Morehouse
THE FORCE IN CALIBRATION SINCE 1925
Morehouse Instrument Company
1742 Sixth Ave.
York, PA 17403-2675
(717) 843-0081
Morehouse Instrument Company is ISO/IEC 17025 / ANSI/NCSLI Z540.3 Accredited
www.mhforce.com

Force Calibration for Technicians and Quality Managers: Top Conditions, Methods, and Systems that Impact Force Calibration Results V2

Calibration might not be glamorous, but it matters! (2022 Edition)

eBook ASIN: B098815K6B

Second edition, October 2022

www.mhforce.com

Table of Contents

Introduction

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

When someone is new to calibration or metrology, the information can be overwhelming. There is so much to digest that people can quickly become overwhelmed. Some have joked that an introduction to metrology is like trying to drink through a firehouse.

Morehouse has created a 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 act as a refresher for those who are more advanced. In either case, the knowledge gained will help you become better and help make better force measurements to make the world a safer place.

We hope you enjoy it!

Figure 1: Force Calibration Basics

1. 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 in the world, the same amount of 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.

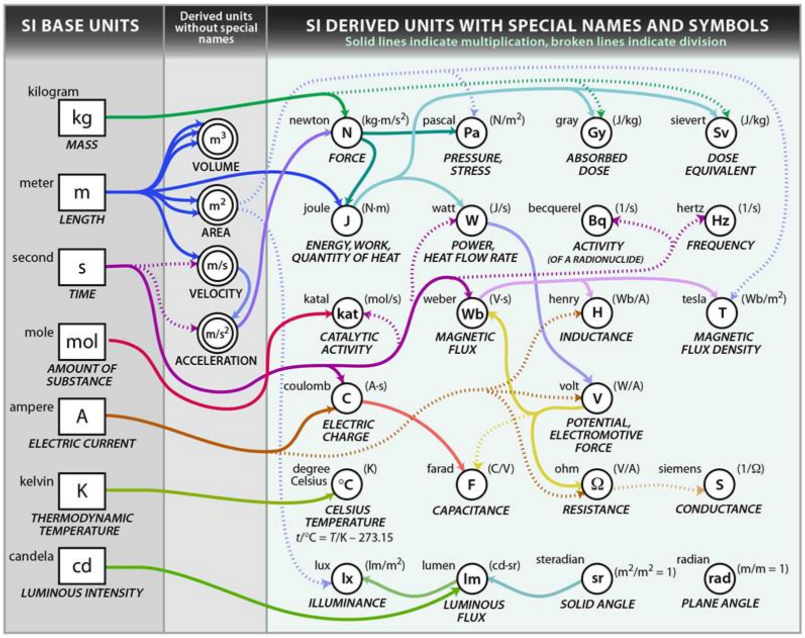


Figure 2: SI Units courtesy of NIST [1]

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain 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. It is essential to make sure the steel is tested, and the cables are appropriately checked for prestress or post-tension. When these measurements are not done correctly, bad things happen, 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 across the country, 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, the measurement of force is performed so frequently that we tend to 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 and might include anything from the materials used to build your house to the cardboard on that toilet paper roll.

2. 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 type. 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' flow 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.

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.

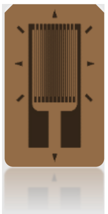


Figure 9: Strain Gauge

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, the gage pattern, placement on the gages, and the number of gages.

When a meter or indicator is hooked up to a load cell, it displays the force measurement value. A load cell may be calibrated at a company like Morehouse using deadweight primary standards known to 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 and verify a testing machine.

3. Compression and Tension Force Calibration

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

What is a Compression Calibration?
When discussing compression calibration, we should think about something being compressed or something being squeezed. I like to describe compression calibration as pushing or squeezing something.

Figure 10: Compression Calibration Examples

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

The key to this type of calibration is making sure everything is aligned and that 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 a Tension Calibration?

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

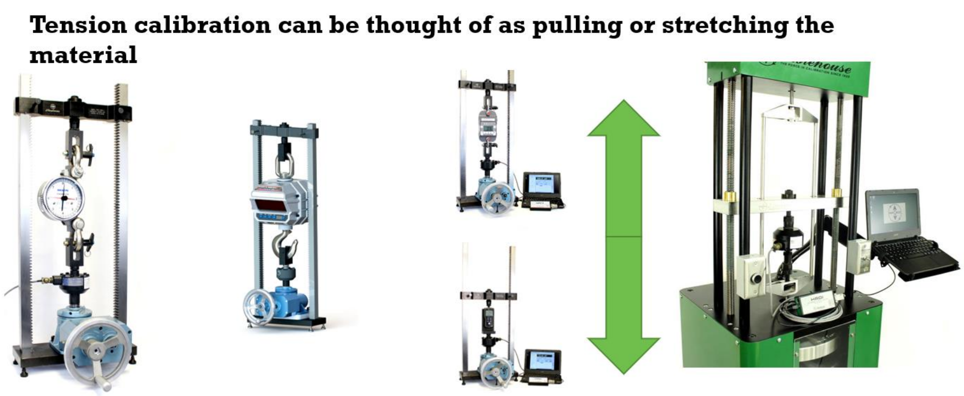


Figure 11: Tension Calibration Examples

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 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."[2] Morehouse follows the ISO 376 standard for several of our products. We also design adapters to help technicians and end-users to replicate and reproduce calibration results.

4. Calibration versus Verification

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

What is a Calibration?

Let me start by stating that there are several definitions of calibration 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 assure drift and other characteristics are kept under control. Thus, in simple terms, calibration can be thought of as validation.

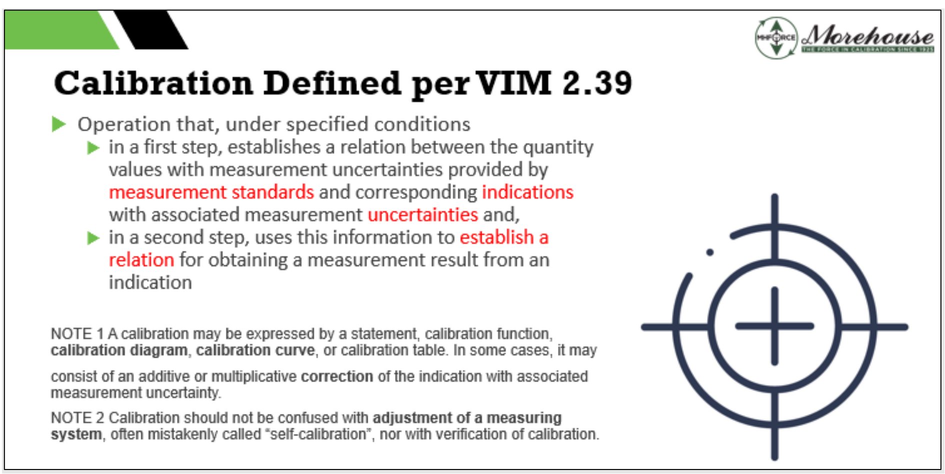


Figure 12: Calibration Definition

The definition from the International Vocabulary of Metrology (VIM) in section 2.39 is interesting in that many people assume calibration is also an adjustment. It is not. The VIM is clear in Note 2, stating, "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 will only report the value of the device 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 better than 0.002 % of applied force, and the end-user later uses this device, then the conditions will vary. It is almost certain that their use conditions do not replicate those exactly of the lab performing the calibration. For example, the temperature, rigidity of the machine, and hardness of adapters could vary, and their machine could introduce torsion, etc. These are only a few of several conditions that can impact the results.

I like 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:

- 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, as 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 a calibration by reporting the applied force and the device's corresponding measurement values for calibration. Then they make a conformity assessment, which is a statement to the end-user that the device is either in or out of tolerance. They typically say a device passes calibration or it fails calibration.

The critical detail here is that to ensure measurement traceability, measurement uncertainties must be reported. **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 how calibration and verification are not the same.

5. Measurement Uncertainty

What is Measurement Uncertainty?

What measurement uncertainty is not is an error. It is imperative to understand the difference between these two terms as they are often confused. Error is the difference between the measured value and the device's actual value or artifact being measurement. In many cases, we try to correct the known errors by applying corrections sometimes from the calibration certificate. These corrections can be a curve, a diagram, a table, 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 included 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 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."

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/en/publications/guides/gum.html.

In general, when you calculate measurement uncertainties following 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, 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 JCGM 100:2008. That tool can be found at https://measurementuncertainty.info/

Why is Measurement Uncertainty Important?

The uncertainty of the measurement is required to 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 may want you to make a statement of conformance on whether the device or artifact is in tolerance or not. 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 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.

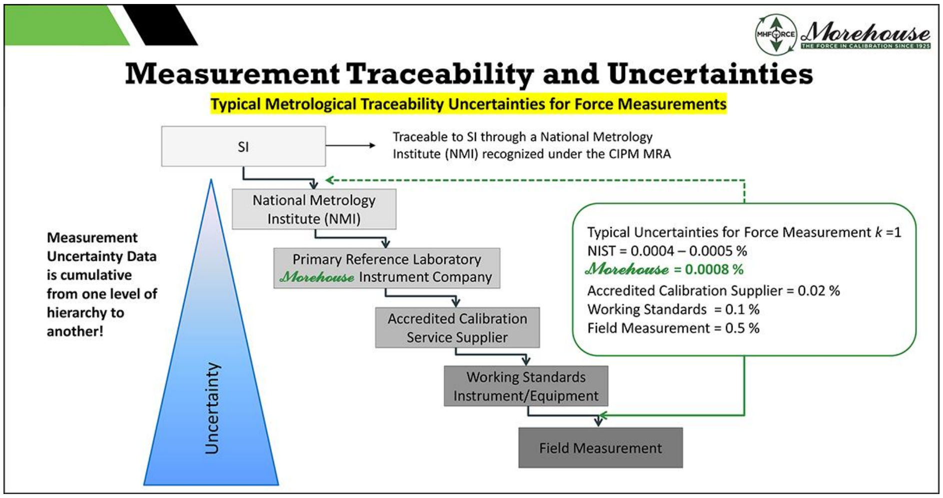


Figure 14: An Example of Measurement Traceability for Force

In simplistic terms, the measurement uncertainty is crucial because you want to know that the laboratory performing the calibration of your device or artifact can perform the calibration. If you need a device to be known to 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. If a laboratory claims traceability to SI through NIST, the larger the uncertainty becomes, the further away from NIST. The above picture shows this concept as 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 several videos on the topics such as measurement traceability, measurememt risk, and measurement confidence. We have a 6-minute easy to understand video that ties everything together. [Measurement Confidence Video]

6. Load Cell Terminology

Non-Linearity, Non-Repeatability, Hysteresis, and Static Error Band 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 certificates of calibration.

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 are available that overcome inadequate specifications. 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 for 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 defined as the algebraic difference between the output at a specific load and the corresponding point on the straight line drawn between the outputs at minimum load and maximum load. It usually is expressed in units of % of full scale. It is usually calculated between 40 - 60 % of the full scale.

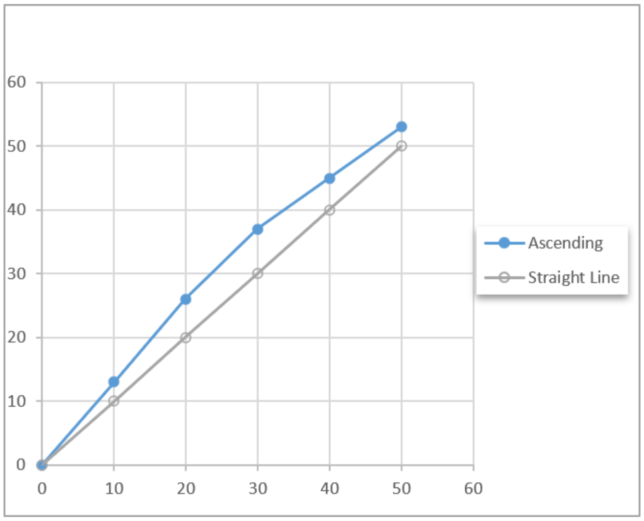


Figure 16: Non-Linearity Expressed Graphically

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 type 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. There are some manufactures who take a less conservative approach and use higher order quadratic equations.

Plot the Non-Linearity baseline as shown below using the formula of force applied * slope + Intercept or y = mx +b. 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 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 Baseline

Non-Linearity Calculations Reducing Ending Zero					
Force Appied (lbf)	Run 1 Adjusted	Non-Linearity Base line	Non-Linearity (%FS)	Non-linearity Line	
0		=(E7*$K$7+$K$8)	=ROUND(ABS(F7-G7)/$F$18*100,3)	Slope=	=(F18-F7)/(E18-E7)
50	0.10008	=(E8*$K$7+$K$8)	=ROUND(ABS(F8-G8)/$F$18*100,3)	Intercept=	0
100	0.20001	=(E9*$K$7+$K$8)	=ROUND(ABS(F9-G9)/$F$18*100,3)		
200	0.40002	=(E10*$K$7+$K$8)	=ROUND(ABS(F10-G10)/$F$18*100,3)		
300	0.60001	=(E11*$K$7+$K$8)	=ROUND(ABS(F11-G11)/$F$18*100,3)	Non-linearity=	
400	0.800015	=(E12*$K$7+$K$8)	=ROUND(ABS(F12-G12)/$F$18*100,3)	(%FS)	=MAX(H7:H19)
500	1.00005	=(E13*$K$7+$K$8)	=ROUND(ABS(F13-G13)/$F$18*100,3)		
600	1.200015	=(E14*$K$7+$K$8)	=ROUND(ABS(F14-G14)/$F$18*100,3)		
700	1.400025	=(E15*$K$7+$K$8)	=ROUND(ABS(F15-G15)/$F$18*100,3)		
800	1.60004	=(E16*$K$7+$K$8)	=ROUND(ABS(F16-G16)/$F$18*100,3)		
900	1.80006	=(E17*$K$7+$K$8)	=ROUND(ABS(F17-G17)/$F$18*100,3)		
1000	2.0001	=(E18*$K$7+$K$8)	=ROUND(ABS(F18-G18)/$F$18*100,3)		
0		=(E19*$K$7+$K$8)			

Figure 18: Non-Linearity Calculations

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.

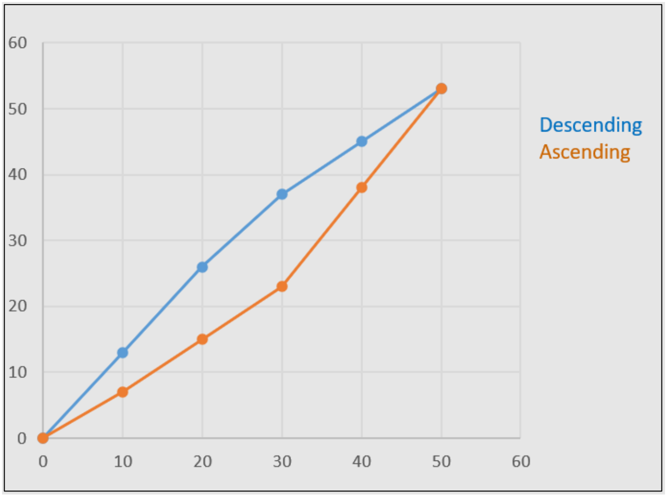


Figure 19: Hysteresis Example

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, then they may want to consider the effect of Hysteresis.
Errors from hysteresis can be high enough that if a load cell is used to make descending measurements, then it must be calibrated with a descending range. The difference in output on an ascending curve versus a descending curve can be significant. For example, an exceptionally good Morehouse 100K precision shear-web 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 %.

At Morehouse, our calibration lab sampled several instruments and recorded the following differences.

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 20: Errors from Hysteresis

Load cells from five different manufacturers were sampled, 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. On average, the difference was approximately 0.06 %. Six of the seven tests were performed using deadweight primary standards, which is accurate within 0.0016 % of the applied force.

Non-Repeatability: The maximum difference between output readings for repeated loadings under identical loading and environmental conditions. Normally 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 do not perform well when the loading conditions are randomized, or the load cell is rotated 120 degrees as required by ISO 376 and ASTM E74.

The calculation on non-repeatability is straightforward. First compare each observed force point's output and run a difference between those points. The formula would look something like this: Non repeatability = ABS(Run1-Run2)/AVERAGE (Run1, Run2, Run3) *100. Do this for each combination or runs, and 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 21: 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 22: Non-Repeatability Calculations

Static Error Band: The band of maximum deviations of the ascending and descending calibration points from a best-fit line through zero output. It includes the effects of Non-Linearity, Hysteresis, and non-return to minimum load. It usually is expressed in units of % of full scale.

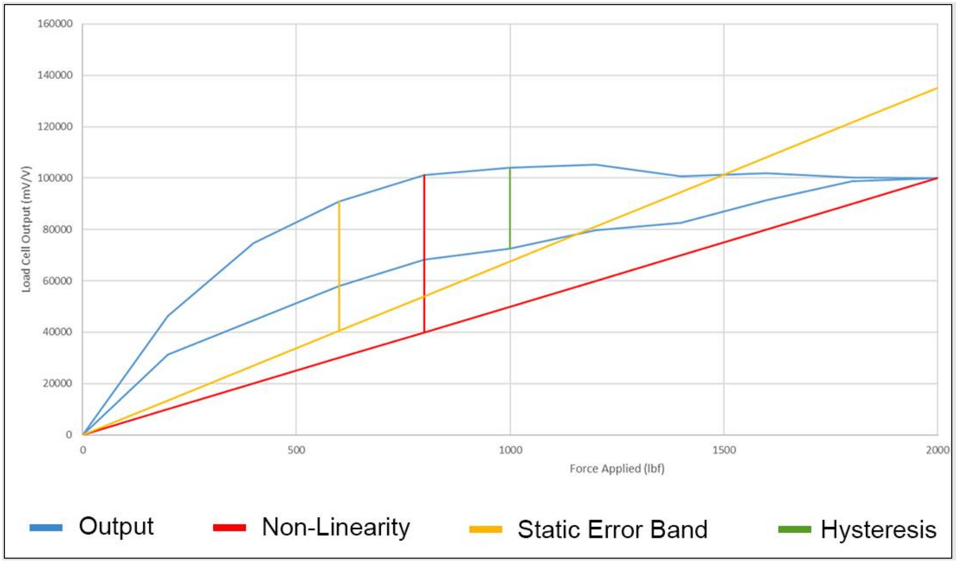


Figure 23: Static Error Band and Other Specifications Displayed Visually

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 are using the load cell described above because static error band would be the better specification to use. The end-user could likely ignore Non-Linearity and Hysteresis and focus on static error band as well as 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.

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, uses 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.

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

7. 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 are going to describe the common types we see used as reference and field standards below. Many other load cells are shown in more commercial applications, such as scales used at supermarket checkouts, weight sensing devices, weighing, and other scales.

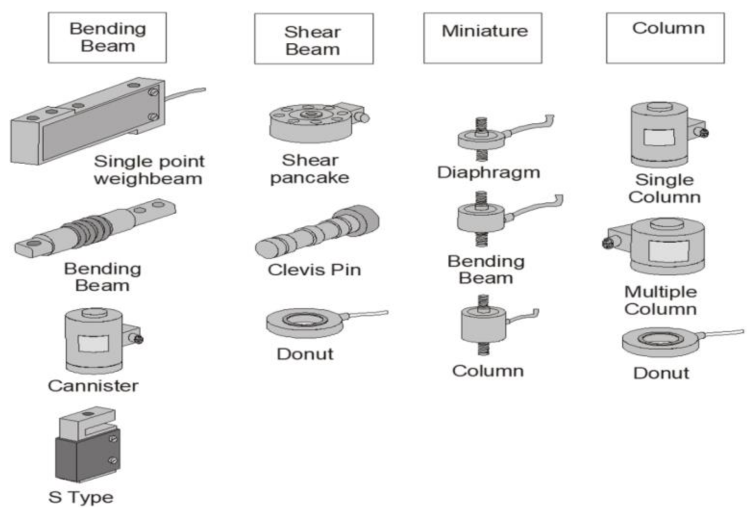


Figure 24: Types of Load Cells

S-beam (S-type)
The S-beam is a bending beam load cell that is 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 length of the deformation. There are generally four strain gauges mounted in the load cell.

