on a six-month or less calibration interval.

Taking a calibration report in mV/V and entering the mV/V values into the meter carries additional errors that are very different from quantifying based on the randomness of the points selected, and the error can vary. The actual results will vary depending on how much the system is used and, on the system's, individual components.

How many decimal places are enough?

Customers have asked us how many decimal places are enough. It's either because they want to maximize the resolution of what they want to purchase, or the other side, where the expectation is for far too much resolution for the equipment, they purchased being requested for what is reasonable.

We have seen a lot from a meter being set to read 100,000.001. That is 100 million counts, though this instrument(readout) wasn't even stable to 1 count. The extra 0.001 meant nothing.

Then there is the other end of how many decimal places are enough, where some say that rounding is impacted, and they might be right depending on what they are trying to accomplish. Many meters round based on an invisible digit to the right of the decimal place anyway. That means if a meter can read 10,000 counts by a resolution of ± 1 count, the meter is likely rounding based on 10,000.X, where X equals 0.1 – 0.9. Thus, 10,000.6 becomes 10,001, and 10,000.3 is becoming 10,000.

How many decimal places are enough? – Repeatability and Resolution

Let us start with a situation where we can set the appropriate resolution to display some degree of repeatability between measurements.

Example #1.

In this scenario, we record three readings: 10,000.5, 10,000.5, and 10,000.5. Our repeatability is perfect. The standard deviation is 0. The resolution is ± 0.5 counts. The resolution is too coarse.

Example #2

Using the same instrument, though we set the resolution to ± 0.2 counts this time, we recorded three readings at 10,000.6, 10,000.4, and 10,000.6. This time, the standard deviation of our measurements is 0.11547.

Example #3

It's the same instrument, though this time, we set the resolution to ± 0.1 counts. We record three readings at 10,000.5, 10,000.4, and 10,000.5. This time, the standard deviation of our measurements is 0.057735.

Out of three examples, setting the resolution to ± 0.1 would result in the best possible scenario for capturing the repeatability, which is often required for any measurement uncertainty budget, so is the resolution of the instrument being tested.

Example #4

Let us take this example a bit further. Suppose the instrument was not repeatable when the resolution was set to ± 0.5 counts.

Say the instrument read 10,000.5, 10,002.5, and 10,003.5. The standard deviation of these three numbers is 1.527525. This example highlights that the instrument might benefit from setting a higher resolution, say 1. Our numbers become 10,001, 10,003, 10,003, which would have lowered our repeatability to 1.154701.

One Rule for Setting the Resolution of the Instrument.

So, how many decimal places are enough? Some of that depends on how stable the unit might be. Many standards say the actual resolution of the instrument depends on the stability at 0 reading. They often recommend calculating the resolution by the fluctuation range when the instrument is at what should be 0 divided by 2. Thus, if we set the resolution to ± 0.1 and the readings fluctuate by 0.0, 0.1, and 0.0, we likely have the appropriate resolution as 0.1 > 0.05 (0.1/2).

What if the resolution was 0.1 and the readings were observed to fluctuate from 0.0, 2.0,1.2? The resolution of ± 0.1 < 1 (2.0/2). Thus, the resolution of the instrument should be set to 1.

Note: There are other rules for handling resolution, though this one is the one we use most of the time at Morehouse. It seems sound, as it is found in many ASTM standards.

How many decimal places are enough? – Reference Standard Uncertainty

Many of us are for taking extra digits if we can. Though are they meaningful?

This one isn't as obvious, though it is worth considering. If the indicator used for the calibration is specified as 0.002 % of the indicated value, does it make sense to record the resolution far past that specification?

Our device reads by 10,000, and we know the best we can measure is ± 0.002 % of that or ± 0.2. Does it make sense to try and measure the extra digit to 0.02?

It would not make sense if that extra digit is not stable per the guidance above. Our measurement uncertainty will not be better than ± 0.002 %, no matter what we do.

Some may argue that observing the extra digit will help with rounding or other calculations by making them more exact.

When considering the uncertainty of the reference standard and applying the rule of maximum fluctuation divided by 2, the actual difference in the measurement result is often insignificant. In this case, "insignificant" means that the probability of that extra digit having an impact on the measurement uncertainty reported to two significant figures is relatively low.

Cabling

Most of the force or torque systems we calibrate yearly consist of load or torque cells, an indicator or readout, cables, adapters, and some shipping or carrying case. Around 90 % of these systems come in with an indicator that is only capable of supplying an excitation to the bridge and measuring a signal coming back from the transducer. This is known as a 4-wire system.

There are significant differences between 4-wire and 6-wire systems. We recommend using a 6-wire system because the advantages far outweigh the continued use of a 4-wire system.

4-Wire Systems

Figure 202: 4-Wire Cable and Diagram.

In understanding the errors associated with a 4-wire cable, we must first understand why this error exists. In general, cable resistance is a function of temperature, and the temperature change on a cable affects the thermal span characteristics of the load cell/cable system. On a 4-wire cable, this will affect thermal span performance, meaning that, as the temperature changes, the resistance of the cable changes and can cause a voltage drop over the cable length. A 4-wire setup cannot compensate for variations in lead resistance.

Substituting a cable of a different gauge or length will produce additional errors. An example of this involves changing to a 28-gauge or 22-gauge cable. On a 28-gauge cable, there will be a loss of sensitivity of approximately 0.37% per 10 feet of 28-gauge cable. On a 22-gauge cable, there will be a loss of sensitivity of around 0.09% per 10 feet of 22-gauge cable.

Considerations for 4-wire systems:

1. If you damage or replace your cable, the system may need to be calibrated immediately following replacement or repair.
2. Operating at different temperatures will change the resistance, which will cause a voltage drop, resulting in a change in measured output.
3. Cable substitution will result in an additional error and should be avoided.
4. Cables used for 4-wire systems should have an S/N or a way to ensure the same cable stays with the system with which it was calibrated. This is a good measurement practice technique that Morehouse highly recommends.

6-wire systems

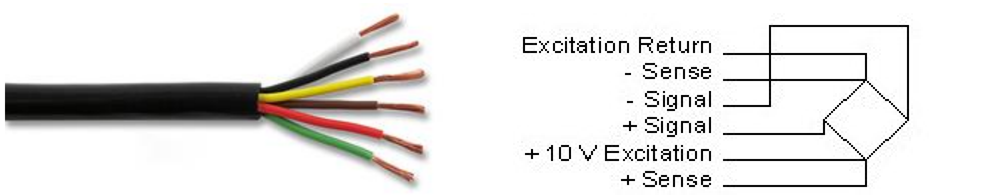


Figure 203: 6-Wire Cable and Diagram.

A 6-wire cable runs to the end of a load cell cable or connector and used with an indicator that has sense lead capability will eliminate errors associated with a 4-wire system. With a 6-wire system, the sense lines are separate from the excitation lines, eliminating effects due to variations in lead resistance. It also allows for long cable runs in outdoor environments with extreme temperatures.

Wiring a 6-wire cable for sense is easy. Use a wire with at least six wires. Run one wire from the positive signal and one from the negative signal. Run two wires from the load cell's positive excitation pin and two from the load cell's negative excitation pin.

Then, wire appropriately to the connector to + Sense, + Excitation, +Signal, - Sense, - Excitation, and – Signal. There might also be a ground wire that can be run to the load cell connector on one end and the meter on the other.

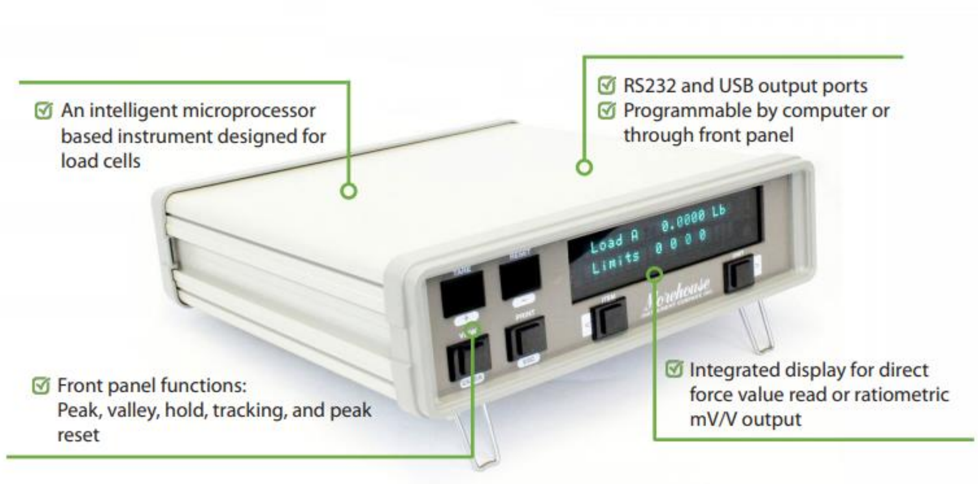


Figure 204: Morehouse 4215 Meter is a 6-wire Sensing Indicator.

However, a 4-wire system cannot be changed to a 6-wire system without calibrating the entire system again. A 6-wire cable is the best choice if you intend to interchange cables or are operating in an uncontrolled environment.

Watch this video on YouTube, showing the observed difference of 0.106 % when using two different lengths but the same gauge and cables.

Excitation and Waveform AC Versus DC

The ASTM E74-18 standard includes reporting criteria that must be on calibration certificates. It states, "The excitation voltage and waveform used for calibration when known."[28] The ASTM E74 includes this because it matters.

At Morehouse, we receive many requests for indicators that can record the output of the Unit Under Test. We have a High Stability 4215 device that can be used for 5 and 10 V DC mV/V calibration of load cells. The 4215 HS or 4215 Plus are good choices, as the DC excitation voltage can be set.

Many other indicators include fixed-value DC excitation voltage.

These are likely not good indicators for capturing the mV/V output of the UUT because the excitation and waveform may not match what the customer is using.

For example, we compared a 10 V excitation on an HBM DMP40 with a Fluke 8508A, both high-end indicators. The results showed a difference in output from Alternating Current (AC) measurements and Direct Current (DC). For this test, we used a load cell simulator on the two indicators; we used a simulator tested at the National Institute of Standards and Technology (NIST) as the reference.

This simulator was used to replicate a load cell's excitation and output response accurately when connected to the experiment indicators. A Fluke 8505A Reference Multimeter was used on the DC indicator side, and an HBM DMP40 Precision Measuring Instrument was used on the AC side. The differences between the simulator setpoint value and measure values by the indicators are reported in the table below. In this table, the first column represents the setpoint values.

Simulator Set Point (mV/V)	HBM DMP40 Predicted Response (mV/V)	NIST FLUKE Predicted Response (mV/V)	Error %	HBM DMP40 AC Difference	NIST FLUKE DC Difference
0.00000	0.000000	0.00000			
-1.00000	-1.000010	-1.00004	-0.003%	0.00001	0.00004
-2.00000	-2.000016	-2.00007	-0.003%	0.00002	0.00007
-3.00000	-3.000036	-3.00010	-0.002%	0.00004	0.00010
-4.00000	-4.000000	-4.00011	-0.003%	0.00000	0.00011
-5.00000	-4.999998	-5.00012	-0.002%	0.00000	0.00012

Figure 205: AC versus DC Indicator Data.

We would use the NIST values to standardize a Morehouse 4215 or Morehouse DSC indicator. At -3.00000 mV/V, we would enter -3.00010 because we want to standardize the indicator to repeat the **NIST** value of **-3.00010** when the -3.00000-set point is selected. To standardize the HBM, we must use a BN100A – Bridge calibration unit for transducer excitation with 225Hz carrier frequency.

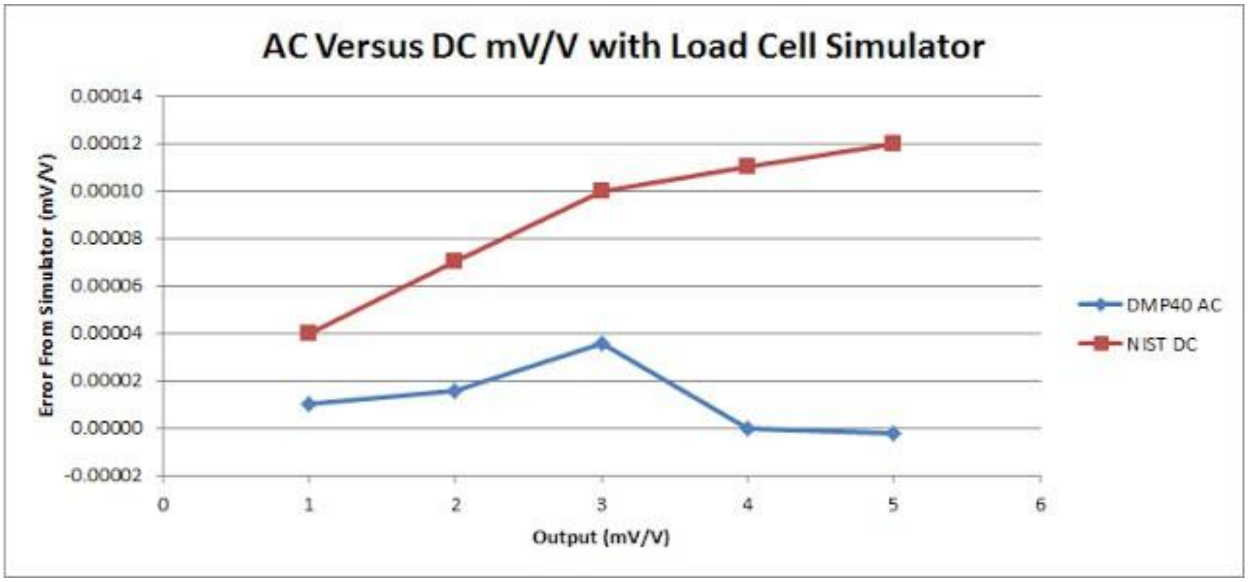


Figure 206: Graph of AC versus DC Indicator Data.

The test data above shows that the difference between AC and DC mV/V can be quantified between these two very high-end indicators, and the difference is about 0.003 %. As depicted in the chart, the DC indicator output consistently involves higher differences when compared to the AC indicator.

The graph shows an AC indicator cannot be interchanged with a DC indicator because the difference between AC and DC measurements is not linear. If a lab is using a DC or AC indicator as a reference, the measurement traceability can only be derived from the type of current used by the reference lab. AC and DC indicators are not interchangeable, and one cannot be substituted for another without recalibration of the entire system if metrological traceability is demonstrated. This book has a section on using a simulator to calibrate meters.

There are also differences in the excitation voltage on a 5-volt versus 10-volt DC system. On the test Morehouse performed, the differences are around 0.01 %, varying depending on the system and setup.

These examples demonstrate that when an indicator is changed, it may need to be thoroughly tested to know the additional contribution to measurement uncertainty. Additionally, AC indicators may produce entirely different results than DC indicators. The best practice is to calibrate your load cell with the indicator it is used with. Substitution can be tricky and requires traceability to SI units using the same excitation voltage and waveform of the primary multimeter.

Excitation 5 Volt Versus 10 Volt DC Excitation

Most load cells are force sensors that receive a voltage (excitation) from a regulated power source (usually a digital indicator or signal conditioner) and send back a low voltage signal (signal) when force is applied. Most load cells are designed to operate at 10V, and many will operate fine at 5V.

For bonded foil gages, two competing factors determine bridge excitation voltage.

1) Higher voltages improve the signal-to-noise ratio of the low output from Wheatstone bridges
2) Higher voltages increase the self-heating of the strain gauge.

Modern instrumentation can give good results at a much lower voltage than when excitation voltages were standardized decades ago. From the electronics standpoint, 10V, 5V, or even 2.5V will not produce a noticeable difference in most applications if they are used at the same voltage they are calibrated at.

On the contrary, the self-heating effect can have a considerable impact. Differing the excitation voltage from how it was calibrated can influence span, temperature compensation, creep, and stability. In the case of high-end reference load cells, it is imperative to maintain the excitation voltage used during calibration.

Testing Using a Morehouse 4215

10 Volt Versus 5 Volt DC Excitation

MODEL: ULTRA PRECISION
MOREHOUSE Load Cell, SERIAL NO. U-7643
10000.00 LBF Compression Calibrated to 10000.00 LBF
MOREHOUSE 4215, SERIAL NO. 61120

	10 VOLT DC EXCITATION	5 VOLT DC EXCITATION		
Applied Load	Values from Fitted Curve	Values from Fitted Curve	Change from Previous	% Change from Previous
200	-0.08219	-0.08217	-0.000020	0.024
1000	-0.41091	-0.41092	0.000010	-0.002
3000	-1.23302	-1.23311	0.000090	-0.007
5000	-2.05548	-2.05567	0.000190	-0.009
7000	-2.87821	-2.87849	0.000280	-0.010
9000	-3.70110	-3.70146	0.000360	-0.010
600	-0.24654	-0.24654	0.000000	0.000
2000	-0.82191	-0.82196	0.000050	-0.006
4000	-1.64421	-1.64435	0.000140	-0.009
6000	-2.46682	-2.46706	0.000240	-0.010
8000	-3.28964	-3.28997	0.000330	-0.010
10000	-4.11258	-4.11296	0.000380	-0.009

Figure 207 Calibration results comparing a 5V and 10V DC Excitation.

At Morehouse, we have tested various load cells and meters using 5- and 10-volt DC excitation and carrier frequencies such as AC versus DC and filter settings.

When we conducted this test, we used our 12,000 lbf deadweight machine, which was within 0.0016 %; we did not move the load cell. We applied a series of forces using the 5V DC indicator setting, switched to the 10V DC setting, and repeated the same series of forces.

The goal was to isolate the difference between 5 and 10V excitation on a Morehouse Shear-web load cell. The above results show a consistent difference on most applied forces of 0.01 %.

We feel our test method was sound, and the difference was noticeable. If the use case was for a reference standard, a change of 0.01 % is likely too high, as the results were consistent in the output change.

The lower voltage on this load cell increased the overall output. We discussed other factors like carrier frequency and filtering settings.

General Information about 5 and 10V excitation on a Load Cell

5V DC Excitation: Load cells with 5V DC excitation are designed to operate with a 5-volt direct current power supply.

10V DC Excitation: Load cells with 10V DC excitation require a 10-volt direct current power supply. This higher voltage can sometimes provide a better signal-to-noise ratio, potentially improving the overall performance of the load cell.

Signal Strength:

5V DC Excitation: A 5V excitation voltage is generally sufficient for many applications, yet it may result in a lower signal strength than a 10V excitation. This could potentially impact the precision of measurements in certain situations.

10V DC Excitation: A higher excitation voltage, such as 10V, can provide a stronger signal. This can be advantageous in applications where a higher level of sensitivity and precision is required.

Noise Sensitivity:

5V DC Excitation: Lower excitation voltages may be more susceptible to electrical noise. Care should be taken to minimize interference in the signal path to ensure accurate measurements.

10V DC Excitation: The higher excitation voltage may contribute to a better signal-to-noise ratio, potentially reducing sensitivity to electrical interference.

Compatibility:

5V DC Excitation: Load cells with 5V excitation are more common and may be preferred in applications where the sensor is specifically designed for 5V operation., smaller load cells like button or pancake cells.

10V DC Excitation: Some load cells are designed to work optimally with 10V excitation. It's essential to check the specifications of the load cell and ensure compatibility with the chosen excitation voltage.

General Rules of Thumbs:

-Smaller load cells are more sensitive to excitation voltage. Most loadcells under 1.5" diameter will be more stable at 5V than 10V.
-Lower capacity loadcell is more sensitive to the excitation voltage
-Higher bridge resistances are less sensitive to excitation voltage. This can allow smaller transducers to use larger excitation voltages.
-Applications that affect heat transfer, like high ambient temperature or vacuum environment, may require lower excitation
-Higher voltage requires a longer warmup time

Conclusion

We have learned that there is a difference in output between excitation and waveform. ASTM E74 and ISO 376 address this by saying any meter substitution must match the same excitation, frequency, and waveform.

Our tests using the same Morehouse 4215 meter and calibration machine, using a Morehouse shear web load cell, showed a difference of about 0.01 % between 5 and 10 volts.

However, it's more of a trap to think any error for most load cells would be within 0.01 %, as these differences depend on the design of the load cell. Some smaller cells will operate better at 5-volt DC excitation, meaning the difference between 5 and 10-volt DC excitation will be much more significant.

Even filtering (filter) settings can make a difference in output, which will be discussed in the next section.

Thus, our conclusion on it is to standardize your process and meters.

Choose the best filtering settings for your application and send all the instructions to the calibration lab performing the calibration, hopefully, Morehouse.

Comparing Filter Settings on Morehouse 4215 Load Cell Meters

A common question at Morehouse we frequently get asked involving our 4215-meter load cell meter is if there is a performance difference between using different filter settings.

We decided to take things further for the section of this book by testing a standard 4215 indicator versus our newer 4215 Plus indicator. We then compared the filter settings of minimal filtering 1-1 with the slowest filtering setting of 2-4.

We hooked up each meter to a load cell simulator and captured roughly 22,000 data points at the 2 mV/V setting on the simulator.

Load Cell Meter Filter Settings

Load cells are transducers that convert force or weight into an electrical signal, and load cell meters interpret and display this signal.
The load cell meter filter settings are adjustments that affect the way the meter processes the incoming signal.

These filters are essential in minimizing noise and providing stable and accurate force readings.
The options for filter settings are often dependent on the manufacturer of the meter. These options range from no filter to some specialized filters.

In general, when we discuss the common filters, we are discussing these.
Low-Pass Filter: Allows low-frequency signals to pass through while attenuating higher frequencies.
High-Pass Filter: Allows high-frequency signals to pass through while attenuating lower frequencies.

Type I filters are suitable for removing most noise yet may leave some jitter on the end digits.
Type I filters provide a linear phase response, preserving the timing relationships of different frequency components.

Type II are more advanced filters optimized for the typical industrial environment.
Type II filters have a non-linear phase response, allowing for potentially lower latency but introducing phase distortion.

There are also some specialized filters worth mentioning. Three of our favorites are the Gaussian, Butterworth, and Bessel filters.

A Gaussian filter, or a Gaussian blur, is commonly used in image and signal processing to reduce noise and smooth images or signals.

It applies a weighted average to each point in the signal, with the weights given by a Gaussian distribution.
This filter is characterized by its bell-shaped response and is often used for blurring and noise reduction.
A Butterworth filter provides a maximally flat frequency response in the passband and is commonly used in

applications where a flat response is crucial.

It has a more gradual roll-off than Chebyshev filters, and while it introduces phase distortion, it is often preferred for applications where a consistent phase response is not critical.
Bessel filters are known for their nearly constant group delay, meaning that all passband frequencies experience similar delays.

This property is helpful in applications where maintaining the phase relationship between different frequencies is important, such as in audio signal processing.

The Morehouse HADI indicator has multiple filters in the advanced settings that can be changed.
The Morehouse 4215 filters are split into Type I and Type II.

Level	1	2	2	4
Setting Time (seconds)	<1	2	10	30
Read Rate (per second)	60	60	30	10

Figure 208 Morehouse 4215 filter settings.

Question: Is there a performance difference between using different load cell meter filter settings?

4215 Standard Load Cell Meter Filter Settings Comparison

Figure 209A Morehouse 4215 Standard Load Cell Meter.

Model	4215 Std	Model	4215 Std
Filter	1-1	Filter	2-4
Min	1.99917	Min	1.99930
Max	1.99953	Max	1.99950
Max Diff	0.00036	Max Diff	0.00020
Average	1.99935	Average	1.99941
Std Dev	0.00004	Std Dev	0.00003

Figure 210 Comparing the Load Cell Meter Filter Differences on the 4215 Standard.

We evaluated the load cell meter filters by choosing the most basic option of Type I, Level 1 (labeled 1-1) and Type 2, Level 4 (labeled 2-4) to compare a worst-case difference or the two extremes. We decided to examine the minimum and maximum readings, take the difference between these two points, and compare each meter's average and standard deviation.

The above results show what we assumed would be the case.

Applying the minimum filter produced a result different from the maximum level of filtering.
However, the standard deviation of these two filters only varied on the 4215 standard by 0.00001 mV/V.

The Average difference between the two options was about 0.00006 mV/V or about 0.003 %.

The maximum deviation of the 22,000 plus readings was between 0.00020 mV/V to 0.00036 mV/V.

4215 PLUS Load Cell Meter Filter Settings Comparison

Figure 211 Morehouse 4215 Plus uses coefficients to solve for Force.

Model	4215 Plus	Model	4215 Plus
Filter	1-1	Filter	2-4
Min	1.99892	Min	1.99898
Max	1.99902	Max	1.99901
Max Diff	0.00010	Max Diff	0.00003
Average	1.99895	Average	1.99900
Std Dev	0.00002	Std Dev	0.00001

Figure 212 Comparing the load cell meter filter differences on the 4215 Standard.

Applying the minimum filter produced a result different from the maximum level of filtering.

However, the standard deviation of these two filters only varied on the 4215 Plus by 0.00001 mV/V.

The Average difference between the two options was about 0.00005 mV/V or about 0.0025 %.

The maximum deviation of the 22,000 plus readings was between 0.00003 mV/V to 0.00010 mV/V.

Model	4215 Plus	Model	4215 Plus	Model	4215 Std	Model	4215 Std
Filter	1-1	Filter	2-4	Filter	1-1	Filter	2-4
Min	1.99892	Min	1.99898	Min	1.99917	Min	1.99930
Max	1.99902	Max	1.99901	Max	1.99953	Max	1.99950
Max Diff	0.00010	Max Diff	0.00003	Max Diff	0.00036	Max Diff	0.00020
Average	1.99895	Average	1.99900	Average	1.99935	Average	1.99941
Std Dev	0.00002	Std Dev	0.00001	Std Dev	0.00004	Std Dev	0.00003

Figure 213 Comparing the Filter Differences on the 4215 Standard Vs the 4215 Plus

Conclusion Comparing Load Cell Meter Filter Settings on Morehouse 4215 Load Cell Meters.

- The filter settings can make a difference in the indicator readings.
- The data speaks for itself on both meters.
- The maximum difference in the average readings was about the same, from 0.0025 % to 0.003 %.
- In addition, the 4215 Plus is a way more accurate meter than its predecessor.
- The data speaks for itself on the improved performance, equating to about a 3-x improvement.

Coefficients Explained

What Coefficients Do

ASTM E74, ISO 376, and other standards may use calibration coefficients better to characterize the performance characteristics of continuous reading force-measuring equipment. These standards may use higher-order fits such as a 2nd or 3rd-order fit (ISO 376) or up to as high as a 5th-order fit (ASTM E74).

Both standards use observed data and fit the data to a curve. In simple terms, these higher-order fits give instructions on predicting an output given a measured input. That output can either be the force at a specific response or the response when the force is known. We can use these equations to accurately predict the appropriate coordinate for any point in the measurement range, typically above the first non-zero point on the curve.

The ASTM E74 standard has additional requirements for higher-order fits. To use a fit above the 2nd-degree (or quadratic) requires the force-measuring device to have a resolution that exceeds 50,000 counts. Common equations, reminiscent of those taught in high school algebra, can characterize nearly any force-measuring device.

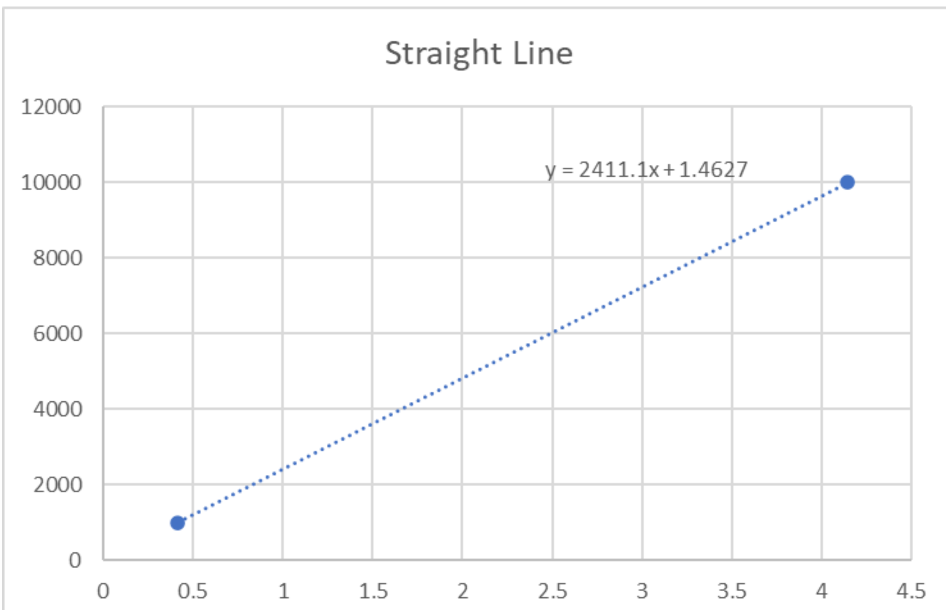


Figure 214: Load Cell Curve Using the Equation for a Straight Line.