Figure 25: S-beam Load Cell

Advantages

- In general, linearity will be enhanced by minimizing the ratio of deflection at the rated load to the length of the sensing beam, thus minimizing the change in the shape of the element.
- Ideal for measuring small forces (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 be different if the load cell is loaded through the threads versus flat against each base.
- Typically, 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

The shear web is a shear beam load cell that is ideal as a calibration reference standard 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 26: Morehouse Ultra-Precision Shear Web Load Cells

Advantages

- Typically have very low creep and are not as sensitive to off-axis loading as 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 lbs., and a 200,000 lbf shear web load cell weighs over 120 lbs.

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.

Button Load Cell

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

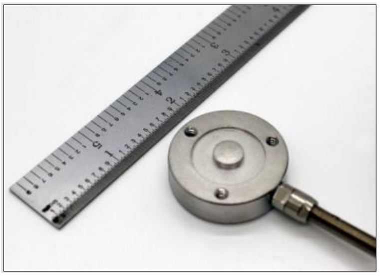


Figure 27: Button Load Cells

Advantages

- Suitable for applications where there is minimal 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 % - 10 % of rated output.
- Do not repeat well in the rotation.

Figure 28: Button and Washer Load Cell Adapters

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

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

Single-Column or High-Stress Load Cells

The single column is a column load cell that is good 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 29: Morehouse Single Column Load Cell

Advantages

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

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 and often do not return to zero as well as 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 is a column load cell that is good from 100,000 lbf through 1,000,000 plus lbf. The load is carried by four or more small columns in this design, each with its complement of strain gauges. The corresponding gauges from all the columns are connected in a series in the appropriate bridge arms. The Morehouse multi-column 600K load cell weighs 27 lbs. and has an accuracy of better than 0.02 % of full scale.

Figure 30: Morehouse Light Weight 600k (26 lbs) Multi-Column Load Cell

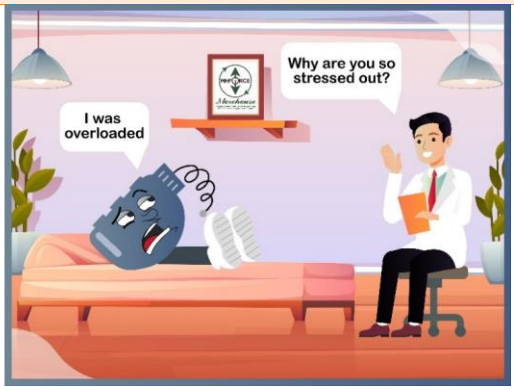
Advantages

- It can be more compact than single-column cells.
- Improved discrimination against the effects of off-axis load components.
- Typically 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 are happy to discuss the advantages and disadvantages based on our experience.



8. 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 get more calibrations done or spending more time getting the measurements correct by using the proper setups, 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 5-7 business days) and provide better customer service.

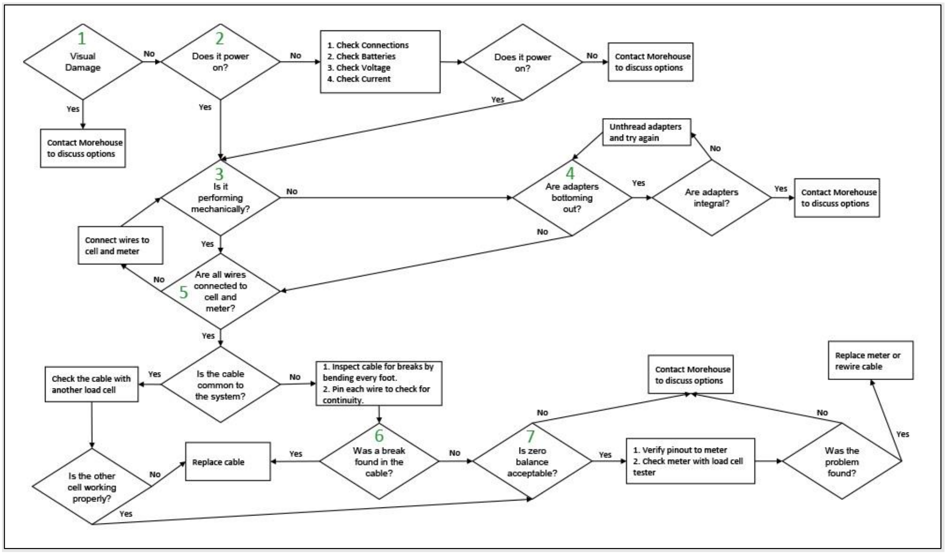


Figure 31: Load Cell Troubleshooting Process

This 7-step process outlined above and explained below 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 32: 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 33: 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 very linear to 90 % of capacity. Then either the indicator stops reading, or the output becomes severely diminished. The data will show poor linearity when using 100 % of the range and incredibly good 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. Make sure any adapters threaded into the transducer are not bottoming out. If an adapter is

bottoming out and is integral, then contact Morehouse to discuss options.

5. Check and make sure 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 is working correctly. If the other load cell is not working, then contact Morehouse to discuss options.
6. Inspect the cable for breaks. With everything hooked up, proceed to test the cable making a physical bend every foot. Pin each connection to check for continuity of the cable.
7. Use a load cell tester or another meter to check the load cell's zero balance. If you do not have a load cell tester, you can check the bridge resistance with an ordinary multimeter. 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 34: 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 tester 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

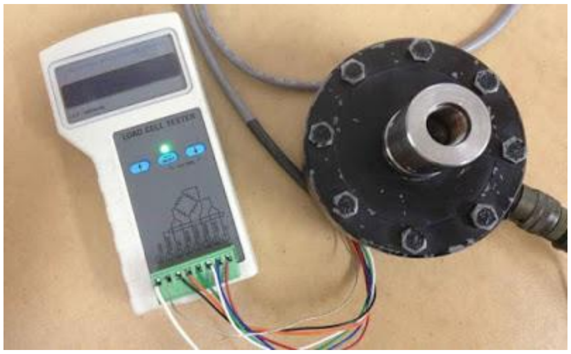


Figure 35: Morehouse Load Cell Tester

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 to 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

9. Indicator Basics

Figure 36: 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 very slightly, and the voltage on the other signal line decreases very slightly.

The indicator reads the difference in voltage between the two signals that may be converted to engineering or force units. There are several types of indicators available, and they have different advantages and disadvantages. The decision for which indicator to use should be based on what meets your needs and has the best Non-Linearity and stability specifications.

Figure 37: Morehouse 4215 High Stability Indicator

Non-linearity and uncertainty specifications

The specification that most users look for in an indicator is the 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 terms of 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 high stability 4215 indicator pictured above with 0.002 % Non-Linearity specification. The Morehouse 4215 meter will display up to 5 decimals in mV/V, which equates to a resolution of between 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 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 or avoid this type of indicator.

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 indicators in conjunction with the Morehouse calibration software, which is included with the indicator. When comparing Non-Linearity, the HADI has better than 0.002 % of full scale, the 4215 has better than 0.005 % of full scale, and the PSD has 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. The indicators often over $10,000 will fall into specifying drift at different intervals such as 90 days (about 3 months) and one year. Most indicators under $2,500 are not going to address 90 days or 1-year stability specifically. Stability can be monitored and maintained by a load cell simulator. However, a user can choose to 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, but these are not portable and are often overkill for general application force systems. The Morehouse HADI with the long-term stability of zero at 0.0005 %/year at room temperature is an excellent choice for under $1,000.00.

Resolution
If you use 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 will generally yield a Lower Limit Factor (LLF) and better Class AA and Class A loading ranges. An excellent indicator to pair with your reference standard to calibrate other load cells is the Morehouse HADI as it can display 4.50000 mV/V stable to within 0.00001 mV/V on a good load cell. The Morehouse 4215 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 with multiple span points and store coefficient files is an excellent choice.

Figure 38: Morehouse Gauge Buster 2 Indicator

Another excellent option is the Morehouse/Admet Gauge Buster with a High Stability option. The indicator comes standard with more than 10-point linearization. However, any system's downfall for direct reading is that it cannot be maintained. As the system drifts, so will the readings. Therefore, 10,000.0 today may equate to 10,000.9 in a year. Consequently, we highly recommend having the output read in mV/V and converting it via software or internally. The Morehouse 4215 Plus can use calibration coefficients, or the Morehouse 4215 and HADI with the software are the best options if one would want drift corrected at the time of calibration.

Commented [HAZ1]: Replace with new C701P indicator

Commented [HAZ2R1]: Remove these and replace

Another excellent option is the Morehouse/Admet Gauge Buster with a High Stability option. The indicator comes standard with more than 10-point linearization. However, any system's downfall for direct reading is that it cannot be maintained. As the system drifts, so will the readings. Therefore, 10,000.0 today may equate to 10,000.9 in a year.

REPLACE WITH THIS

Aother excellent option is the Morehouse C705P. The indicator comes standard with 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 the units need to be toggled between mV/V and force units as only one can be displayed at a time. 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 would want drift corrected at the time of 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 different length cables. In fact, 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.

To learn more about the difference between a 4-wire and 6-wire system, read this blog.

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 PSD, HADI, and 4215 handle load cells with output up to

4.5 mV/V.

Figure 39: Morehouse PSD Indicator

Ease of use
This is a preference-based consideration. Some ease-of-use examples are eliminating 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 PSD is the winner. If you want a portable system that could run on laptop power and capture readings, the HADI is the winner.

Figure 40: 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. There are multiple span points that can be programmed to get closer to the nominal value. This meter is a direct replacement and upgrades over some other meters on the market.

Ruggedness

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

Number of load cell channels required.

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

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 many times a matter of personal preferences. The HADI indicator comes first for several selection criteria, but these may not be the criteria that matter for your individual needs. Choose the indicator that meets your needs with 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. If you need a stable system and can carry a laptop with you, the HADI may make the most sense. 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.

The topics covered in this section cover the basics about selecting the right equipment and knowing the proper terminology; the next section will cover more advanced applications.

10. Force Calibration System Accuracy

At Morehouse we are frequently asked about Accuracy, with a question 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 simply 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. Only when we know these parameters can we correctly provide a complete system with the right indicator and appropriate adapters. To further clarify, below is a detailed explanation based on these basic premises and ground rules:

1. The definition of Accuracy per the VIM.
2. You cannot have a system that is more accurate than the reference standard used to calibrate it.
3. Agreement on the calibration method for portability of the data.
4. Other manufactures 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.

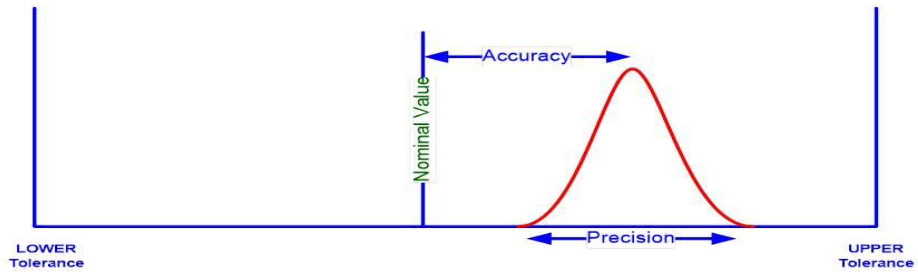


Figure 41: Measurement Accuracy Expressed Graphically

Simply put, 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, if we had a 10,000 lbf load cell and the accuracy specification was ± 0.05 % of full scale, then we should expect the system to read 10,000 ± 5 lbf when used under the same calibration conditions, and that specification should be repeatable.

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 different loading conditions can significantly affect the output and Accuracy of the force-measuring system. Therefore, we need to understand the application, know the expectations, and provide the complete system with the appropriate indicator and adapters.

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

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

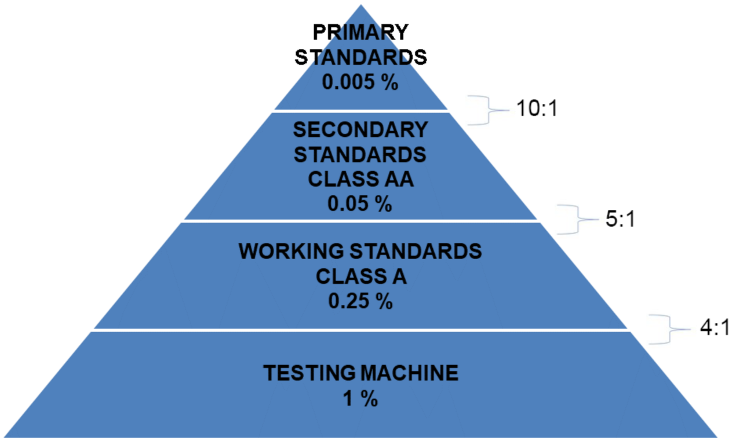


Figure 42: ASTM E74 Pyramid of Ratios

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 classifications shown here.

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 the example.
2. Barely acceptable - using a hypothetical laboratory.
3. Disaster - using a hypothetical laboratory.

In these examples we will demonstrate measurement risk as far as capability is concerned.

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 %.

Morehouse 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)	0.09
Total Risk	0.00%
Upper Limit Risk	0.00%
Lower Limit Risk	0.00%
TUR =	**29.39471822**
Simple Guard Band with Subtraction Uncertainty Only	
Guard Band LSL	9995.170
Guard Band USL	10004.830
Guard Band Limits to Assure 2 % RISK or Less	
Guard Band LSL	9995.175
Guard Band USL	10004.825

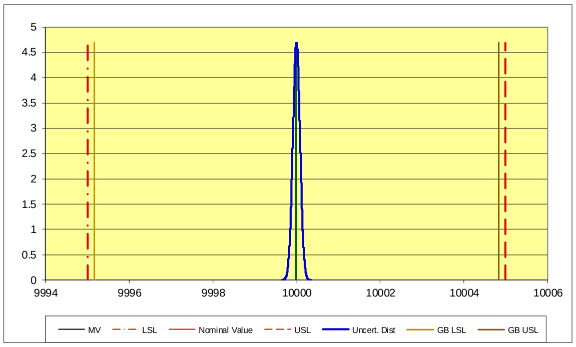


Figure 43: Morehouse Does the Calibration with Primary Standards

When a 10,000 lbf force-measuring system has a specification of ± 5 lbf or 0.05 % of full scale, applying generally 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 when compared with 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 perfect 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

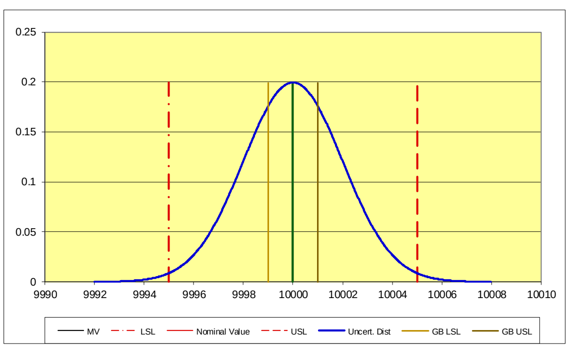


Figure 44: A Lab Using Load Cells as Standards Does the Calibration

Lastly, we have the 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, but the best they can do is ± 10 lbf. Their graph shows that 31.73 % of the curve will be outside of the specification limit at 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.

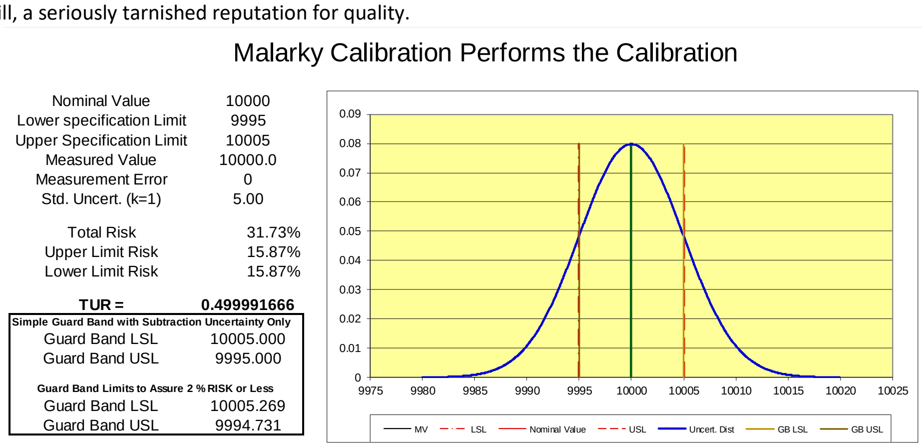


Figure 45: A Lab Using Load Cells as Standards Calibrated by Other Load Cells Does the Calibration

3. Agreement on the calibration method for 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. Commercial type of calibration consisting of a 5 to 10 pt. 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 to the much larger Calibration and Measurement Capability Uncertainty parameter (sometimes referred to as 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.

On a 10,000 lbf load cell, the expected performance 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 take it into account.

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.

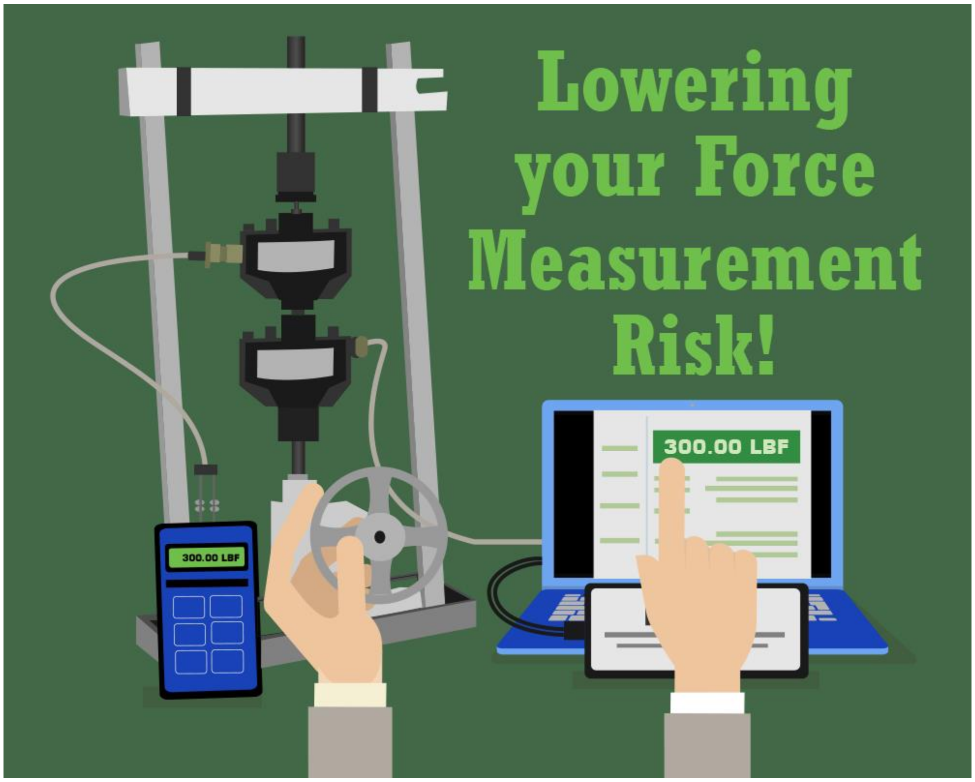
4. **Other manufactures may overpromise and underdeliver.**

Figure 46: Averages Hide the Extremes

Morehouse will not overpromise and underdeliver a solution. However, other manufacturers have different methods to test 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 simply do not understand metrology and consequently promote terrible, often impossible, measurement practices. Some notable examples include:

1. Averages are used to specify a tolerance. Figure 5 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 the right way. It is easy to say you can do things, apply some force, and report results without clearly knowing its use. This is clearly an exploitation of the customer.
3. The resolution is equal to Accuracy. This is a large complex issue with respect to 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. Not considering the location of the measurement when making conformity assessment a "pass" or a "fail."