Straight Line Fits

Straight-line equations such as y = mx + b is common practice for force-measuring devices. You would typically find the slope of the line, which could predict other points along the line. The standard formula of y = mx + b, where m designates the slope of the line, and where b is the y-intercept. We can modify this formula to use coefficients, which would become Response = A_1 * (Force) + A_0.

The figure above shows the straight-line plot, in which there is typically a significant deviation from using this equation compared to the actual response of the load cell. This deviation means that we cannot predict precisely enough for the measurements we need to make. Thus, a straight line may introduce additional errors. Determine if a straight line gives us enough precision, which often depends on how linear the force-measuring device is. Typically, this is characterized as nonlinearity; the error on most good force-measuring equipment is often less than 0.05 %.

Y	X
Applied Force lbf	Actual Readings (mV/V)
200	0.08279
1000	0.41415
2000	0.82851
3000	1.24302
4000	1.65767
5000	2.07242
6000	2.48726
7000	2.90216
8000	3.31709
9000	3.73203
10000	4.14696

Figure 215: Data to Plot the Line in Figure 1.

When we use this equation, y is the Force applied, and x is the output of the force-measuring device. If you wanted to solve for the output of the readings when they know the Force applied, you could plot the actual readings against the force applied by changing what x and y are.

One could use the same formula to solve for x. We take the formula y = Mx + B and solve for x to do this. The formula then becomes Mx = (y-B), which we then divide (y-B) by m. Thus, x = (y-B)/M. Simple, right?

As we move to higher-order equations, the formulas become more complex.

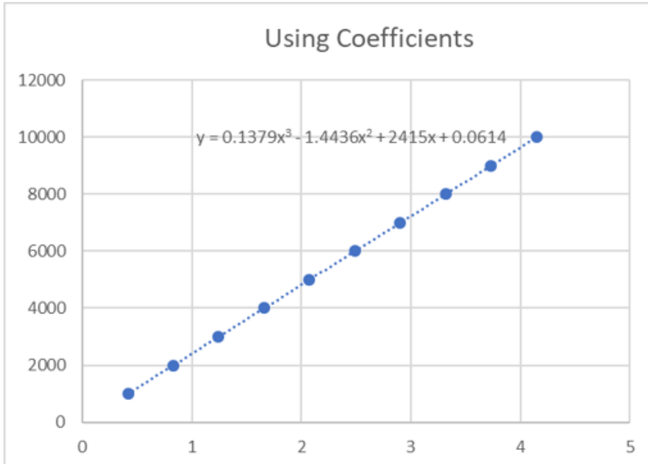


Figure 216: Higher-Order Polynomial Equations.

Polynomial Equations Using Least Squares

Like a simple straight line, this analysis begins with data points plotted on an x- and y-axis graph. ASTM E74, ISO 376, and other standards use the least squares method because it is the smallest sum of squares of errors. It is the best approximate solution to an inconsistent matrix. The least squares method is a statistical procedure that finds the best fit for a set of data points. The method works by minimizing the sum of the offsets or residuals of points from the plotted curve.

The method used in ASTM E74 contains a formula that is a bit more complex than a straight line. Section 7.1.2 of the ASTM E74 standard states, " A polynomial equation is fitted to the calibration data by the least squares method to predict deflection values throughout the verified range of force. Such an equation compensates effectively for the nonlinearity of the calibration curve. The standard deviation determined from the difference of each measured deflection value from the value derived from the polynomial curve at that force provides a measure of the error of the data to the curve fit equation. A statistical estimate, called the lower limit factor, LLF, is derived from the calculated standard deviation and represents the width of the band of these deviations about the basic curve with a probability of approximately 99 %."[29]

The polynomial equation often uses higher-order equations to minimize interpolation errors and best replicate the line. The figure above shows a plot from the actual readings in mV/V and curve fit to a 3rd-order equation. Instead of using the equation for a straight line (y=Mx+B), we have a formula that uses x values that are raised to higher powers, such as Response(mV/V) = $A_0 + A_1 * F + A_2 * F^2 + A_3 * F^3$. These are often called coefficients. On a calibration report, they are often referred to as A_0, A_1, A_2, A_3. Let us look at a second-degree polynomial equation from a calibration report.

COMPRESSION CALIBRATION DATA 2ND-ORDER FIT

FORCE APPLIED lbf	MEASURED OUTPUT RUN 1 - 0° mV/V	MEASURED OUTPUT RUN 2 - 120° mV/V	MEASURED OUTPUT RUN 3 - 240° mV/V	FITTED CURVE mV/V	EXPANDED UNCERTAINTY lbf	FORCE STANDARD USED
500	-0.08758	-0.08761	-0.08764	-0.08753	0.035	M-9500
1000	-0.17383	-0.17391	-0.17385	-0.17394	0.037	M-7471
2000	-0.34681	-0.34681	-0.34673	-0.34678	0.046	M-7471
5000	-0.86545	-0.86545	-0.86543	-0.86544	0.087	M-7471
7000	-1.21131	-1.21135	-1.21137	-1.21132	0.120	M-7471
10000	-1.73024	-1.73026	-1.73021	-1.73031	0.160	M-7471
12000	-2.07635	-2.07636	-2.07641	-2.07642	0.190	M-7471
15000	-2.59579	-2.59584	-2.59581	-2.59574	0.240	M-7471
17000	-2.94214	-2.94220	-2.94210	-2.94207	0.270	M-7471
20000	-3.46159	-3.46170	-3.46166	-3.46174	0.320	M-7471
22000	-3.80826	-3.80840	-3.80837	-3.80829	0.350	M-7471
25000	-4.32819	-4.32829	-4.32830	-4.32829	0.400	M-7471

The Expanded Uncertainty is the aggregate uncertainty of the Morehouse measurement process, which includes the uncertainty of the reference standards used for calibration and the resolution. It is stated with a coverage factor of *k*=2, such that the confidence interval corresponds to approximately 95 %.

POLYNOMIAL EQUATIONS

The following polynomial equation, described in ASTM E74-18, has been fitted to the force and measured output values observed at calibration using the method of least squares

Response (mV/V) = $A_0 + A_1F + A_2F^2$
where: F = Force (lbf)
A_0 = -1.122919E-03
A_1 = -1.728071E-04
A_2 = -1.117887E-11

Force (lbf) = $B_0 + B_1R + B_2R^2$
where: R = Response (mV/V)
B_0 = -6.493560E+00
B_1 = -5.786788E+03
B_2 = -2.155799E+00

STANDARD DEVIATION mV/V	RESOLUTION lbf	LOWER LIMIT FACTOR lbf
0.000072	0.058	0.997

Note: The lower limit factor applies only when the calibration equation is used to determine the force.

Figure 217: Calibration Report from Morehouse Showing a 2nd-degree Equation.

The calibration report in the above figure shows the formulas to solve for Response and an additional formula to solve for the Force.

The formula for Force is found by switching the x- and y-axis, as discussed in the previous section. If you wanted to generate coefficients to solve for Force or find the B coefficients, you would use the Predicted Response for the x-values and Force for the y-values. Morehouse has a spreadsheet available for download that will use these formulas to help interpolate values not on the calibration certificate.

*Note: Additional information on calculating the calibration equation is found in Section 8 of the ASTM E74 Standard titled Calculation and Analysis of Data. Microsoft Excel functions such as INDEX and LINEST are handy tools for using the least squares method. One would first take the average of the three runs and then could use a formula @INDEX(LINEST(**AVERAGE OF RUNS**:OFFSET(**AVERAGE OF RUNS**,COUNT(**FORCE***

***APPLIED VALUES**)-1,0),**ZERO**:OFFSET(**ZERO**,COUNT(**FORCE APPLIED VALUES**)-1,0)^{1,2,3,4,5}),6) - This example is for the 5th order polynomial, 4th Order would use the same formula ^{1,2,3,4}),5), 3rd order ^{1,2,3}),4), 2nd order ^{1,2}),3), ^{1}),2).*

ASTM E74 gives further guidance in Annex A1 on determining the degree of best-fitting polynomial for high-resolution force-measuring instruments.

MOREHOUSE CALIBRATION LOAD POINTS

Instrument Type	Load Cell	**MODE:**	Compression
Capacity:	25,000	**Serial No.**	Test for Article

ENTER LOAD CELL BEING CALIBRATED CAPACITY
ENTER HERE 25,000 LBF

POSITION	LOAD APPLIED	PREDICTED Response
1	0.0	-0.00112
2	500.0	-0.08753
3	2,500.0	-0.43321
4	5,000.0	-0.86544
5	7,500.0	-1.29780
6	10,000.0	-1.73031
7	12,500.0	-2.16296
8	15,000.0	-2.59574
9	17,500.0	-3.02867
10	20,000.0	-3.46174
11	22,500.0	-3.89494
12	25,000.0	-4.32829
13		-0.00112
14		-0.00112
15		-0.00112

CURRENT UNCERTAINTY 0.997

A COEFFICIENTS

A0	-1.12292E-03
A1	-1.72807E-04
A2	-1.11789E-11
A3	
A4	
A5	

B COEFFICIENTS

B0	-6.49356E+00
B1	-5.78679E+03
B2	-2.15580E+00
B3	
B4	
B5	

ENTER LOAD CELL BEING CALIBRATED CAPACITY
ENTER HERE 21,000 LBF

POSITION	LOAD APPLIED	PREDICTED Response
1	0.0	-0.00112
2	500.0	-0.08753
3	2,100.0	-0.36407
4	4,200.0	-0.72711
5	6,300.0	-1.09025
6	8,400.0	-1.45349
7	10,500.0	-1.81683
8	12,600.0	-2.18027
9	14,700.0	-2.54380
10	16,800.0	-2.90744
11	18,900.0	-3.27117
12	21,000.0	-3.63500
13		-0.00112
14		-0.00112
15		-0.00112

CURRENT LLF 0.997

ENTER mV/V VALUES IN PREDICTED RESPONSE
TO FIND THE ACTUAL LOAD APPLIED

POSITION	PREDICTED Response	LOAD APPLIED
1	0.00000	-6.5
2	-0.36407	2100.0
3	-0.72711	4200.0
4	-1.09025	6300.0
5	-1.45349	8400.0
6	-1.81683	10500.0
7	-2.18027	12600.0
8	-2.54380	14700.0
9	-2.90744	16800.0
10	-3.27117	18900.0
11	-3.63500	21000.0
12		-6.5
13		-6.5
14		-6.5
15		-6.5

CURRENT LLF 0.997

Figure 218: Morehouse Spreadsheet.

The formula for Response is used when you know the target force you wish to achieve and need to know what the device should read at that point.

For example, when reading the calibration certificate, if you want to apply 20,000 lbf of force, you will load the force-measuring device until it reads -3.46174 mV/V. However, if you want to apply 21,000 lbf of Force, you must use the above equation to solve for Force. This equation is **Response** = -1.122919E^{-03} + -1.728071E^{-11} * (**21,000)** + -1.117887E^{-11} *** (21,000^2).** Thus, to generate 21,000 lbf, the device should read -3.63500 mV/V. Morehouse has developed a simple spreadsheet where anyone can generate load tables and plug these equations in to solve for Force or Response.

Examining What the Coefficients Mean

A0 and B0 denote the constants associated with the y-intercept, marking the point where the equation intersects with the y-intercept.

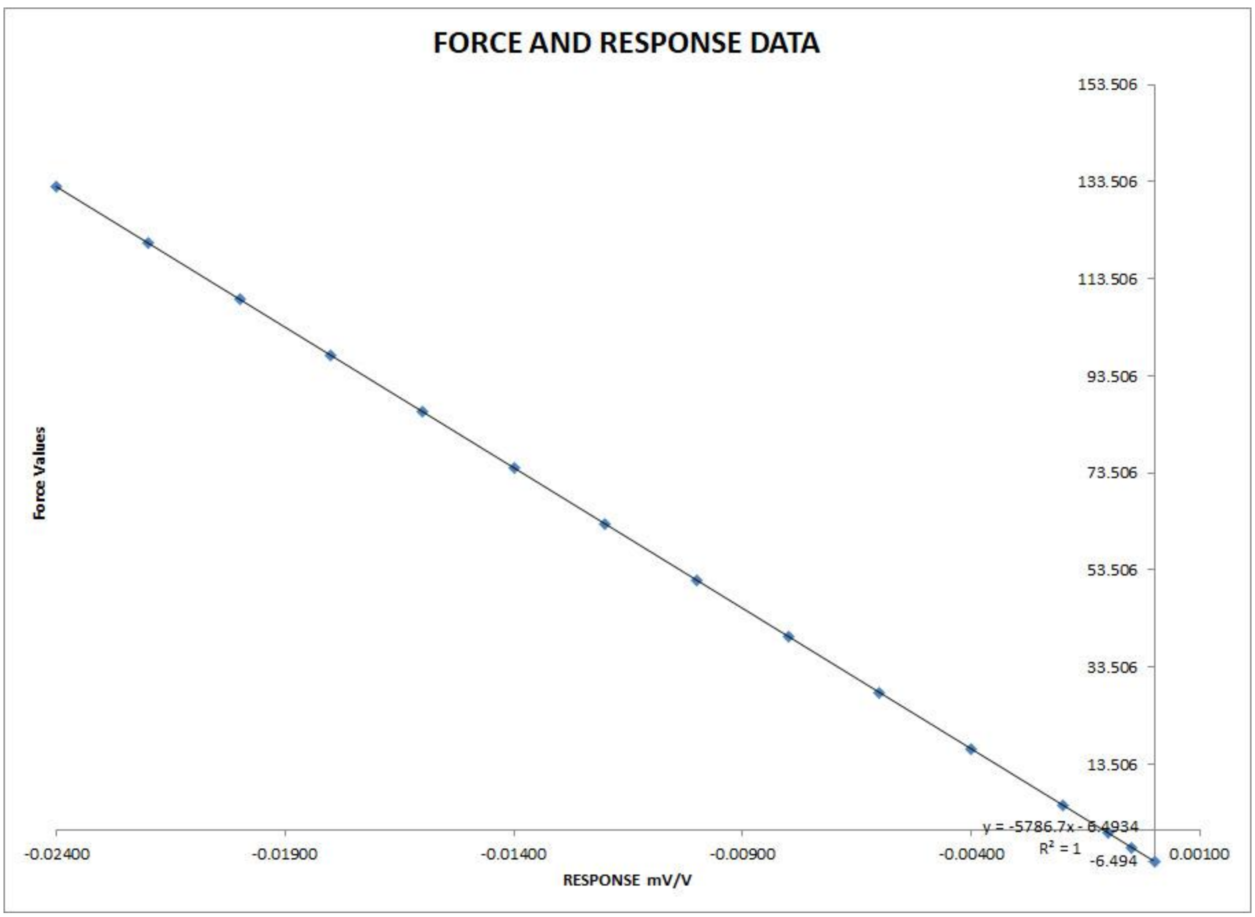


Figure 219: The Relationship of Force versus Response at Very Low Responses.

Many end-users do not like this data because they want to see 0 displayed on a device when they 0 the instrument. However, that is not how math works.

In this example, when the meter reads 0, the force value will be -6.49365 lbf or sometimes a rounded number, which would be -6.5 lbf as B_0 = -6.49356. This is because of the way the polynomial equation works in that Force (lbf) is equal to $B_0 + B_1$ * (Response)+B_2 * (Response^2). Simply put, B_1, B_2, and higher are multiplied by the 0 on the meter, except for the first one. The meter will read 0.0 when the Response equals A_0 or -0.00112 mV/V.

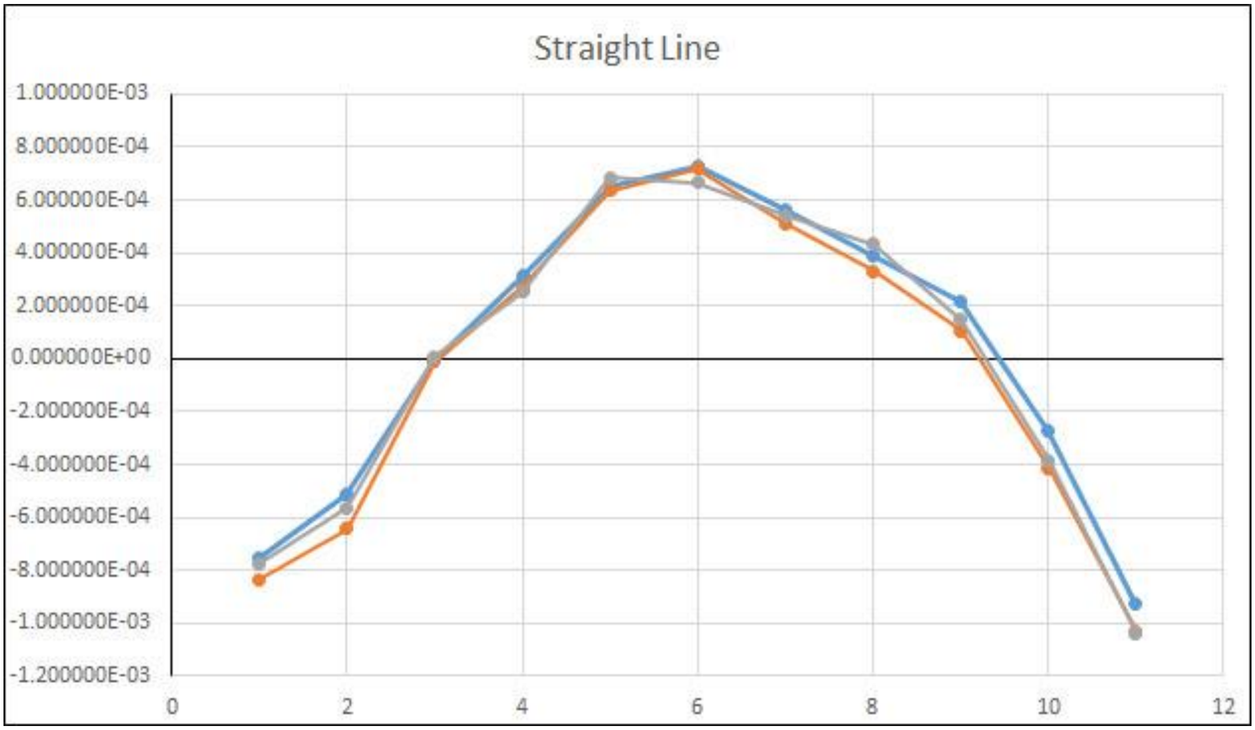


Figure 220: Deviation Between Actual Reading and Fitted Curve Using a Straight-Line Fit.

A_1 * F and B_1 * R are linear terms. F is the Force Applied, and R is the response (often in mV/V). In the above figure, we show the deviations from the fitted curve by drawing a straight line through all the points and then subtracting the predicted Response from the actual force-measuring device reading.

We use this method because if we showed three data runs with minimal changes, the lines would all blend, as shown in the figure above. The deviations are much more significant when using a straight line, and the reproducibility is less. The ASTM LLF, representing a large portion of the reproducibility error, jumps from 0.997 lbf, as shown in the above figure, to 8.14 lbf, or about eight times worse.

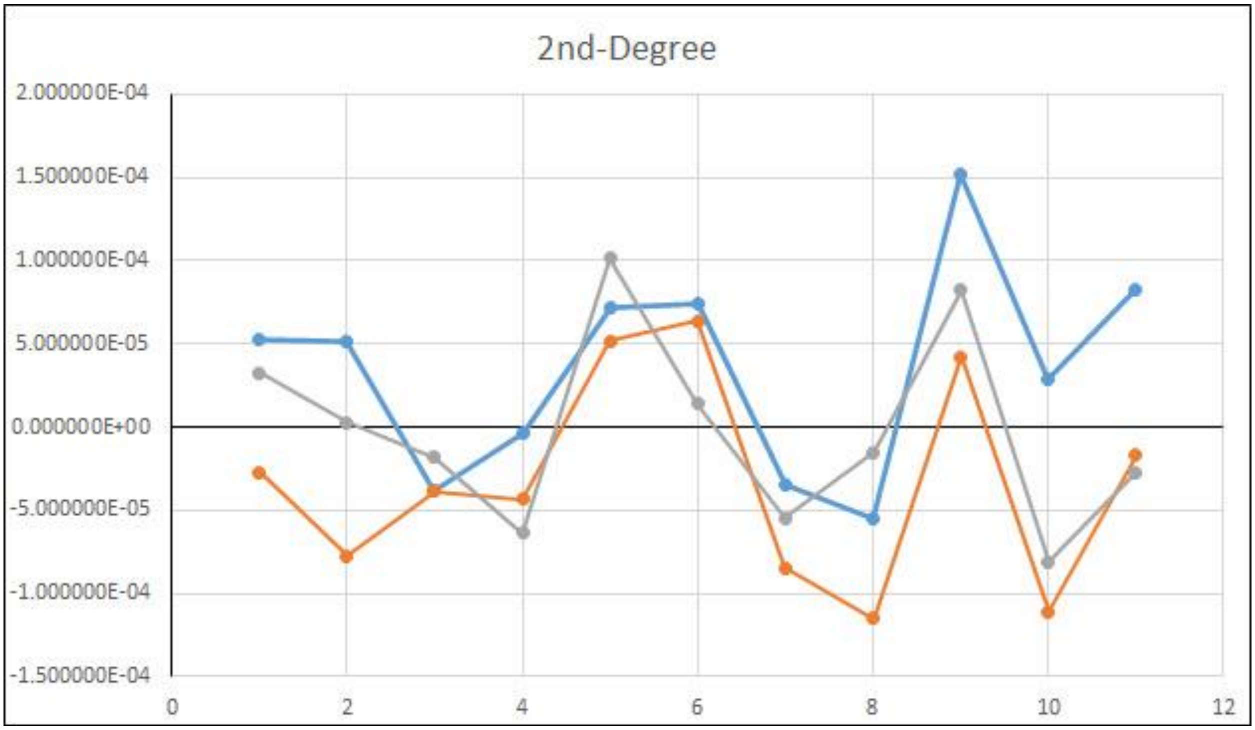


Figure 221: Deviation Between Actual Reading and Fitted Curve Using a Quadratic Fit.

$A_2 * F^2$ and $B_2 * R^2$ are quadratic terms.

A positive quadratic coefficient causes the ends of the parabola to point upward, while a negative quadratic coefficient causes the parabola to point downward. When we characterize the force-measuring device using a quadratic term, we get an ASMT LLF of 0.997 lbf; this will be the second-best fit as only the Quintic will be a little better.

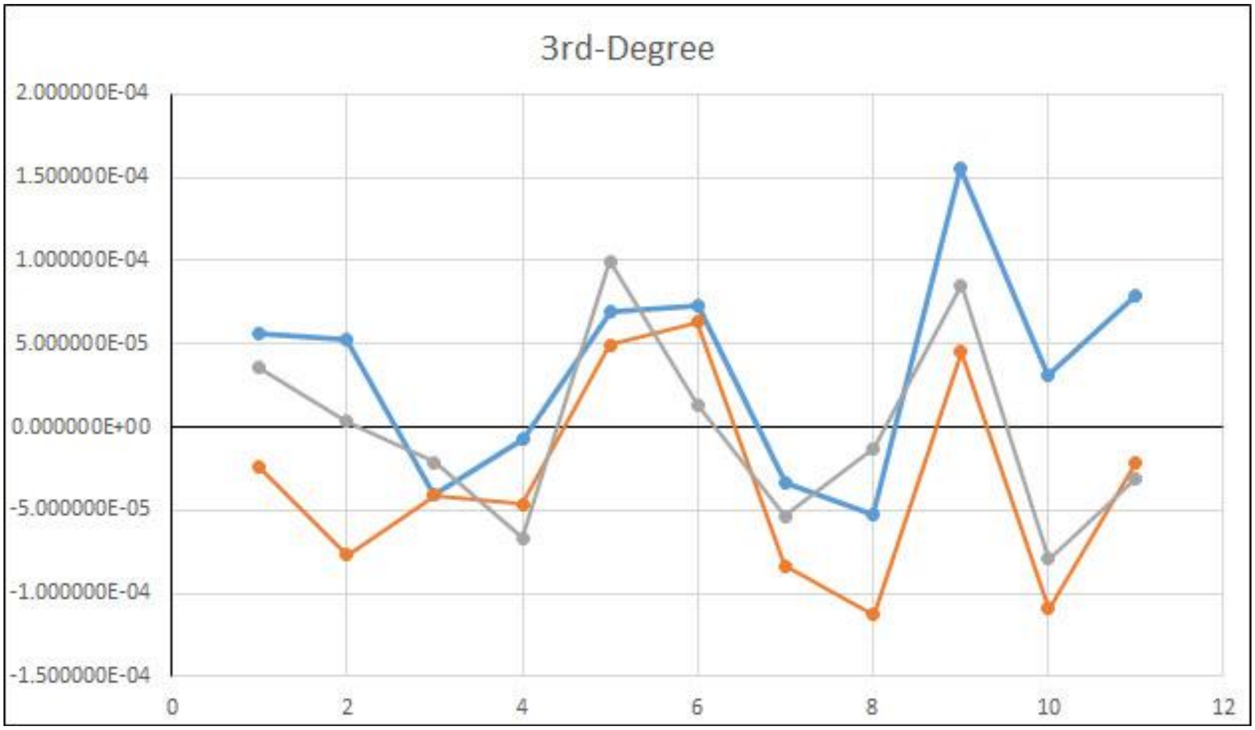


Figure 222: Deviation Between Actual Reading and Fitted Curve Using a Cubic Fit.

$A_3 * F^3$ and $B_3 * R^3$ are cubic terms.

This coefficient functions to make the graph "wider" or "skinnier" or to reflect it. If negative or the more significant the coefficient, the skinnier the graph. In our example, the cubic fit is slightly worse than the quadratic by about 0.15 lbf.

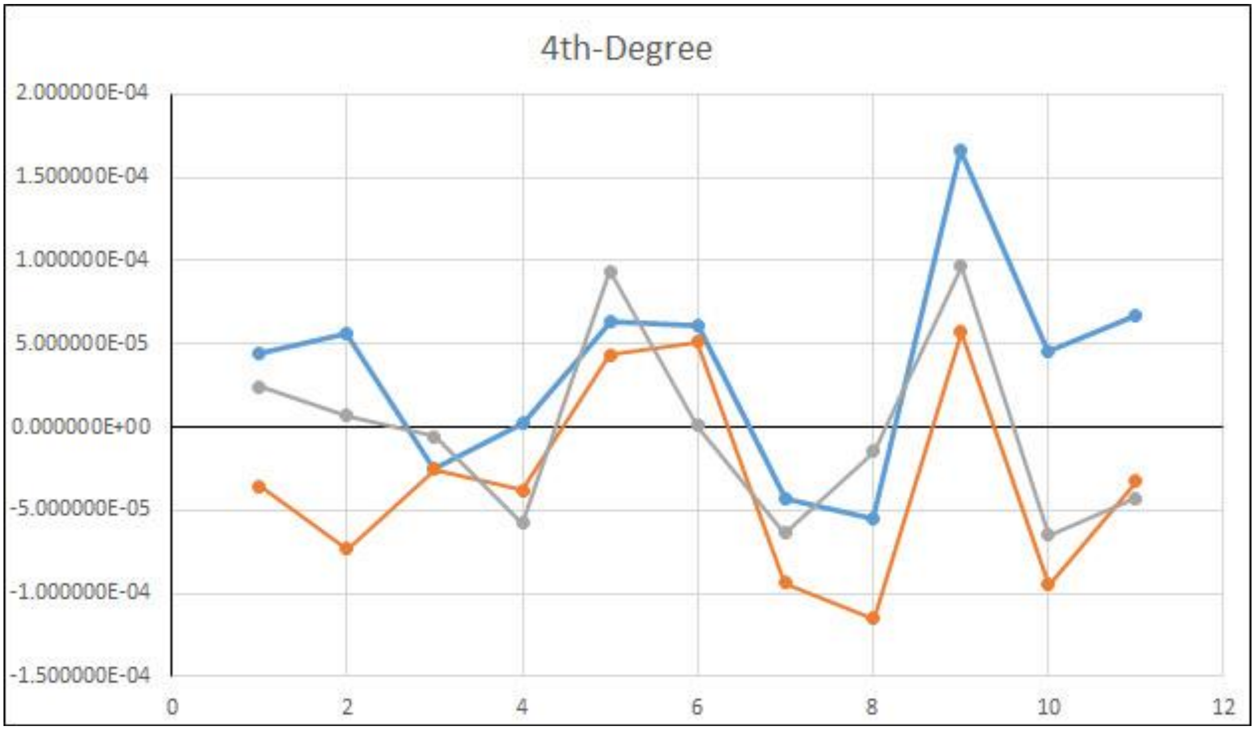


Figure 223: Deviation Between Actual Reading and Fitted Curve Using a Quartic Fit.

$A_4 * F^4$ and $B_4 * R^4$ are the quartic terms.

These have zero to four roots, one, two, or three extrema, zero, and one or two inflection points. The absence of typical symmetry often makes the solution much more complex. There can be different inflection points, and they can have various roots. In our example, the Quartic fit is slightly worse than the quadratic by about 0.17 lbf.

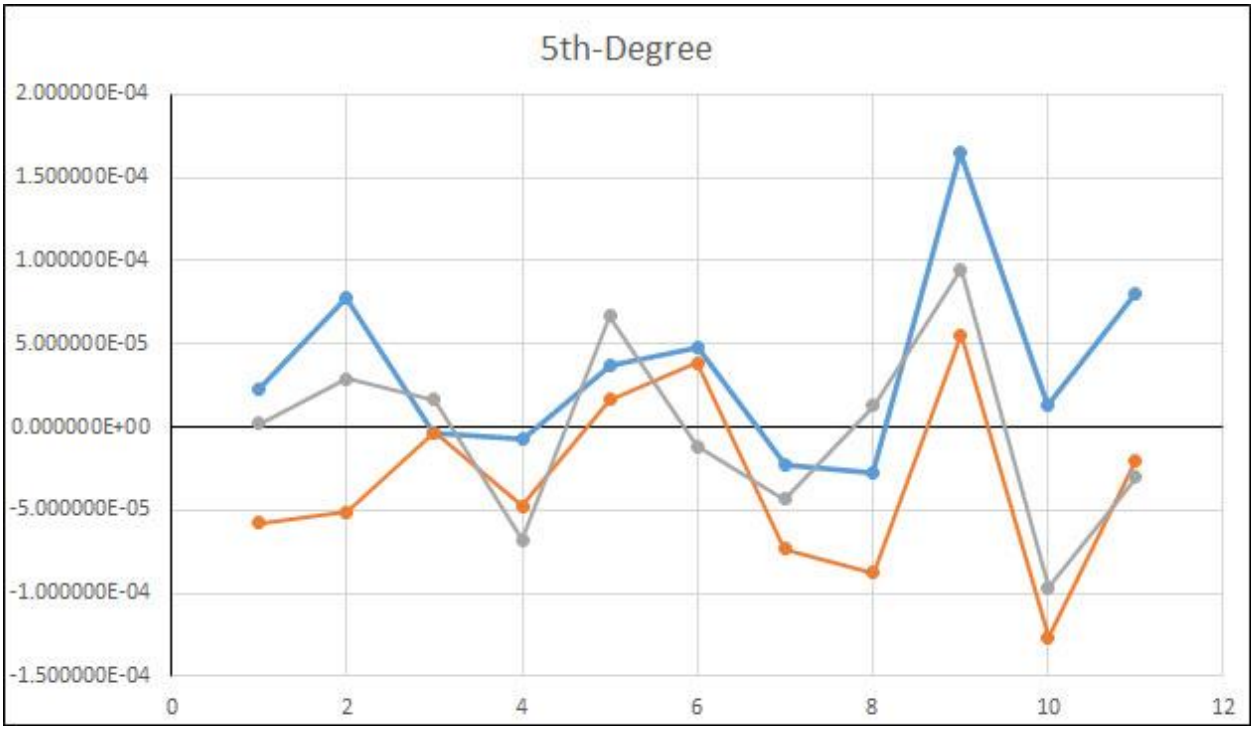


Figure 224: Deviation Between Actual Reading and Fitted Curve Using a Quintic Fit.

$A_5 * F^5$ and $B_5 * R^5$ are the quintic terms. These have one to five roots, zero to four extrema, one to three inflection points, and no general symmetry. In this example, the Quintic fit is better than the quadratic by about 0.17 lbf. The Quintic fit is the best overall fit.

Fit Summary	
Order Fit	ASTM llf
1	8.140
2	0.997
3	1.147
4	1.167
5	0.827

Figure 225: ASTM LLF for Each Fit Using the Same Data Set.

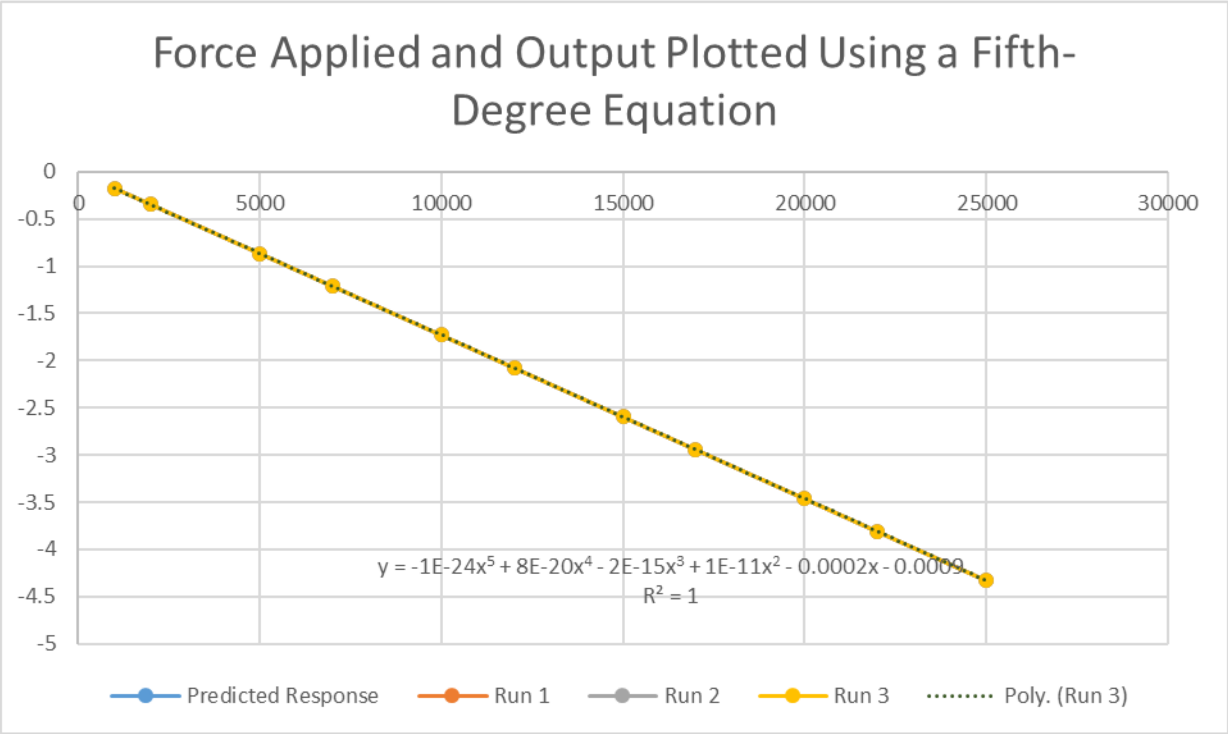


Figure 226: Showing the Plotted Values Versus the Force Applied.

Higher-order equations allow the line to take on different forms to best characterize the force-measuring device. The equations are like instructions telling the line to turn up or down, have a parabola, be narrow or wide, and in which directions; since we are dealing with such slight deviations, it is tough to see any of these behaviors on a graph, as shown above.

Suppose the force-measuring device is very repeatable but not as linear. In that case, the quartic or quintic function may best characterize the device by producing a curve that deviates at several points from linear behavior. The above figure shows that the R-squared value is 1, which means the curve coefficients best represent the line. This is because R-squared is a statistical measure representing the proportion of the variance for a dependent variable, explained by an independent variable or variables in a regression model.

The different standards have requirements that need to be met for higher-order equations. Implementing good measurement practices, having deadweight machines with very low uncertainties, and following published standards allow Morehouse to produce data with repeatable results.

We need to graph those deviations to show the actual behavior of the force-measuring device. The coefficients may best characterize the performance of the force-measuring device and allow the end-user to predict what the device should read at specific force points along the calibrated range.

The A_0 and B_0 coefficients will never be zero unless we force them to be, which is not the intent of the standards. Thus, when the indicator displays 0, and the equation to solve for force is used, the value at 0 will be the B_0 coefficient.

Load Cell Simulator Calibration Requirements to Calibrate my Digital Indicator: Is it Worth it?

We have been asked more frequently about the benefits of calibrating everything as a system versus calibrating the load cells and indicators separately and intermixing them using a calibrated load cell simulator.

Being able to intermix any load cell and meter combination makes a lot of sense.

If someone needs two load cells and a meter to do a specific job, they can check out the two load cells and a meter and adapters and perform the calibration or test.

The other unused load cells would then be available for someone else. If done correctly, this would be quite beneficial. Yet, many disadvantages and obstacles remain, such as maintaining(calibrating) a load cell simulator with enough span points, establishing metrological traceability, and correctly calculating its measurement uncertainty.

Every meter needs calibration, contributing to a larger overall measurement uncertainty.

As you do not have a married system, you need to establish traceability for both the load cell and meter independently.

Let's start by dealing with ISO 376 and ASTM E74 standards requirements. These are standards required for calibrating force-proving instruments, most known as load cells, to calibrate other force-measuring instruments, force machines, hardness machines, and testing machines, using ASTM E74, ASTM E4, ASTM E-10, ASTM E-18, ISO 376, ISO 7500 and so on.

ISO 376 and ASTM E74 requirements for meter calibration

ISO 376 in section C.2.11 Effect of a replacement indicator states,

"The deviation between the two indicators should be determined (there are several methods, e.g., calibration of both indicators, use of a common bridge simulator), and the uncertainty of this deviation should be estimated (including factors such as the calibration uncertainty of the indicators and the stability of the common bridge simulator). If corrections are made, the uncertainty of the deviation should be taken into account. If no corrections are made, the deviation and its uncertainty should be considered." [30]

Section 5 of the standard goes into more detail about when an electrical measurement is made. A summary of those requirements is as follows:

1. The calibration of the indicator shall be traceable to national standards. The replacement indicator shall be calibrated over a range equal to or greater than the range for which it is used with the

force-proving instrument. The resolution of the replacement indicator shall be at least equal to the original indicator's resolution when used with the force-proving instrument.

2. The units shall be of the same quantity: 5V, 10V, AC, or DC.
3. It is recommended that the replacement indicator be no greater than 1/3 of the uncertainty of the entire system.

Additionally, ISO 376 mentions programming indicators using span points.

If one does not use the calibration equation and programs point into an indicator that allows points from the calibration curve to be input so that the display is in units of force or torque but carries out linear interpolation between these points, the effect of this approximation to the curve should be investigated, and an uncertainty contribution should be included.

ISO 376 section 3.1 defines a force-proving instrument as a "whole assembly from the force transducer through to, and including, the indicator."[31]

One might be thinking, I do not calibrate following ISO 376. Maybe one only uses the ASTM E74 standard or a commercial calibration.

ASTM E74 is a bit more prescriptive in the requirements for substitution. Section 12 is explicitly titled Substitution of Electronic Indicating Instruments Used with Force-Measuring Systems.

The standard acknowledges that it might be desirable to treat the indicator and force-measuring instrument separately.

A huge benefit is if you purchase the same indicators, one could be used as a backup if the primary unit fails. Hence, there is a possibility of circumventing the costly calibration of the entire system.

Then, the standard goes on to list conditions that shall be satisfied to substitute a metrologically significant element of the electronic indicating instrument.

ASTM E74 Section 12.1.1 specifically states, "The electronic-indicating instrument used in the initial calibration and the instrument to be substituted shall each have been calibrated and their measurement uncertainties determined. The electronic indicating instrument to be substituted shall be calibrated with traceability to the SI over the full range of its intended use, including both positive and negative values if the system is used in tension and compression. The calibrated range shall include a point less than or equal to the output of the force transducer at the lower force limit, and a point equal to or greater than the output of the force transducer at the maximum applied force. A minimum of five points shall be taken within this range. The measurement uncertainty of each electronic indicating instrument shall be less than or equal to one-third of the uncertainty for the force-measuring system over the range from the lower force limit to the maximum force."[32]

To summarize, you must calibrate a simulator to comply with the standard. The simulator needs to be capable of both positive and negative values if the load cells are used in both positive and negative directions.

The simulator must have at least one point less than or equal to the lowest force point value in the range and one for the highest point.

Below is a picture of a Morehouse simulator. This simulator likely cannot be used to satisfy these requirements.

Figure 227 Morehouse Budget mV/V Load Cell Simulator.

The first point is 0.5 mV/V, and the last one is 4 mV/V. If someone had a 4 mV/V (10,000 Force Units) load cell and the verified range of force was 500 through 10,000 Force Units, the simulator at 0.5 mV/V would be 1,250 Force Units. If the verified range of forces started at 200, a 0.08 mV/V first step would be required.

Note: The best high-end simulators typically have the first step of 0.04 mV/V or lower, as 0.04 mV/V on a 2 mV/V load cell equates to a 2 % llf. A simulator that starts at 0.1 mV/V would equate to a 5 % llf on a 2 mV/V load cell.

2 mV/V is 5,000 Force Units. The end-user would need to raise their Class A verified range of forces to 1,250 FU using this simulator. This situation does not work for many, as they want to capture force values from the first non-zero calibrated point, typically below 5 % of the load cell's capacity.

The ASTM E 74 standard gives further guidance by stating the measurement uncertainty of the indicator shall be determined by one of the methods in Appendix X2. It recommends that the simulator has a series of mV/V steps of the measurement range with similar impedance characteristics and then states this requirement in section 12.1.2.

"The measurement uncertainty of the transducer simulator shall be less than or equal to one-tenth of the uncertainty for the force-measuring instrument." ASTM E74 further states, "Excitation voltage amplitude, frequency, and waveform shall be maintained in the substitution within limits to ensure that the affect on the calibration is negligible. It is the user's responsibility to determine limits on these parameters through measurement uncertainty analysis and appropriate tests to ensure that this requirement is met. Substitution of an interconnect cable can have a significant effect on calibration. If an interconnect cable is to be substituted, see Note 15."[33]

This is interesting as the interconnect cable for the simulator does not always share the same connection as the load cell. If the system is not 6-wire, meticulous care will be needed to ensure the same gauge wire and length is used for the simulator to meter connection as that of the load cell.

Note 15 goes into more detail, and Morehouse covers much of this in our section about four and six-wire indicators.

Appendix X2 details all the steps necessary to determine the uncertainty. Morehouse fully supports ASTM E74 and feels the membership is incredible. For around $ 100.00, one can join and access a catalog of standards. This author believes this is one of the best deals in the industry. Signing up is simply at astm.org.

The summation of what is needed is as follows:

1. At least five readings for each polarity over the range must be taken.
2. The points need to be less than or equal to the first point in the Class A or AA verified range of forces, and the capacity needs to have a point equal to or greater than the maximum output observed during calibration. So, if loading a 10,000 Force Unit load cell to 11,000 Force Units, which might read 4.4 mV/V, a 4.0 mV/V simulator is not good enough.
3. The load cell simulator shall provide at least one point for every 20 % interval throughout the range. (Interesting tidbit here as the standard says five points, though the simulator needs to have the low force point and an additional 5 points to cover up to capacity or higher for a total of six points throughout the range)
4. Section 8. Calculation and Analysis of Data of the ASTM E74 standard provides guidance to determine the standard deviation Type A uncertainty component for calibration of the indicator.
5. The excitation voltage, waveform, and other characteristics need to be maintained.
6. In no case can someone substitute a meter without meeting the measurement uncertainty and traceability requirements.

Okay, so the benefits might still outweigh the additional headache of using a simulator and being able to separate one's load cells from the indicator or decouple the system.

However, there are a lot more error sources one needs to be aware of.

One of the error sources we see missed quite a bit is not having the load cell calibration excitation and waveform match that of the meter being used. A good example is many USB digital indicators providing less than 10 V DC output. To comply with these requirements, one must calibrate their load cells at the same excitation and waveform as the meter. If the USB meter puts out 5 VDC, then the load cell calibration should be at 5 VDC.

Additional error sources include Calibration Uncertainty (Gain Error), Zero Offset, Temperature Effect on Sensitivity, Quantization Error, Normal Mode Voltage, Power Line Voltage Variation, Non-Linearity, Temperature Effect on Zero, Gain and Zero Stability, Common-Mode Voltage, Noise, Electrical Loading, Error Signals due to thermal EMF, Difference in cabling if not a true 6-wire system. All these error sources should be evaluated.

When the amount of work required to capture all these error sources, dot all of the I's and cross all of the T's is considered, we often find it much more sensible to consider buying one digital indicator per load cell. Most of these USB-type digital indicators, like the Morehouse HADI, are excellent, very reasonably priced, and can easily accommodate the goal of scheduling equipment.

If a load cell or a meter malfunctions, only one piece of equipment is down, and work can continue.

Morehouse can work with anyone to get that equipment back up quickly. If a HADI indicator gets run over, dropped, or damaged, we could replace and calibrate the load cell with the new meter as a system quickly—in less than two weeks.

I believe marrying one indicator to a load cell is often less risky and more cost-effective. It provides all the benefits of using different-size load cells for various measurements. Going down the substitution route requires separate calibration for the load cell and each indicator.

The long-term cost is typically much larger, as is the overall measurement uncertainty.

You are effectively now paying for two calibrations instead of one system calibration.

Typical Error Sources for Meter Substitution

When calculating Measurement Uncertainty for a meter to be used for substitution, the following are typical error sources:

Simulator Uncertainty includes the resolution of the meter, calibration of the simulator and the associated reference standard uncertainties, stability of the simulator, and the ratio uncertainty. At Morehouse, we achieve about ± 0.00005 mV/V uncertainty on our high-end simulator using different cables for positive and negative output as the polarity switch introduces additional uncertainty.

On the meter side, non-linearity, stability, environmental, ref uncertainty from the simulator, additional cable Uncertainty, noise or resolution, repeatability, and reproducibility are all additional measurement uncertainty components.

In our experience, most who use meter substitution add about 0.02 % - 0.04 % uncertainty to their systems. This is too much uncertainty for ASTM Class AA calibrations that are expected to be better than 0.05 %, too much for ISO 376 Class 00, 0.5, and likely too much for Class 1 & 2. The requirement for an ASTM Class A is to be better than 0.25 %.

The contribution to uncertainty is often significant, though manageable.

Morehouse does offer calibration of load cell simulators to comply with either ASTM E74 or ISO 376. Below is a page from our calibration report for one of our reference standard simulators.

These simulators have high-quality aged resistors and steps from 0.04 – 4.4 mV/V. The standard deviation is less than the resolution, hence the importance of having the resolution as part of the overall measurement uncertainty.

CERTIFICATE OF CALIBRATION

AS RECEIVED / AS RETURNED

CALIBRATION & ISSUE DATE: 10/26/2021
Page: 2 of 5
REPORT NO.: 1773J2621

MOREHOUSE SIMULATOR MODEL: 0404-8 SERIAL NO.: 1773
CALIBRATED TO: 4.40 mV/V POSITIVE & NEGATIVE ASCENDING

With Indicator:
Morehouse Electrical Standard MODEL: Agilent 3458A SERIAL NO.: US28028943

Calibration Procedure: ASTM E74-18 Method B

Ambient Temperature at Calibration: 22.8 °C

Nominal Excitation Voltage: 10 VOLTS DC

The output was sensed at the connector.

POSITIVE RAW DATA-MEASURED OUTPUT WITH INITIAL & RETURN ZEROS

SIMULATOR VALUE mV/V	MEASURED OUTPUT RUN 1 mV/V	MEASURED OUTPUT RUN 2 mV/V	MEASURED OUTPUT RUN 3 mV/V
0.00	0.00000	0.00000	0.00000
0.04	0.03999	0.03999	0.03999
0.08	0.07998	0.07998	0.07998
0.20	0.19998	0.19999	0.19999
0.40	0.39997	0.39997	0.39998
0.80	0.79999	0.79999	0.80000
1.20	1.20000	1.20000	1.20001
1.60	1.60001	1.60001	1.60001
2.00	2.00000	2.00002	2.00002
2.40	2.40000	2.40001	2.40001
3.20	3.20005	3.20006	3.20006
4.00	4.00002	4.00002	4.00000
4.40	4.40000	4.40000	4.40000
0.00	0.00000	0.00000	0.00000

Figure 228 Morehouse Page from Simulator Calibration Report in mV/V.

Morehouse Budget Load Cell Simulator

Back to the simulator, that likely is not enough to calibrate the meters for substitution. Why would anyone want this? The best answer is cost.

The Morehouse budget simulator costs around $ 600.00 compared with a higher-end model costing over $ 4,500.00 plus calibration. So, what? It does not allow me to calibrate my meter. That is technically correct, though it is a potent tool.

Our simulator allows the end-user to do the following:

1. Perform cross-checks on equipment.
2. Help control stability/drift.
3. Verify that the coefficients are correctly entered in our 4215 Plus and C705P meters; both use the actual coefficients from the calibration report. Verify coefficients for other programs, such as Morehouse calibration software.
4. Check for linearity issues in any meter.
5. Use as a diagnostic tool to rule out the load cell meter, leaving the load cell, cables, or adapters as the issue.
6. It can be used to calibrate A/D offset and gain settings.
7. It can be used to set up a new indicator before system calibration.

Meter Substitution Conclusion

When accessing overall measurement uncertainty, I always strive to do what yields the lowest overall measurement uncertainty to limit the overall risk. Calibrating everything as a system is much better, keeping the measurement traceability chain clean.

Adding a load cell simulator and its associated measurement uncertainty and the calibration of several meters can be challenging.

Many people struggle with calculating measurement uncertainty for "married" systems, and adding more requirements creates additional uncertainty and headaches.

There is a risk/reward scenario for separately calibrating the indicator and load cells. Much additional work is required to comply with either ISO 376 or the ASTM E74 standard. It might be worth it if that extra work saves time and money.

Any meter used for substitution must have the same characteristics, excitation, and waveform.

Plus, the overall uncertainty increases by an additional 0.02 – 0.04 %, which will be absorbed by everyone else down the metrological traceability pyramid.

Though unsuitable for meter calibration following ISO 376 or ASTM E74, our budget simulator can save a lot of time when troubleshooting equipment and verifying that everything was keyed incorrectly via coefficients from a calibration report without breaking the bank.

We can provide higher-end simulators for indicator substitution, though the cost is likely over $5000.00, depending on the exact steps and requirements.

The topics covered in this section cover many situations that could lead to not getting the expected performance or calibration result you might require. At Morehouse, we constantly produce more content related to measurement errors, load cell design, and many other topics. If you want to learn more, subscribe to our newsletter and read our blog.

How To Calculate Measurement Uncertainty for Force

All ISO/IEC 17025 accredited calibration laboratories must submit uncertainty calculations for their Calibration and Measurement Capability (CMC) uncertainty claims included in the accreditation scope. If any assumptions are made to determine the uncertainty budgets, they must be specified and documented. ISO/IEC 17025 laboratories shall calculate measurement uncertainties using the method detailed in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM).[34]

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."[35]

ILAC P14:09/2020 requires:
"4.1 The scope of accreditation of an accredited calibration laboratory shall include the calibration and measurement capability (CMC) expressed. in terms of:
a) measurand or reference material;
b) calibration or measurement method or procedure and type of instrument or material to be calibrated or measured;
c) measurement range and additional parameters where applicable, e.g. frequency of applied voltage;
d) measurement uncertainty."[36]

Many often ask, "How do I calculate Measurement Uncertainty for my force system?" It is a great question, and the answer varies depending on several factors. We can provide guidance for identifying all significant contributions to measurement uncertainty in the calibration of force-measuring instruments.

This guidance is an overview of evaluating measurement uncertainty in the calibration of force-measuring instruments to support CMC in the scope of accreditation, calibration certificates, or measurement reports.

> Morehouse has several additional guidance documents and tools to make uncertainty calculation easy. You can find these tools on our website.

Force-measuring instruments generally fall into two categories.

a) Force-measuring instruments for the calibration of other force-measuring equipment.
   Note: Any calibration laboratory performing calibration to further disseminate the unit of force would fall into this category.
b) Force-measuring instruments for measurement of force.
   Note: The end use of a force-measuring instrument is for an application where there is a "go/no-go"

or “Pass/Fail” scenario, where the testing stops, and there is no further dissemination of force. Examples: material testing machines, weighing force-measuring instruments

NPL Guide 102:[37]
Calibration is required to ensure that the force measurement meets the user's needs and achieves the required degree of uncertainty. The calibration of a force measurement system requires an understanding of traceability, standards, options, and procedures and an analysis of the data.

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

Machine Type	**Principle of operation**	**Uncertainty attainable**	**Category**
Deadweight machines	A known mass is suspended in the Earth’s gravitational field, generating a force on the unit under test.	± 0.001 %.	Primary or Secondary
Hydraulic amplification machines	A small deadweight machine applies a force to a piston-cylinder assembly, and the pressure thus generated is applied to a larger piston-cylinder assembly.	± 0.02 %.	Secondary
Lever amplification machines	A small deadweight machine with a set of levers that amplify the force	± 0.02 %.	Secondary
Strain-gauged hydraulic machines	The force applied to an instrument is reacted against by strain-gauged columns in the machine's framework.	± 0.05 %.	Secondary
Reference force transducer machines	A force transfer standard is placed in series with the instrument to be calibrated (typically in a material testing machine).	± 0.05 %.	Secondary

Figure 229: Figure from NPL Guide 102.

Guidelines for calculating CMC uncertainty.

Type A Uncertainty Contributions

The GUM states that all data analyzed statistically is treated as a Type A contribution with a normal statistical distribution.[38] Typical examples are:

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

Repeatability contribution is required by the GUM, A2LA R205, and UKAS (United Kingdom Accreditation Service) M3003.

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

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

Type B uncertainty contributions.

Per the GUM, Type B evaluation of standard uncertainty may include:[39]

- Previous measurement data
- Experience with or general knowledge of the behavior and properties of relevant materials and instruments
- Manufacturer's specifications
- Data provided in calibration and other certificate(s)
- Uncertainties assigned to reference data taken from handbooks.

A2LA R205 clarifies these type B contributions by requiring:[40]

- 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

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

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

Note 2: Several laboratories using primary standards have found the Repeatability of a top-quality force-measuring instrument in a deadweight machine to be less than 2 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 insignificant reproducibility and repeatability between technicians. These three error sources, which may be insignificant using deadweight primary standards, may become significant at the next measurement tier.

Common error sources for force include:

- Alignment
- Using a different hardness of the adapter than 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 4-wire system.
- Using electronic instruments (indicators) that were not used during calibration.
- An excitation voltage that is different from the voltage used at the time of calibration is used.
- Variations in bolting a force transducer to a base for calibration while the 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.

Specific Guidance

Force-measuring instruments for the calibration of other force-measuring equipment are:

1. Force-measuring instruments calibrated in accordance with the ASTM E74 standard.
2. Force-measuring instruments not calibrated to any known standard.
3. Force-measuring instruments for measurement or verification of force.
4. Force-measuring instruments calibrated in accordance with ISO 376.

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

Force-measuring instruments calibrated following the ASTM E74 standard.

This section can be used as guidance for the force-measuring instruments calibrated following ASTM E74 and used for ASTM E4 and other calibrations to determine the laboratory's CMC. The ASTM E4 Annex gives additional detail on calculating the measurement uncertainty for the ASTM E4 verification/calibration.

The contributions to the CMC uncertainty are:

Type A Uncertainty Contributions

1. ASTM LLF reported as 1 Standard Deviation (k=1). ASTM LLF is reported with k= 2.4.
   Note: 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 required.
2. Repeatability conducted with the Best Existing Force-measuring instrument.
3. Repeatability and Reproducibility

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

Type B Uncertainty Contributors

1. Resolution of the Best Existing Force-measuring instrument
2. Reference Standard Resolution (if applicable)
3. Reference Standard Uncertainty
4. Reference Standard Stability
5. Environmental Factors
6. Other Error Sources

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

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

Table 1: Example of a Single Point Uncertainty Analysis for Force-Measuring Instruments Calibrated by the ASTM E74 Standard.

1. Force-measuring instruments calibrated according to the ASTM E74 standard are continuous reading force-measuring instruments. Any uncertainty analysis should be conducted on several test points used throughout the loading range.
2. There are Excel spreadsheets available for calculating measurement uncertainty from various force calibration laboratories. If the spreadsheets are used, the laboratory should validate the spreadsheet templates.
3. The % Contribution Column is useful in determining significant contributors to uncertainty.

The Morehouse website has additional information for force-measuring instruments calibrated following the ASTM E74 Standard and a spreadsheet tool.

Force-measuring instruments not calibrated to a published standard or commercial calibrations.