11. 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 that do the 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 with the expectations in this section. The bottom-line is the lab performing the calibration should have the discussions that matter per the specification. 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:

- 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 47: 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 needs to be calibrated in both modes. After the basics are discussed, the question becomes that of needing calibration 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 of this would be 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 to this 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 be used to make descending or decremental measurements when only ascending or incremental calibration was performed. Ascending and descending calibration is typically required for low cycle fatigue machines, nuclear requirements, and universities conducting a lot of research and development.

The final error we see is the force-measuring device not matching the calibration results because the end-user is using 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, when using mass weights to perform force measurement, the errors can be quite high, 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 a Descending Mode.

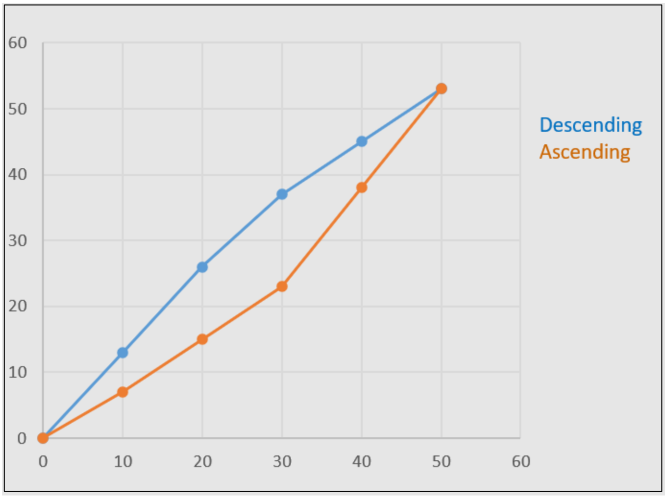


Figure 48: Descending Versus Ascending Calibration Curves

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.

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 were to use the ascending calibration curve to make descending measurements, then 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 49: 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 known to be accurate within 0.0016 % of the applied force.

The conclusion from these tests is clear: If a load cell is used to calibrate 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, they will need to have 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 both increasing and decreasing forces, the same force values should be applied for the increasing and decreasing directions of force application, but 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]

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

Capacity 1000000 lbf Compression, Calibrated from 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
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.

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

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

12. 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 introduction in 1974 and 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 that the standards were completely different and that these standards 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 throughout the world are not aware 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 needs to 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 data runs 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: ISO 376 statement. The thought is that the force does not need to be held for 30 seconds, rather that the target force should be approached slowly and should 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.

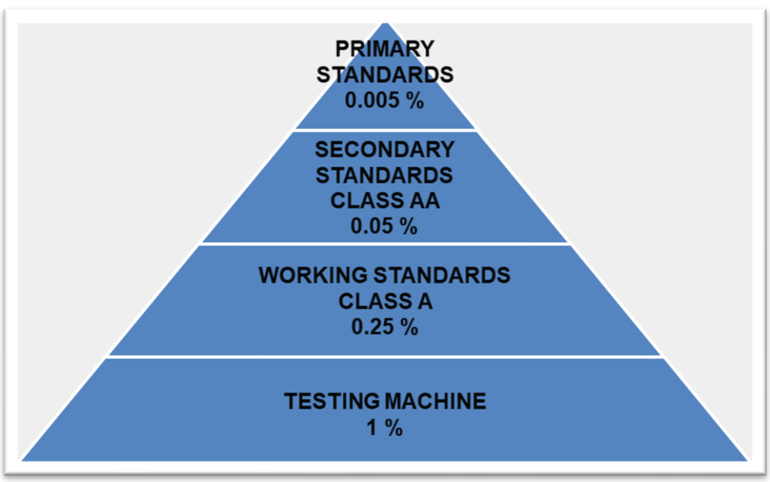


Figure 51: ASTM E74 Test Accuracy Ratio Pyramid

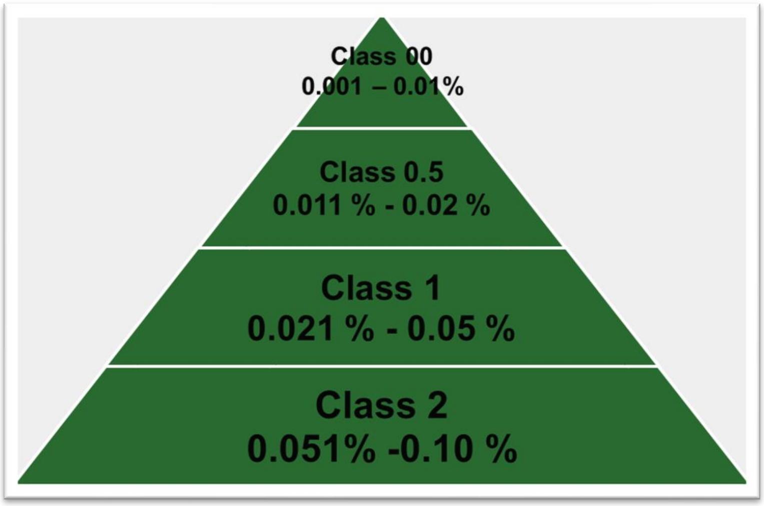


Figure 52: ISO 376 Expanded Uncertainty of Applied Calibration Force

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 calibration and the corresponding values taken from the calibration equation.

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

Figure 53: Formula in ASTM E74 to Calculated the Pooled Standard Deviation

The equation uses the differences and divides 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.

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 Class AA verified range of forces is assigned by multiplying the LLF by 2,000, assuming the non-zero force point is taken below this value and that the resolution of the force-measuring instrument is less than the LLF.

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. ASTM E74 works on a 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 certain characteristics of the force-proving instrument are met and rates the device's performance based on its characteristics. ISO 376 uses either four runs of data and a creep test or six runs of data to characterize the force-proving instrument and the associated relative error. ISO 376 then takes the highest error percentage per point for each parameter and assigns a class based on the highest error shown in the figure below.

Force-proving instruments where only increasing data is used (four runs of data) are tested for reproducibility, repeatability, resolution, interpolation, zero, and creep. Force-proving instruments where 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, but 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 meets the criteria as well. What ISO 376 does very well is that it accounts for the uncertainty of the applied calibration force within the standard. A force-proving device cannot have an uncertainty of less than the reference used for calibration, as shown in the figure above.

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 on this topic.

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 54: 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, if this criterion is not demonstrated, then the end devices not meeting the stability criteria of 11.2.1 Section shall be recalibrated at intervals that shall ensure the stability criteria are not exceeded during the recalibration interval.[7]
- ISO 376 allows for a maximum validity of the calibration certificate to not 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 wave form 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.

Read more about force measurement errors in this blog.

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, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads.

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

Figure 56: 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 provide calibration to ISO 376, ASTM E74, or both standards. If you need calibration in accordance with either standard, then it is important 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 simplifies 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 57: Sample from Morehouse Scope Showing ASTM and ISO 376 Capability

ASTM E74 and Accuracy Statements

The current ASTM E74-18 standard is titled *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 on 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 "lions share" of the overall measurement uncertainty, which is completely missed if only the specification sheet is used.

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

The major flaw is the specification sheet does not provide the end-user with a lot of what they need. 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 provides guidance on how to perform these tests, such as randomizing force application conditions. This randomization, which is 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 58: 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 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 in the 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. What we are saying is that the ASTM LLF, which is the expected performance of the load cell, is better than 0.005 % of full scale. However, this is only one component to the much larger Calibration and Measurement Capability Uncertainty Parameter, which is referred to as CMC.

It is under the same conditions that Morehouse used for calibration that the device is expected to perform better than 0.005 % of full scale. On a 10,000 lbf load cell, the expected performance should be better than 0.5 lbf (10,000 * 0.005 %). So, what we are saying is 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 is used to determine the usable range for 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 59: Morehouse Precision Load Cell

Many people get confused with load cell specifications and what they mean. When a company says the load cell is accurate to 0.01 % of full scale, what does that mean? If calibrated using the ASTM E74 standard, the meaning differs from a pure accuracy specification. The ASTM E74 calibration is much more robust than a simple single-run commercial calibration or a calibration in which acceptance limits are reduced by measurement uncertainty and a pass/fail conformity assessment is made.

We created a simple to use ASTM E74 Load Cell Selection Guide to help everyone understand load cell specifications that reference the ASTM E74 standard. For example, when we specify a load cell is good to better than 0.01 % of full scale, we are saying 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 60: Precision Load Cell Accuracy Chart

The above figure breaks the ASTM E74 criteria down. On a 1,000 lbf load cell, the ASTM E74 llf (how well the load cell performs when conditions are varied or reproducibility) 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 applied Force.

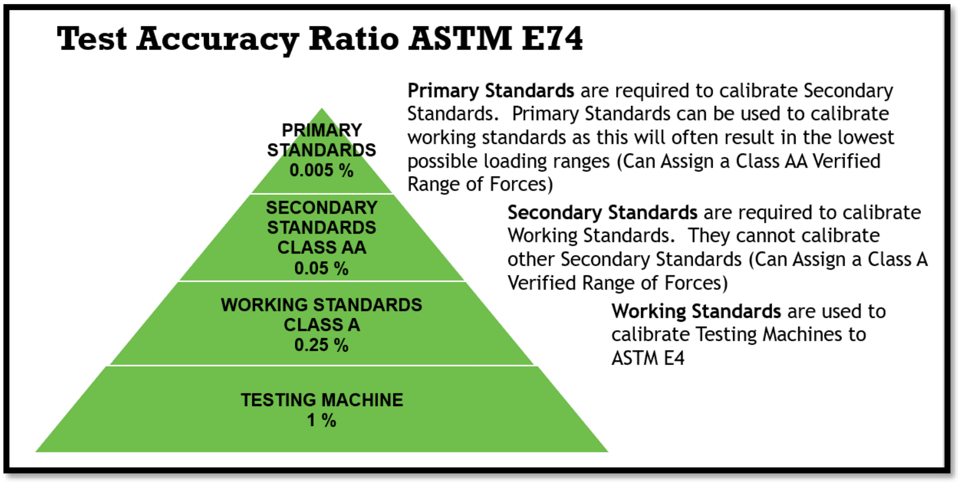


Figure 61: ASTM E74 Test Accuracy Ratio Pyramid

This correlates well with the above picture showing the different accuracy ratios. Working standards need to be better than 4:1 when compared to the accuracy of the testing machine. Secondary standards, those calibrated by primary standards, need to 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 applied Force.

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 62: Morehouse Spreadsheet Inputs

Our easy-to-use spreadsheet calculates everything for you based on entering the capacity of load cell and units. Anything in Orange would be filled in. The table includes a Custom field where someone can make assumptions on the specification to see what the useable range would be.

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 llf = 0.05 lbf			ASTM llf = 0.1 lbf			ASTM llf = 0.2 lbf			ASTM llf = 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 63: 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 for the end-user to make the most informed decision about which load cells meet the appropriate specification.

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. Thus, there is no way you can purchase a load cell from them and expect to maintain 0.01 % of full scale when their scope of accreditation says their measurement uncertainty is higher than that.

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 too continually be better. Investing in employee education, equipment, and learning as much as possible.)

13. 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, but once we start to examine the issue, it takes a series of questions to answer. The most common answer is, "Well… that depends on what your expectations are."

If your expectation is only performance, without regard to price and ergonomics, the answer is vastly different than if the best value is a consideration. Therefore, to fully answer this question we will address some basics regarding the selection of a load cell as a reference standard. The factors to consider are price, actual performance characteristics, specifications, ergonomic issues, and 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.

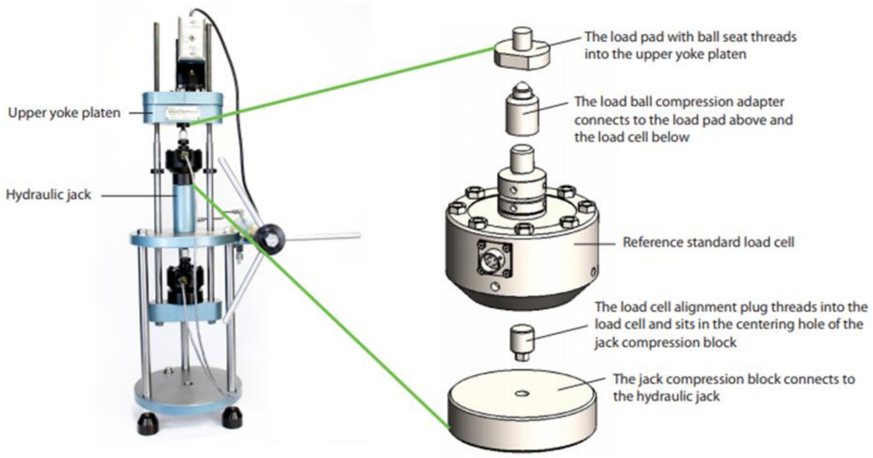


Figure 1: Morehouse UCM Showing Adapters to Mount a Reference Standard Load Cell in Compression

The reference load cell is mounted in compression and the breakout picture shows the adapters that are 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 are machined, sometimes heat-treated, and use connections such as ball adapters, and sphericals. These ball adapters considerably 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. Figure 2 shows a load cell with a load ball compression adapter being set up for calibration. The expectation from anyone making force measurements should be to replicate use. Not doing so can produce significant errors. Several articles and papers show dramatic differences in load cell output and performance by using different adapters. Depending on the device, these errors can range from 0.01 % to 5 %.

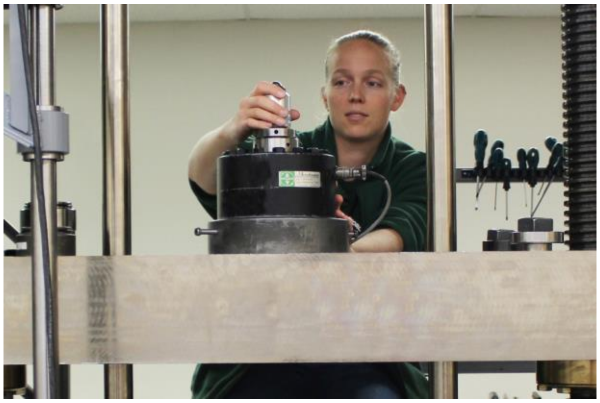


Figure 2: Load Cell Calibration in a Morehouse Deadweight Machine

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, consider a calibration at Morehouse and at 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 goes up to 0.01 % of applied force or higher. 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 are going for the absolute lowest value possible, go with NIST or buy a deadweight machine from Morehouse.

Let us compare 0.002 % to 0.01 % or 0.05 % using transfer standards (non-deadweight) such as a load cell in a dynamic calibrating machine. Most likely, 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.

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, then 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, then they may hear, "Can you wait a year to have a specialty load cell made?" That is what we did 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 $50,000 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 3: 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, and the price is roughly 1/10 of the highest performing load cell we know about, plus the $30,000, plus calibration.

Test No.: 684/288900-16 Page 5 of 7
Calibration Date: August 22, 2016

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 4: 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 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. These may not matter if the calibration is performed following a standard such as ISO 376 or ASTM E74; then these specifications are likely irrelevant. These standards use higher-order curve fitting routines and rely on the use of polynomial equations.

Some may fail to consider how good the load cell is between calibrations. You can have great calibration numbers, but then 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 really want to know is the expected performance of the load cell. Both ASTM E74 and ISO 376 are standards that do an excellent job of giving us the right expectation. 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 to perform to these standards because these are the performance characteristics that tell you how good the load cell is. They are not made up of numbers. They are a guarantee of how reproducible the measurement should be when used in a similar environment.

Figure 5: Performance Characteristics that Matter

There are some simple things that 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. This is because 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 they 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.

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.

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

Figure 6: Morehouse Ultra-Precision Load Cell

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

The figure above shows an example of a shear web load cell. Typically, this is the best design for many compression and tension applications. Other manufacturers make this style of load cell, and many are great if they have 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. In fact, what is guaranteed is an ASTM E74 Class A lower limit better than 4 %. The load cells often calibrate much better than that.

Pairing your load cell with the right meter is essential to maintaining performance. Suppose you have a Morehouse Ultra-Precision load cell, or HBM TOPT-Transfer load cell, and pair it with a commercial off the shelf lower performance meter. You will not get the full benefit of the load cell because the meter will severely limit the performance characteristics.

We do get asked, "What is the best meter I can use with my load cell?" The answer is an HBM DMP-41 and the price tag is 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 (Figure 4) shows a Morehouse 1,000,000 lbf load cell using a 4215 indicator. The 4215 indicator has about 400,000 counts compared to 2,500,000 on the HBM DMP 41.

However, buying the best load cell and meter usually requires some method to physically lift and mount 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 on the expected performance. For example, consider our lightweight compression-only multi-column load cell. The load cell is not suitable 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 but weighs about five times more than this load cell.

Figure 7 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, chances are we can source it, put together a complete system including transportation cases, and provide the best level of calibration next to NIST.

14. Force Versus Mass

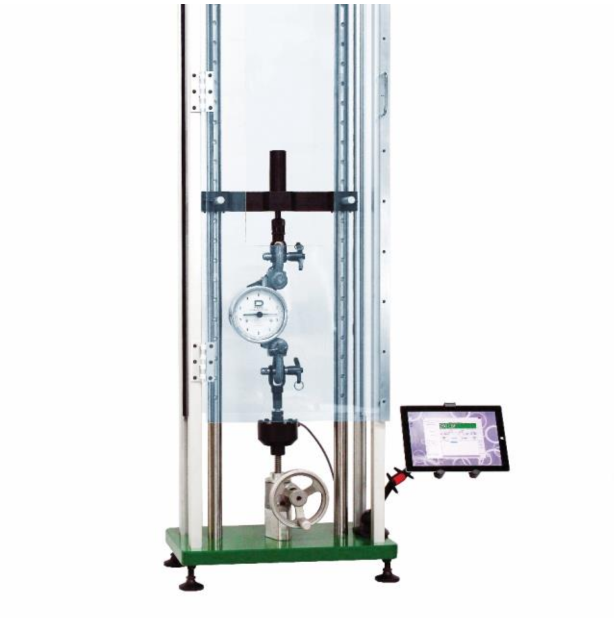


Figure 64: Morehouse Tensiometer

Using mass weights to calibrate force devices can result in a large measurement error.

When metrologists talk about measurement error, we 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, then 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. This is a measurement error for which there can be many different causes. In discussions with many professionals inside the weighing industry, we have found that some labs use mass weights to calibrate force devices. These include dynamometers, crane scales, handheld force gauges, and many other types of weighing 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 takes additional factors into account: air density, material density, and gravity. It is the effect of gravity that 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/s2 at the former compared to 978.0 cm/s2 at the latter). A force-measuring device calibrated in one location using mass weights then deployed somewhere else will produce different physical elements and the resulting measurement errors can be significant.

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, and so on.

Luckily, NOAA's website has a tool for predicting local gravity anywhere on Earth (ngs.noaa.gov). Here 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 properly can have many consequences. If we were shipping steel by the tonnage, we would ship less steel, reducing our cost and upsetting our customer. If a scale calibrated in York with mass weights is used by a steel supplier in Houston without correction, they would ship more steel per ton.

Note that dynamometers, crane scales, tension links, handheld force gauges, and other 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 it is impractical to have the mass weights necessary to calibrate on-site. Therefore, calibrating using force may be the only practical method to certify the device.

Figure 65: 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 that scale is 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 without correction, 1,000 lb. applied would read as 999.5 lb. 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 be used to calibrate in mass, using a correction formula, or in force. More information on the portable and benchtop calibrating machines can be found at mhforce.com.

Unless otherwise specified, Morehouse calibrates in pounds-force. To convert to mass measurements,we use a formula:

Force = M x g / 9.80665 (1 – d/ D)

Where M = mass of weight in kg, g = gravitational constant at fixed location in m/s^2, d = air density in kg/m^3, and D = material density kg/m^3

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.