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

The contributions for the CMC uncertainty are:

Type A Uncertainty Contributions

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

Type B Uncertainty Contributions

1. Resolution of the Best Existing Force-measuring Instrument.
2. Reference Standard Resolution (if applicable)
3. Reference Standard Uncertainty
4. Reference Standard Stability
5. Environmental Factors
6. Other Error Sources
7. Specified Tolerance: if not listed and making ascending measurements only. If making ascending and descending measurements, use Static Error Band (SEB) or a combination of Non-Linearity and Hysteresis. If the force-measuring instrument is calibrated with an indicator and set up to have a tolerance, then it may not be necessary to include Non-Linearity, Hysteresis, or SEB.
   Note: If the force-measuring instrument is going to be used at points different from the points at which it was calibrated, then SEB, non-linearity, or hysteresis may need to be used.
8. Hysteresis is only if the force-measuring instrument is used to measure decreasing forces, and SEB is not used.

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

Table 2: Example of a Single Point Uncertainty Analysis for a 10,000 FORCE UNITS Force-measuring Instrument with Not Calibrated to a Published Standard (Hysteresis was Included in the Uncertainty Budget).

The Morehouse website has additional information for force-measuring instruments not calibrated to a published standard or commercial calibrations and a spreadsheet tool.

Force-measuring instruments for measurement or verification of force.

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

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

Measurement uncertainty in the measurement of force:

In this case, the reference standard is the force-measuring instrument used to measure force.

Type A Uncertainty Contributions

1. Repeatability
2. Repeatability and Reproducibility

Type B Uncertainty Contributions

1. Resolution of the Best Existing Force-measuring instrument (if applicable)
2. Reference Standard Resolution (if applicable)
3. Reference Standard Uncertainty
4. Reference Standard Stability
5. Environmental Factors
6. Other Error Sources
7. Specified Tolerance: If a specified tolerance is not given, SEB, Non-Linearity, or Hysteresis could be used.

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

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

Force-measuring instruments calibrated following the ISO 376 standard.

Per EURAMET-cg-04, the evaluation of measurement uncertainty in calibrations of transducers per ISO 376 should account for the following uncertainty contributions in relative terms:[41]

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

Type A Uncertainty Contributions

1. Repeatability of the Best Existing Force-measuring Instrument.
2. Repeatability and Reproducibility

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

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

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

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

The Morehouse website has additional information for force-measuring instruments calibrated following the ISO 376 Standard and a spreadsheet tool.

How To Comply with ILAC P-14 when Reporting Expanded Uncertainty

ILAC P-14 is a mandatory policy document for laboratories accredited to the ISO/IEC 17025 standard. How can a laboratory ensure that expanded uncertainty is reported in compliance with ILAC Policy Measurement Uncertainty in Calibration, ILAC P-14?

In ILAC P-14, section 5 relates to calibration certificates. The summarized criteria are:

1. Measurement Uncertainty shall be reported in compliance with the GUM.
2. The measurement result should be reported as $y \pm U$, or $U / |y|$, and the coverage factor and coverage probability shall be stated.
3. At most, the expanded uncertainty shall be given to two significant digits, and proper rounding rules apply.
4. Contributions to uncertainty shall include relevant short-term contributions that can reasonably be attributed to the customer's device.
5. The uncertainty reported shall not be less than the measurement uncertainty described by the CMC.
6. The Measurement Uncertainty shall be presented as the same unit as that of the measurand or in a term relative to the measurand (e.g., percent)

Below are three examples of how Morehouse calculated expanded uncertainty at the time of calibration and reported it in compliance with ILAC P-14. For the examples presented here, we focus on section 5.4 of ILAC P-14:09/2020:
"Contributions to the uncertainty stated on the calibration certificate shall include relevant short-term contributions during Calibration and contributions that can reasonably be attributed to the customer's device. Where applicable, the uncertainty shall cover the same contributions to uncertainty that were included in evaluation of the CMC uncertainty component, except that uncertainty components evaluated for the best existing device shall be replaced with those of the customer's device. Therefore, reported uncertainties tend to be larger than the uncertainty covered by the CMC. Contributions that cannot be known by the laboratory, such as transport uncertainties, should normally be excluded in the uncertainty statement. If, however, a laboratory anticipates that such contributions will have significant impact on the uncertainties attributed by the laboratory, the customer should be notified according to the general clauses regarding tenders and reviews of contracts in ISO/IEC 17025."

To replicate the results found on a Morehouse Certificate of Calibration, use this Excel template.

Example 1: 50,000 lbf Tension Link

The relevant short-term contributions to uncertainty are:

1. The uncertainty of the reference standard used for calibration.
2. The resolution of the tension link.
3. The repeatability of the tension link.

Typically, the resolution of a tension link is dominant and does not show any deviation. Usually, customers do their repeatability studies in their applications. Thus, we are limited to contributions 1 and 2.

Company	
Company Name	Calibrations R Us
Date	4/20/2022
Instrument Type	Tension Link
Instrument Serial Number	TL-Smaple
Meter Serial Number	
Force Units	lbf
Mode Type	Tension

Enter Information and Data From Morehouse Certificate

Uncertainty	
Ref Exp Unc in a % or numerical form?	Percentage
Ref Exp if % Unc k = 2	0.0020%
mV/V % Unc k = 2	
Readability	10.000000
ASTM LLF (From Cert)	
Round SIG FIG	5.0

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
2.8873	5.7745	5.7745	0.11549%	5.77454
2.8857	5.7714	5.7714	0.05771%	5.77714
2.8907	5.7815	5.7815	0.03854%	5.78146
2.8938	5.7875	5.7875	0.02894%	5.78751
2.8976	5.7953	5.7953	0.02318%	5.79528
2.9024	5.8048	5.8048	0.01935%	5.80476
2.9080	5.8160	5.8160	0.01662%	5.81595
2.9130	5.8260	5.8260	0.01456%	5.82888
0.5346	1.0693	1.0693	0.00238%	10.69308
2.9292	5.8585	5.8585	0.01172%	5.85966

Enter Force Applied and Reduced Run Data From Certificate

Tension Uncertainty Analysis at the Time of Calibration

Test Point #	Force Applied lbf	Fitted Curve or Average or Measured Output	Force Applied k = 2	Force Applied k = 2	Force Applied uw k = 1	mV/V k = 1	mV/V uv k = 1	Resolution UUT Res	Resolution Readability	Resolution ures Res/3.464	ASTM llf k = 2.4	ASTM llf ur k = 1
1	5000.0	5000.0	0.0020%		0.050	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
2	10000.0	10010.0	0.0020%		0.100	0.0000%	0.0000	1.0	10.000000	2.8840	0.0000	0.0000
3	15000.0	15000.0	0.0020%		0.150	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
4	20000.0	20000.0	0.0020%		0.200	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
5	25000.0	25000.0	0.0020%		0.250	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
6	30000.0	30000.0	0.0020%		0.300	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
7	35000.0	35000.0	0.0020%		0.350	0.0000%	0.0000	1.0	10.000000	2.8868	0.0000	0.0000
8	40000.0	40020.0	0.0020%		0.400	0.0000%	0.0000	1.0	10.000000	2.8854	0.0000	0.0000
9	45000.0	450020.0	0.0020%		0.450	0.0000%	0.0000	0.1	10.000000	0.2887	0.0000	0.0000
10	50000.0	50010.0	0.0020%		0.500	0.0000%	0.0000	1.0	10.000000	2.8863	0.0000	0.0000
11												
12												
13												

Figure 230: Expanded Uncertainty for a 50,000 lbf Tension Link.

The inputs to calculate our expanded uncertainty at the time of calibration are:

1. The uncertainty of the reference standard: 0.0016 % of applied force
2. The resolution of the tension link: 10 lbf

This uncertainty does not include any contribution from bias. Therefore, the end-user must calculate the additional error for any bias. They could apply 50,040 lbf to generate 50,000 lbf of force, use an equation, or account for the bias by other acceptable means.

Additional uncertainty contributions from varying pin sizes are also not accounted for. Morehouse will use the pins sent in with the device or use the manufacturer's recommended pin size. We have observed errors up to 20 times that of a manufacturer's specifications from not using the right size pin.

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
2.8873	5.7745	5.7745	0.11549%	5.77454
2.8857	5.7714	5.7714	0.05771%	5.77714
2.8907	5.7815	5.7815	0.03854%	5.78146
2.8938	5.7875	5.7875	0.02894%	5.78751
2.8976	5.7953	5.7953	0.02318%	5.79528
2.9024	5.8048	5.8048	0.01935%	5.80476
2.9080	5.8160	5.8160	0.01662%	5.81595
2.9130	5.8260	5.8260	0.01456%	5.82888

0.5346	1.0693	1.0693	0.00238%	10.69308
2.9292	5.8585	5.8585	0.01172%	5.85966

Figure 231: Expanded Uncertainty of 50,000 lbf Tension Link at the time of Calibration.

The columns in the uncertainty table are:

- uc = Standard Uncertainty
- U = Expanded Uncertainty with a coverage factor of 2 for approximately 95 % Confidence; in this case, it would be 95.45 %, as the degrees of freedom are quite high. *
- The next columns are U rounded to whatever significant figures are typed in, and what is reported on our certificates under Expanded Uncertainty, U converted to a percentage, and U as response units, which is the force applied multiplied by U as a %.

Example 2: 50,000 N Load Cell

The load cell is submitted for a 10-PT calibration. The relevant short-term contributions to uncertainty are:

1. The uncertainty of the reference standard(s) used for calibration.
2. The resolution of the load cell.
3. The repeatability of the load cell at the time of calibration.
4. The uncertainty of our voltage reference (0 if a meter was sent in with the load cell for calibration).

We used our Fluke 8508 and Deadweight Primary Standard in this example.

Company	
Company Name	Calibrations R Us
Date	4/20/2022
Instrument Type	Load Cell
Instrument Serial Number	U-Sample
Meter Serial Number	MY025154
Force Units	N
Mode Type	Tension

Uncertainty	
Ref Exp Unc in a % or numerical form?	Percentage
Ref Exp if % Unc k = 2	0.0020%
mV/V % Unc k = 2	0.0010%
Readability	0.000010
ASTM LLF (From Cert)	

Round SIG FIG	2.0

Enter Information and Data From Morehouse Certificate

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
0.0665	0.1331	0.1300	0.00260%	0.00001
0.1175	0.2350	0.2300	0.00230%	0.00002
0.1715	0.3431	0.3400	0.00227%	0.00003
0.2265	0.4530	0.4500	0.00225%	0.00004
0.2818	0.5637	0.5600	0.00224%	0.00004
0.3373	0.6747	0.6700	0.00223%	0.00005
0.3930	0.7859	0.7900	0.00226%	0.00006
0.4487	0.8973	0.9000	0.00225%	0.00007
0.5044	1.0088	1.0100	0.00224%	0.00008
0.5602	1.1204	1.1200	0.00224%	0.00009
	0.0000	0.0000		
	0.0000	0.0000		

Enter Force Applied and Reduced Run Data From Certificate

	Tension Uncertainty Analysis at the Time of Calibration												
		Fitted Curve or	Force Applied	Force Applied	Force Applied	mV/V		Resolution			ASTM llf	
	Force Applied	Average or			uw		uv			ures		ur
Test Point #	N	Measured Output	k = 2	k = 2	k = 1	k = 1	k = 1	UUT Res	Readability	Res/3.464	k = 2.4	k = 1
1	5000.0	0.40001	0.0020%		0.050	0.0005%	0.0250	12499.7	0.000010	0.0361	0.0000	0.0000
2	10000.0	0.80002	0.0020%		0.100	0.0005%	0.0500	12499.7	0.000010	0.0361	0.0000	0.0000
3	15000.0	1.20003	0.0020%		0.150	0.0005%	0.0750	12499.7	0.000010	0.0361	0.0000	0.0000
4	20000.0	1.60004	0.0020%		0.200	0.0005%	0.1000	12499.7	0.000010	0.0361	0.0000	0.0000
5	25000.0	2.00005	0.0020%		0.250	0.0005%	0.1250	12499.7	0.000010	0.0361	0.0000	0.0000
6	30000.0	2.40006	0.0020%		0.300	0.0005%	0.1500	12499.7	0.000010	0.0361	0.0000	0.0000
7	35000.0	2.80007	0.0020%		0.350	0.0005%	0.1750	12499.7	0.000010	0.0361	0.0000	0.0000
8	40000.0	3.20008	0.0020%		0.400	0.0005%	0.2000	12499.7	0.000010	0.0361	0.0000	0.0000
9	45000.0	3.60009	0.0020%		0.450	0.0005%	0.2250	12499.7	0.000010	0.0361	0.0000	0.0000
10	50000.0	4.00010	0.0020%		0.500	0.0005%	0.2500	12499.7	0.000010	0.0361	0.0000	0.0000
11												
12												
13												

Figure 232: Expanded Uncertainty for a Load Cell with a 10 PT Calibration.

The inputs to calculate our expanded uncertainty at the time of calibration are:

1. The uncertainty of the reference standard: 0.0016 % of applied force.
2. The resolution of the load cell: 0.0361 N.

3. The Fluke meter used for calibration: 0.001 % of applied force.
4. The resolution of the load cell: 0.0361 N.

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
0.0665	0.1331	0.1300	0.00260%	0.00001
0.1175	0.2350	0.2300	0.00230%	0.00002
0.1715	0.3431	0.3400	0.00227%	0.00003
0.2265	0.4530	0.4500	0.00225%	0.00004
0.2818	0.5637	0.5600	0.00224%	0.00004
0.3373	0.6747	0.6700	0.00223%	0.00005
0.3930	0.7859	0.7900	0.00226%	0.00006
0.4487	0.8973	0.9000	0.00225%	0.00007
0.5044	1.0088	1.0100	0.00224%	0.00008
0.5602	1.1204	1.1200	0.00224%	0.00009

Figure 233: Expanded Uncertainty of 50,000 N Load Cell at the time of Calibration.

The columns in the uncertainty table are:

- uc = Standard Uncertainty.
- U = Expanded Uncertainty with a coverage factor of 2 for approximately 95 % Confidence; in this case, it would be 95.45 %, as the degrees of freedom are quite high.
- The next columns are U-rounded to whatever significant figures are typed in. What is reported on our certificates under Expanded Uncertainty, U converted to a percentage, and U as response units, which is the force applied multiplied by U as a %.

Company	
Company Name	Calibrations R Us
Date	11/10/2021
Instrument Type	Morehouse Load Cell
Instrument Serial Number	P-SAMPLE
Meter Serial Number	US28028943
Force Units	lbf
Mode Type	Compression

Uncertainty	
Ref Exp Unc in a % or numerical form?	Percentage
Ref Exp if % Unc *k* = 2	0.0020%
mV/V % Unc k = 2	0.0010%
Readability	0.000010
ASTM LLF (From Cert)	0.0107

Round SIG FIG	5.0

Enter Information and Data From Morehouse Certificate

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
0.0045	0.0090	0.0090	0.08980%	0.00004
0.0045	0.0091	0.0091	0.01810%	0.00004
0.0046	0.0093	0.0093	0.00926%	0.00004
0.0048	0.0096	0.0096	0.00639%	0.00004
0.0050	0.0100	0.0100	0.00502%	0.00004
0.0053	0.0106	0.0106	0.00423%	0.00004
0.0056	0.0112	0.0112	0.00374%	0.00005
0.0060	0.0119	0.0119	0.00340%	0.00005
0.0063	0.0127	0.0127	0.00317%	0.00005
0.0067	0.0135	0.0135	0.00300%	0.00006
0.0072	0.0143	0.0143	0.00287%	0.00006

Compression Uncertainty Analysis at the Time of Calibration												
		Fitted Curve or	Force Applied	Force Applied	Force Applied	mV/V		Resolution			ASTM llf	
	Force Applied	Average or			uw		uv			ures		ur
Test Point #	lbf	Measured Output	k = 2	k = 2	k = 1	k = 1	k = 1	UUT Res	Readability	Res/3.464	k = 2.4	k = 1
1	10.0	-0.04181	0.0020%		**0.000**	0.0005%	**0.0001**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
2	50.0	-0.20908	0.0020%		**0.001**	0.0005%	**0.0003**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
3	100.0	-0.41816	0.0020%		**0.001**	0.0005%	**0.0005**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
4	150.0	-0.62724	0.0020%		**0.002**	0.0005%	**0.0008**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
5	200.0	-0.83631	0.0020%		**0.002**	0.0005%	**0.0010**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
6	250.0	-1.04538	0.0020%		**0.003**	0.0005%	**0.0013**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
7	300.0	-1.25445	0.0020%		**0.003**	0.0005%	**0.0015**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
8	350.0	-1.46350	0.0020%		**0.004**	0.0005%	**0.0018**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
9	400.0	-1.67256	0.0020%		**0.004**	0.0005%	**0.0020**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
10	450.0	-1.88160	0.0020%		**0.005**	0.0005%	**0.0023**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
11	500.0	-2.09064	0.0020%		**0.005**	0.0005%	**0.0025**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
12												
13												

Figure 234: Expanded Uncertainty of 500 lbf Load Cell calibrated following the ASTM E74 Standard.

Example 3: 500 lbf Load Cell

The load cell is calibrated following ASTM E74. The relevant short-term contributions to uncertainty are:

1. The uncertainty of the reference standard(s) used for calibration.
2. The resolution of the load cell.
3. The reproducibility condition of the load cell is defined as the ASTM lower limit factor (LLF).
4. The uncertainty of our voltage reference (0 if a meter was sent in with the load cell for calibration).

This is a case where the calibration is performed following the ASTM E74 standard. The standard is very descriptive in how to calculate the LLF. LLF can be thought of as the reproducibility of the calibrated load cell. I like to call it the expected performance of the load cell when used under the same conditions. The results will change as soon as conditions are changed, like using different adapters, different temperatures, and different setups in machines that are not as plumb, level, square, rigid, and have low torsion as our deadweight machines.

Compression Uncertainty Analysis at the Time of Calibration											
	Fitted Curve or	Force Applied	Force Applied	Force Applied	mV/V		Resolution			ASTM llf	
Force Applied	Average or			uw		uv			ures		ur
lbf	Measured Output	k = 2	k = 2	k = 1	k = 1	k = 1	UUT Res	Readability	Res/3.464	k = 2.4	k = 1
10.0	-0.04181	0.0020%		**0.000**	0.0005%	**0.0001**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
50.0	-0.20908	0.0020%		**0.001**	0.0005%	**0.0003**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
100.0	-0.41816	0.0020%		**0.001**	0.0005%	**0.0005**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
150.0	-0.62724	0.0020%		**0.002**	0.0005%	**0.0008**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
200.0	-0.83631	0.0020%		**0.002**	0.0005%	**0.0010**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
250.0	-1.04538	0.0020%		**0.003**	0.0005%	**0.0013**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
300.0	-1.25445	0.0020%		**0.003**	0.0005%	**0.0015**	239.1	0.000010	**0.0007**	0.0107	**0.0044**
350.0	-1.46350	0.0020%		**0.004**	0.0005%	**0.0018**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
400.0	-1.67256	0.0020%		**0.004**	0.0005%	**0.0020**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
450.0	-1.88160	0.0020%		**0.005**	0.0005%	**0.0023**	239.2	0.000010	**0.0007**	0.0107	**0.0044**
500.0	-2.09064	0.0020%		**0.005**	0.0005%	**0.0025**	239.2	0.000010	**0.0007**	0.0107	**0.0044**

Figure 235: Individual Contributors for an ASTM E74 Calibration.

We need to refer to our appendix for the ASTM E74 calibrations in this example. We are calling out various inputs, such as the uncertainty of the force applied, our multimeter, the device's resolution at each force point, and the lower limit factor LLF. Pairing the load cell with an indicator and calibrating it as a system is recommended.

It is possible that the expanded uncertainty reported might not contain contributions from the LLF. Morehouse follows ILAC-P14 and replicates the same practices NIST uses in the appendix of calibration certificates. All older certificates do not include the LLF in the expanded uncertainty calculation. Newer certificates in 2022 include this information because the LLF is the expected performance of the device, as described above.

Uncertainty Calculation				
uc	U	U	U	U
u	k = 2	Rounded	As a %	Response Units
0.0045	0.0090	0.0090	0.08980%	0.00004
0.0045	0.0091	0.0091	0.01810%	0.00004
0.0046	0.0093	0.0093	0.00926%	0.00004
0.0048	0.0096	0.0096	0.00639%	0.00004
0.0050	0.0100	0.0100	0.00502%	0.00004
0.0053	0.0106	0.0106	0.00423%	0.00004
0.0056	0.0112	0.0112	0.00374%	0.00005
0.0060	0.0119	0.0119	0.00340%	0.00005
0.0063	0.0127	0.0127	0.00317%	0.00005
0.0067	0.0135	0.0135	0.00300%	0.00006
0.0072	0.0143	0.0143	0.00287%	0.00006

Figure 236: Expanded Uncertainty of 500 lbf Load Cell calibrated following the ASTM E74 Standard at the time of Calibration.

Looking at the uncertainty table, we have the following:

- uc = Standard Uncertainty
- U = Expanded Uncertainty with a coverage factor of 2 for approximately 95 % Confidence; in this case, it would be 95.45 %, as the degrees of freedom are quite high.
- The following columns are U-rounded to whatever significant figures are typed in and what is reported on our certificates under Expanded Uncertainty. U converted to a percentage, and U as response units is the force applied multiplied by U as a %.

Interlaboratory Comparison (ILC)

Many force calibration laboratories need help proving their measurement capability. The ISO/IEC 17025:2005 listed interlaboratory comparisons (ILCs) in section 5.9.1. However, historically, ILCs were not organized or completed because other less complicated methods were acceptable for monitoring the validity of the results.

The current ISO/IEC 17025:2017 standard still has the requirements of 5.9.1 in section 7.7.1 and adds other quality control tools. The ISO/IEC 17025:2017 standard also significantly changed to ensure the validity of results and now mandates proficiency testing (PT) or interlaboratory comparisons (ILCs). Section 7.7.2 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."[1]

What is Proficiency Testing?
According to ISO/IEC 17043:2010, proficiency testing (PT) is the "evaluation of participant performance against pre-established criteria by means of interlaboratory comparisons."[2]

What is Interlaboratory Comparison?
According to ISO/IEC 17043:2010, interlaboratory comparison (ILC) is the "organization, performance, and evaluation of measurements or tests on the same or similar items by two or more laboratories in accordance with predetermined conditions."[3]

How Morehouse Can Help You Satisfy Section 7.7.2 of ISO/IEC 17025:2017
Morehouse can help laboratories satisfy ISO/IEC 17025:2017, Section 7.7.2, with an ILC rental kit. Morehouse does not offer PT because it would be a conflict of interest. However, we have partnered with Sapphire Proficiency Testing (www.sapphire-testing.com).

Morehouse has two ILC rental kits, one with a 100k load cell and one with a 25k load cell. They are calibrated per ASTM E74 in compression. The ASTM E74 standard establishes an expected performance for each load cell.

Figure 237: ILC rental kit with 25K load cell and 4215 indicator.

Figure 238: ILC rental kit with 100k load cell and 4215 indicator.

The ASTM E74 data is used in an uncertainty analysis to quantify the uncertainty of the system. After establishing the ASTM calibration and uncertainties, Morehouse will continually calibrate the load cell using our deadweight frames with a 10-pt calibration. This calibration serves as the short-term reference value. The ILC rental kit includes adapters, a transportation case, a cable, and 4215 indicators.

Once the end-user receives the ILC rental kit, they will perform their tests. If the rental kit is used to help validate the system, then data will be sent with the system. If the end-user wants a formal report, data will not be sent. Morehouse and the end-user will send data to a third-party PT provider like Sapphire Proficiency Testing.

How an ILC rental kit works.

1) We use **deadweight primary standards** known to be within 0.0025 % of applied force to calibrate the artifact. Next to a deadweight calibration by a National Metrology Institute such as NIST, this is the most accurate method to verify you are making measurements within your claimed CMC uncertainty parameter.

Figure 239: Morehouse 120,000 lbf deadweight machine.

2) We help **control the drift** and keep the uncertainties low. All instrumentation drifts over time. If a laboratory tries to ensure the validity of its systems, the closer the tests are to the calibration, the lower the uncertainty values become.
3) We can help **establish your CMC uncertainty** parameter. The ILC is a great starting point for calculating your capability by comparing the Morehouse artifact against another artifact, preferably with a deadweight calibration performed. If done correctly, the comparison can help establish your capability. The term for this is dissemination error.
4) We will ship the rental kit with a **"fresh" calibration**. The calibration will be performed 1-2 days before shipment. This allows the end-user to validate their system and get up and running quickly.
5) We have partnered with Sapphire Proficiency Testing to provide an **independent third-party review** of the data and issuance of a report. If this option is requested, the ILC will be blind, and the cost will be higher because we will contract Sapphire Proficiency Testing to run the data.
6) We allow for **21 days** from shipment to return of equipment. This provides at least one week for you to make the measurements, assuming a worst-case scenario five-day shipment. We encourage anyone with a transit time longer than three days to opt for a 2nd-day shipment, allowing two weeks for testing.

ILC Data Analysis

If you want to receive a formal report for the ILC, Morehouse has partnered with Sapphire Proficiency Testing to handle the data.

If a formal report is not needed, then Morehouse will send copies of the certificate and the rental kit. Then, you can keep the certificate and conduct your own ILC. In this case, Morehouse is not responsible for ensuring the validity of the results because we have sent the answers with the expectation that the end-user will use that data to improve their measurement process.

Make Better Measurements

Morehouse wants to help you make better force measurements. Our goal is to provide a low overall uncertainty for direct comparison. The low uncertainty allows for a more robust method to ensure laboratories meet their claimed CMC uncertainties. This service is offered to:

1) help laboratories validate their CMC claims and make the necessary adjustments to their systems as needed.
2) satisfy the ILC requirement.

How to Gain Confidence in Your Measurements

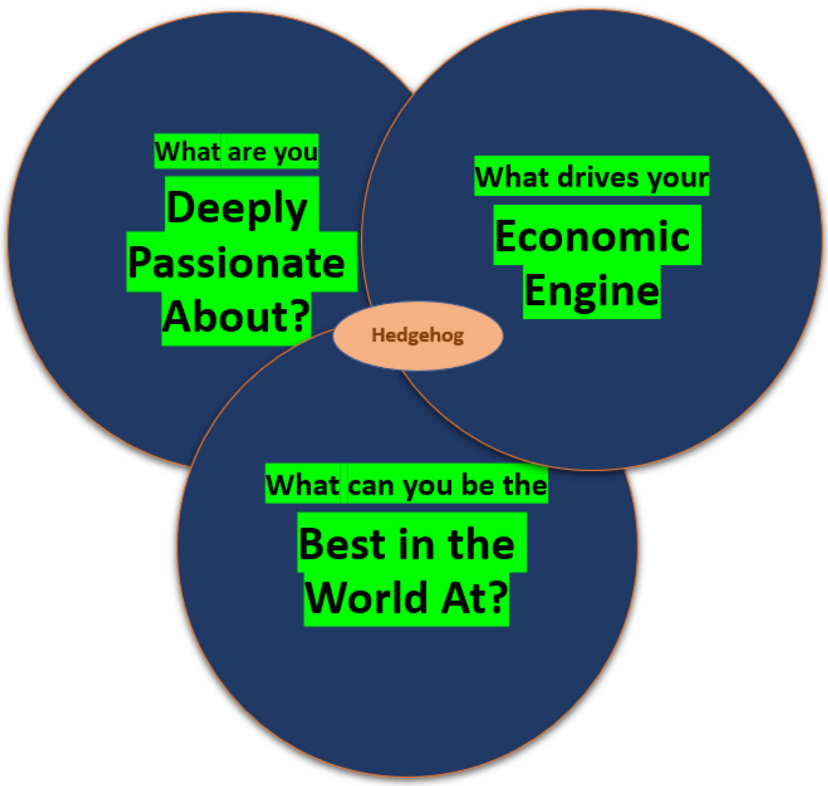


Figure 240: Hedgehog Concept.

There is a concept in the book *Good to Great* by Jim Collins. Jim Collins uses three intersecting circles to determine your Hedgehog Concept. The Hedgehog Concept is based on asking three questions.

They are:
What are you passionate about?
What can you be the best in the world at?
What drives your economic engine?

The Hedgehog Concept is not a goal, a strategy, an intention, or anything else arbitrarily set to say in front of others or used as marketing jargon. We can all say we are world-class, best in class, or whatever words we use to convince someone we are. However, the Hedgehog Concept is more deeply rooted in understanding your company.

Correctly understanding the Hedgehog Concept is understanding what you can be the best at by aligning the three circles. Great companies understand this concept, yet good companies butcher it. Good companies understand that what they are good at will only make you good. Great companies focusing solely on what they can do better than any other organization are on the path to greatness.