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

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 66: Morehouse Force to Mass Spreadsheet

Morehouse has a spreadsheet to help with these conversions from force to mass, and mass to force. The speadsheet will allow load cells to be converted from force to mass, as well as 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 values that are not nominal values. If this is an issue, we recommend purchasing weights or equipment capable of generating Forces correctly. Morehouse can supply such equipment. If the decision is made to convert the mass weights to force, an uncertainty analysis will need to be performed.

Mass to Force						
Mass lbs	Force Desired lbf	Actual Force lbf	Actual Mass (lbs) Required	Difference in lbf	Gravity & Bouyancy Bias	Additional UNC
250.0	250.0	249.6	250.4	0.4	-0.155%	0.01001%
500.0	500.0	499.2	500.8	0.8	-0.155%	0.01001%
1000.0	1000.0	998.5	1001.5	1.5	-0.155%	0.01001%
1500.0	1500.0	1497.7	1502.3	2.3	-0.155%	0.01001%
2000.0	2000.0	1996.9	2003.1	3.1	-0.155%	0.01001%
2500.0	2500.0	2496.1	2503.9	3.9	-0.155%	0.01001%
3000.0	3000.0	2995.4	3004.6	4.6	-0.155%	0.01001%
Note: This sheet is to calculate potential differences from Mass to Force and correct for them. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.						

Figure 67: Morehouse Mass to Force Tab

The above figure shows the large errors that are often unaccounted for by using mass weights for a force application. Examples would include using mass weights with a torque arm, using mass weights to calibrate a load cell, force gauge, crane scale, or any application that requires 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 that many labs claim is only a fraction of the total error shown.***

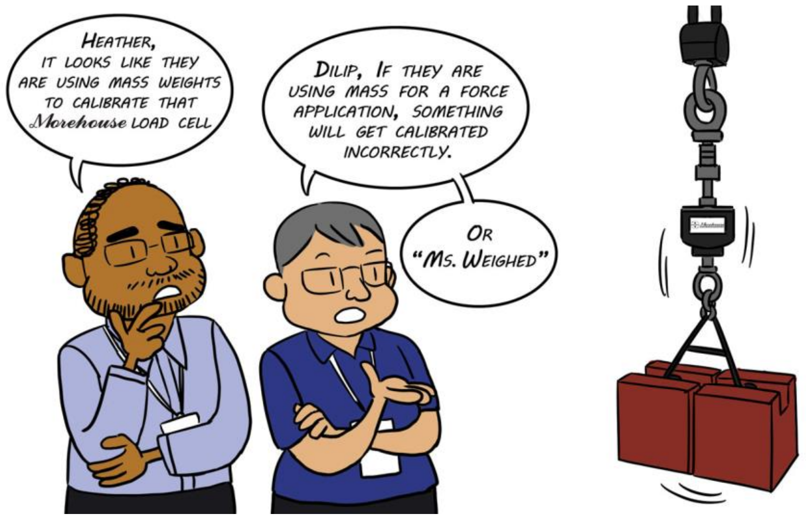


Figure 68: Cartoon Showing a Load Cell being Misweighed

15. 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? For aircrafts, it is about knowing the 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 with cargo and fuel. The airplane can have a good CG on takeoff, and the decreased fuel can cause an imbalance to develop during the flight. Knowing the weight is also important because the structural strength of the aircraft has limits on 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 would have the capability to 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 lead 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 lbs.

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 69 Morehouse Aircraft and Truck Scale Calibrator

1. We can control the equipment we purchase for calibration. To achieve proper calibration, equipment should be used that is plumb, level, square, and rigid. The above Figure is a Morehouse Aircraft and Truck Scale Calibrator. This new machine was designed to minimize 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 with 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 a magnitude from two to ten times the tolerance.

   Also, the right equipment is stable, with enough resolution to not have a significant impact on the overall uncertainty. Deadweight machines would be the best, but they are not the most cost-effective and generally 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 can generally apply forces to within 0.5 lbf, which can be limited if the proper load cell and indicator combination is not used. 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 that 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. Stability could be influenced by the adapters and the Unit Under Test (UUT).

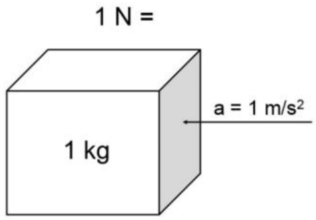


Figure 70 Force Units

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 site of calibration. 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 errors from gravity, as well as material and air density.

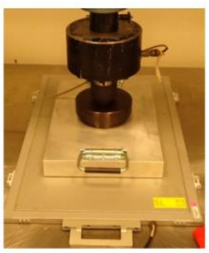
   Mass, under almost every terrestrial circumstance, is the measure of matter in an object. Measuring force takes additional factors into account: air density, material density, and gravity. It is the effect of gravity that can produce significant errors when comparing mass and force measurements. Gravity 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).

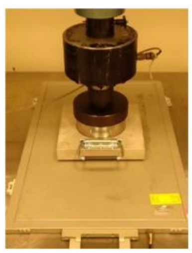
   A force measuring device calibrated in one location using mass weights then deployed somewhere else will produce different strains on the physical element. The resulting measurement errors can be significant. Correcting the difference in force and mass measurements is possible. When a device is adjusted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

More information on converting force to mass and formulas can be found in our blogs.

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 71 Difference in Adapters

3. We can control the adapters we use to simulate the footprint of the tires. 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 is different 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 becomes apparent quickly that this scale, like several others, will not be within the specification if different size tires are used that vary from the footprint of the adapter used during calibration. Therefore, it is imperative that all scales be calibrated with the appropriate adapters to simulate the application best.

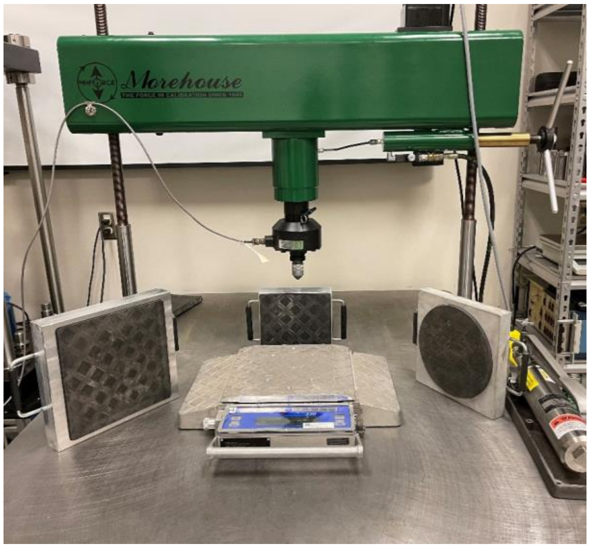


Figure 72 A Truck Scale Tested with 3 Different Size Adapters

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. The adapters, all made by Morehouse, are shown from left to right as a 10 x 10-inch pad, 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 73 Data from Using the Blocks Pictured Above

The test was performed, and the output was recorded above. Any point shown in green is within the manufacturer's specification of 1 % of the applied load. When using the recommended size adapter, we were able to meet the manufacturer's specification because we used an adapter that we designed to match the tire footprint. The numbers above, when using a 12 x12 block (actual rubber footprint 10 x 10) in red, show a noticeable difference outside of the allowable tolerance. Thus, further supporting that any scale calibration should be done with the proper size adapter.

The Morehouse Aircraft Scale Calibrator was designed to be the best option for calibration of 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 not using the proper equipment, units, or adapters can make achieving tolerances 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. If the uncertainty of the measurement is not less than the tolerance required, there will be a significant risk. Most legal metrology, ASTM E617-18, 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, resolution of both the reference and the UUT, 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 0.03 % 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. This all depends on several additional factors that are covered in our Uncertainty Propagation paper found here.

If you need to get the most accurate measurement out of your scale and want to 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 designed to maintain a high degree of accuracy required for proper scale certification. It can be used with all kinds of truck and aircraft scales and aircraft weighing kits.

Calibrating these scales correctly is essential to the safety of you or people you may know.

16. 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 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 there are 3 things that 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 74: Figure Showing Pin Size Diagram

In general, 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 75: Figure 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 very significant as the manufactures 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 during calibration used in the field. Not using the appropriate pin size will almost certainly 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 the significant errors as **not using the proper pin size**; it can be enough to fail the instrument during calibration.

Figure 76: Shown above are pins labeled A and B, 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 77: Shackle pins were measured using these coordinates.

A maximum variation of 0.0055 isn't much, is it? 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.

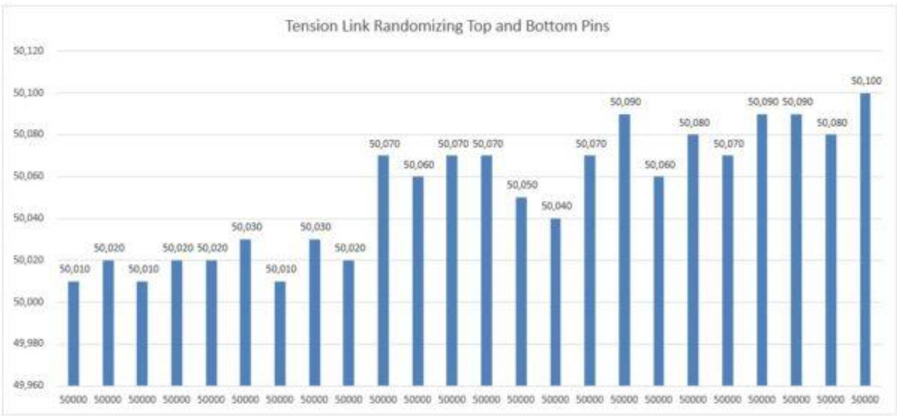


Figure 78: Tension Link Randomizing Top and Bottom Pins

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 79: 24 Tests on the Same Instrument and 13 Failed

13 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. Adapters pictured below are designed with sphericals to limit misalignment.

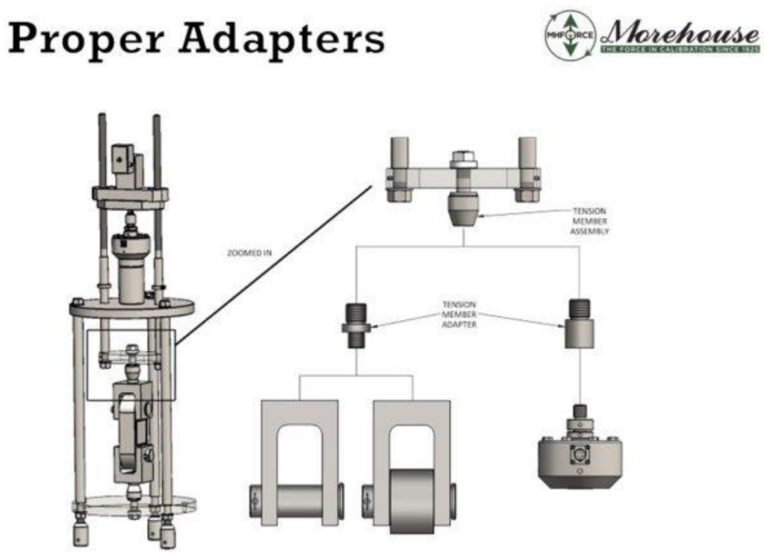


Figure 80: Morehouse UCM with Tension Member Adapters

Morehouse Clevis assembly for tension adapters are 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 mhforce website has more information on Morehouse Quick change Tension Members and our Youtube Channel has an Easy to Follow White Board Video on Tension Link Calibration.

Tension Link Calibration Safety Notes

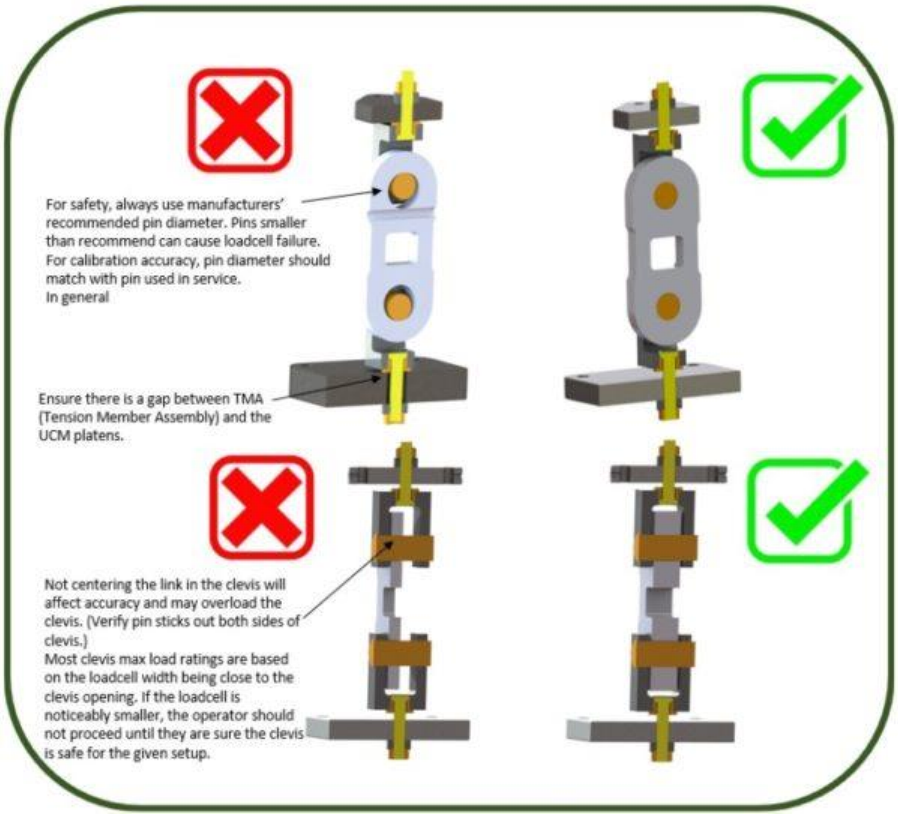


Figure 81: Tension Link Calibration Safety Notes

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 none cylindrical hole or very large chamfers. This effectively reduces the contact area on the pin and will decrease the maximum load capacity of the pin.

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

17. Replicating Equipment Use

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

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

In this section, we will look at common error sources, and examine how calibration setups in the Morehouse deadweight and calibrating machines best replicate field use. Specifically, we will review field use in the context of 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 82 Compression/Tension Machine that Does Not Replicate Field Use

The force-measuring instrument's end-user must ensure that the laboratory performing the calibration 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 are capable of replicating use if they used the customer's adapters and independent setups for compression and tension. However, this takes more time and raises the cost, 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 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
- Using an excitation voltage that is different from the voltage used at the time of calibration
- Variations in bolting a force transducer to a base for calibration while the application is different
- Electronic cabling regarding shielding, proper grounding, use or non-use of sensing lines, 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 realized value from the deadweight calibration

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

The primary focus of this chapter is not using independent 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

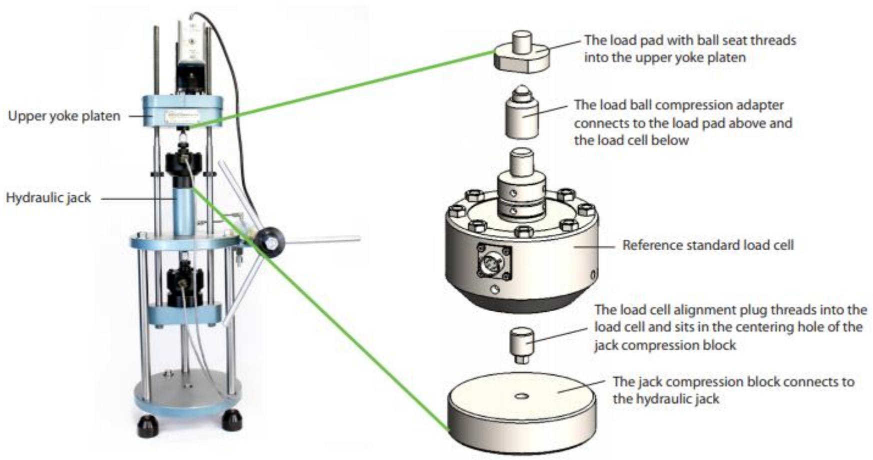


Figure 83 Morehouse Universal Calibrating Machine with a Compression Setup for the Unit Under Test

At Morehouse, we often get asked 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 on the market to calibrate all different types of force instruments. However, the most important answer is that our Morehouse machines allow the end-user to best replicate 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 84 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

To replicate field use, different setups need to be made with different adapters for tension than compression. The two Morehouse Universal Calibrating Machine figures above show different setups for compression and tension. These are drastically different from the figure Compression/Tension Machine that 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 being used for both compression and tension calibrations.

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

Figure 85 Morehouse Tension Adapters Designed Using Recommendations from ISO 376 [10]

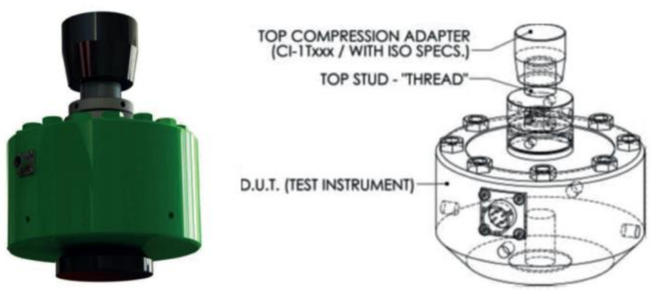


Figure 86 Morehouse Compression Adapters Designed Using Recommendations from ISO 376

Most 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 87 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 for. These errors include using different adapters than what was 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, which is 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 our customers and provide 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 to provide reproducible results. Our calibrating machines are designed to allow the end-user to best replicate most field use cases. 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 use 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, then 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 is using the device.

18. 5 Must-Have Characteristics of Great Force Equipment

Equipment used to measure force is going to be made to minimize off-center loading, bending, and torsion. To do this force, machines need to be:

1. Plumb
2. Level
3. Square
4. Rigid
5. Free of Torsion

All of the machines shown are designed with these 5 things in mind. Equipment used to measure force must replicate how most instruments are used in the field.

Figure 88: A Morehouse Primary Standard Automated Deadweight Machine

Plumb - Exactly vertical or true

Morehouse 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 89: An Example of Level Using a Morehouse UCM

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 movement to the center of a slightly bowed glass tube
Morehouse 100,000 lbf 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 90: An Example of Square Using a Morehouse BCM

Square - for Force Machines this is about having four right angles.
Morehouse 10,000 lbf Benchtop Machine. The adjustable beam and bottom base form the 4 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 91: 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 which will impact 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 92: An Example of Low Torsion Using a Morehouse Portable Calibrating Machine

Torsion – the action of twisting or the state of being twisted. Free of torsion means free of being twisted 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.

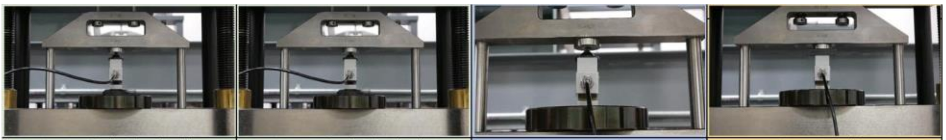
Want to see a simple video explaining what makes a great force machine? Our Youtube Channel has an Easy to Follow White Board Video on [What makes a great force machine](#).

19. Loading Conditions

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. When everything is designed correctly, the performance characteristics or specifications are typically excellent. However, these specifications apply under ideal loading conditions and not necessarily what the end-user might experience in 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 performing the calibration of 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 93: 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. In this example we use an S-beam load cell, but 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 S-beam load cell's output using different adapters and varying 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. Top and bottom thread loading may be the least common loading application we see 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.

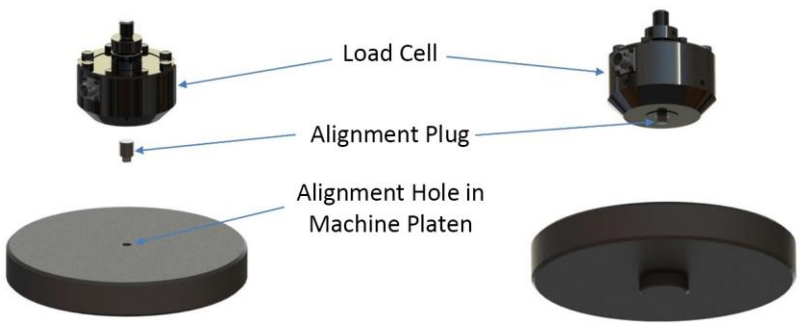


Figure 94: Morehouse Alignment Plug

Knowing that the S-beam load cells are so sensitive to any off-center loading, we highly recommend using machines that are 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 pictures on the far left and far right. 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, even 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 about how the S-beam load cell is being 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 are more concerned with accreditation and decision rules, rather than severely impacting the results.

Different Compression Adapters

Figure 95: 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 at 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 that of 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 three main disadvantages of not installing the adapter.

Figure 96: 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. We demonstrate this in our two-day force fundamentals class, and each time we produce significant errors. As part of this demonstration, we ran two full ASTM E74 calibrations, one without a threaded adapter and the other with a locked threaded adapter in place. The maximum difference in output was 0.044 %, as shown in the table below.

Force Applied	With Threaded Adater Installed	Without Threaded Adapter Installed	Difference in Output
200	-0.08190	-0.08193	-0.037%
1000	-0.40955	-0.40939	0.039%
2000	-0.81919	-0.81883	0.044%
3000	-1.22893	-1.22839	0.044%
4000	-1.63876	-1.63808	0.041%
5000	-2.04868	-2.04789	0.039%
6000	-2.45870	-2.45782	0.036%
7000	-2.86881	-2.86787	0.033%
8000	-3.27902	-3.27804	0.030%
9000	-3.68931	-3.68834	0.026%
10000	-4.09971	-4.09876	0.023%
		Maximum Difference	0.044%

Figure 97: A Comparison Showing a Maximum Difference of 0.044 %

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 performing the calibration and have them shoulder load the load cell.

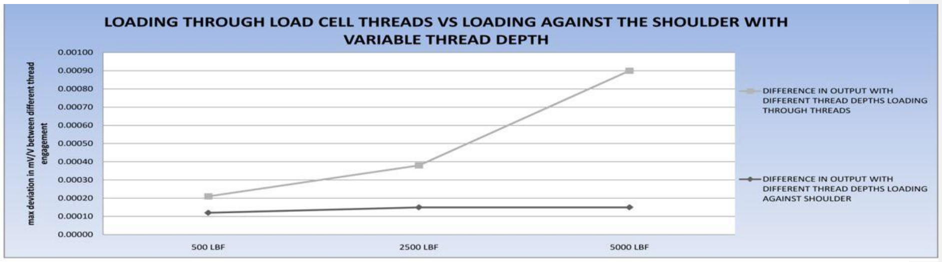


Figure 98: Graph Showing the Errors of Using Adapters with Different Thread Depths

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 99: Comparison Calibration Data Showing a 42 % Improvement in the ASTM E74 LLF When a Threaded Adapter is Installed

Want to see a simple video on why an integral adapter should be installed in 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.

The force was applied to the load cell using a Morehouse 120,000 lbf deadweight machine S/N M-7471. 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. For the purpose of this test, the load cell was kept at the same orientation, 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 100: 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. For load cells calibrated in compression, there may be a noticeable difference in output. The output is dependent on a variety of 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 to load flat against the base, while other labs may load the cell through the threads. It is crucial for you, the end-user, to 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 are aware of other labs whose standard procedure is to load the cell through the bottom threads. There is a difference for shear web type load cells, and we can put a number on the potential difference between these two calibration methods.

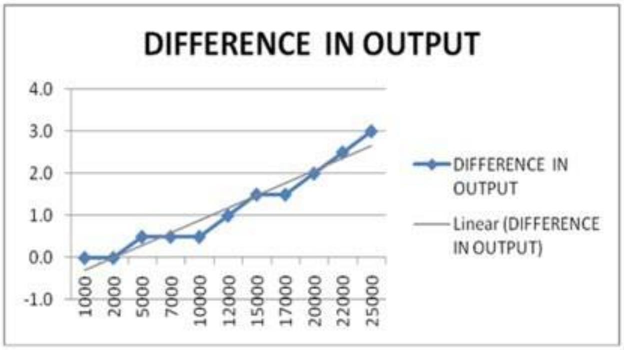


Figure 101: Graph Showing a 0.012 % by Varying the Loading Conditions

We took a standard Morehouse shear web style 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 (0.0016 % is what is found on our scope of accreditation). The results listed 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 are using with the force-measuring instrument for calibration. 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, our recommendation is to have the force-measuring equipment checked or calibrated to ensure any additional errors are accounted for.

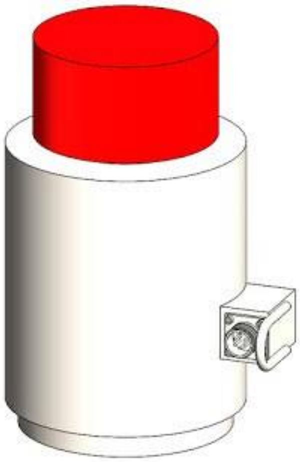


Figure 102: Multi-Column Load Cell

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 are using 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. When we informed them about the error, they sent the original top-loading block. When tested with the original block, it resulted in an output of 1,000,180 lbf when loaded to 1,000,000 lbf.

   Using the new adaptor, we figured the measurement error between the different top blocks (adaptors). The Expanded Uncertainty would have increased from 269 lbf with the original top adaptor to 1,490 lbf with the newly fabricated adaptor. The individual contribution to the overall measurement uncertainty was dominant.

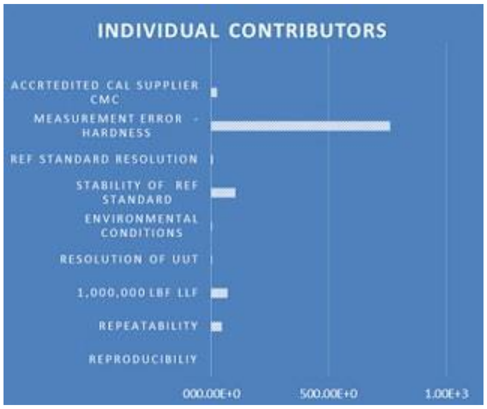
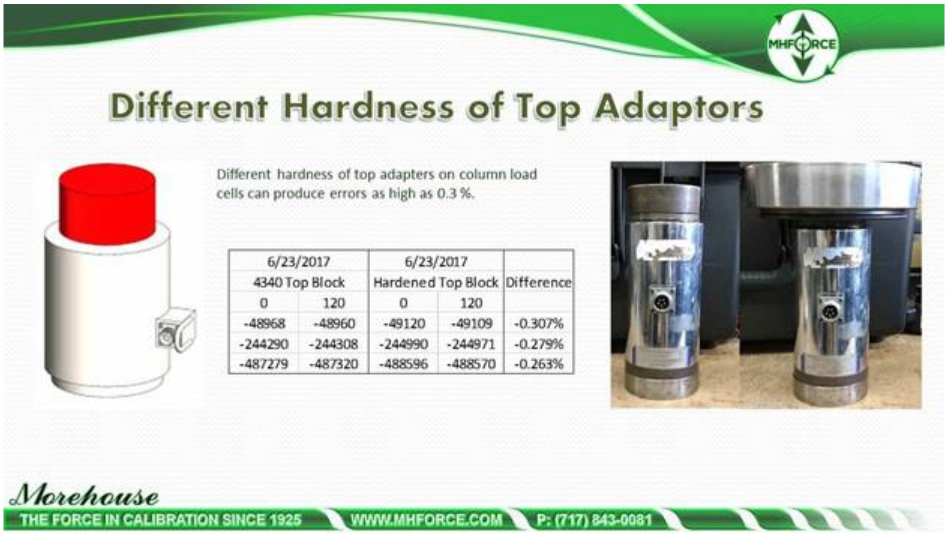


Figure 103: Individual Uncertainty Contributors

2. A customer sent in a single-column load cell and asked Morehouse to calibrate the load cell with our adapters. Since we want to make superior measurements, we contacted the customer to ask for their blocks and advised that there could be a change in the output 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 not acceptable 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 104: 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 % difference in strain between using two types of steel. The error gets much worse if the material is significantly softer. Softer material might cause more load to be transferred through the outside surfaces and not the center.

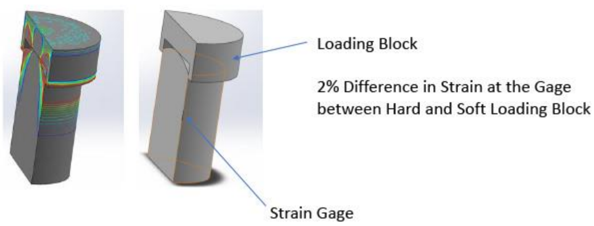


Figure 105: Effect of Loading Block on Column Type Load Cell

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 amount of shift will change the stress distribution. Therefore, the key to an accurate calibration is to use the same adapters

that were 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 differences of using different top adapters are 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 106: 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 have done this test 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 107: Morehouse 200 lbf through 600,000 lbf Concrete test Kit with the Proper Adapters to Ensure Reproducible Results and Limit Measurement Error

Different types of 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. If these force-measuring devices were used for calibration, there could have been failures. 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 consistent measurements today. Plus, pairing a top adapter with a load cell can improve stability and often extend the calibration dates. Less frequent calibrations equal more overall cost savings and a safer world.

Flat Base

Figure 108: Multi-Column 300K Load Cell with a Non-Ground Base

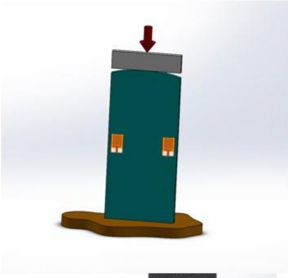
Installing a non-flat base on a multi-column cell can cause an error. The actual test results we observed on a multi-column cell are shown below. We received the load cell and tested it with the non-ground base attached to it. We set up the load cell in our 2,250,000 lbf force machine and exercised it 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 and stoned the bottom of the load cell to make sure it was as flat as we could make it 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%

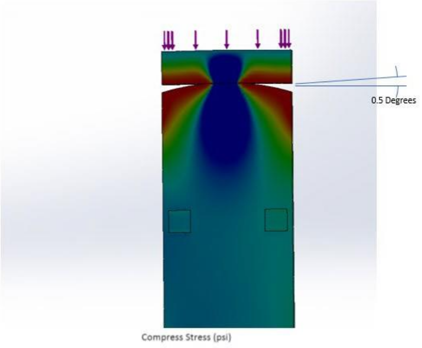
Figure 109: Shows Five Times the Measurement Error with a Non-Flat Base

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 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 110: Stress Analysis with Radius Surface 0.5 Degree from Level

Most compression force-measuring instruments are intentionally designed with some sort of 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 practice to 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

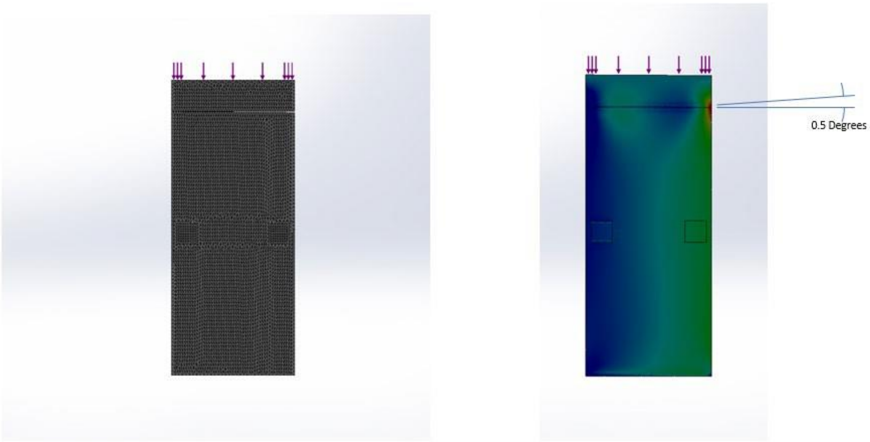


Figure 111: Stress Analysis with Flat Surface 0.5 Degree from Level

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 have 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.

20. Adapter Considerations

Several force measurement errors can result from using adapters that are different from what the force-measuring instrument 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 the time of calibration.

Figure 112: 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 stress distribution on the force-measuring instrument and produce errors that range from minimal to an output difference more significant than the allowable tolerance.

If the calibration laboratory did not use the appropriate adapters, or if your laboratory is not using similar adapters, there could be substantial errors. For example, we have observed errors as high as 2 % of the full-scale output from varying the loading condition and adapters. The fact is, 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 adapters that are not machined correctly, which may not allow for a distortion-free load path.

Why is it critical to reduce misalignment error? 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.

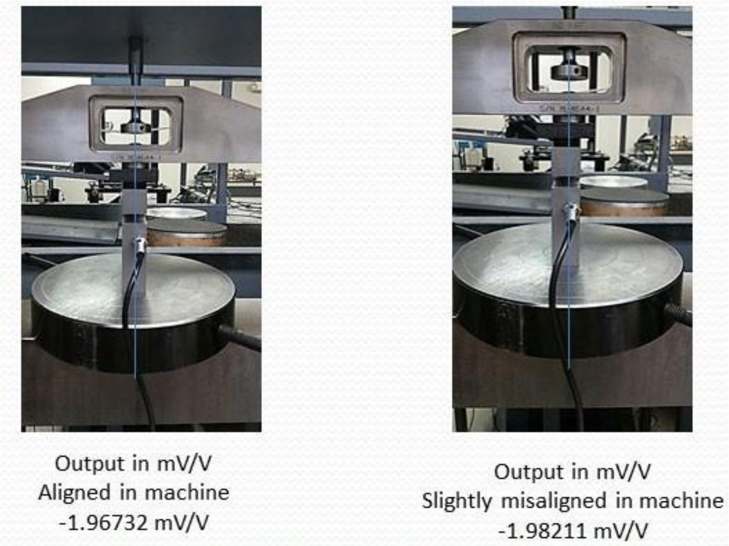


Figure 113: S-beam load cell with slight misalignment producing a 0.752 % error.

When the load cell was aligned and calibrated properly, 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 end up adjusting a machine that is actually "in tolerance," and a recall may result from this simple error. Alignment plugs and base plates with alignment holes shown below can drastically reduce misalignment errors.

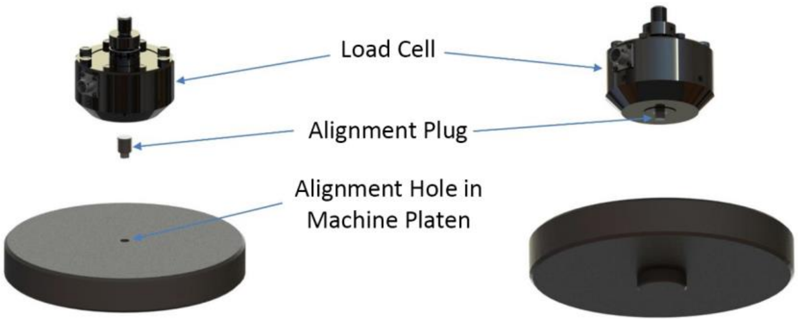


Figure 114: Morehouse Alignment Plug

Figure 115: Proper Way to Thread an Alignment Plug: Thread is Past Flush and Into Cell

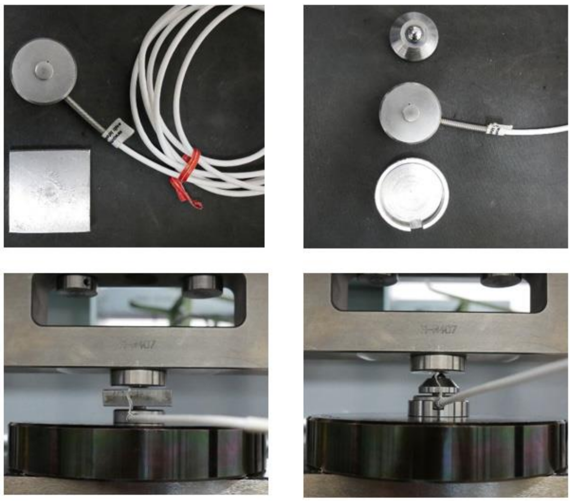
When using alignment plugs that thread into the bottom of your load cells, make sure they are threaded flush to the load cell's bottom. Once they are flush, thread the adapter an extra turn into the cell. Make sure that none of the threads are exposed below the load cell base. If one or more threads is exposed, the load will be generated through the cell's internal threads and 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 116: Improper Way to Thread an Alignment Plug: Thread is Not Engaged Enough into the Load Cell

Figure 117: 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 shown above improve alignment and yield better calibration results. Usually, the results are better by a factor of 5 when using the above adapters compared with a technician trying 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 118: Typical Button Load Cell Calibration Versus One with Morehouse Adapters

The data in 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 better than 0.25 % of full scale even with the proper adapters. We have seen some specifications where the end-user is expecting 0.1 % of full scale or better. However, without the proper adapters, 1 % of full scale is nearly impossible to achieve.

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, but 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, but these adapters will not turn a worn button load cell with a 5-10 % error into a cell with an error of better than 0.5 % of full scale.

In general, we see improvements with a magnitude 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 119: 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 decides to use 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, then 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 to 50,000 lbf with two different size load pins. When loaded with a smaller pin of 1.85 inches, the device read 49,140 compared to a 2-inch pin and reading 50,000 lbf.

Figure 120: Tension Link Difference in Output with Pin Size

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

Figure 121: Morehouse Clevis Kits

Read more about our Quick-Change Tension Adapters and Clevis Assemblies that simplify tension 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, while 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

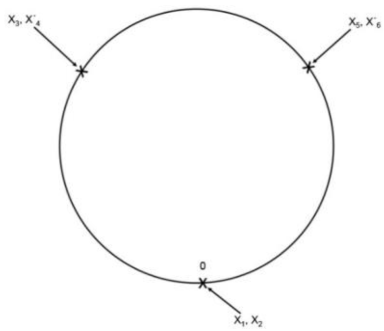


Figure 122: Diagram of Different Positional Tests at 120 Degrees Rotation

There are additional tests 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 are using a good load cell with the proper adapters and 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. To do this, force machines need to be:

1. Plumb – exactly 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, all sorts of alignment errors can happen, which will impact 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, then 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 run 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 needs to be performed for each combination (as shown below) and then take the maximum of the three calculations.

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 123: 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 have items calibrated where the calibration method does not test for Reproducibility? 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 a term LLF (lower limit factor), which is really a Type A uncertainty calculation that quantifies the equipment's Reproducibility from 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, 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, different machines, and different 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 potentially include not only different appraisers but also different: gages, labs, and environment (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. That is, 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 and focus on the ANOVA method and show how the calculations are performed.

Many of the Reproducibility definitions above use different operators, different laboratories, and various equipment. If the lab only has one location, then we can remove different laboratories. Some parameters, such as force measurement, where one lab rarely has two of the same size machines, rely on capturing the measurement process's Reproducibility by comparing operators. The ideal solution is to set up SPC (Statistical Process Controls) procedures that can obtain long-term Reproducibility. However, using ANOVA and other methods can capture a process's Reproducibility in the short term, which is accepted.

Morehouse offers a training course on SPC several times a year. Check out our website for further details on the training.