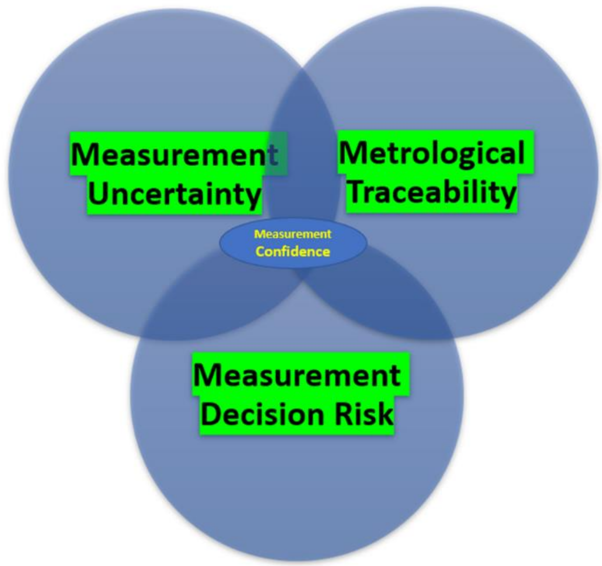


Figure 241: Achieving Measurement Confidence Requires all Three Circles to be Understood.

Anyone wanting to learn more should pick up a copy of Good to Great. The point in discussing the Hedgehog Concept is that we can relate this theory to metrology. We can use three intersecting circles to ensure our measurements have the appropriate level of risk for our application. We can ensure that we calculate our measurement uncertainty correctly, our measurements are metrologically traceable, and we calculate our measurement decision risk using the decision rules that give us the appropriate risk at both the bench and producer's level. We have fulfilled the requirements to have confidence in our measurements.

What is Measurement Confidence?

If you look around your office, a room in the house, or your company, you might see things like doors, windows, furniture, and tables; you may be watching this on your cell phone, tablet, or computer. All of which are manufactured using measurements. Many take measurements for granted in our daily activities, such as powering on appliances like phones or coffee makers and trusting weather forecasts without thinking. Other activities ensure our safety and comfort, such as doors and windows opening and closing while ensuring a good seal, our houses withstanding a strong wind gust, or the floor not collapsing under a load.

Do you know what provides that assurance of safety and comfort?
All these items have been assured using a measuring tool calibrated by following a specification, a published standard, or a method.

So, what if any of these things fail? Does anyone typically question the measurement? Should they? If the person or place responsible for calibrating the equipment has stated that something was good and failed, they may not have a robust system to establish measurement confidence.

Let's look at the system that assures measurement confidence.

3.1 [VIM3: 2.26; VIM2: 3.9; VIM1: 3.09]
measurement uncertainty
uncertainty of measurement
uncertainty

parameter characterizing the dispersion of the **values** being attributed to a **measurand**, based on the information used

NOTE 1 A way to interpret measurement uncertainty is as indecision or doubt, either about the essentially unique true value of the measurand that remains after making a measurement, or about the measured value to be chosen to represent a measurement result.

NOTE 2 The parameter characterizing dispersion is either positive or zero. It may be, for example, a **standard uncertainty** (or a specified multiple of it), or the half-width of an interval, having a stated **coverage probability**.

NOTE 3 Measurement uncertainty includes components arising from systematic effects, such as components associated with **corrections** and values attributed to quantities of **measurement standards**. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.

NOTE 4 Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by **Type A evaluation** from the probability distribution of the values from series of **measurements** and can be characterized by standard deviations. The other components, which may be evaluated by **Type B evaluation**, can also be characterized by standard deviations, evaluated from probability distributions based on experience or other information.

NOTE 5 In general, for given information, as mentioned in the definition, it is understood that the measurement uncertainty is associated with a stated value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

NOTE 6 Measurement uncertainty is generally part of a **measurement result**. If instead a measurement result is reported as a single **measured value**, then only significant digits should be reported.

Figure 242: VIM definition of Measurement Uncertainty.

Measurement Uncertainty

The Vocabulary of International Metrology (VIM) defines Measurement Uncertainty as a "parameter characterizing the dispersion of the values being attributed to a measurand, based on information used."[42] The above figure has a further explanation from the VIM.

One way to interpret measurement uncertainty is to quantify doubt about the measurement result. Since we do not make perfect measurements, we must consider the error sources associated with that measurement. When all the errors are correctly evaluated, we can describe how well we made the measurement or our measurement uncertainty.

Some measurement uncertainty components arise from systematic effects, such as corrections and assigned quantity values of measurement standards. These components can be evaluated by Type A or Type B evaluation.

Measurement uncertainty is comprised of many components. Those components derived from a series of measurements usually take the form of Type A. They may be evaluated by Type A evaluation from the probability distribution of the values from a series of measurements and can be characterized by standard deviations.

The other components, which may be evaluated by Type B evaluation, can also be characterized by standard deviations, evaluated from probability distributions based on experience or other information. Each contributor to measurement uncertainty is expressed as standard uncertainty.

Metrological Traceability

The Vocabulary of International Metrology (VIM) defines Metrological Traceability as “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.”

NOTE 1 The reference mentioned in this definition is sometimes thought of in different ways. Probably most commonly, the reference is considered to be the definition of a unit through its practical realization (for example, a realization of the definition of a unit of the SI; “traceable to the SI”). However, sometimes the reference is thought of as the realization itself, that is, a quantity.”[43]

That measurement traces back to the International System of Units (SI). These SI units are time, length, and mass for force and torque. The pyramid starts with SI at the top, then NMI (National Measurement Institute), like NIST. If NIST calibrates the force weights, then the next tier would be a Primary Reference Laboratory, like Morehouse.

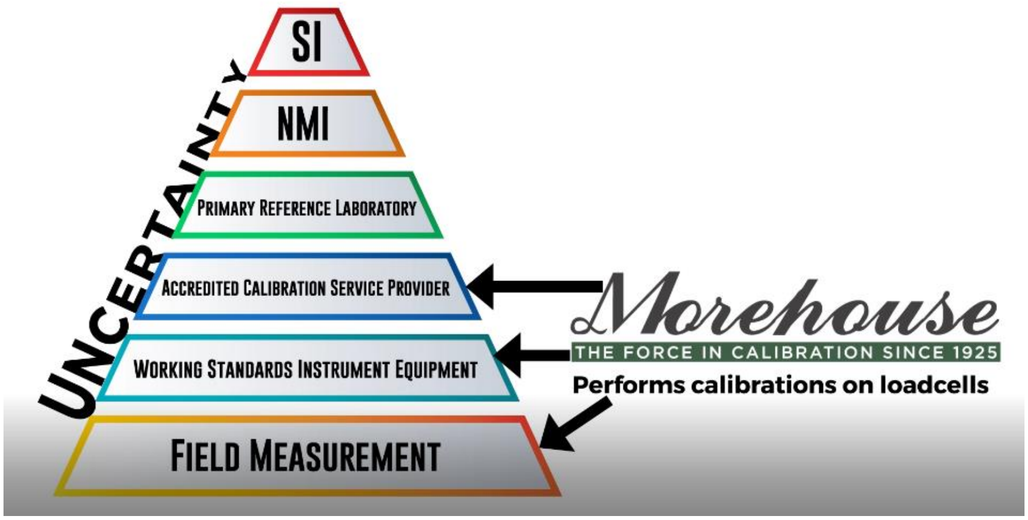


Figure 243: Measurement Pyramid.

Morehouse calibrates load cells for the three lower tiers, accredited calibration suppliers, followed by working standards, who calibrate field equipment.

Measurement uncertainty also keeps us honest. If we think about making a conformity assessment of “pass” or “fail,” the larger your measurement uncertainty, the more likely you are to “fail” an instrument. Using the analogy of a parking space, the lines are your tolerance limits. When measurement uncertainty is small, you have a parking space large enough to park easily. This means you have more space, or range, to “pass” an instrument.

Figure 244: When the Uncertainty is small.

However, you have less room to park when your uncertainty is larger. This means you have less range, sometimes no range, to "pass" an instrument.

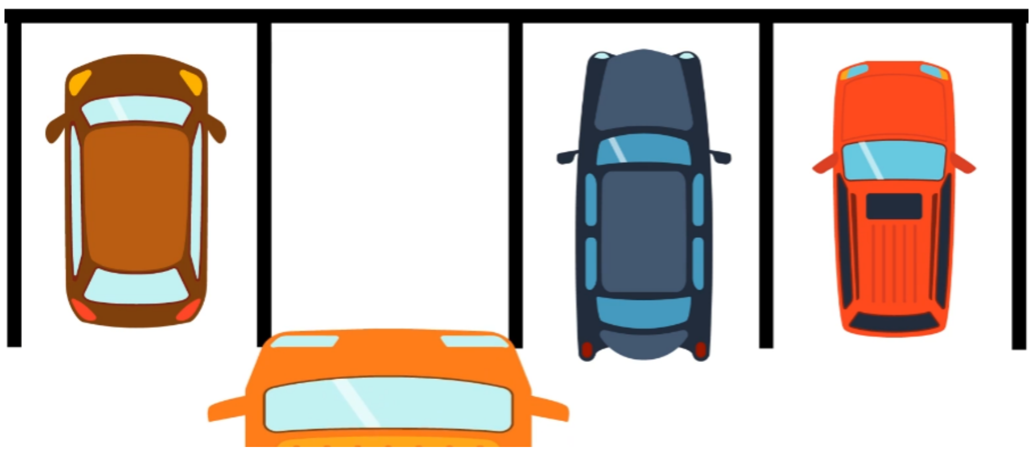


Figure 245 When the Uncertainty is large.

Measurement Decision Risk

When discussing decision rules, we describe how measurement uncertainty is accounted for when stating conformity with a specified requirement. For most, the conformity statement is binary, meaning either a Pass or a Fail. Some standards recommend setting the limits so a fail occurs if the total risk (Probability of False Accept - PFA) is larger than 2 %.

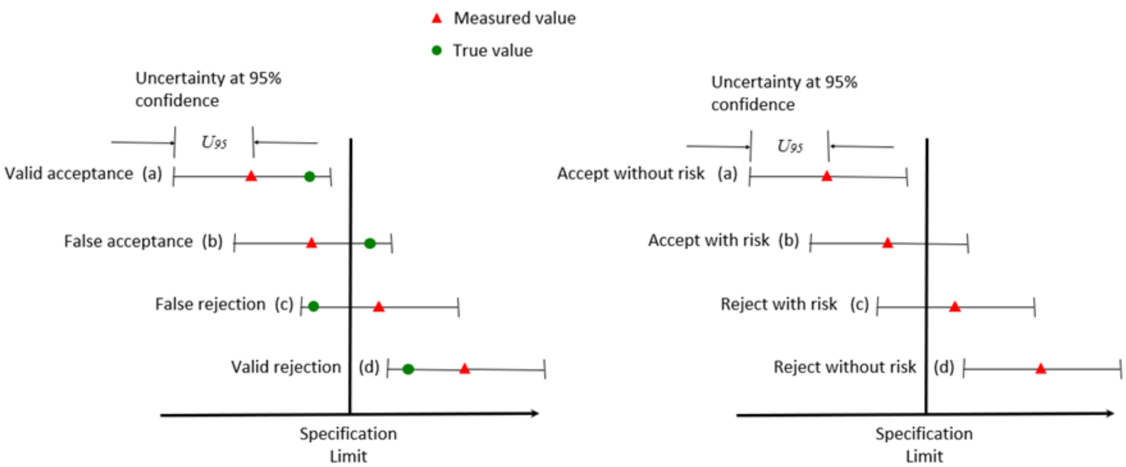


Figure 246: Image adapted from JCGM 106 Example.

Note: A graphic indicating "accept" or "reject" without risk implies that while there might still be a minimal level of risk, it is considered negligible. The expectation is that there is a close to 100 % certainty that the measurement outcome will result in either acceptance or rejection with a very high level of confidence.

ISO/IEC 17025:2017 states, "the laboratory shall document the decision rule employed, taking into account the level of risk."[44]
ISO/IEC 17025 does not specify what the decision rule must be. However, there are other documents that any lab manager should be aware of when it comes to evaluating measurement risk and decision rules. The documents include:

- ILAC G8:09/2019 Guidelines on Decision Rules and Statements of Conformity
- JCGM 106:2012 Evaluation of measurement data – The role of measurement uncertainty in conformity assessment
- UKAS LAB 48: Decision Rules and Statements of Conformity
- ISO/IEC 17025 2017 General requirements for the competence of testing and calibration laboratories
- Handbook for the Application of ANSI Z540.3-2006: Requirements for the Calibration of Measuring and Test Equipment
- The Metrology Handbook 3rd Edition Chapter 30
- NCSLI-RP18 Estimation and Evaluation of Measurement Decision Risk
- ASME B89.7.3.1-2001 Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications
- ASME B89.7.4.1-2005 Measurement Uncertainty and Conformance Testing: Risk Analysis
- ISO 14253-5 Part 1: Decision rules for proving conformity or nonconformity with specifications.

In addition to reading and understanding the documents above, the test and calibration provider must understand the customer requirements for conformance decisions. When the measurement result is reported with confidence, one must adhere to the following:

- The proper evaluation measurement uncertainty.
- If using TUR, the proper calculation of TUR must be used.
- Proof of metrological traceability.
- Proper application of measurement decision rules to address the risk required in reporting any statements of conformity.
- Many of the decision rules found in documents such as ANSI/Z540.3 Handbook and ILAC-G8:09/2019 use Test Uncertainty Ratio or TUR to help calculate their Global measurement risk. The TUR is just one of the formulas that can be used in conformity assessment.

$$\mathbf{TUR} = \frac{\textbf{Span of the } \pm \textbf{ UUT Tolerance}}{\mathbf{2 \text{ x } k_{95\%}(\textbf{Calibration Process Uncertainty})}}$$

Figure 247: TUR Formula found in ANSI/NCSL Z540.3 Handbook.

TUR is defined in the handbook as the ratio of the span of the tolerance of a measurement quantity subject to calibration to twice the 95% expanded uncertainty of the measurement process used for calibration.

$$\text{TUR} = \frac{\text{Span of the} \pm \text{Tolerance}}{2 \text{ x } k_{95\%}\left(\sqrt[2]{\left(\frac{\text{CMC}}{k_{\text{CMC}}}\right)^2 + \left(\frac{\text{Resolution}_{\text{UUT}}}{\sqrt[2]{12}}\right)^2 + \left(\frac{\text{Repeatabiliity}_{\text{UUT}}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 248: Example of a TUR Formula adapted from the ANSI/NCSL Z540.3 Handbook.

The formula for TUR consists of the span of the tolerance in the numerator. The denominator includes temporary and non-correctable influences incurred during the calibration, such as repeatability, resolution, error in the measurement source, operator error, error in correction factors, environmental influences, and others.

When discussing TUR, we must standardize definitions because when significant contributions to Measurement Uncertainty are omitted, every subsequent measurement will be suspect and bad things may happen!

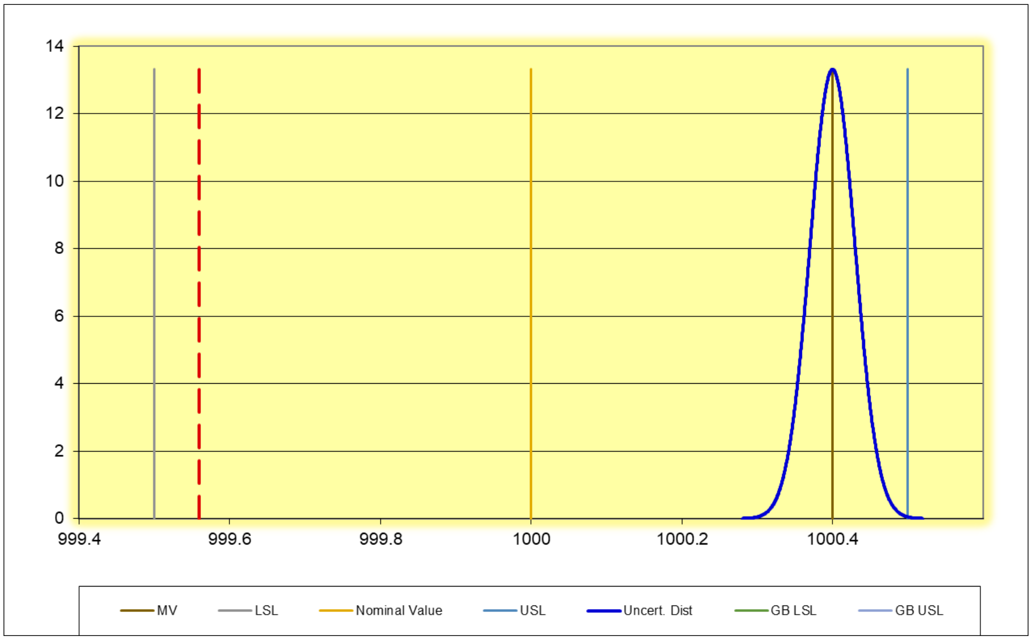


Figure 249: Specific Risk Example with Small Uncertainty associated with a “Pass”.

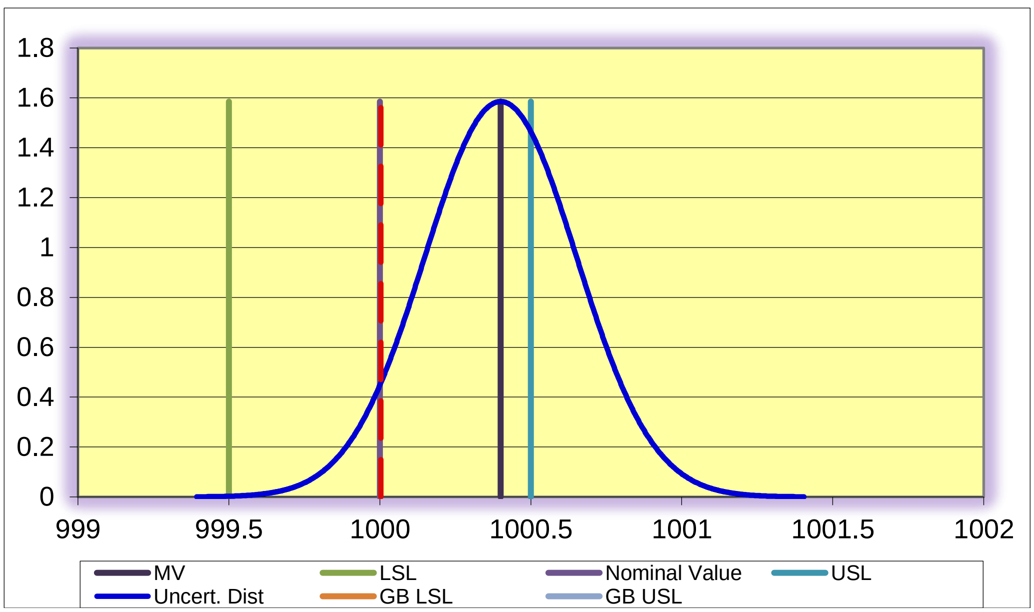


Figure 250: Specific Risk Example with Large Uncertainty associated with a “Fail”.

When we use the appropriate formula and illustrate the concept, we have the lower and upper specification limits at 999.5 and 1000.5. Next, we have the measurement location at 1000.4. The calculated calibration process uncertainty determines the width of the distribution for the measurement.

Note: Some methods involve integrating a joint probability density function. These methods typically use two input values, one for TUR and one for EOPR (End of Period Reliability). This concept is covered well in JCGM 106 Evaluation of measurement data – The role of measurement uncertainty in conformity assessment and other documents.

The larger the measurement uncertainty, the larger the risk relating to the measurement location. The smaller the uncertainty, the lower the risk; such is the case in this example when Morehouse performs the calibration.

The ways to reduce the risk are simple:

- Follow the formula for TUR per the correct interpretation as defined in ANSI/NCSL Z540.3 Handbook.
- Find calibration labs like Morehouse with the lowest measurement uncertainties (CMC in the formula).
- Buy better equipment that is repeatable and has sufficient resolution.
- Control the environmental conditions as required to facilitate calibration.
- Raise the tolerance requirements.

To ensure confidence in our measurements and make the world a safer place to live in, we need to:

1. Evaluate measurement uncertainty correctly.
2. Ensure metrological traceability.
3. Select and apply the Decision Rule appropriately chosen to make a statement of conformity.

Decision Rules

Understanding Measurement Risk: The Basics

Measurement decision risk is the probability that an incorrect decision will result from a measurement.

There are two commonly referred to risk types in metrology. These are the Probability of False Accept (PFA) and the Probability of False Reject (PFR).

The PFA is like consumer risk in that the risk level is passed to the end user. In this case, the calibration laboratory calibrates the MT&E and calls it In Tolerance when there is a possibility that the MT&E may be Out of Tolerance (OOT). The probability of OOT is determined when the appropriate risk-based methods are used.

The PFR is similar to producers' risk in that the risk level produces excess work for the calibration laboratory. This might equate to a laboratory adjusting MT&E that isn't OOT.

There are Decision Rules that can control both PFA and PFR.

Decision rules can be a complex topic, and some excellent guidance documents are multiple pages in length beyond the scope of this document. Yet, we wanted to make sure anyone reading this has some basic information and lists the references.

Decision Rules

ISO/IEC 17025 defines a decision rule as a "rule that describes how measurement uncertainty is accounted for when stating conformity with a specified requirement."[45] ISO/IEC 17025 does not specify the decision rule that must be used. However, there are other documents that any lab manager should be aware of when evaluating measurement risk and Decision Rules.

Some of these documents include:

- ISO/IEC 17025 2017 *General requirements for the competence of testing and calibration laboratories*
- ILAC G8:09/2019 *Guidelines on Decision Rules and Statements of Conformity*
- ASME B89.7.3.1-2001 *Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications*
- ASME B89.7.4.1-2005 *Measurement Uncertainty and Conformance Testing: Risk Analysis*
- ISO 14253-1 *Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Decision rules for verifying conformity or nonconformity with specifications.*
- JCGM 106:2012 *Evaluation of measurement data – The role of measurement uncertainty in conformity assessment*
- UKAS LAB 48: *Decision Rules and Statements of Conformity*

- Handbook for the Application of ANSI Z540.3-2006: *Requirements for the Calibration of Measuring and Test Equipment*
- The Metrology Handbook 3rd Edition Chapter 30
- NCSLI-RP18 Estimation and Evaluation of Measurement Decision Risk
- Decision Rule Guidance – An in-depth guidance document on decision rules written by Henry Zumbrun, Greg Cenker, and Dilip Shah

Global versus Specific Risk

Figure 251: Global versus Specific Risk.

Understanding the differences between specific and global risk is a complex topic. We will explain the difference between specific and global risk without getting into too much detail.

In metrology, risk is a crucial factor influencing the decision-making process based on measurement results. Two primary types of risk are considered in this context: specific risk and global risk. Both types of risk are fundamentally different, and understanding these differences can help make more accurate and reliable decisions.

Specific Risk

As the name suggests, specific risk is specific to a given test measurement result. It is the probability that a test measurement result indicates a product is within specifications when it is outside specifications. This is often called the probability of false acceptance (PFA) or false acceptance risk (FAR). The PFA is also known as Type II error or Consumers' Risk.

The proper terminology is Conditional (Specific) False Accept Risk, often used when dealing with a specific instrument, typically a recalibration scenario.

This risk arises due to the inherent uncertainty in the test measurement.

Specific Risk or Bench Level risk can be calculated by integrating the Probability Density Function (PDF) of the test measurement uncertainty outside of the specification limits.

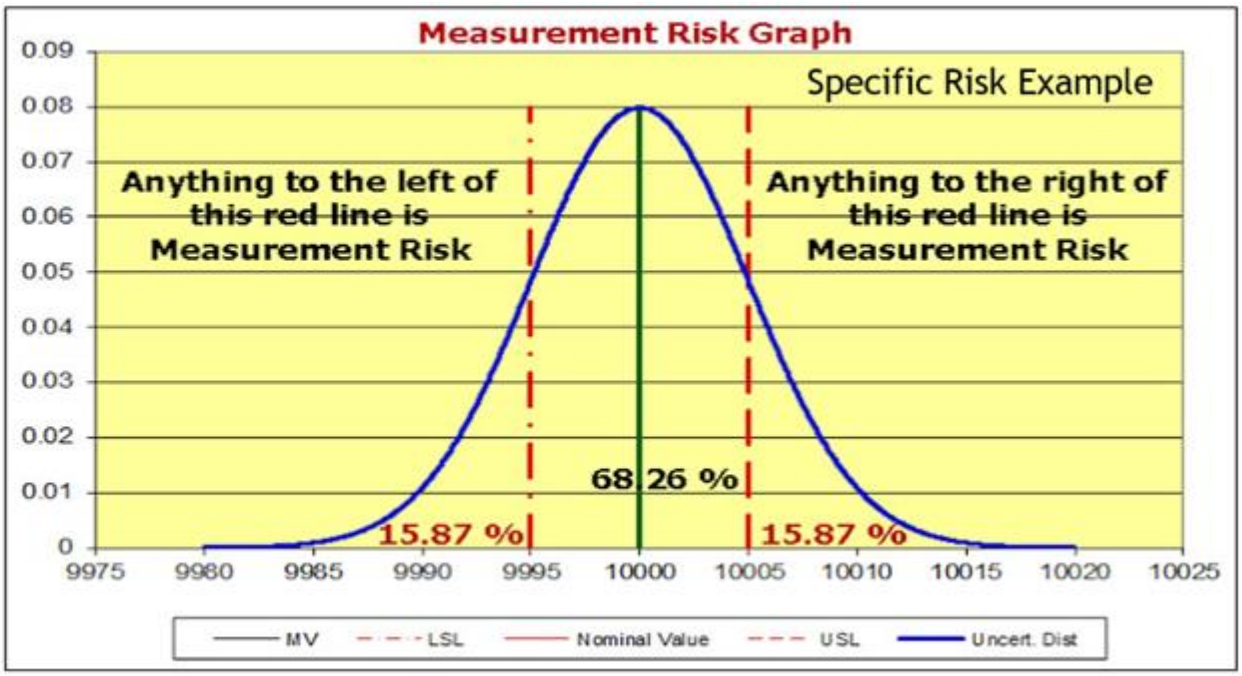


Figure 252 Example Showing Specific or Bench-Level Risk.

The specific risk is illustrated where the upper tail of the probability curve falls above the upper specification limit or the lower tail falls below the lower specification limit. The area to the left and right of the specification limit shown as a dotted red line represents the probability (specific risk) of incorrectly accepting a product given this measurement result.

Global Risk

On the other hand, global risk, also known as the Unconditional Probability of False Acceptance (PFA), is the probability that a test measurement on any population of products, if individually measured, would result in an incorrect pass determination.

Unlike specific risk, global risk considers the test measurement probability distribution and the probability of encountering a product at that measured value. This requires integrating the joint PDF of the test measurement and the PDF of the unit under test.

It's important to note that global risk cannot be calculated without specifying a distribution of values for the product obtained from prior knowledge and measurements.

Often, one might see reliability numbers such as 95 % EOPR (End of Period Reliability) with a 95 % Confidence Interval, which is the prior knowledge being discussed. In this case, the requirement would be to have at least 58 like calibrations where the measured values were within the tolerance limits.

More information on Reliability can be found later in this book. If neither the EOPR nor a Test Uncertainty Ratio (TUR) threshold is met, one could choose to use Specific Risk methods or another method or decision rule.

The critical difference between specific and global risks lies in their scope and application. While specific risk is tied to a particular test measurement result, global risk is often a broader concept considering any test measurement on any product.

This means that while specific risk can be high for a particular measurement, the global risk may still be low if the overall product distribution is well within the specification limits.

The type of risk one can accept is likely based on their risk tolerance. If the application is critical, one might choose a specific risk model versus a global risk model that primarily deals with the population of similar instruments.

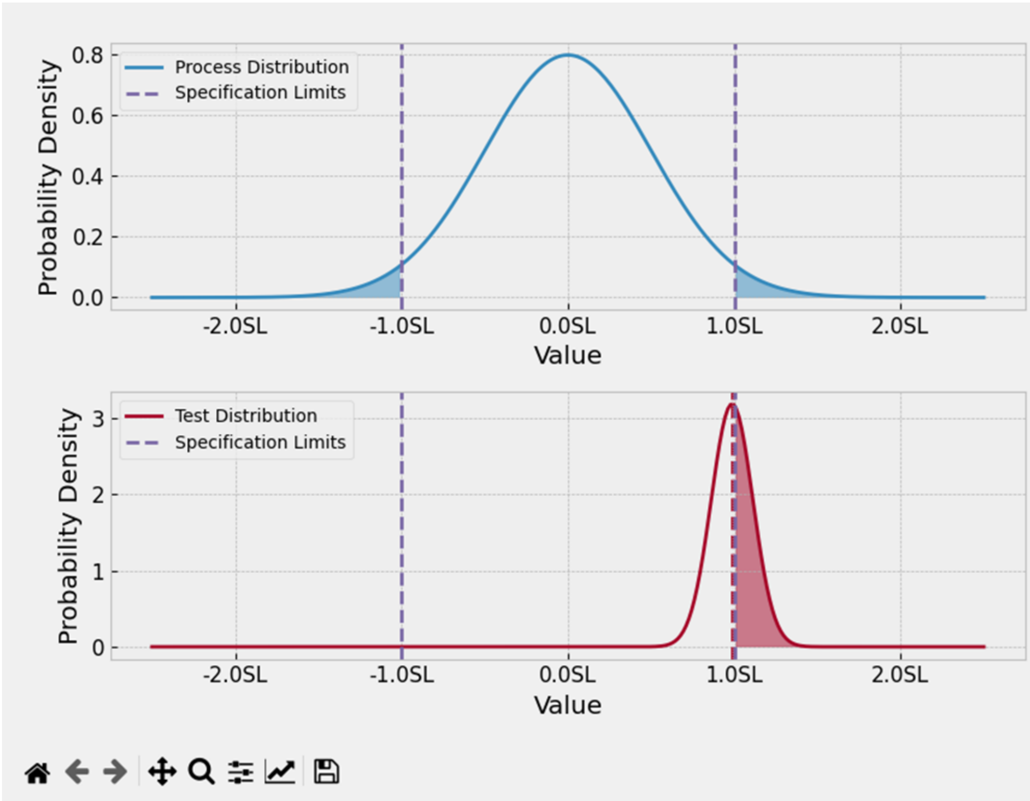
An Example Using Both Specific and Global Risk

We want to measure the speed of a car. Using a global risk model, we may base the speed on the car's time from point A to Point B. We can say the distance is one mile, and we will measure the time it takes using a stopwatch. The speed limit on the stretch of road is 60 mph. Thus, we expect it to take one minute.

The car enters point A, traveling at 90 mph, and then 0.5 miles into the drive, travelling at 30 mph. When we take our reading, the stopwatch reads for 1 minute. The average speed is 60 mph.

If we wanted to look at the car's speed using Specific Risk, we might have a radar gun at Point A or B. In this example, the car is clocked at 90 mph at point A and 30 MPH at point B. Each point is 30 MPH above or below the speed limit. It is a very different picture than if we use the stopwatch method. When we look at the speed individually, we look at specific risk. We have global risk if we look at them together and average them.

Note: This example may highlight an extreme, though each type of risk method has its place.

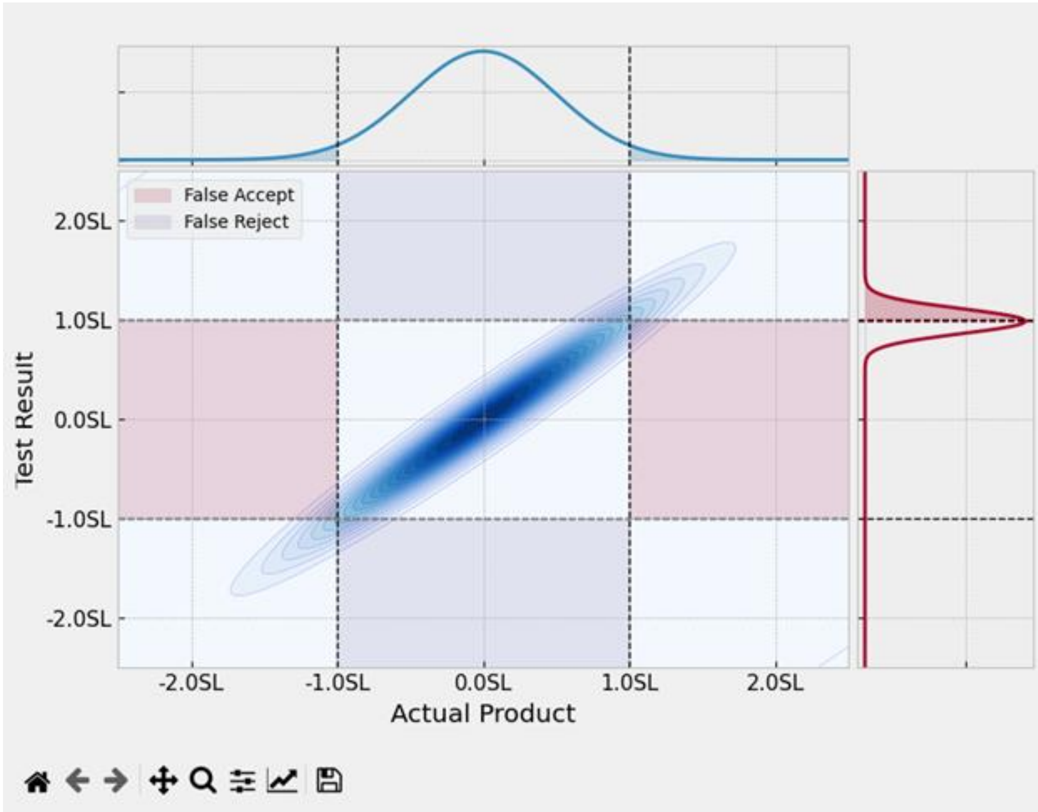


Process Risk	Specific Measurement Risk	Global Risk
Process Risk: 4.6%	TUR: 4.0	Total PFA: 0.79%
Upper limit risk: 2.3%	Measured value: 0.99	Total PFR: 1.5%
Lower limit risk: 2.3%	Result: ACCEPT	-
Process capability index (Cpk): 0.67	Specific FA Risk: 46%	-

Figure 253 SUNCAL Software showing both Specific and Global Risk

Using SUNCAL software, the figure above shows both specific and global risks. When looking at the bottom Probability density function (Specific Risk), the area outside of the specification limit is 46 % (Shown in Red).

This would be the value for PFA we would use if making a specific measurement; if we combine both probability density functions, we could model a more global approach.



Process Risk	Specific Measurement Risk	Global Risk
Process Risk: 4.6%	TUR: 4.0	Total PFA: 0.79%
Upper limit risk: 2.3%	Measured value: 0.99	Total PFR: 1.5%
Lower limit risk: 2.3%	Result: ACCEPT	-
Process capability index (Cpk): 0.67	Specific FA Risk: 46%	-

Figure 254 Specific and Global Risk Examples Showing Monte Carlo Analysis

The image above shows that with enough samples, we should expect about 0.79 % of our population data to be accepted when non-conforming and about 1.5 % to be found nonconforming when conforming.

The number drastically differs from when we pulled one piece and measured its performance at a 46 % probability that what is being measured is non-conforming. Global risk often assumes at least one probability density function is centered.

ASME B89.7.4.1-2005 describes both risk levels quite well. [46]

Specific Risk or Bench Level risk mitigation can be considered “controlling the quality of the workpieces,” while program-level risk strategies are described as “controlling the average quality of workpieces.”

Bench Level (specific risk) is an instantaneous liability at the time of the measurement, and program level (global risk) is more about the average probability that incorrect acceptance decisions will be made based on historical data.

In conclusion, specific and global risk methods are crucial in metrology. Understanding the differences between them can help make more accurate decisions based on the level of risk tolerance a company may have, reducing the probability of false acceptance and ensuring the quality and reliability of products.

The Force of Decision Rules: Applying Specific and Global Risk to Star Wars

Introduction

Decision rules are the Force of metrology. They guide us in making accurate and precise measurements, even in the face of uncertainty. But like the Force, decision rules can be complex and challenging to understand. That's why I'm writing this article.

This article uses examples from the first Star Wars movie, Episode IV: A New Hope, to demystify decision rules and make them more understandable for everyone. Specifically, the focus will be on specific and global risk examples.

Our aim is for readers to grapple with the concept of measurement risk and its connection to decision rules to gain a comprehensive understanding of the fundamental principles by the conclusion of this article. Furthermore, we hope you can put into practice some of the ideas presented here in your work within the field of metrology.

Star Wars and Measurement Uncertainty

In the expansive and mesmerizing Star Wars galaxy, where the Force ebbs and flows, epic intergalactic battles unfold, and the destinies of heroes and villains hang in the balance, the concept of measurement uncertainty and its impact on history might appear to be distant, like a star in a far-off galaxy.

However, when we take a closer look, the Star Wars saga offers profound insights into the nature of measurement uncertainty in the context of critical decisions.

These decisions range from the precision required for our fleet of X-wing fighters to hit a 2-meter target with a 0.5-meter proton torpedo when targeting the Death Star to the intricacies of using global risk models to create a clone army with remarkably low variation in overall body size.

Destroying the Death Star – Specific Risk Example

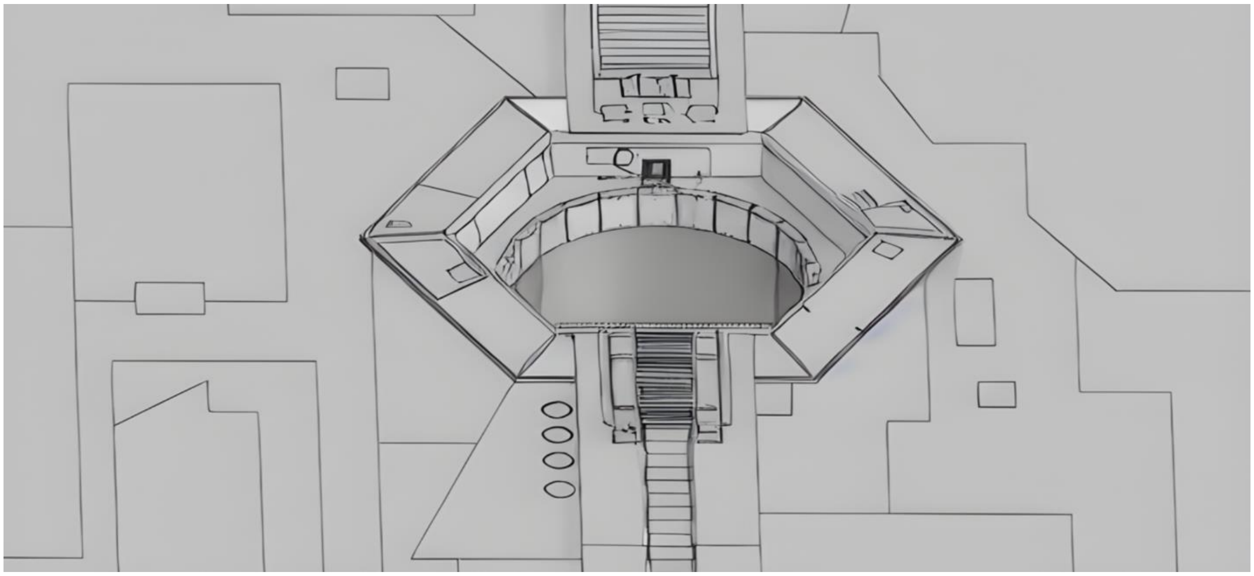


Figure 255: Death Star Exhaust Port Measuring 2 Meters.

Our rebel fleet is quickly gathering after receiving the Death Star plans in which it is uncovered that a torpedo can be fired into the 2-meter exhaust port vent, which would impact the core and trigger a catastrophic explosion.

Knowing that our torpedo measures 0.5 meters and that the empire does not think an X-wing can get close enough to take the shot, we need to devise a plan that will ensure that if we can take the shot, we will make it.

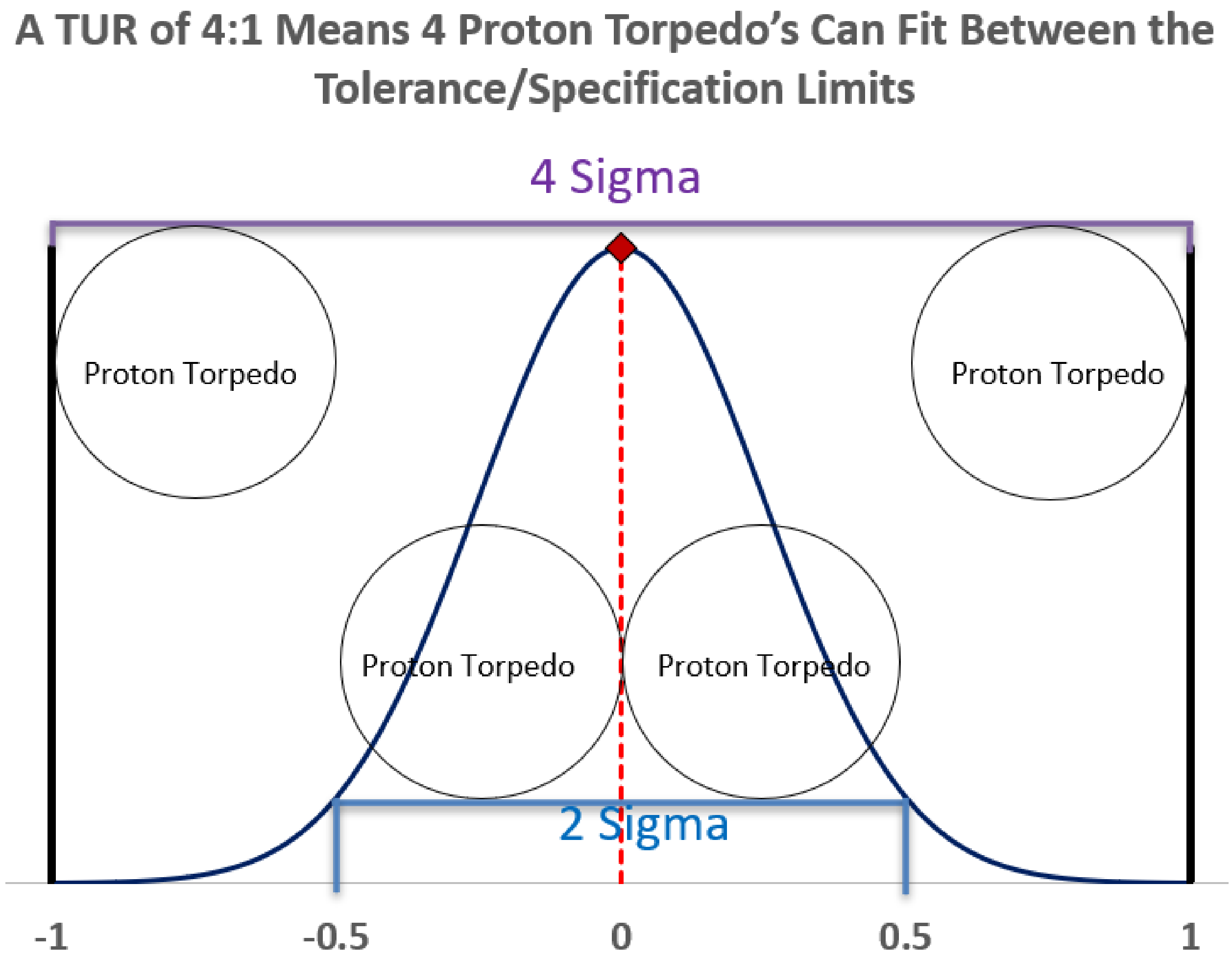


Figure 256: Risk Showing Sigma Levels.

As we devise our plan, we know that the 2-meter-wide vent port would allow as many as four proton torpedoes to fit side by side.

When we discuss terms like Test Uncertainty Ratio (TUR), we are saying the measurement uncertainty is four times less than tolerance, or the tolerance is 4 times more than the measurement uncertainty.

In addition, terms like 2 Sigma and 4 Sigma can be demonstrated using this concept.

2 Sigma means that 95.45 % (consistency?) of the population (process output) lies within 2 standard deviations of the mean.

That population is represented above; 2 standard deviations would fit approximately two proton torpedoes.

The larger Gaussian (normal) distribution is drawn at 4 sigma, meaning that 99.9937 % of the process output would meet the requirements.

If we went the other way, as with a TUR of 2:1, we could not use higher than 2 Sigma, as only two torpedoes would fit between our specification limits.

Most commercial calibration labs typically use a coverage factor, k =2, for 95.45 % Confidence (2 Sigma).

Our example will use k = 2 for our expanded measurement uncertainty.

Setting our Tolerance/Specification Limits.

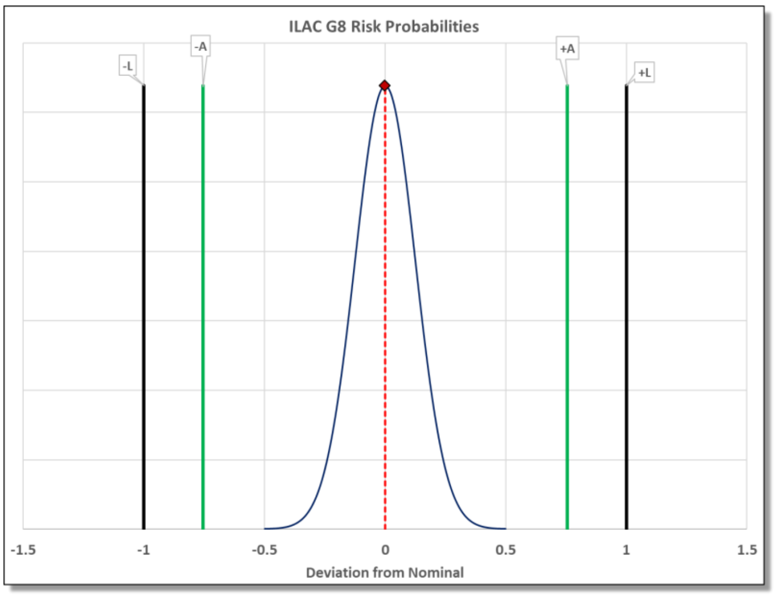


Figure 257: Probability Density Function for our Calibration Process Uncertainty.

Ideally, we know using simple math that our tolerance is ± 1 meter.

If our torpedo is 0.5 meters, the center location of our shot must be between -0.75 and 0.75 meters.

Considering the torpedo as our measurement uncertainty, we would subtract the Measurement Uncertainty from the tolerance.

The span of the tolerance is 2 meters, and if we subtract the size of our 0.5-meter torpedo, we have 1.5 meters of space left to fit the torpedo. Since that tolerance is symmetrical, we can divide by 2, which leaves us ± 0.75 meters.

Any shot taken that falls between ± 0.75 meters should go into the port and destroy the Death Star.

Simple, right?

What if we change our requirement to allow for some additional risk?

What if we followed the older ILAC G8: 2009 decision rule that allowed for 2.5 % risk per each tail of our normal distribution?

Star Wars Example – AL for 2.5 % Maximum risk

Risk Calculator	
Upper Tolerance T_U	1
Lower Tolerance T_L	-1
Nominal Value (default = blank, otherwise 0)	
Measured Value xm	0.0000
Measurement Unc um	0.1250
Maximum Allowable Risk	2.50%
Tolerance T	2.00

Probability of Conformance (p_c)	100.000%
Probability of NonConformance (1 - p_c)	0.000%

Setting the Guard Band Upper and Lower AL	
Guard Band Upper G_U (AL = TL - w)	0.7550
Guard Band Lower G_L (AL = TL + w)	-0.7550

Setting AL based on Probability of Conformance	
Probability of Conformance (pc)	97.50%
r	0.9800
w = U_{95} * *r*	0.24500
C_m (TUR)	4.00000

Setting AL based on Guard Band w	
Upper Acceptance Limit	PASS
Lower Acceptance Limit	PASS

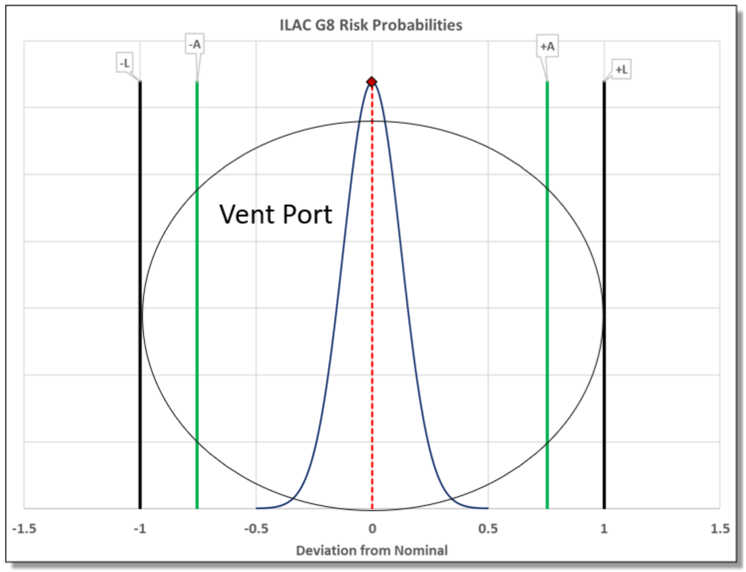


Figure 258: Allowing for 2.5 % risk, our Guard banded Acceptance Limits would become ± 0.7550.

Conformance Probability Table	
Conformance Probability , P_c	Guard Band Multiplier, *r* Two Sided
0.0668	-0.750
0.1590	-0.499
0.3085	-0.250
0.5000	0.000
0.6914	0.250
0.8000	0.421
0.8500	0.518
0.9000	0.641
0.9500	0.822
0.9545	0.845
0.9750	0.980
0.9800	1.027
0.9900	1.163
0.9990	1.545

Figure 259: Conformance Probability Table.

What we are calculating is our Conformance probability for 97.50 % Confidence. We calculate the Guardband Multiplier by using the formula in Excel of Norm.S.Inv(0.975)/2.

We then use this number of 0.845 as our GB Multiplier as follows.

*For the Guardband upper limit, we have 1 – (GB Multiplier * Coverage Factor * Standard Measurement Uncertainty)*

*1 – (0.980 * (2 * 0.125)) = 0.7550*

*For the Guardband lower limit, we have -1 + (GB Multiplier * Coverage Factor *Standard Measurement Uncertainty)*

*-1 + (0.980 * (2 * 0.125)) = -0.7550*

The formula can be simplified to Acceptance Limit = Tolerance Limit ± Guardband multiplier * Expanded Measurement Uncertainty.

ILAC-G8:09/2019 simply states, "Often the guardband is based on a multiple r of the expanded measurement uncertainty U where $w = rU$. For a binary decision rule, a measured value below the acceptance limit AL = TL – w is accepted." [1]

Thus, if our measured value or shot is right at 0.7550, our risk will be limited to 2.5 %. If our X-wing takes the shot and the torpedo falls between the limits of ± 0.7550, there would be a 97.5 % chance that the shot would destroy the Death Star.

What if Luke takes the shot, and the measured value is 0.99?

Star Wars Example – Measured Value not Centered

Risk Calculator	
Upper Tolerance T_U	1
Lower Tolerance T_L	-1
Nominal Value (default = blank, otherwise 0)	
Measured Value xm	0.9900
Measurement Unc um	0.1250
Maximum Allowable Risk	2.50%
Tolerance T	2.00

Probability of Conformance (p_c)	53.188%
Probability of NonConformance ($1 - p_c$)	46.812%

Setting the Guard Band Upper and Lower AL	
Guard Band Upper G_U (AL= TL - w)	0.7550
Guard Band Lower G_L (AL = TL + w)	-0.7550

Setting AL based on Probability of Conformance	
Probability of Conformance (pc)	97.50%
r	0.9800
$w = U_{95} * r$	0.24500
C_m (TUR)	4.00000

Setting AL based on Guard Band w	
Upper Acceptance Limit	FAIL
Lower Acceptance Limit	PASS

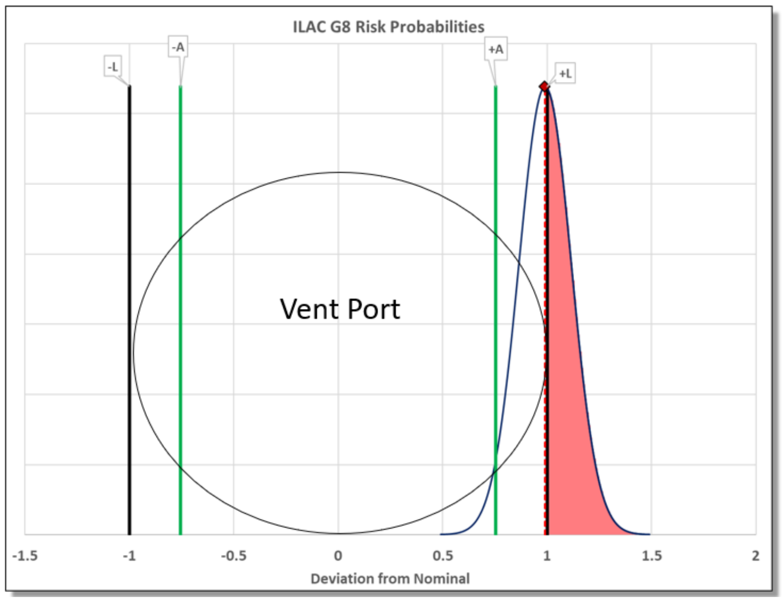


Figure 260: When the measured value is 0.99, the risk is above 46 %.

In this case, we can see that about 46.812 % of our 0.5-meter torpedo or 0.23406 meters of torpedo will hit the side of the vent, and the Death Star will not be destroyed.

Although this example uses a physical example of the torpedo either going into the hole or hitting the side of the vent port, the hope is it conveys the concept of specific risk.

Specific risk (also called bench-level risk) is based on a specific measurement result.

It triggers a response based on measurement data gathered during the test.

Depending on the method, it may be characterized by one or two probability distributions.

Any representation with only one probability distribution is always a specific risk method.

In our example, we used the size of the torpedo as our standard uncertainty of the calibration process, then multiplied that by a coverage factor of *k* = 2 to use as our Expanded Uncertainty of the calibration process.

Destroying the Death Star – Global Risk Example

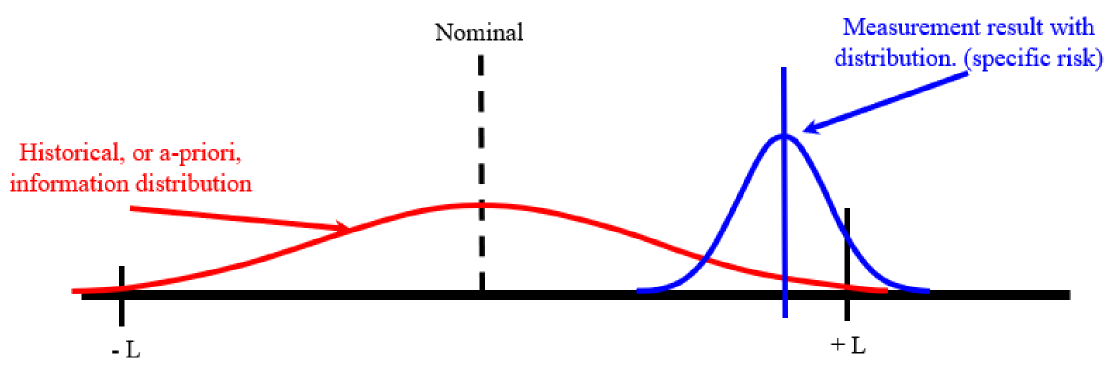


Figure 261: Global Risk is Based on Two Probability Density Functions.

Global risk (also called process-level risk) is often based on a future measurement result.

It is used to ensure the acceptability of a documented measurement process.

It is based on expected or historical information and is usually characterized by two probability distributions.

If we look at the same example, we might say that the X-wing is not that much different from the T-16 skyhopper that he used to blast womp rats.

Using the fact that Luke was such a skilled shot, the best amongst all his friends on Beggar's Canyon, we could use this *a piori* knowledge in a global risk scenario.

Based on Luke's history, the historical context suggests that he will be able to hit the target.

One curve is our specific risk curve.

If the shot was measured at 0.99, there was a 46.812 % chance the shot would not go in; however, this new knowledge, or curve, suggests, by using the law of averages, that the shot has a 99.11 % chance of going in.

Say what now?

That's more in line with how global risk works.

We are no longer controlling the quality of individual workpieces; we are controlling the average quality of workpieces. To control that average quality, we need to have the data.

$$EOPR = \frac{\text{Number of in-tolerance results}}{\text{Total number of calibrations}}$$

In simplistic terms, End of Period Reliability is defined as the number of calibrations that meet acceptance criteria divided by the total number of calibrations.