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 124: 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 shown below, which may drastically improve repeatability and Reproducibility between operators)

The example below uses two technicians recording readings at the same measurement point on the same equipment. 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 useful tool that can do the same calculation with a 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 125: ANOVA Excel Example

The results shown 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 more than you would expect to see 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 126: How to Calculate Reproducibility and Repeatability from the ANOVA Excel Example

Reproducibility is found by taking the square root of the between-groups 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. If the reference load cell is calibrated in accordance with the ASTM E74 or ISO 376 standard, then this issue becomes moot because both standards capture reproducible conditions at the time of calibration.

However, if 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, then the system should be calibrated again. Companies that are not using these calibration standards will have additional error sources that may be difficult to quantify. It is our recommendation that companies should use legal metrological standards for calibration of 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 two standards are calibrated by deadweights, then comparing one standard with another will show any additional measurement errors in the machine from 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.

21. 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 would need to compare the same force point with a tare load versus without.

In our lab, we have 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. However, the reproducibility does because we created a new variable by applying an additional 10 %, which introduces more stress onto the material. This creates more deflection, which the fractional change in length is measured by the strain gauges in the load cell.

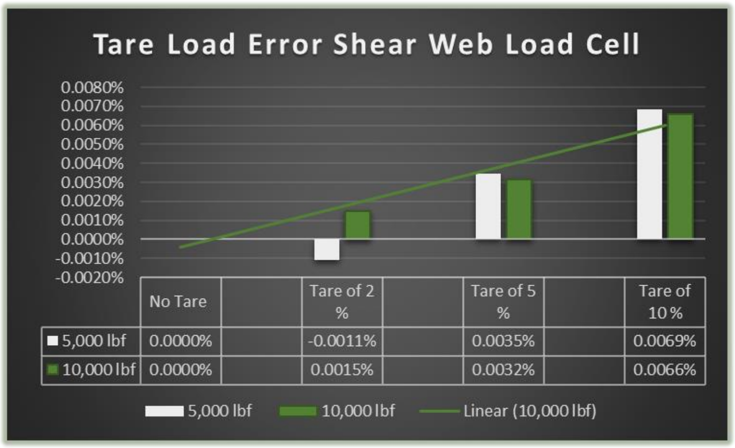


Figure 127: Load Cell Tare Load % Error Graph

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 into 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 will have to be raised off of 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 zeros 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 first have the 10,000 lbf load cell calibrated to 10,200 lbf. Then compare the calculated deflection values at 10,200 lbf, deflection values at 200 lbf, and compare that against the calculated value at 10,000 lbf (see example below). Assuming the instrument fits the calibration curve well, the difference should be insignificant.

Force	No Tare	Tare 2 %	Error
5000	-2.06036	-2.06034	-0.001%
10000	-4.12286	-4.12292	0.001%

Figure 128: 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 zeros the load cell 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 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 first have the 10,000 lbf load cell calibrated to 10,500 lbf. Then compare the calculated deflection values at 10,500 lbf, deflection values at 500 lbf, and compare that against the calculated value at 10,000 lbf (see example below). Assuming the instrument fits the calibration curve well, the difference should be insignificant.

Force	No Tare	Tare 5 %	Error
5000	-2.06036	-2.06043	0.003%
10000	-4.12286	-4.12299	0.003%

Figure 129: Load Cell Tare 5 % Readings

This example uses a Morehouse Ultra-Precision Load Cell. We have observed errors from 0.003 – 0.006 % from 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 zeros the load cell 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 first have the 10,000 lbf load cell calibrated to 11,000 lbf. Then compare the calculated deflection values at 11,000 lbf, deflection values at 1,000 lbf, and compare that against the calculated value at 10,000 lbf (see example below). Assuming the instrument fits the calibration curve well, the difference should be insignificant.

Force	No Tare	Tare 10 %	Error
5000	-2.06036	-2.06050	0.007%
10000	-4.12286	-4.12313	0.007%

Figure 130: 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. **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 = 0.2648421D-05
L = 3,000.00
T= 299.70 Lbf
A0 = 0.1673432D+00

TCF = (2*0.2648421D-05*3000*299.70)-0.1673432D+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

At Morehouse, we educate our customers and provide tools to explain how we correct for tare weights. 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 for more testing to be done to capture error sources. If the tare weight is higher than 5 %, we recommend to

calibrate 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.

22. Indicators for Force Calibration Equipment

The selection of an indicator for your load cell calibration system can impact the measurement results. This section covers:

- setting up an indicator via span points
- Four-wire versus six-wire
- shunt calibration
- the importance of matching the excitation and waveform if separate measurement traceability is required

The best practice is to pair an indicator with a load cell and have them calibrated 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 and is usually stated in mV/V, where mV/V is the ratio of the output voltage 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 131: Morehouse Precision Shear Web Load Cell Specification Sheet

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 relative change in resistance is measured by the indicator. This 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 very slightly,and the voltage on the other signal line decreases very slightly; the difference in voltage between these two signals is read by the indicator.

Recording these readings in mV/V is often the most accurate method for measurement. Many indicators on the market can handle metric ratio measurements and 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 of these will use some linear equation to display the non-programmed points along the curve or line.

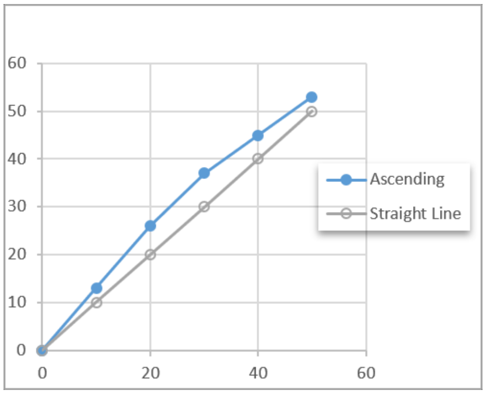


Figure 132: Load Cell Curve Versus a Straight Line

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, which is found on the load cell specification sheet shown above, indicates how much deviation there is. Non-linearity is defined as the algebraic difference between the output at a specific load, usually the largest applied force, and the corresponding point on the straight line drawn between minimum load and maximum load. Of course, other 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.

When programming an indicator via span points, it 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 from this method because the force-measuring system will always have some non-linear behavior.

		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 133: Programming an Indicator with a 2-pt Span Calibration

The figure above is an example of 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 the 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, as well as thermal characteristics. In addition, what the reference lab achieves is short-term and does not include the system's stability or adapters, which are 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 defined as the average of replicate indications minus a reference quantity value. [25]

When we talk about bias, we discuss the difference between the calculated values and the applied force values. In the example above, the worst error is 3.2 lbf, around 0.08 % of applied force when 4,000 lbf is applied.

Using Least Squares Method

Many indicators do not allow the end-user to enter anything other than span points. They do not allow the use of the "best-fit" or least-squares method. However, many indicators do have USB, IEEE, RS232, or other interfaces that will enable computers to read and communicate with the indicator. When software can communicate with an indicator, a regression analysis method can be used, which often better characterizes the force-measuring system.

This regression analysis method begins with a set of data points to be plotted on an x- and y-axis graph. 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. The formula often uses higher-order equations to minimize the error and best replicate the line. The figure below shows a plot from the actual readings in mV/V and fit to a 3rd order equation.

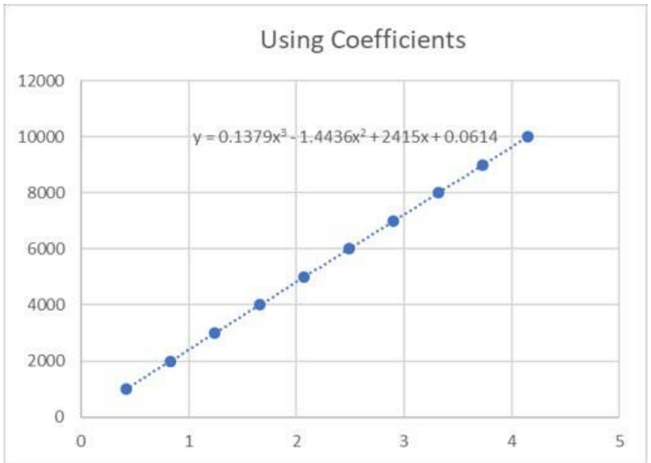


Figure 134: Graph of a 3rd Order Least Squares Fit

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(Response) +-1.4436(Response)^2 + 0.1379 (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, 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 135: Bias or Measurement Error When Using Coefficients

The overall difference in the errors between these two methods is relatively 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 % of full scale. The worst point, at 4,000 lbf, has a difference of 3.06 lbf, or a 2413% difference between errors. Using coefficients will often require 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%

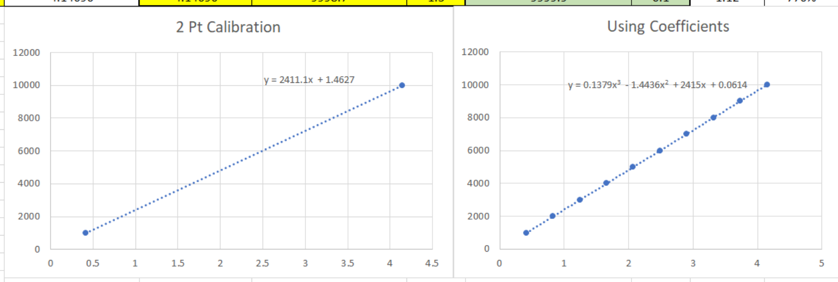


Figure 136: Difference Between 2-pt Span and Coefficients on the Same Load Cell

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 137: Morehouse Calibration Report with Two Sets of Coefficients

There are two sets of coefficients and equations in the certificate shown above.

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. The A set of coefficients is often used by calibration laboratories 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, then they would load the reference standard to -4.13641 mV/V.

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 is performing a calibration to ASTM E4 or ISO 7500. 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 138: Morehouse 4215 Plus Indicator

However, the mV/V value needs to be converted to know if 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 139: 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. To solve for a response when force is known, one would use =LINEST(Response,Force^{1,2,3,}). 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 point.

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, it becomes more challenging to spot trends, which is an ISO/IEC 17025 requirement. "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 is merely reading the Actual Reading mV/V values at the time of each calibration. It is much easier to establish the baseline or monitoring the results based on units that are rarely adjusted.

Adjustments could happen if an indicator failed, or a simulator is used to standardize the indicator. However, this is another error source related to the electrical side. If the indicator and load cell are paired and stay together as a system, this point is moot.

We recommend that you keep your load cells and indicator 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 Incator Lowers Measurement Errors for further explanation.

Figure 140: 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, then the indicator needs to 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, N and reduces 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

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

MHFORCE Morehouse THE FORCE IN CALIBRATION SINCE 1925

Morehouse Instrument Company is ISO/IEC 17025 / ANSI/NCSLI Z540.3 Accredited

www.mhforce.com

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 141 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 142 5,000 lbf Morehouse Load Cell B Coefficient Error

We have done testing on various scenarios using the formula for B coefficients embedded into a 4215 Plus meter. We have developed an algorithm into 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 decided to follow 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 143 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 here is 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 144 2-PT mV/V Values Entered into the 4215 Meter

The errors change quite a bit 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 that allows coefficients to be entered. In these systems, we specify the accuracy from anywhere of 0.005 % to 0.025 % of full scale. These do not include drift effects, which is usually better than 0.02 % on these systems. For other systems that have a 5 or 10 pt. calibration, and 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 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 error that is very different to quantify based on the randomness of the points selected, and the error can vary. The actual results will vary on how much the system is used and on the individual components of the system.

Cabling

Most of the force or torque systems we calibrate each year consist of load or torque cells, an indicator or readout, cables, adapters, and some sort of 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 145: 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 simply cannot compensate for variations in lead resistance.

Substituting a cable of a different gauge or a different length will produce additional errors. A known example of this involves changing 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 of measured output.
3. Cable substitution will result in an additional error and should be avoided.
4. Cables used for 4-wire systems should have a S/N or a way to make sure the same cable stays with the system that it was calibrated with. This would be a Good Measurement Practice Technique that Morehouse highly recommends.

6-wire systems

Figure 146: 6-Wire Cable and Diagram

A 6-wire cable that is run 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. Simply run two lines from the load cell's positive excitation pin and two wires from the load cell's negative excitation pin. The remaining 2 wires are run to positive and negative sense. The 6 wires then feed into the indicator with positive excitation and positive sense running to the indicator. Negative excitation and sense are run to the appropriate indicator connections and positive and negative signal.

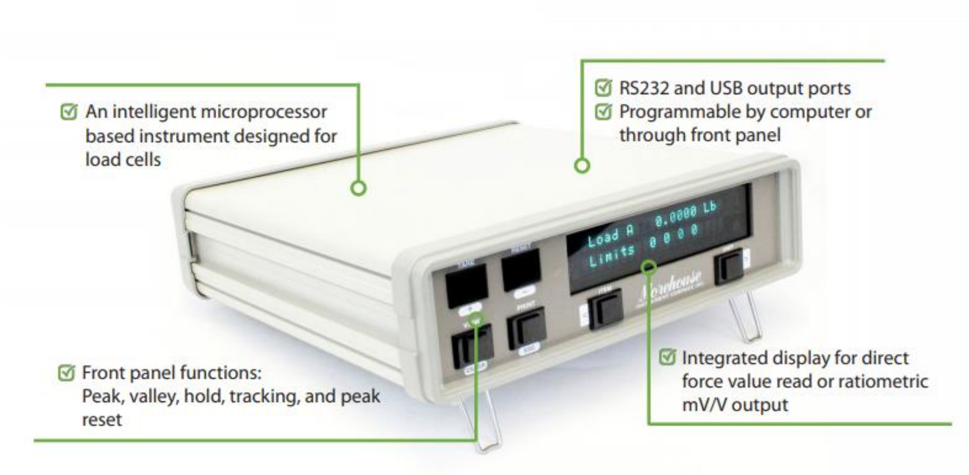


Figure 147: Morehouse 4215 Meter is a 6-Wire Sensing Indicator

However, a 4-wire system cannot be changed to a 6-wire system without a recalibration of the entire system. A 6-wire cable is the best choice if you intend on interchanging 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.

Verification through Shunt Calibration

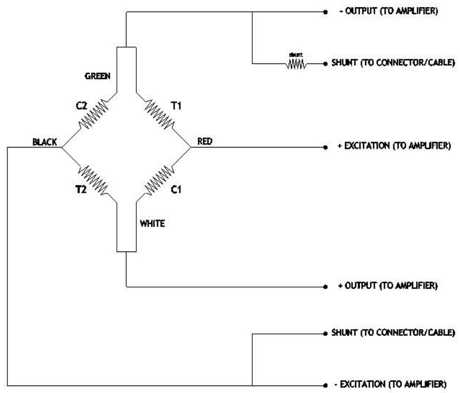


Figure 148: Load Cell Bridge with a Shunt Calibration

Shunt calibration is an inexpensive way to verify that the load cell and indicator system is not drifting too much or has been damaged. This practice uses a known resistor across the load cell bridge (ex. 30k Ohm) and monitoring the system. Shunt calibration involves simulating the input of strain by using a resistance value. It is accomplished by shunting or connecting a large resistor of known value across the load cell bridge.

Excitation and Waveform

The ASTM E74-18 standard includes reporting criteria that needs to be on certificates of calibration. It states, "The excitation voltage and waveform used for calibration when known."[28] The ASTM E74 includes this because it matters.

At Morehouse, we get a lot of requests for indicators that can be used to 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. Although they vary in output from 4 – 6 volts excitation, we have other indicators that are meant to be used as a system with the reference standard load cells. They are not good indicators to capture the mV/V output of the UUT because the excitation and waveform will not match what the customer is using.

For example, we compared a 10 V excitation on an HBM DMP40 with a Fluke 8508A, both of which are 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 different indicators; we used a simulator that was tested at the National Institute of Standards and Technology (NIST) as the reference.

This simulator was utilized to accurately replicate the excitation and the output response of a load cell when connected to the indicators in the experiments. On the DC indicator side, a Fluke 8505A Reference Multimeter was used, and on the AC side, a HBM DMP40 Precision Measuring Instrument was used. 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 149: AC versus DC Indicator Data

If we want to standardize a Morehouse 4215 or Morehouse DSC indicator, then we would use the NIST values. 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 -3.00000 set point is selected. If we want to standardize the HBM, we would need to use a BN100A – Bridge calibration unit for transducer excitation with 225Hz carrier frequency.

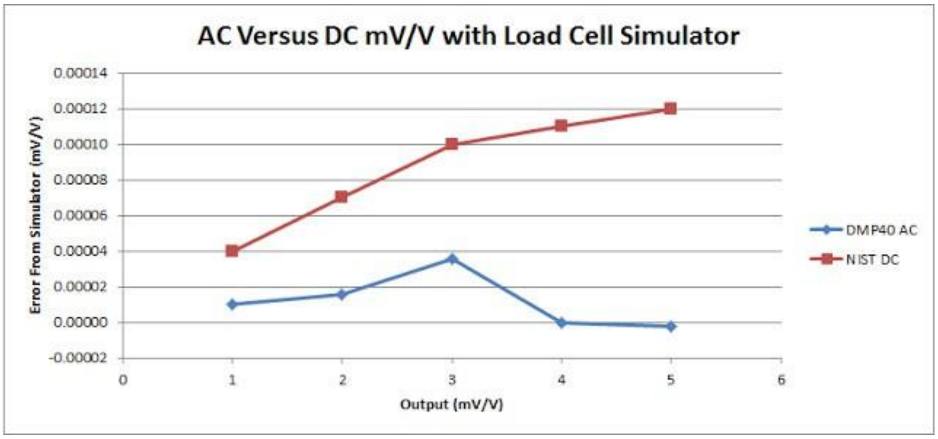


Figure 150: Graph of AC versus DC Indicator Data

Looking at the test data above, it appears 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 that 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 in lieu of another one without recalibration of the entire system.

There are also differences in the excitation voltage on a 5-volt versus 10-volt DC system. On the test Morehouse has performed, the differences are around 0.01 %, and they vary 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 have your load cell calibrated with the indicator it is used with. Substitution can be tricky and requires traceability back to SI units using the same excitation voltage and waveform of the primary multimeter.

23. Calibration Coefficients Explained

What Coefficients Do

ASTM E74, ISO 376, and other standards may use calibration coefficients to better 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 how best to predict 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. Almost any force-measuring device can be characterized using fairly standard equations, which many will remember from high school algebra class.

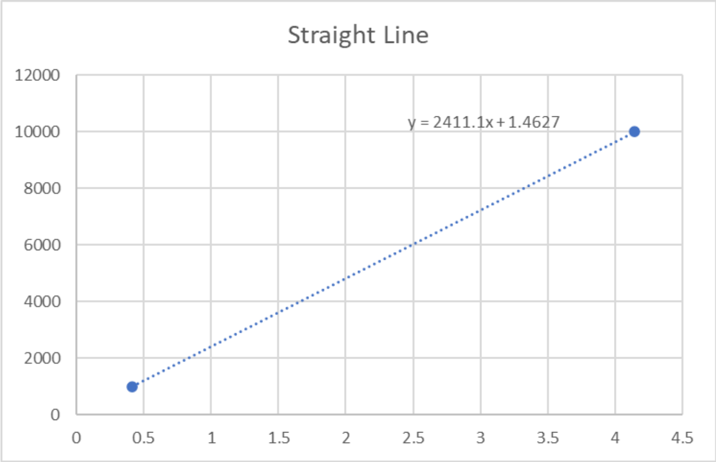


Figure 151: Load Cell Curve Using the Equation for a Straight Line

Straight Line Fits

Straight-line equations such as y = mx + b are quite 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 above Figure shows that the force-measuring device deviates a bit from the line. This deviation means that we cannot predict precisely enough for the measurements we need to make. Thus, a straight line may introduce additional errors. To determine if a straight line gives us enough precision, it is often dependent 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 152: 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 is and what y is.

One could use the same formula to solve for x. To do this, we take the formula y = Mx + B and solve for x. The formula then becomes Mx = (y-B), which we then divide (y-B) by m. Thus, x = (y-B)/M. Pretty simple, right? When we get to higher-order equations, the formulas get more complicated.

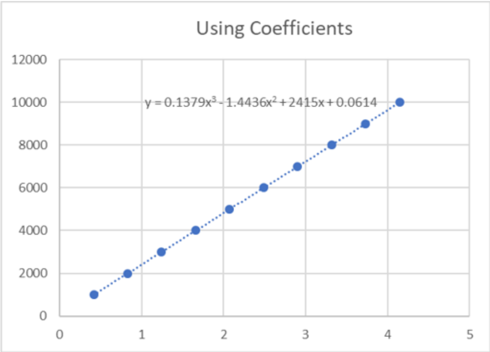


Figure 153: Using Least Squares Method or Higher-Order Equations

Using Least Squares and Higher-Order Equations

Like a simple straight line, this method of regression analysis begins with a set of data points that are plotted on an x- and y-axis graph. ASTM E74, ISO 376, and other standards use the method of least squares because it is the smallest sum of squares of errors. It is the best approximate solution to an inconsistent matrix, often involving multiple x- values.

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 the error and best replicate the line. The figure above shows a plot from the actual readings in mV/V and 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) = $A_0 + A_1 * F + A_2 * F^2$ where: $A_0 = 0.0614$, $A_1 = 2415$, $A_2 = -1.4436$, and $A_3 = 0.17379$. 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 these numbers and dissect them 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 154: 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 that are not on the certificate of calibration.

Note: Additional information on how to calculate the calibration equation is found in Section 8 of the ASTM E74 Standard titled Calculation and Analysis of Data. If using Microsoft Excel functions such as INDEX and LINEST are very useful tools for using the method of least squares. 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 155: 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, in reading the calibration certificate, if you want to apply 20,000 lbf of Force, you would load the force-measuring device until it reads -3.46174 mV/V. However, if you want to apply 21,000 lbf of Force, you need to use the equation found above 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 either Force or Response.

Examining What the Coefficients Mean

A0 and B0 is the constant at which the equation crosses the y-intercept.

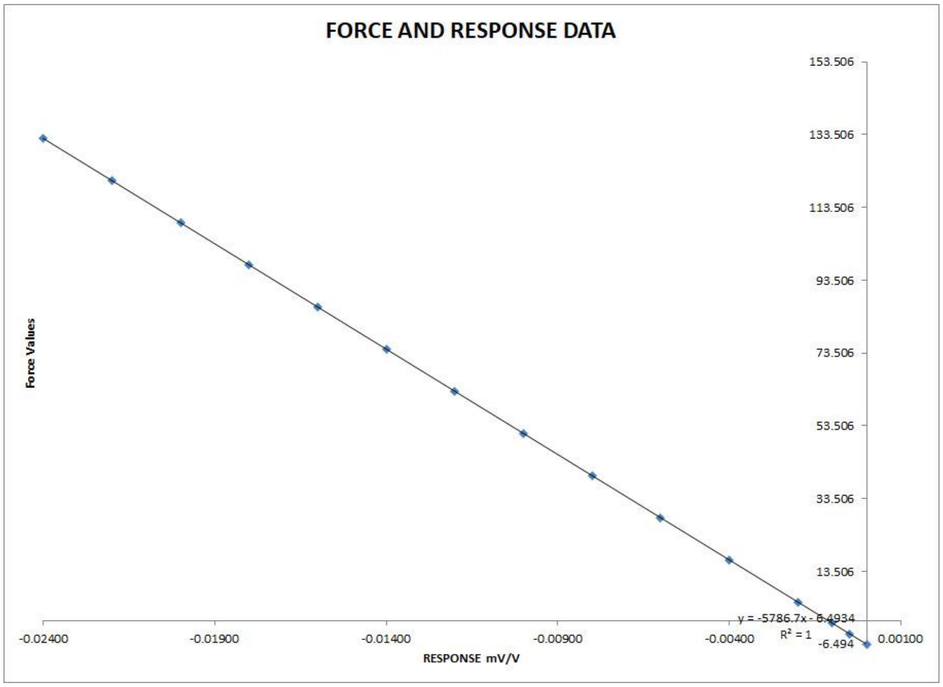


Figure 156: The Relationship of Force versus Response at Very Low Responses

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 the 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 the equation is 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 is equal to A_0 or -0.00112 mV/V.

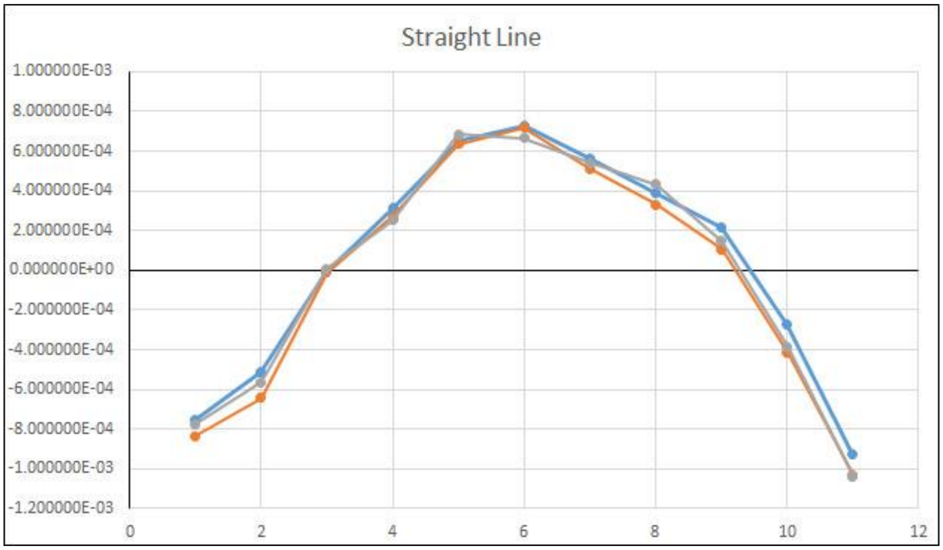


Figure 157: Deviation Between Actual Reading and Fitted Curve Using a Straight Line Fit

A_1 * F and B_1 * R is the linear term. F is the Force Applied and R the response (often in mV/V). In the above figure above we show the deviations from the fitted curve by drawing a straight line through all of the points and then subtracting the predicted Response from the actual force-measuring device reading.

We use this method because if we showed three runs of data, with very small changes, then the lines would all blend together, as shown in the above figure. When using a straight line, the deviations are much larger, and the overall reproducibility is less. The ASTM llf, which represents 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.

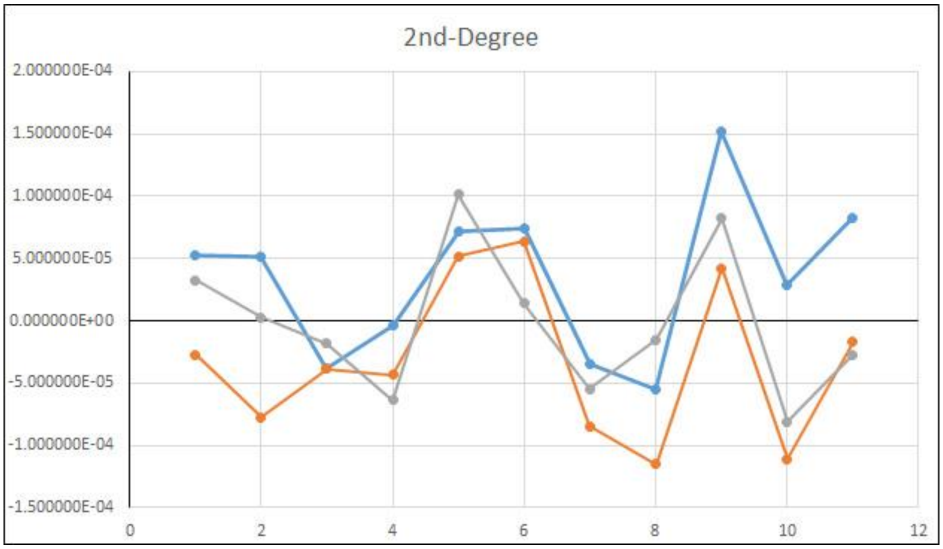


Figure 158: Deviation Between Actual Reading and Fitted Curve Using a Quadratic Fit

$A_2 * F^2$ and $B_2 * R^2$ is the quadratic term

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 is going to be the 2nd best fit as only the Quintic will be a little better.

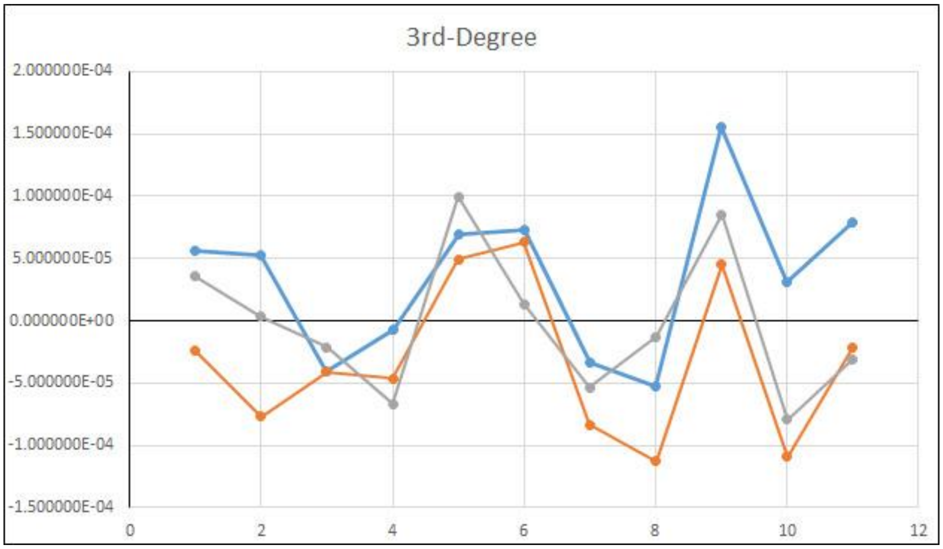


Figure 159: Deviation Between Actual Reading and Fitted Curve Using a Cubic Fit

$A_3 * F^3$ and $B_3 * R^3$ is the cubic term.

This coefficient functions to make the graph "wider" or "skinnier" or to reflect it. If negative or the greater the coefficient, the skinnier the graph. In our example, the cubic fit is a little worse than the quadratic by about 0.15 lbf.

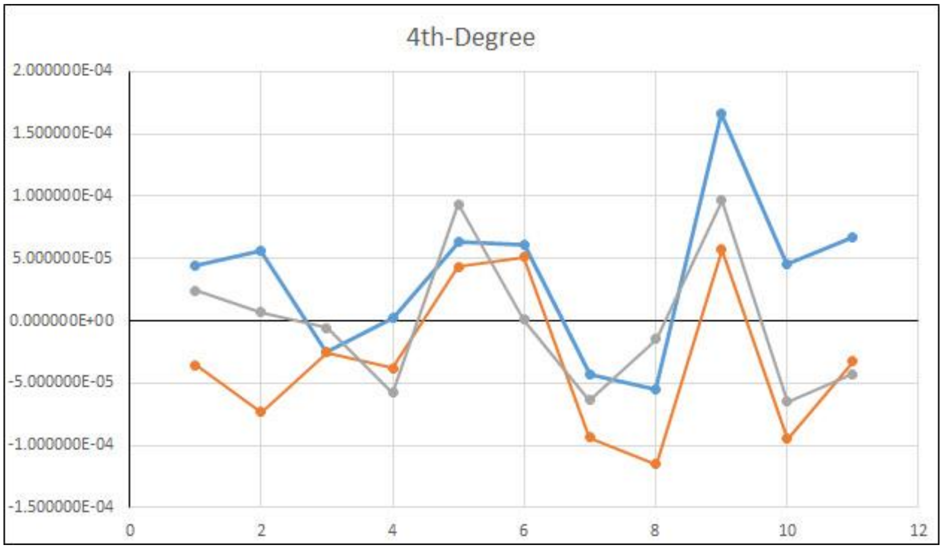


Figure 160: Deviation Between Actual Reading and Fitted Curve Using a Quartic Fit

$A_4 * F^4$ and $B_4 * R^4$ is the quartic term.

These have zero to four roots, one, two or three extrema, zero, and one or two inflection points. There is often no general symmetry, and it is much more complicated to solve. There can be different inflection points, and they can have various roots. In our example, the Quartic fit is a little worse than the quadratic by about 0.17 lbf.

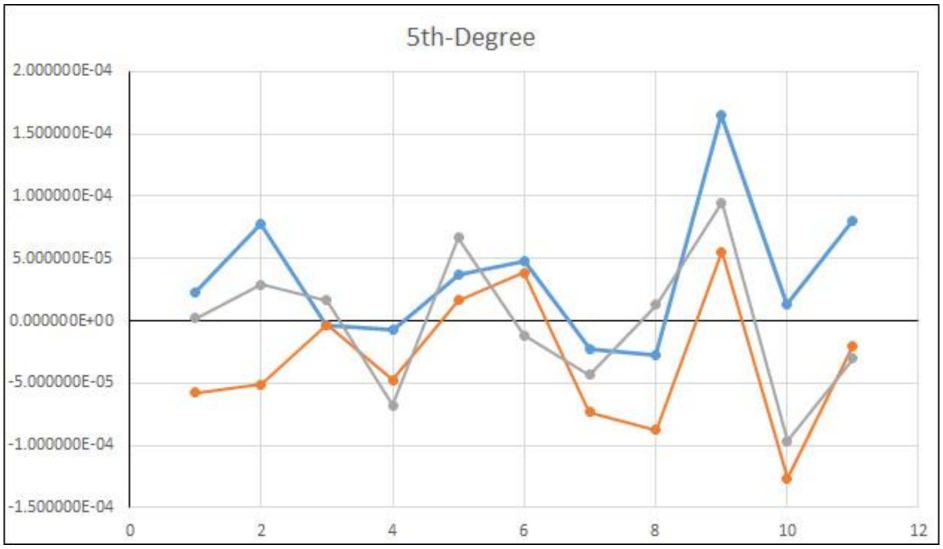


Figure 161: Deviation Between Actual Reading and Fitted Curve Using a Quintic Fit

$A_5 * F^5$ and $B_5 * R^5$ is the quintic term. 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 162: ASTM llf for Each Fit Using the Same Data Set

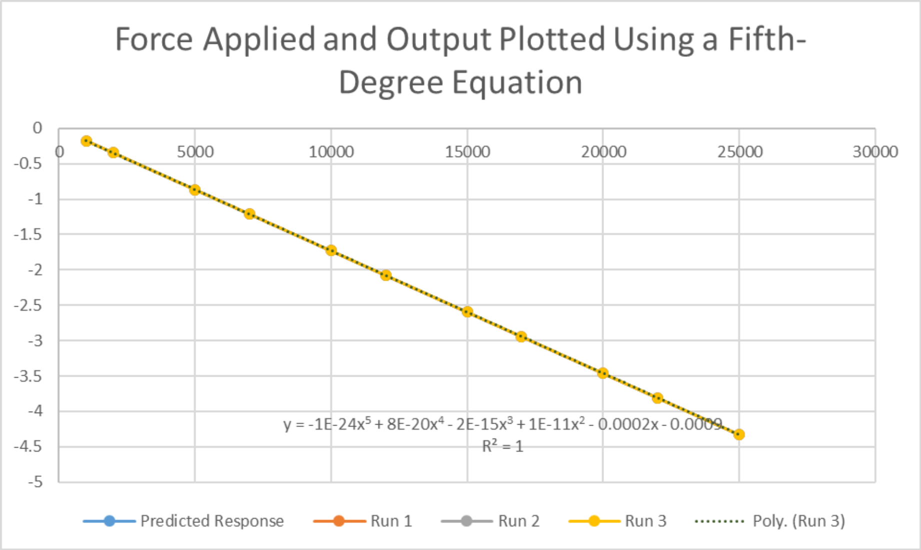


Figure 163: Showing the Plotted Values Versus the Force Applied

Higher-order equations allow the line to take on different forms to characterize the force-measuring device best. The equations are similar to instructions telling the line to turn up, down, have a parabola, be narrow, or wide, and in which directions; since we are dealing with such small deviations, it is tough to see any of these behaviors on a graph, as shown above.

If the force-measuring device is very repeatable, but not as linear, then the quartic or quintic function may best characterize the device by producing a curve that deviates at several points from linear behavior. We see in above figure 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.

24. Load Cell Simulator Calibration Requirements to Calibrate my Digital Indicator: Is it Worth it?

We have been asked a bit more frequently lately 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 load cells that are not used would then be available for someone else to use. If done correctly, there is quite a bit of benefit. However, there are quite a bit of disadvantages and obstacles to overcome.

Let's start by dealing with the requirements of both ISO 376 and ASTM E74 standards. These are standards required for calibrating force-proving instruments, most known as load cells, to calibrate other force-measuring instruments, force machines, hardness machines, 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]

Additionally, ISO 376 makes mention of programming indicators using span points.
If one does not use the calibration equation and programs points 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 in doing this is if you purchase the same indicators, one could be used as a backup if the primary unit fails.

The expensive calibration of the entire system could potentially be avoided.
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 will need to have a simulator calibrated 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 164 Morehouse Budget mV/V Load Cell Simulator

The first point is 0.5 mV/V and the last one 4 mV/V. If someone had a 4 mV/V (10,000 Force Units) load cell and the range of verified force was 500 through 10,000 Force Units, the simulator at 0.5 mV/V is 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. Using this simulator, the end-user would need to raise their Class A verified range of forces to 1,250 FU. A situation that 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 cells 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 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 a user 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 affect 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 need to be made 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 has an article explaining why 4-wire systems are not ideal. That article can be found

Appendix X2 details all the steps necessary to determine the uncertainty. Morehouse fully supports ASTM E74 and feels the membership is incredible. For under $ 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.

Summary of Top Requirements for Load Cell Simulator Calibration Needed for Meter Substitution
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 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 likely 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 simulator.

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.

These 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.

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 Uncertainties, Noise or Resolution, Repeatability, and Reproducibility.

In our experience, most who choose to 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. For an ASTM Class A the requirement is to be better than 0.25 %.

The contribution to uncertainty is often significant, though somewhat manageable.

Morehouse does offer calibration of load cell simulators to comply with either standard. 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 165 Morehouse Page from Simulator Calibration Report in mV/V

Morehouse Budget Load Cell Simulator

Back to the simulator, that likely is not good enough to calibrate the meters for substitution. Why would anyone want this? The best answer is cost.

The simulator is around $ 600.00 compared with a higher-end model that costs 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 very powerful tool.

Our simulator allows the end-user to do the following:

1. Perform cross-checks on equipment
2. Help control stability/drift
3. Verify coefficients are correctly entered in our 4215 plus, C705P meter; 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 setting.
7. It can be used to set up a new indicator prior to system calibration.

Meter Substitution Conclusion

Morehouse is not the calibration police, and we are here to serve our customer's requirements best. Personally, I feel it is much better to calibrate everything as a system. I always strive to do what yields the lowest overall measurement uncertainty to limit the overall risk.

There is a risk/reward scenario for separately calibrating the indicator and load cells. There is a lot of additional work required to comply with either ISO 376 or the ASTM E74 standard. If that extra work saves time and money, it might be worth it. 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 not suitable for meter calibration following ISO 376, or ASTM E74, our budget simulator can save a lot of time when troubleshooting equipment and verifying 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 are constantly producing more content that relates to measurement errors, load cell design, and many other topics. If you are interested in learning more, subscribe to our newsletter and read our blog.