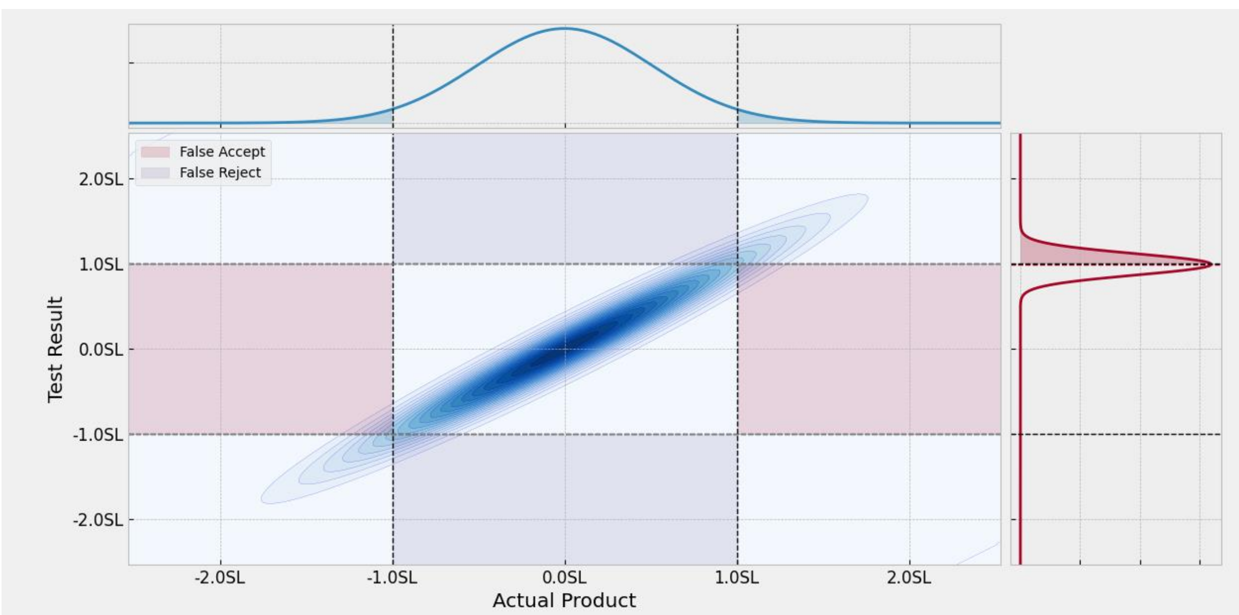
Reliability Considerations may include:

- Reliability decreases with time after calibration
- How much testing is required to demonstrate Reliability with confidence?
- *A priori* knowledge of the M&TE

This formula to determine "In-Tolerance" Reliability from historical data is easy to replicate in Excel. The formula is **Sample Size = ln(1-Confidence)/ln(Target Reliability).**

When we use this formula for 95 % EOPR at a 95 % Confidence Interval, we need 59 samples with 0 failures or rejects as this will give us an estimation of our process.

Thus, if Luke successfully targeted 59 womp rats out of 59 shots, we would now have our reliability data and could start to use global risk models.



Process Risk	Specific Measurement Risk	Global Risk
Process Risk: 5.0%	TUR: 4.0	Total PFA: 0.89%
Upper limit risk: 2.5%	Measured value: 0.99	Total PFR: 1.5%
Lower limit risk: 2.5%	Result: ACCEPT	-
Process capability index (Cpk): 0.65	Specific FA Risk: 47%	-

Figure 262: SunCal Software Screen Grab.

Setting this example up in Suncal shows our Specific Risk to be the same.

The global risk, however, shows a 0.89 % chance we would say something is good when it is bad or a 1.5 % chance, we would say something is bad that is good.

When using any risk model, the Expanded Measurement Uncertainty, including contributions for the Device Under Test, always determines the risk level or the acceptance zone.

If the risk is to be controlled to less than 2 %, a 4.6:1 TUR can limit the risk Probability of False Accept Risk to less than 2 %.

This is where effort needs to be made by the team that oversees what equipment to purchase to ensure the proper ratio is maintained.

For Instance, the example shows a 4:1 TUR ratio.

If equipment could be procured with a 10:1 TUR ratio, the total PFA would drop to 0.44 %, and the PFR would drop to 0.47 %.

This brings us to the following example of using Global Risk to manufacture a clone army.

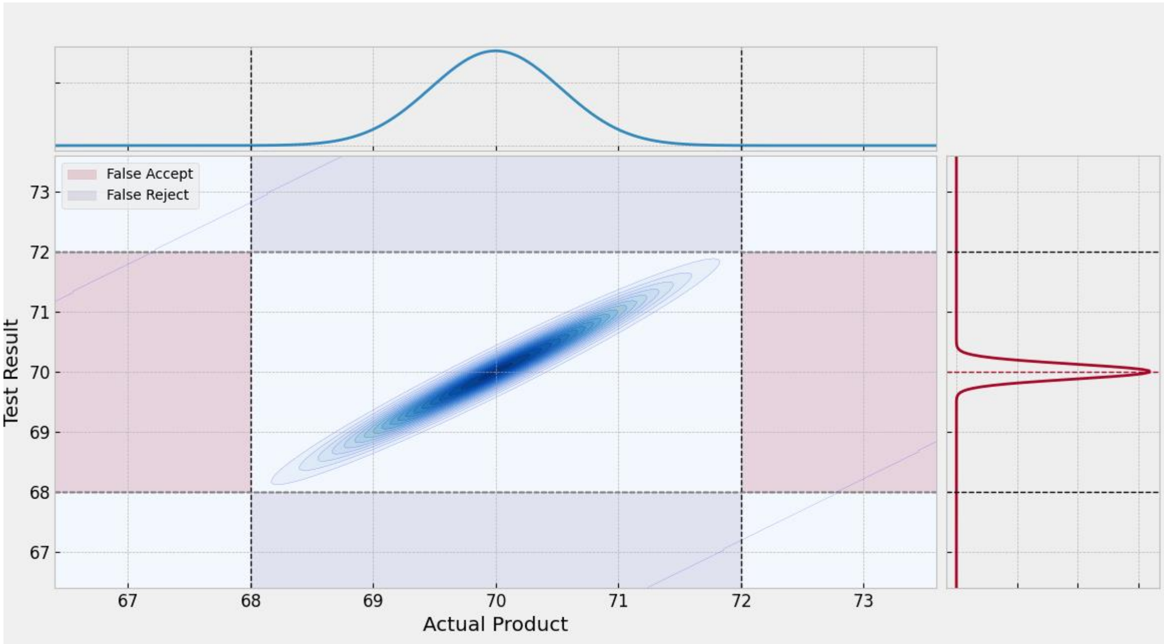
Star Wars Global Risk: Building a Clone Army

We want to build an army of clones to defeat the Rebellion.

The optimum height is 70 inches ± 2 inches to fit our clones with the same gear and maximize cloning efficiencies.

Our measurement system has a TUR of 8:1, meaning our Calibration Process Uncertainty is 0.25 inches.

The question becomes, what is the probability of saying a clone conforms to the specification when it does not?



Process Risk	Specific Measurement Risk	Global Risk
Process Risk: 0.017%	TUR: 8.0	Total PFA: 0.0039%
Upper limit risk: 0.0084%	Measured value: 70	Total PFR: 0.012%
Lower limit risk: 0.0084%	Result: ACCEPT	-
Process capability index (Cpk): 1.3	Specific FA Risk: 6.4e-56%	-

Figure 263: Suncal Software Showing Global Risk Calculations.

Using the Suncal software, we key in our lower specification of 68, our upper specification of 72, and 0.125 as our Expanded Uncertainty of the calibration process.

When using these values, we find about 0.0039 % or 3.9 per million are expected to be said to be in conformance when they are not.

This translates to about 1 out of every 500,000 being too tall and thus demonstrated in Star Wars Episode IV: A New Hope by a stormtrooper hitting their head as they were taller than their counterparts.

Shifting the focus toward design, particularly regarding headgear, recalls the importance of Luke's experience when he dons the Storm Trooper gear and exclaims, "I can't see a thing." This underscores the need to concentrate on essential aspects when designing and testing models based on our risk assessments.

Consider this: if we invest heavily in building an army of clones yet equip them with armor that impairs their vision, can we realistically expect to rule the galaxy?

As basic as it may sound, such oversights occur daily in manufacturing and measurement.

Numerous organizations overlook the crux of the matter: understanding the right requirements and ensuring that the products they design conform precisely to those requirements and specifications.

Star Wars Risk Conclusion

Using Star Wars as an example highlights the cost-saving potential of managing measurement uncertainty in global and specific risk scenarios. ASME B89.7.4.1-2005 effectively delineates these risk levels.

In ASME B89.7.4.1-2005, specific risk mitigation equates to "controlling the quality of individual workpieces," while program-level risk strategies involve "controlling the overall quality of workpieces." [45]

Specific risk is akin to immediate financial liability at the moment of measurement. This concept aligns with using specific risk or bench-level measurements for standards that are vital in precise measurements, similar to the precision required to fire a proton torpedo into the Death Star's vent port.

In manufacturing, the focus often shifts to managing average quality, where program-level risk pertains to the average likelihood of making incorrect acceptance decisions based on historical data.

In both cases, investing in equipment that reduces the Test Uncertainty Ratio offers substantial cost savings by minimizing rework and ensuring more accurate acceptance and rejection decisions.

The Suncal software is free from Sandia National Laboratories and can be downloaded here.

Measurement Confidence Action Plan

How confident are you with the measurements you are making?

We encourage you to pull out a piece of paper and write down Measurement Uncertainty, Metrological Traceability, and Measurement Decision Risk. Under each topic, list items where you can improve. Put at least one item per group. The outcome will be to have confidence in the measurements we make.

Some might think I cannot improve my metrological traceability. Are you going to an NMI or a laboratory with Primary Standards for your calibrations? Should you be? Are you closing the loop with Statistical Process Control and Interlaboratory Comparisons (ILC) or Proficiency Tests (PT)? Do you understand how your calibration provider calculates their measurement uncertainty? Might it be worthwhile to understand what you are getting from them?

The point is there is always something we miss.

More information on decision rules can be found in our decision rule guidance document, which is available for free at https://mhforce.com/documentation-tools/.

Sample Calculation of TUR

Example: A customer sends a **10,000 lbf** load cell for calibration with an accuracy specification of **± 0.05 % of full scale**. The calibration provider uses a Universal Calibrating Machine to perform the calibration. When **10,000 lbf** is applied, the unit reads **10,001 lbf**. The display resolution is **1 lbf**.

Step 1: Calculate the numerator.

$$\text{TUR} = \frac{\text{Span of the} \pm \text{Tolerance}}{2 \times k_{95\%}\left(\sqrt[2]{\left(\frac{\text{CMC}}{k_{\text{CMC}}}\right)^2 + \left(\frac{\text{Resolution}_{\text{UUT}}}{\sqrt[2]{12}}\right)^2 + \left(\frac{\text{Repeatability}_{\text{UUT}}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 264: TUR Formula Nominator.

The device is a **10,000 lbf** load cell with an accuracy specification of **± 0.05 %.**

10,000 * 0.0005 = ± 5 lbf

The upper specification limit is 10,000 + 5 = 10,005 lbf

The lower specification limit is 10,000 – 5 = 9,995 lbf

Therefore, the Span of the ±Tolerance is 10,005 – 9,995 = 10 lbf

$$TUR = \frac{10\ lbf}{2\ x\ k_{95\%}\left(\sqrt[2]{\left(\frac{CMC}{k_{CMC}}\right)^2 + \left(\frac{Resolution_{UUT}}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatability_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 265: TUR Formula with the Numerator added.

Step 2: Calculate the denominator.

Everything is calculated to **1 standard deviation (Standard Uncertainty)** for this calculation.
Calibration and Measurement Capability (CMC)

$$\text{TUR} = \frac{\text{Span of the} \pm \text{Tolerance}}{2 \times k_{95\%}\left(\sqrt[2]{\left(\frac{\text{CMC}}{k_{\text{CMC}}}\right)^2 + \left(\frac{\text{Resolution}_{\text{UUT}}}{\sqrt[2]{12}}\right)^2 + \left(\frac{\text{Repeatability}_{\text{UUT}}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 266: CMC portion of the denominator.

CMC is the uncertainty at the calibrated force. The Universal Calibrating Machine has an uncertainty of **0.02**

% at 10,000 lbf.

The CMC is **10,000 * 0.0002 = 2 lbf**

***k*$_{CMC}$ is 2**, which was listed on the calibration provider's certificate.

Dividing the CMC by 2, the standard uncertainty is reported at **one standard deviation**. In most cases, the **CMC uncertainty component is reported at approximately 95 %**, and **a coverage factor of *k* = 2** is used.

$$TUR = \frac{10\ lbf}{2\ x\ k_{95\%}\left(\sqrt[2]{\left(\frac{2\ lbf}{2}\right)^2 + \left(\frac{Resolution_{UUT}}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatability_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 267: TUR Formula with CMC added.

UUT Resolution

$$TUR = \frac{\text{Span of the} \pm \text{Tolerance}}{2\,x\,k_{95\%}\left(\sqrt[2]{\left(\frac{CMC}{k_{CMC}}\right)^2 + \left(\frac{Resolution_{UUT}}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatabiliity_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 268: Resolution portion of the denominator.

Resolution$_{UUT}$ the force instrument, is calculated by dividing the force applied by the output at the applied force and then multiplying this by the instrument's readability.

The **Resolution$_{UUT}$** is **(10,000 lbf / 10,000 lbf) * 1 = 1 lbf**

To convert **1 lbf** resolution to standard uncertainty, it is either divided by the **square root of 12** or the square root of 3, depending on the Type of resolution.

$$TUR = \frac{10\ lbf}{2\ x\ k_{95\%}\left(\sqrt[2]{\left(\frac{2\ lbf}{2}\right)^2 + \left(\frac{1\ lbf}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatability_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 269: TUR Formula with Resolution added.

Repeatability

$$TUR = \frac{\text{Span of the} \pm \text{Tolerance}}{2\,x\,k_{95\%}\left(\sqrt[2]{\left(\frac{CMC}{k_{CMC}}\right)^2 + \left(\frac{Resolution_{UUT}}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatability_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 270: Repeatability portion of the denominator.

For this example, **five replicate readings** are taken.

Repeatability is obtained by applying a force of **10,000 lbf** to the **Unit Under Test (UUT)** five times, and the sample standard deviation of five replicated measurements is calculated.

Repeatability of sample size five: **(10,000, 10,001, 10,000, 10,001, 10,001) = 0.54772**
Since the repeatability is already expressed as one standard deviation, the divisor is 1.

$$TUR = \frac{10\ lbf}{2\ x\ k_{95\%}\left(\sqrt[2]{\left(\frac{2\ lbf}{2}\right)^2 + \left(\frac{1\ lbf}{\sqrt[2]{12}}\right)^2 + \left(\frac{0.54772}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 271: TUR Formula with Repeatability added.

Other Error Sources

$$TUR = \frac{\text{Span of the} \pm \text{Tolerance}}{2\,x\,k_{95\%}\left(\sqrt[2]{\left(\frac{CMC}{k_{CMC}}\right)^2 + \left(\frac{Resolution_{UUT}}{\sqrt[2]{12}}\right)^2 + \left(\frac{Repeatability_{UUT}}{1}\right)^2 + \cdots (u_{Other})^2}\right)}$$

Figure 272: Other error sources in the denominator.

Other error sources attributed to the **CPU** can be considered for the **UUT**. Some examples are environmental influences, errors in correction factors, etc. For this example, other error sources are inherent in repeatability and **CMC**.

$$TUR = \frac{10\ lbf}{2\ x\ k_{95\%}\left(\sqrt[2]{\left(\frac{2\ lbf}{2}\right)^2 + \left(\frac{1\ lbf}{\sqrt[2]{12}}\right)^2 + \left(\frac{0.54772}{1}\right)^2}\right)}$$

Figure 273: TUR Formula with all error sources added.

Calculate the Denominator

Sum of all the contributors = **SQRT((2/2)^2+(1/3.464)^2+(0.54772/1)^2) = 1.1762**

$$\textbf{TUR} = \frac{10\ lbf}{2\ x\ k_{95\%}\ (1.1762)}$$

Figure 21: TUR Calculated.

The specification of **10 lbf** is divided by: **2 * *k* at 95 %** Calibration Process Uncertainty (***k* = 2** for this example)

$$\textbf{TUR} = \frac{\mathbf{10\ lbf}}{\mathbf{2\ x\ 2.35231}} \qquad \textbf{TUR} = \frac{\mathbf{10\ lbf}}{\mathbf{4.70462}}$$

Figure 274: TUR Calculated.

TUR = 2.1256

Load Cell Specific Risk Example

How to Calculate Specific Risk: Step-by-Step Instructions

Many people struggle with decision rules and how to calculate risk. This article was written to provide step-by-step instructions to calculate Measurement Uncertainty, Guard Band Acceptance Limits, and Probability of False Acceptance (PFA).

Load Cell Specific Risk Example Calculation:

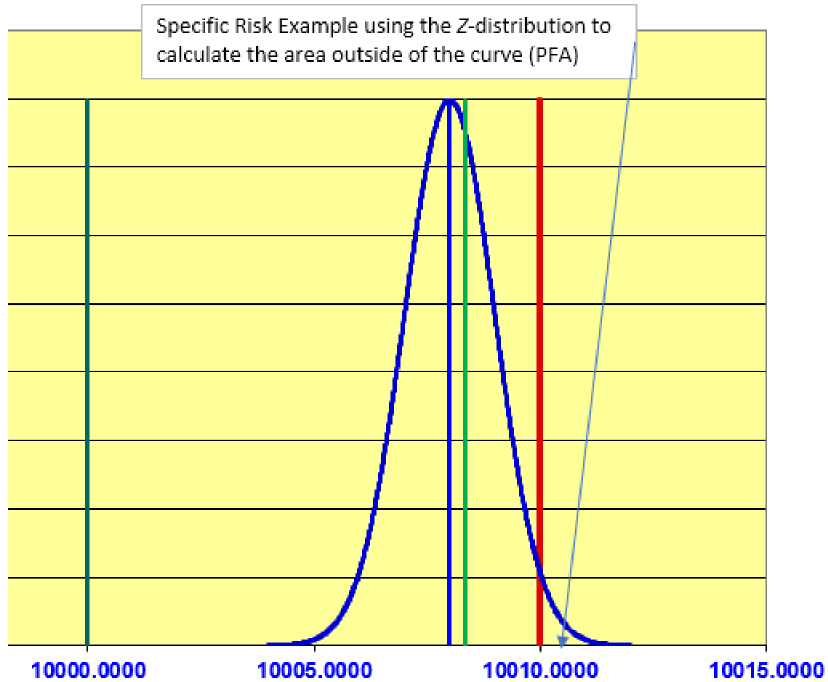


Figure Load Cell Specific Risk Example

To Calculate PFA, the Excel function is NORM.DIST.
Risk upper = NORM.DIST(Measured value, Upper Tolerance Limit, Standard Uncertainty, TRUE)
Risk Lower = 1- NORM.DIST(Measured value, Lower Tolerance Limit, Standard Uncertainty, TRUE)
PFA = Risk upper +Risk Lower

Load Cell Specific Risk Example

A customer sent their 10,000 N load cell in for calibration. The purchase order indicates calibration to the manufacturer's specification.

Since the purchase order is incomplete regarding pass/fail criteria and how measurement uncertainty is taken into account, the customer is contacted and presented with several options based on their risk requirements.

The customer decides to rewrite the order. The new purchase order reads calibrate using a tolerance of 0.1 % of full scale (± 10 N), taking measurement uncertainty ($U_{95.45\,\%}$) into account using specific risk calculations. Fail if the PFA for either side > 2.5 % otherwise pass.

Step 1 Calibrate the equipment.

We will need to determine the Standard Uncertainty (*k* =1) of the Measurement Process for this calibration. For simplistic sake, we will look at the 10,000 N point.

10,000 N force was applied three times and the instrument read 10,000 10,002 10,001.

Taking the standard deviation of these numbers =stdev(10,000 10,002 10,001) we get 1
The resolution of the equipment is 1 N.
The CMC of the reference standard is 0.2 N.

$$\left(\sqrt[2]{\left(\frac{\mathbf{CMC}}{\mathbf{k_{CMC}}}\right)^2 + \left(\frac{\mathbf{Resolution_{UUT}}}{\sqrt[2]{\mathbf{12}}}\right)^2 + \left(\frac{\mathbf{Repeatability_{UUT}}}{\mathbf{1}}\right)^2 + \cdots (\mathbf{u}_{Other})^2}\right)$$

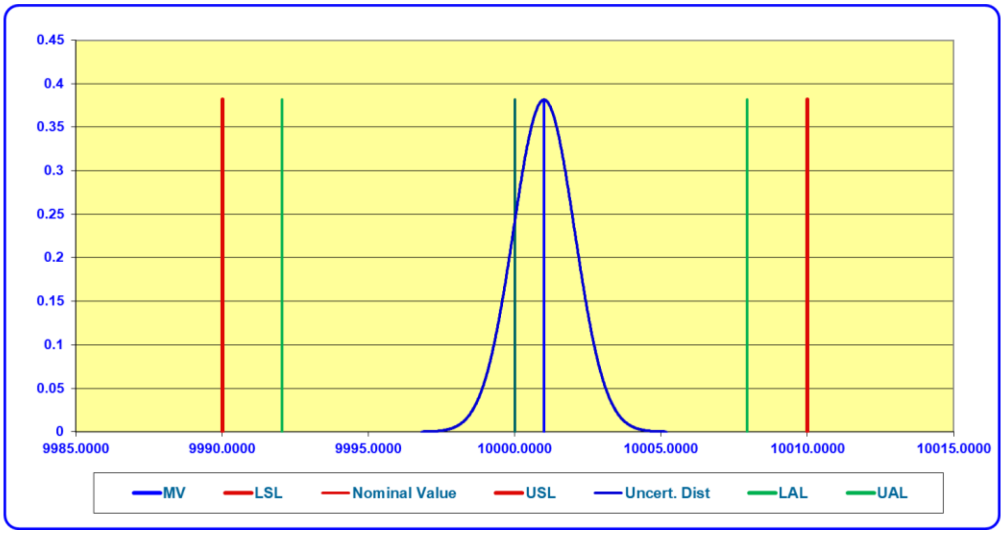
Thus, the formula for Standard Uncertainty of the Measurement Process becomes.

$$\left(\sqrt[2]{\left(\frac{0.2}{2}\right)^2 + \left(\frac{1}{\sqrt[2]{12}}\right)^2 + \left(\frac{1}{1}\right)^2}\right) = 1.04563 \text{ N}$$

We now have everything we need to calculate Guard Banded Acceptance Limits and PFA
A 10,000 N load cell has a tolerance of ± 0.1 % of full scale.
The measured value is 10,000 N.
Upper Tolerance = 10,010 N.
Lower Tolerance = 9,990 N.
Measured Value = 10,001 N.
Standard Uncertainty = 1.04563 N.

Step 2 Calculate Acceptance Limits

We are calculating our conformance probability for 97.50 % confidence in symmetrical tolerances. We calculate the Guard band Multiplier by using the formula in Excel of **NORM.S.INV (0.975)/2.**
We then use this number of 0.98 as our GB Multiplier as follows.
*For the Guard band upper limit, we have 10010 – (GB Multiplier * Coverage Factor * Standard Measurement Uncertainty)*
*10010 – (0.980 * (2 *1.04563)) = 10007.9506*
*For the Guard band lower limit, we have 9990 + (GB Multiplier * Coverage Factor *Standard Measurement Uncertainty)*
*9990 + (0.980 * (2 * 0.125)) = 9992.0494*



Load Cell Specific Risk Graph showing the GB Acceptance Limits to limit PFA to 2.5 %

Thus, our acceptance limit is between *9992.0494 and 10007.9506 as any measured value between these two values will have less than 2.5 % PFA.*

Step 3 Calculate PFA

Risk Upper = NORM.DIST(10001, 10010, 1.04563, TRUE) = 0 %
Risk Lower = 1- NORM.DIST(10001, 9990, 1.04563, TRUE)) = 0 %
Total Risk = 0 %

Additional Proof

One can use the Upper or Lower GB Acceptance Limit to verify the GB acceptance limits.
Risk Upper = NORM.DIST(10007.950603, 10010, 1.04563, TRUE) = 2.5 %

Reducing Your Measurement Risk

Bad measurements can lead to big problems. Just think about some of the disasters that have been caused by poor decision-making.

The BP oil refinery explosion in Texas, the Hubble telescope's focus issue, the Space Shuttle explosion, the Spirit of Kansas Stealth Bomber crash, Cox Health's overdosing of 152 cancer patients, Paris Trains, and another BP oil rig disaster are all examples of tragedies that could have been prevented with better measurement practices.

The 2016 film Deepwater Horizon is an excellent film showcasing how a blowout caused an explosion, killing 11 people and a catastrophic oil leak.

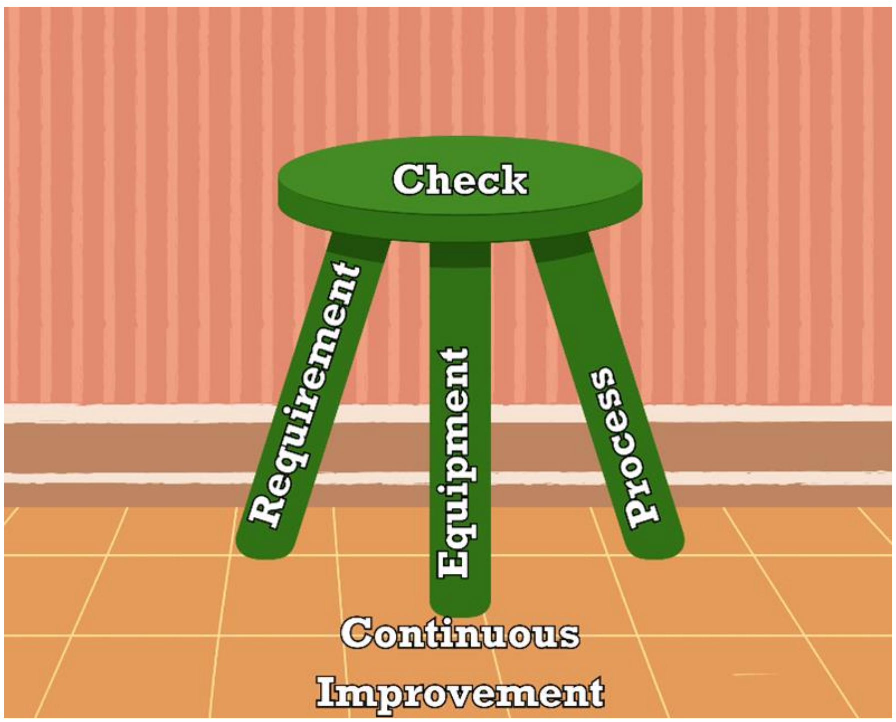


Figure 275: 5 Simple Rules to Reduce Your Measurement Risk

So, how can we avoid these issues? Here are five simple rules to reduce your measurement risk:

1. **Understanding the Right Requirements**: This first rule involves knowing what is needed to accomplish the task. The more accurate the system, the higher the costs to procure and calibrate the equipment. Buying the wrong equipment will often lead to more frequent calibrations, often costing more. The recommendation before any purchase is to discuss the intended purchase with those calibrating it. Technicians often will know what equipment frequently fails calibration.

2. **Purchasing the Right Equipment**: Not all tools are created equal. Make sure you're using the right equipment for the job. Using the wrong equipment can lead to inaccurate measurements and more significant problems. So, always ensure that your equipment suits the task at hand.
3. **Have the Right Processes** – This rule requires a training program and proof of training (records) to validate the individuals calibrating or using the equipment. A process should be in place that ensures all aspects of the standards are being carefully satisfied in the calibration process. Use Proper Adapters and ensure the instrument's calibration matches its use in the field or lab.
4. **Check Your Work**: Technicians are human, and humans make mistakes. Always double-check your measurements to make sure they're accurate. It's easy to overlook a small error, yet that small error can have big consequences. So, take the time to verify your work.
5. **Stay Vigilant**: Don't let success make you complacent. Always be on the lookout for potential risks and take the necessary precautions to prevent them. It's easy to let your guard down when things are going well, but that's when mistakes can happen. So, stay alert and stay safe.

The first three requirements are the legs of the stool. If one is neglected, it will be hard to sit on the stool. Checking the work helps ensure accuracy. The floor or support structure is continually improving to keep everything in place.

A tremendous foundational tool is a measurement assurance program based on control charts and a well-laid-out Proficiency Test or Inter Laboratory Comparison plan.

Remember, it's better to be safe than sorry.

Following these rules can help reduce your measurement risk and prevent potential disasters. It's all about being proactive and taking the necessary steps to ensure accuracy and safety.

After all, the ultimate objective is to develop products that function effectively and are safe for use. Those adhering to established guidelines will clearly understand the necessary equipment—in terms of physical tools and the calibration standards required in a laboratory setting—to validate the accuracy of reported measurement uncertainty. This comprehensive approach ensures not only the functionality and safety of the products but also builds credibility by providing transparent and precise measurement data.

It is said that if an error is missed at one stage of a process, it takes ten times more to correct it at the next stage. So, more checks and balances help minimize any potential errors. Failure to follow these rules often results in more money spent to develop custom solutions that are hard to measure or use a commercially available unit that can't control the risks in that the company saves $ 15,000.00 on procuring a piece of equipment only to spend $1,000,000.00 in scrap.

Reliability/End of Period Reliability

Reliability/End of Period Reliability

$$EOPR = \frac{\text{Number of in-tolerance results}}{\text{Total number of calibrations}}$$

Figure 276 Simple Formula to Calculate EOPR

Reliability is defined as the number of calibrations resulting in as-received IN – Tolerance Results divided by the total number of calibrations.

Reliability Considerations may include:

- Reliability decreases with time after calibration.
- How much testing is required to demonstrate reliability with confidence?
- *A priori* knowledge of the M&TE

Reliability decreases with time after calibration.

Reliability Analysis of M&TE should be based on similar instrumentation manufacture, model #, and calibration intervals. What should be avoided is intermixing different M&TE with different calibration intervals, environments, and conditions.

The example above estimates the EOPR by simple division, which provides “a” number yet disguises the confidence associated (it is not “the” number). For example, if a particular make/model instrument were calibrated 100 times with no “Out of Tolerance” (OOT) noted, using simple math, we discover the EOPR is 100 %. This is a false statement. Although 100 out of 100 items were found to be “In-Tolerance,” the true reliability is somewhere between two reliability confidence bounds. If the servicing lab has an EOPR target of 99 % with 90 % confidence and zero failures, the worst-case EOPR is assumed to be the lower calculated confidence bound.

As mentioned, an estimate of reliability can be calculated using binomial confidence bounds. What is a binomial confidence bound? It is the statistical equivalent of putting a “tolerance” around the target reliability. Like a typical specification, it might be read as 100 N ± 1 N at 95 % confidence. In this example, the value of 100 N is bound by 99 to 101 N. If the measured value is 100.08 N, the measurement is considered “In-Tolerance.” The true value, however, is unknown. It is unknown because of the measurement uncertainty involved. The true value lies within the measured value and the associated uncertainty. This is the case for any measurement situation, as uncertainty is unavoidable.

How much testing is required to demonstrate reliability with confidence?

The formula to determine “In-Tolerance” Reliability from historical data is easy to replicate in Excel. The formula is Sample Size = ln(1-Confidence)/ln(Target $_{\text{Reliability}}$)

Note: There is a lot more to calculate reliability than this simple formula. Our Decision Rules Guidance document, written by several industry professionals, provides the full code to estimate confidence bounds. The above formula is a starting point for knowing how many samples would be required if they all passed.

Load Cell Reliability – Example Calculations

Over the years, many of us at Morehouse have been asked what value one should use for Reference Standard Stability when a system is new.

You may think: "I need a reliable number for my uncertainty budget. What should I use?" The answer is variable as it depends on several factors.

One of the key factors is figuring out how stable someone needs the load cell system to be to meet their measurement uncertainty requirements. Is 89 % EOPR acceptable with 95 % confidence, or is 95 % End-of-period reliability (EOPR) the goal?

The other reaction we often receive is, "No one does that because there are too many variables." Load cell reliability will depend on the **complete system** and its use.

The use would include anything that could influence the results.

Force measurement is mechanical, such as using different adapters and different cables, changing thread engagement, overloading the load cell, using the meter, and increasing the number of loading cycles.

So, after being asked numerous times, we decided to tackle the question, "What should I expect for stability with year-to-year annual calibrations?"

We started by finding enough samples to meet the 95 % confidence interval criteria, with 95 % End-of-period reliability, which seemed daunting.

What is required to calculate the Reliability of a Load Cell System?

In simplistic terms, End of Period Reliability is defined as the number of calibrations that meet acceptance criteria divided by the total number of calibrations.

This formula to determine "In-Tolerance" Reliability from historical data is easy to replicate in Excel.

The formula is **Sample Size = ln(1-Confidence)/ln(Target Reliability).**

When we use this formula for 95 % EOPR at a 95 % Confidence Interval, we need 59 samples with 0 failures or rejects.

Knowing that Reliability decreases with time after calibration and that anyone wanting a performance of better than 0.05 % will likely need calibration performed annually, we decided that our sampling needed to include load cells on an annual calibration cycle.

Thus, we went on to pull 59 samples with a calibration interval of around 365 days to demonstrate Reliability with the appropriate confidence.

Of the 60 samples pulled, 6 failed the criteria of being better than 0.05 % from 10 % of the range to 100 %. Upon investigation of the six failures, one load cell was found to have a loose calibration top adapter, which warranted removal from the data set.

Two of those points were higher than 0.05 %.

Reliability Constraints	
Reliability Target =	95.0 %
Confidence Target =	95.0 %
Calculated Sample Size =	59

(Used to establish initial sample size)

☐ Correct to "True" EOPR?

Calibration History Results	
Calibrations or Sample Size, n =	60
Failures/Rejects, c =	3
Confidence Level =	95%
Failure Rate =	5.00%
Unreliability (worst case) =	12.42%
R(t) =	87.58%

Actual Samples 60

Upper Confidence Limit = 98.96%
Lower Confidence Limit = 87.58%

UUT Constraints	
Assumed EOPR =	95.00%
Use Add. Ref. Std. Samples?	☐
Max PFA =	2.00%

93 Additional samples needed

Reference EOPR with Additional Samples	
Samples needed to meet R(t) =	153
Failures/Rejects, c =	3
Confidence Level =	95%
Failure Rate =	1.96%
Unreliability (worst case) =	4.99%
Reliability (Sample size adj.) =	95.01%

Figure 277: Reliability Formula in Use.

After scrubbing the data, we found that 3 out of 60 failed the criteria of a change of less than 0.05 %.

The loose calibration adapter is a known error source known to make load cells much less reliable.

Thread Depth Comparison - Shear Web Load Cell

0.25 " Backed Off | Integral Adapter Installed

Percent of Full Scale	Percentage Difference In Loading Conditions
10%	0.184%
50%	0.174%
100%	0.138%

Figure 278: Morehouse Load Cell Potential Error when Threaded Adapters are not Locked in.

Above is a picture of a Morehouse shear web load cell loaded with the adapter locked in compared to the same load cell loaded with 0.8 inches of engagement.

The difference in output is over 0.138 % and enough to demonstrate a priori knowledge that any load cells with loosely threaded adapters could skew the results and should be removed.

The adapters are made to be locked in place for a reason.

Another load cell had an entry error of 45 % instead of 0.045 % (oops). Thus, after removing one load cell, we sampled an additional load cell, ending with 60 samples and three failures.

According to the initial calculations, we would need another 93 samples for our load cell reliability target based on a one-year stability of 0.05 % or better.

Meaning we would need to continue sampling or raise the stability criteria.

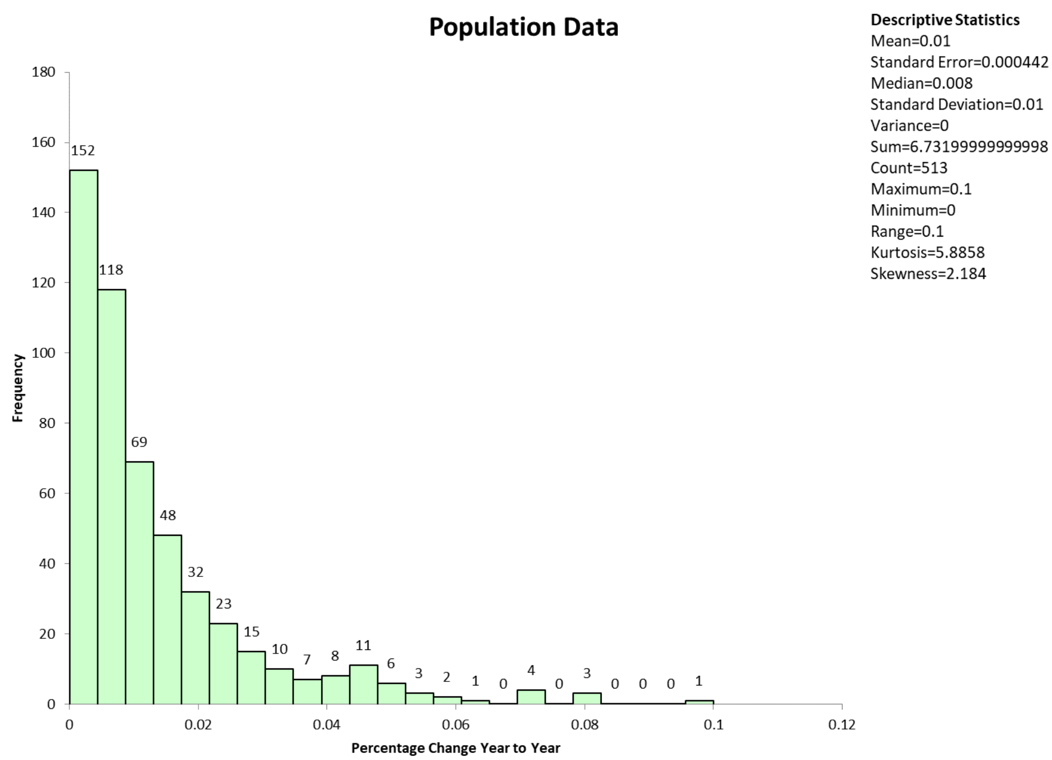


Figure 279: 171 Load Cells Analyzed by One-Year Percentage Change.

As shown above, we pulled 171 load cells and sampled the stability criteria at 10 %, 50 %, and 100 % test points. Anything below 10 % would have too low of a resolution to use.

For instance, on a 4 mV/V load cell, a change of 0.00005 mV/V would result in a 0.06 % change at the 2 % point. Most indicators used for load cell calibrations are not even stable to ± 0.00002 mV/V, which could account for a shift in stability of 0.025 % at a 2 % point.

On top of that, most indicators significantly contribute to the overall Reliability of the load cell.

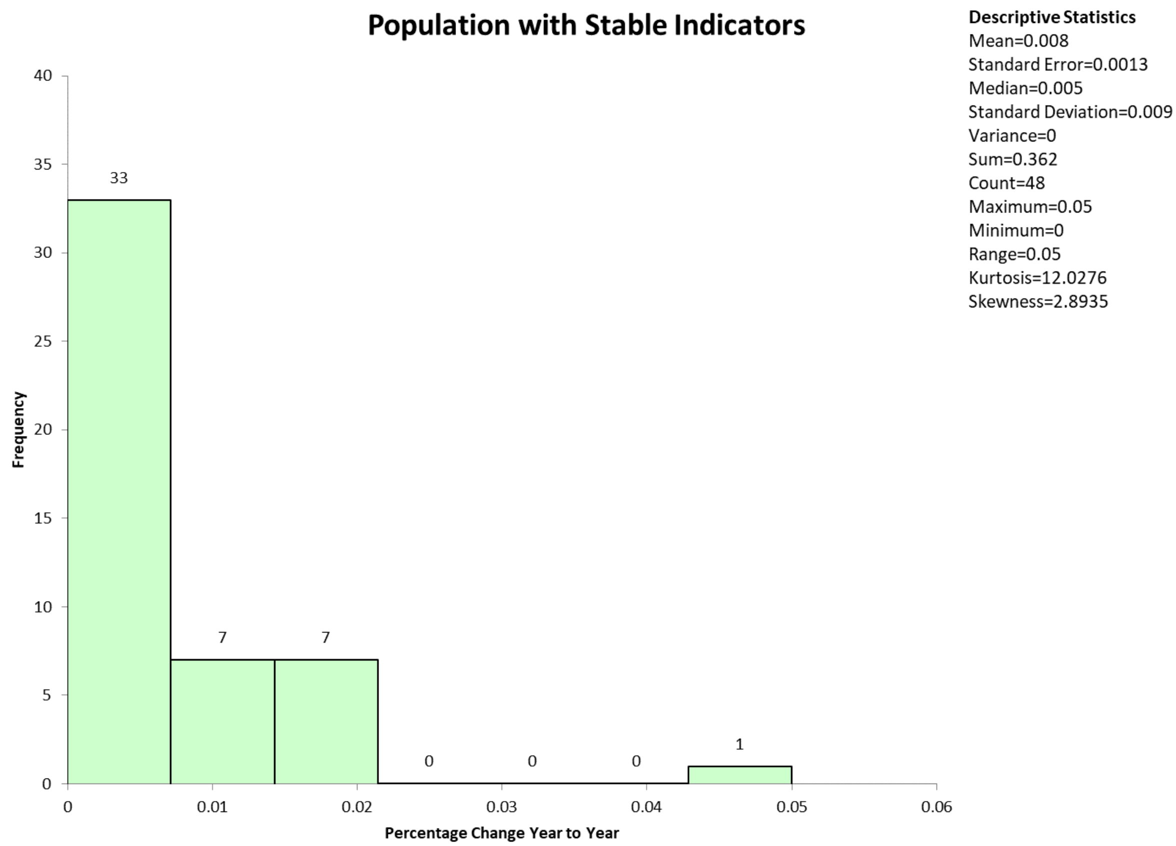


Figure 280: Population with High-End Stable Indicators.

We tested the indicator influencing load cell reliability by pulling out any indicator other than our 3458A and DMP 40. With the other indicators pulled out, we were left with 48 samples; only 1 was over 0.02 %.

With 95 % confidence, these load cells are at least 91.66 % reliable for a year-to-year change greater than 0.02 %.

Reliability Constraints	
Reliability Target =	95.0 %
Confidence Target =	95.0 %
Calculated Sample Size =	59

(Used to establish initial sample size)

☐ Correct to "True" EOPR?

Calibration History Results	
Calibrations or Sample Size, n =	513
Failures/Rejects, c =	14
Confidence Level =	95%
Failure Rate =	2.73%
Unreliability (worst case) =	4.23%
R(t) =	95.77%

Actual Samples 513

Upper Confidence Limit = 98.50%
Lower Confidence Limit = 95.77%

Figure 281: Entire Population Data.

With a total of 513 samples from 171 load cells, we had enough data to say with a 95.77 % or better confidence limit that Morehouse load cells from 25 lbf through 1,000,000 capacities paired with a 4215, HADI, Agilent 3458A, HBM DMP 40, or GTM indicator could achieve 0.05 % or better stability for a 1-year calibration cycle when appropriately used from 10 % through 100 % of capacity.

There is more with EOPR as the rules to establish EOPR can be subjective.

- Rules such as how many first-time calibrations are counted.
- How many broken instruments should be included?
- Should we include calibrations with different due dates?
- What about post-dating and so on?

We included the one-year after the initial calibration numbers in the data set for new instruments.

About 20 % of the population data consisted of a load cell and meter combination back for a second calibration.

Including these instruments would tend to skew the data. Load cells will experience a shift within their early years of use.

Many would call this a break-in period. Depending on the load cell and material, the shift could be predictable. For instance, load cells loaded in only one direction usually have a balance shift in the same direction.

Typically, the shift will decrease logarithmically with increasing loading cycles.

Sometimes, the shift is due to material hardening with use, gauging, or other factors.

Whatever the reason, we typically see this occurring during those first few calibration cycles.

Our initial round included load cells paired with good indicators, and three points at 10 %, 50 %, and 100 % capacity per load cell were sampled.

Thus, it would be possible for the 50 % and 100 % test points to skew the data.

What if we did a further analysis on the 10 % point?

The Load Cell Reliability at the 10 % Test Point

Of the 14 failures, nine occurred at the 10 % test point.

Reliability Constraints	
Reliability Target =	95.0 %
Confidence Target =	95.0 %
Calculated Sample Size =	59

(Used to establish initial sample size)

☐ Correct to "True" EOPR?

Calibration History Results	
Calibrations or Sample Size, n =	171
Failures/Rejects, c =	9
Confidence Level =	95%
Failure Rate =	5.26%
Unreliability (worst case) =	9.00%
R(t) =	91.00%

		Upper Confidence Limit =	97.57%
Actual Samples	171	Lower Confidence Limit =	91.00%

Figure 282: The 10 % Force Point Test Point Data.

The 10 % test point had a failure rate of 5.26 % of the population.

At the same time, the failure rate of the 50 % and 100 % test points were both under 2 %.

At the 50 % point, there were three failures out of 171 samples, resulting in 95 % Confidence that the stability is 95.53 % reliable.

At the 100 % point, there were two failures out of 171 samples, resulting in 95 % Confidence that the stability is 96.36 % reliable.

If we raised the stability target to 0.06 %, the 95 % reliability target at 95 % confidence at the 10 % point would become 93.95 %. And a stability target of 0.07 % would result in 95.53 % reliability.

If we lowered the target to 0.032 %, the 95 % reliability target at 95 % confidence at the 10 % point would become 74.43 % for the population.

At the 50 % point, it would be 91.00 %, and at the 100 % point, it would be 91.72 % reliable.

89 % End of Period Reliability Rule

We discussed 95 % Confidence and 95 % EOPR, though the standard rule to control false acceptance is to accept the 89 % EOPR rule as appropriate to limit risk to less than 2 %.

The theory is that when a process or system has high Reliability, most error sources are under control. More information can be found in Subclause 5.3 in Z540.3 standard.

The basis is that the calibration process uncertainty should be small enough to detect EOPR confidently.

In our case at Morehouse, the calibration process uncertainty did not exceed 0.01 % of the applied force, and most of the population was controlled to be better than 0.005 %.

Without an extremely good UUT and acceptable reference Standards, providing minuscule PFA or relatively good equipment, it would not be possible to observe a high in-tolerance reliability.

This means that if our Measurement Uncertainty was 0.05 %, we could not claim 0.05 % reliability with confidence.

Reliability Constraints	
Reliability Target =	95.0 %
Confidence Target =	95.0 %
Calculated Sample Size =	59

(Used to establish initial sample size)

☐ Correct to "True" EOPR?

Calibration History Results	
Calibrations or Sample Size, n =	513
Failures/Rejects, c =	43
Confidence Level =	95%
Failure Rate =	8.38%
Unreliability (worst case) =	10.68%
R(t) =	89.32%

95% Confidence the process is at least 89.33% reliable.

Upper Confidence Limit = 93.87%

Lower Confidence Limit = 89.32%

Figure 283: EOPR of 89 % was achieved for a Stability Target of 0.036 % or less.

If we were interested in population data for 89 % EOPR, we could meet that number using a load cell reliability target of all data points showing a reliability better than 0.036 %. Of our 513 samples, 43 would fail to be lower than 0.036 % for 89.32 % EOPR at 95 % Confidence.

A number I typically advise people to use for the first year of 0.032 % has an EOPR of 87.61 %.

However, I am more confident that this number will increase when a 4215 High Stability model, 4215 plus, or Fluke 8588A, is used as the reference indicator.

Load Cell Reliability – Conclusion

All load cells or metals will change with frequent loads applied.

Therefore, it's important to determine if a given shift is normal for that load cell or if it is a warning sign of damage. Shifts that trend lower and are not erratic do not indicate a cell going bad.

Shifts that are erratic or get worse with identical loading cycles require troubleshooting.

Possible causes include electrical leakage, fatigue, poor gaging, bad material, overload, bad solder joints, and unstable loading conditions.

The first few calibration cycles are typically when the most change occurs.

If someone wants to maintain an overall reliability of 95 % with 95 % confidence of 0.05 % or better, then care must be taken in selecting the overall system.

Our data shows that maintaining 0.02 % stability with high-end indicators is possible.

In our sampling, with 95 % confidence, we were at least 91.66 % reliable when we filtered out the data only to include meters costing USD 15,000.00 or above.

However, there might be other solutions to control the stability of the meter.

A load cell simulator is one solution that can be used as a check standard to help control and monitor the indicator stability.

Other Comments on Reliability:

- Calculating Reliability alone may not be enough to ensure confidence in your measurement.
- Calculating Confidence Intervals can give insight into actual Reliability.
- Typically, many labs struggle with getting enough samples. In this case, it may be prudent to seek a calibration provider to increase the acceptance zone to issue a pass, utilizing reference standards with low measurement uncertainty.
- The system's end-user should look at their requirement for Reliability and evaluate calibration intervals, accordingly, as shortening intervals may be a solution that allows the desired reliability target to be met.

Other Considerations

The True Cost of Long Force Calibration Lead Time

If you run a calibration laboratory or perform calibrations in the field, your most significant assets are your people and equipment. Running any calibration business requires the scheduling of equipment.

How much revenue are you sacrificing when you do not have your equipment? What is the True Cost of Long Force Calibration Lead Times? How much is lost from being unable to turn our force calibration equipment around for your customers? Do you lose a customer or job because you do not have the equipment for weeks or months? What is the value of that lost income?

Force Calibration Lead time issues lead to more lost time and more cost to you. Morehouse is not the least expensive calibration solutions provider, though the overall cost can be dramatically less when all things are considered.

Force Calibration Lead time has many implications. The cost of not having your equipment for weeks, maybe months, can be large. These include downtime, communication breakdowns, scheduling delays, and lost revenue.

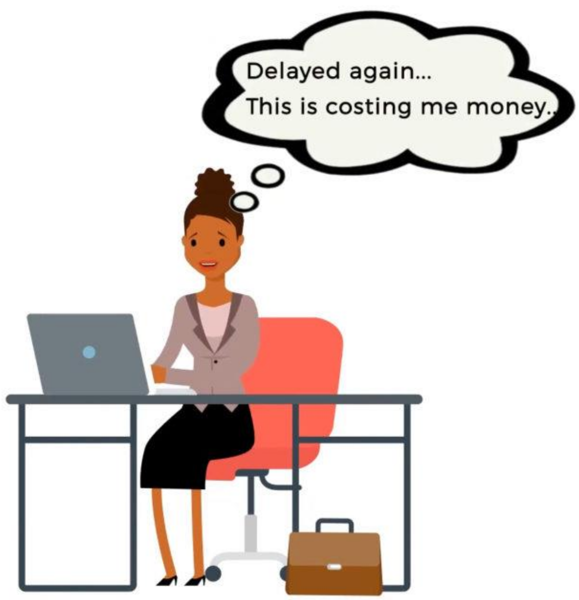


Figure 284: Long force Calibration Lead Times Impact More than the Bottom Line.

The problems with downtime include:

The inability to use your equipment means work gets bottlenecked.

Overtime may be required to catch up when the equipment comes back from calibration.

Communication delays

What is the impact of continually checking on the status of an item out for calibration?

There's an economic cost, and delays can lead to employee frustration.

Scheduling delays

How much does shifting your calibration work to your customer's schedules cost?

Less revenue

No equipment equals delayed or lost revenue.

Figure 285: No Equipment = Lost Revenue.

What happens when you invest in getting your calibration equipment returned quickly?

Your company can benefit when a calibration lab can do the following quickly:

Provide a quotation.
Receive your items.
Contact you with any issues.
Calibrate your equipment.
Pack and return your calibration equipment.
Morehouse takes great pride in our ability to provide quick quotations.
We respond to requests in hours, not days. Your equipment will be unpacked, inspected, and staged for climatization when we receive it.

We want to do it quickly if we must contact you with any issues.

The contract is reviewed against your calibration requirements. The review is done promptly to mitigate calibration lead time delays. Items are then put on the schedule for calibration to ensure our 7 - 10-day guarantee, or we can reach out to you with any potential concerns.

Calibration of your equipment

The technician works through the daily schedule on one of our many force or torque calibration machines. Morehouse has more than five deadweight machines known to be within 0.002 % of applied force, which is twenty to fifty times more accurate than most other calibration labs.

Once calibration is complete, we will pack and return your equipment. Items are returned within 7 - 10 days of receipt. Expedited options are available for an even faster turnaround.

You have only so much time. It should not be spent waiting on equipment. Morehouse can lower your overall calibration cost, measurement uncertainty, and calibration headaches, resulting in less overall cost.

Glossary of Terms

This section contains a glossary of common terms in force measurement. It is essential to have these for reference because most of these terms are used when speaking about the characteristics of load cells, discussions on measurement uncertainty, and calibration standards.

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 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, however that does not mean that your equipment will be put in the same equipment 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 be within 0.0016 % of applied force. However, if someone sends in an instrument 36 inches long, we cannot fit it in that machine, therefore, the best we can do is 0.01 % of applied in our elongated Universal Calibrating Machine.

Environmental Factors: Environmental conditions, like temperature, influence the force transducer output. The most common specification is the temperature effect on the force-measuring instrument's specification sheet. It is important to note that any deviation in environmental conditions from the temperature at which the force-measuring instrument was calibrated 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, 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.

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.

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 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 calibrated following 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.[46]

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. In almost all cases, there will be additional errors if the end-user fails to calibrate the force-measuring instrument with the same adapters 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.

Weights used for force measurement require the correction of the effects of local gravity and air buoyancy. They must be determined to be within 0.005 % of their values by comparison with reference standards that are traceable to the International System of Units (SI). 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.

Note: When considering using mass weights for a force application, some customers may expect nominal values and specific force-measuring instruments, which often require the end-user's selection of force points. As such, discussing if the end-user expects nominal force values is recommended.

Rated Output or RO: The output corresponding to capacity, equals 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.

> Repeatability can be calculated 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. This test determines 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.
Zero should never be considered as a first test point for this application. 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.
Reproducibility calculations between technicians can be 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.

Static Error Band: The band of maximum deviations of the ascending and descending calibration points centered on the best-fit straight line through zero output (0,0). It includes the effects of Non-Linearity, Hysteresis, and non-return to minimum load. SEB is usually expressed in units of % of full scale. Thus, a SEB of 0.02 % of FS would have a maximum error of 0.02 % of its full-scale capacity. SEB is a helpful tool in determining how accurate a load cell is.

Additional Information

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

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.

Subscribe to the Morehouse Insider Newsletter

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

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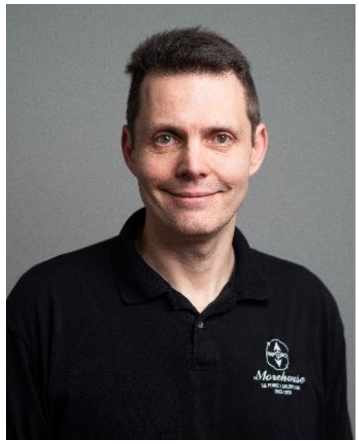
Author Bio Henry Zumbrun



Henry A Zumbrun has over 25 years of industry experience in Metrology, specifically in force and torque measurements. From its founding in 1920 to the present time, **Morehouse Instrument Company** has grown from a local machine shop to one of the most respected names in the calibration and measurement world. Henry likes to think he has helped impact force and torque measurements by helping several organizations be better and make better measurements.

Henry is passionate about helping any lab make better force measurements. He is also passionate about Metrology, training, outreach, and running a business based on doing what's right. He is aligning Morehouse so that everyone comes to work with a purpose. That purpose is simple: We create a safer world by helping companies improve their force and torque measurements. We all work as a team and help improve what we can control.

Henry supports continuous learning and, in addition to several degrees, is a **Six Sigma Blackbelt, Lean Champion**, and **Stanford Strategy Business Strategy Class** graduate. He has also completed the LMI leadership program, Sandler Management Program, Sales Training, and OSHA 10. He is a current Vistage member and constantly learns from several mentors and his business coach how to make a meaningful impact beyond what a typical business would do.

Henry has taught various classes and sessions at **NCSLI, MSC, ASQ, A2LA**, etc., authored several published papers, written this book titled **"Force Calibration for Technicians and Quality Managers: Top Conditions, Methods, and Systems that Impact Force Calibration Results,**" and was the primary Author on the **"G126 - Guidance on Uncertainty Budgets for Force Measuring Devices"** for **A2LA.** Henry is a contributing author to **NCSLI RP-3** and **LM-1**. He is also a co-host of the **Metrology Today Podcast.**

Henry wrote the Chapter on Force in the **Metrology Handbook, 3rd Edition**, and wrote and reviewed the Decision Rules and Measurement Uncertainty Chapter with Dilip Shah. He has been part of the **ASTM E28** committee for decades and has made several contributions to the **ASTM E74** and **E2428** standards through the committee.

NCSL International awarded Henry the **2022 Education and Training Award**.

Stay informed with the latest insights and tips on metrology by signing up for weekly updates from Henry. Visit https://mhforce.com/new-force-calibration-ebook-2024-edition/ to subscribe and receive tips and resources directly in your mailbox.

Have any questions? Henry can be reached at hzumbrun@mhforce.com or follow Henry on LinkedIn at http://www.linkedin.com/in/mhforce/.

Thank You

Your time is valuable. Morehouse, and I thank you for taking the time to read this book. I have poured over twenty-five years of my life's knowledge into this book in hopes it can help you make better measurements.

I have been privileged to work with some amazing people along the way and create a vast network of friends who have helped make me better and helped me continue learning along the way. There is so much more information out there on measurements and so many great resources. I could literally spend another ten years and made this book over one-thousand pages. Though, this book is meant to capture most of the concepts and provide the guidance for continued learning.

In that regard, I hope you find this book a valuable reference, filled with insights and practical knowledge on force calibration.

The entire Morehouse team is fully supportive of your efforts to achieve accurate and reliable measurements, and we are here to help you maintain the highest standards in your work.

Your success in force calibration is our priority, and we are ready to assist you in any way we can.