25. How To Calculate Measurement Uncertainty for Force

All calibration laboratories accredited by A2LA are required to submit uncertainty calculations for their Calibration and Measurement Capability (CMC) uncertainty claims included in the accreditation scope. If there are any assumptions made to determine the uncertainty budgets, they must be specified and documented. A2LA accredited calibration laboratories shall calculate measurement uncertainties using the method detailed in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM).[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 P14:01/2013 requires:
"5.1 The scope of accreditation of an accredited calibration laboratory shall include the calibration and measurement capability (CMC) expressed. in terms of:
a) measurand or reference material;
b) calibration/measurement method/procedure and/or type of instrument/material to be calibrated/measured;
c) measurement range and additional parameters where applicable, e.g., frequency of applied voltage;
d) uncertainty of measurement."[36]

A2LA R205 requires:
"6.3 Accredited Calibration Certificates
1) The laboratory shall meet the requirements of ILAC P14:01/2013 ILAC Policy for Uncertainty in Calibration section 6.1 to 6.5."
"6.8 Scopes of Accreditation
1) The laboratory shall meet the requirements of ILAC P14:01/2013 ILAC Policy for Uncertainty in Calibration section 5.1 to 5.4."[37]

Many people often ask, "How do I calculate Measurement Uncertainty for my force system?" It is indeed a great question, and the answer varies depending on several different factors. We can provide guidance for identifying all significant contributions to measurement uncertainty in the calibration of force-measuring instruments.

This document provides guidance for the evaluation of measurement uncertainty in the calibration of force-measuring instruments to support CMC in scope of accreditation, calibration certificates, or measurement reports.

Morehouse has several additional guidance documents and tools to make uncertainty calculation easy. You can these tools on our website.

Force-measuring instruments generally fall into two categories.

a) Force-measuring instruments for calibration of other force-measuring equipment.
   Note: Any calibration laboratory performing calibration to further disseminate the unit of force would fall into this category.
b) Force-measuring instruments for measurement of force.
   Note: The end 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:[38]
Calibration is required to ensure that the force measurement meets the needs of the user and achieves the required degree of uncertainty. The calibration of a force measurement system requires an understanding of traceability, standards, options, 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 which can reliably reproduce forces and can be compared to primary standards using a force transfer standard, which is a calibrated force transducer, 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 and generates a force on the support.	± 0.001%.	Primary or Secondary
Hydraulic amplification machines	A small deadweight machine applies a force to a piston-cylinder assembly and the pressure thus generated is applied to a larger piston-cylinder assembly.	± 0.02 %.	Secondary
Lever amplification machines	A small deadweight machine with a set of levers which amplify the force	± 0.02%.	Secondary
Strain-gauged hydraulic machines	The force applied to an instrument is reacted against by strain-gauged columns in the machine's framework.	± 0.05%.	Secondary
Reference force transducer machines	A force transfer standard is placed in series with the instrument to be calibrated (typically in a material testing machine).	± 0.05%.	Secondary

Guidelines for calculating CMC uncertainty.

Type A Uncertainty Contributions

The GUM states that all data that is analyzed statistically is treated as a Type A contribution with a normal statistical distribution.[39] 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:[40]

- 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:[41]

- 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, it is important that the end user of the force-measuring instrument is replicating how it was calibrated or that the laboratory performing the calibration is replicating how the instrument is going to be used. Fixturing and adapters used with the force-measuring instrument may have a significant contribution to the overall uncertainty of the force-measuring instrument.

Note 1: For the parameter of force, some laboratories have top-quality force calibration machines such as deadweight machines. These machines are classified as primary standards and if correctly designed some of the above error sources can be insignificant. 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. Resolution of a top-quality force-measuring instrument can be better than 1 ppm, if high-quality indicators reading six decimal places or more are used. It is also common to find reproducibility and repeatability between technicians to be insignificant. 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 adapter than was used for calibration
- Using different size adapters than what were used for calibration
- Loading against the threads instead of the shoulder
- Loading through the bottom threads in compression
- Temperature effects on non-compensated force-measuring instruments
- Temperature effect coefficients on zero and rated output
- Cable length errors on a 4-wire system
- Using electronic instruments (indicators) that were not used during calibration
- Using an excitation voltage that is different from the voltage used at the time of calibration
- Variations in bolting a force transducer to a base for calibration while application is different
- Not replicating via calibration how the equipment is being used
- Electronic cabling regarding shielding, proper grounding, use or non-use of sensing lines, cable length
- Failure to exercise the force-measuring instrument to the capacity it was calibrated at, prior to use
- Difference between the output of a high-quality force transducer when compared against the current machine and the realized value from the deadweight calibration

Specific Guidance

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

Force-measuring instruments calibrated in accordance with the ASTM E74 standard

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

The contributions for the CMC uncertainty are:

Type A Uncertainty Contributions

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

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

Type B Uncertainty Contributors

1. Resolution of the Best Existing Force-measuring instrument
2. Reference Standard Resolution (if applicable)
3. Reference Standard Uncertainty
4. Reference Standard Stability

5. Environmental Factors
6. Other Error Sources

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

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

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

1. Force-measuring instruments calibrated in accordance with the ASTM E74 standard are continuous reading force-measuring instruments and any uncertainty analysis should be conducted on several test points used throughout the loading range.
2. There are Excel spreadsheets available for calculating measurement uncertainty from various force calibration laboratories. If the spreadsheets are used, the laboratory should conduct validation of the spreadsheet templates.
3. The % Contribution Column is useful in determining significant contributors to uncertainty.

The Morehouse website has additional information for force-measuring instruments calibrated in accordance with 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 chooses to define its own 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, then use Static Error Band (SEB) or a combination of Non-Linearity and Hysteresis. If the force-measuring instrument is calibrated with an indicator and setup to have a tolerance, then it may not be necessary to include Non-Linearity, Hysteresis, or SEB.
   Note: If the force-measuring instrument is going to be used at points different from the points it was calibrated at, then SEB, Non-Linearity, or Hysteresis may need to be used.
8. Hysteresis: only if the force-measuring instrument is used to measure decreasing forces and SEB was not used.

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

Table 2: Example of a Single Point Uncertainty Analysis for a 10,000 FORCE UNITS Force-measuring Instrument with Not Calibrated to a Published Standard (Hysteresis was Included in yhe 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 for verification of a press or force application. They are not to be used to further disseminate the unit of force.

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

Measurement uncertainty in the measurement of force:

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

The Morehouse website has additional information for force-measuring instruments for measurement or verification of force and a spreadsheet tool.

Force-measuring instruments calibrated in accordance with the ISO 376 standard

Per EURAMET-cg-04 the evaluation of measurement uncertainty in calibrations of transducers per ISO 376 should account for the following uncertainty contributions in relative terms:[42]

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), which was calibrated per ISO 376. All uncertainty contributions should be combined, and the Welch-Satterthwaite equation should be used, to determine the effective degrees of freedom for the appropriate coverage factor for a 95 % confidence interval.

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

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

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

The Morehouse website has additional information for force-measuring instruments calibrated in accordance with the ISO 376 Standard and a spreadsheet tool.

26. 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. The expanded uncertainty shall be given to, at most, two significant digits, and proper rounding rules applies.
4. Contributions to uncertainty shall include relevant short-term contributions that can reasonably be attributed to the customer's device.
5. 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. Normally customers do their own 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

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

Enter Information and Data From Morehouse Certificate

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												
		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	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 166: 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 size 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 manufacturers' 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 167: 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)

In this example, we used our Fluke 8508 and our Deadweight Primary Standard.

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 168: 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 169: 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 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 %.

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 170: Expanded Uncertainty of 500 lbf Load Cell calibrated in accordance with the ASTM E74 Standard

Example 3: 500 lbf Load Cell

The load cell is calibrated in accordance with 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. The LLF can be thought of as the reproducibility of the load cell calibrated. I like to call it the expected performance of the load cell when used under the same conditions. As soon as conditions are changed, like using different adapters, different temperatures, different setups in machines that are not as plumb, level, square, rigid, and have low torsion as our deadweight machines, the results will change.

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 171: Individual Contributors for an ASTM E74 Calibration

In this example, we need to refer to our appendix for the ASTM E74 calibrations. We are calling out various inputs such as the uncertainty of the force applied, our multimeter, the resolution of the device at each force point, and the lower limit factor LLF. It is recommended to pair the load cell with an indicator and calibrate as a system.

It is possible that the expanded uncertainty reported might not contain contributions from the LLF. Morehouse follows ILAC-P14 and replicates the same practices that NIST uses in the calibration certificates appendix. 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 7: Expanded Uncertainty of 500 lbf Load Cell calibrated in accordance with 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 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 %.

27. Interlaboratory Comparison (ILC)

Many force calibration laboratories need help proving out 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 but it adds other quality control tools. The ISO/IEC 17025:2017 standard also made a significant change 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).

Contact Craig Glunt at 614-832-9142 or cglunt@sapphire-testing.com for more information.

Morehouse has two ILC rental kits available, 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 is used to establish an expected performance for each load cell.

Figure 172: ILC rental kit with 25K load cell and 4215 indicator

Figure 173: 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 the ASTM calibration has been performed and uncertainties established, 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 comes with adapters, a transportation case, cable, and 4215 indicators.

Once the end-user receives the ILC rental kit, they will perform their tests. If the rental kit will be used to help validate the system, then data will be sent with the system. If the end-user wants a formal report, then 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 174: 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 is trying to ensure the validity of their systems, then 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 be used to 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 2nd-day shipment, which would allow 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 along with 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 very 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

28. How to Gain Confidence in Your Measurements

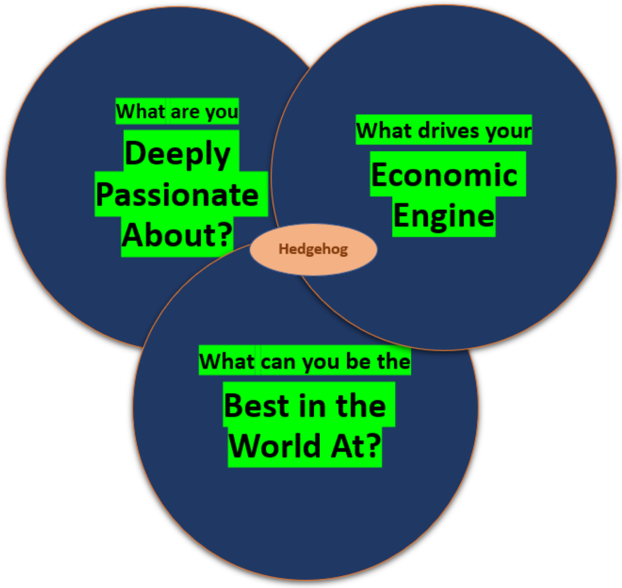


Figure 175: Hedgehog Concept

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, 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.

Proper understanding of the Hedgehog Concept is understanding what you can be the best at by aligning the three circles. Great companies understand this concept and good companies butcher it. Good companies understand that what they are good at will only make you good. Great companies that focus solely on what they can potentially do better than any other organization are on the path to greatness.

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 make sure 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.

Like being a great company, when these circles intersect, we can say our measurements are "Great" or better known to metrologists as measurement confidence. Morehouse has partnered with our good friend and ally in spreading great metrological practices Dilip Shah of E=mc3 Solutions to put together a 6-minute video better explaining these concepts. We realize everyone learns differently, so we encourage everyone to read this blog, watch the video, and then write an action plan.

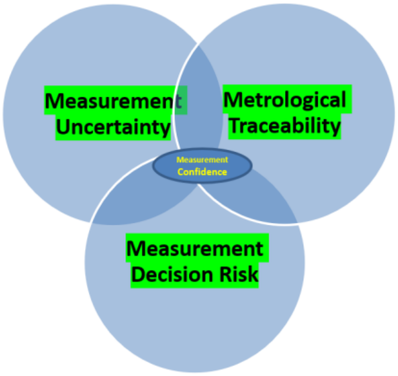


Figure 176: Measurement Confidence Concept

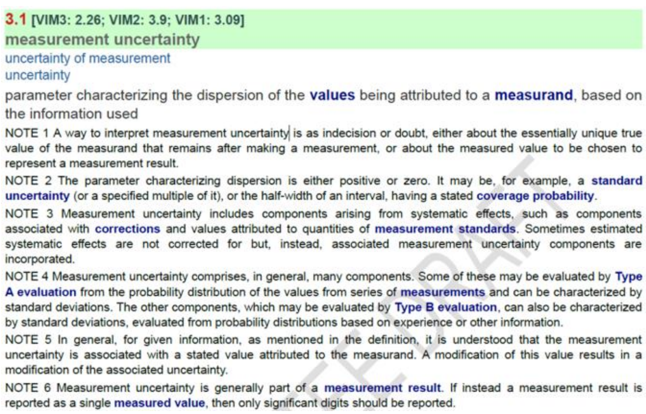
What is Measurement Confidence?

If you look around your office, a room in the house, or your company, you might see things like doors, windows, furniture, tables; you may be watching this on your cell phone, tablet, or computer. All of which are manufactured using measurements. Many of us take measurements for granted in our daily activities, such as powering on appliances like phones or coffee makers, and trusting weather forecasts without giving a thought. 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 that was 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 it fails, they likely may not have in place a system robust enough 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 177: 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."[43] Fig above 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 that are derived from a series of measurements typically 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."[44]
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.

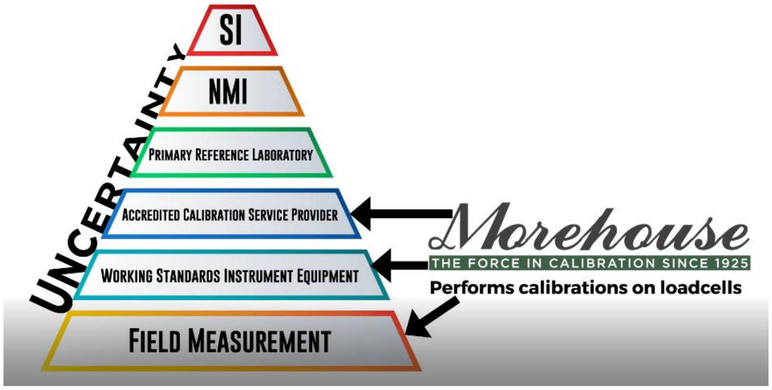


Figure 178: Measurement Pyramid

Morehouse performs calibrations on load cells for the three lower tiers, accredited calibration suppliers, followed by working standards, who in turn 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 easily park. This means you have more space, or range, to "pass" an instrument.

Figure 179: When the Uncertainty is small

However, when your uncertainty is larger, you have less room to park. This means you have less range, and sometimes no range at all, to "pass" an instrument.

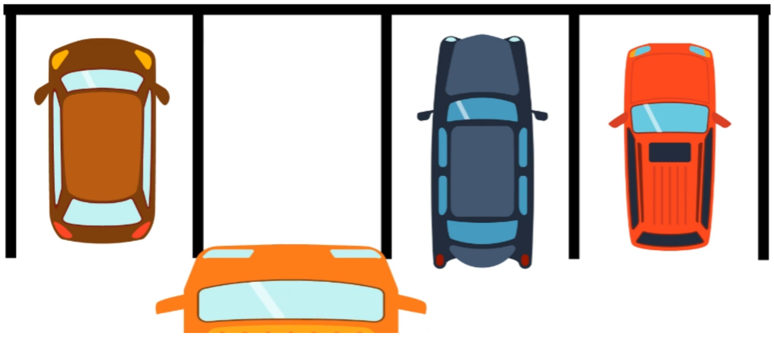


Figure 180 When the Uncertainty is large

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, and some standards recommend setting the limits, so a fail occurs if the total risk (Probability of False Accept - PFA) is larger than 2 %.

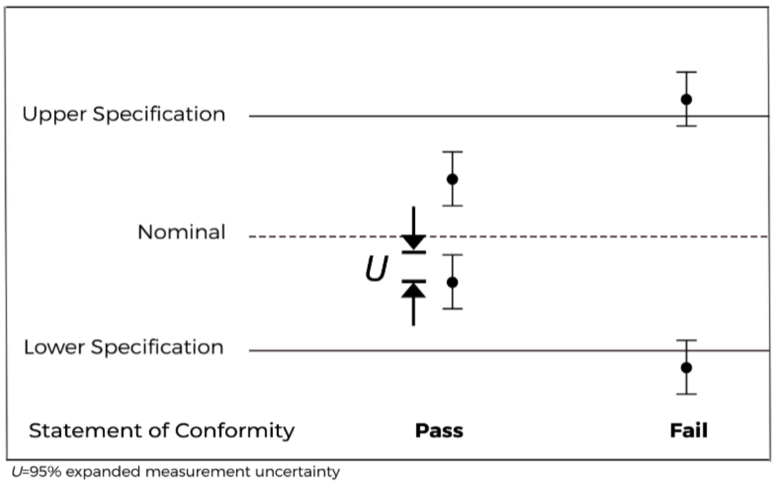


Figure 181: Statement of Conformity

ISO/IEC 17025:2017 states, “the laboratory shall document the decision rule employed, taking into account the level of risk.”[45] 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 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 182: 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 183: 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!

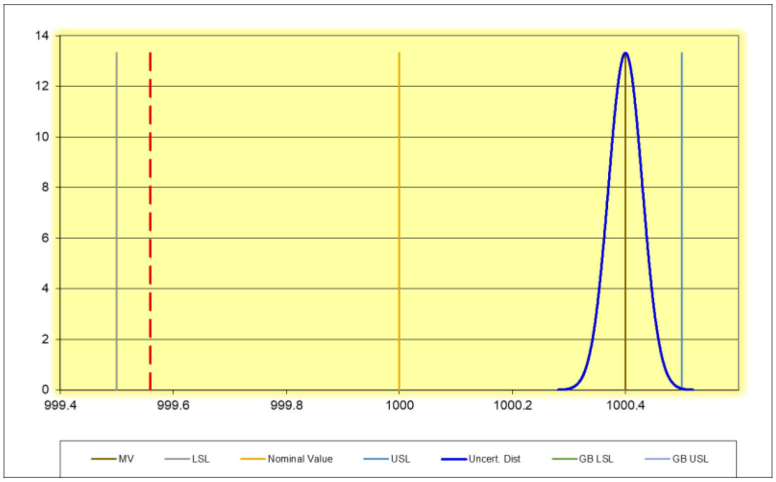


Figure 184: Small Uncertainty associated with a "Pass"

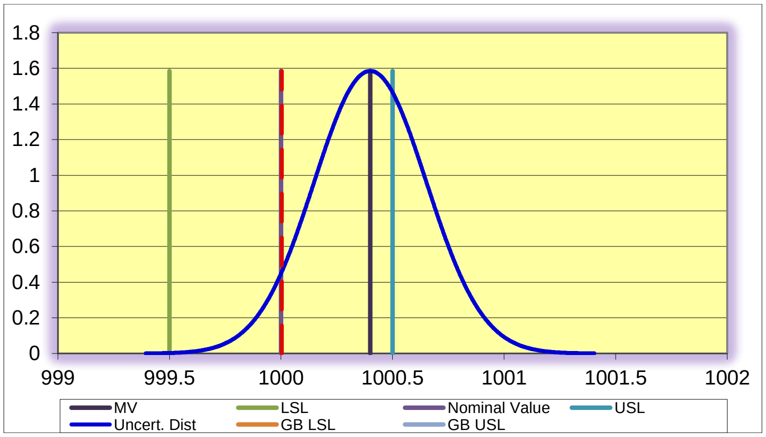


Figure 185: Large Uncertainty associated with a "Fail"

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 location of the measurement at 1000.4. The calculated calibration process uncertainty determines the width of the distribution.

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, such as 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.

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.

Measurement Confidence Action Plan

How confident are you with the measurements you are making?

Now that you have read the article and hopefully watched the video, 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 be thinking, 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 is calculating their Measurement Uncertainty? Might it be worthwhile to understand what you are getting from them?

The point is there is always something we miss.

29. Glossary of Terms

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

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

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

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

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 then multiplied by a coverage factor (k) of 2.4 and then multiplied by the average ratio of force to deflection from the calibration data. The LLF is a statistical estimate of the error in forces computed from the calibration equation of a force-measuring instrument when the instrument is calibrated in accordance with this practice.

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

Non-Linearity: The quality of a function that expresses a relationship that is not one of direct proportion. For force measurements, Non-Linearity is defined as the algebraic difference between the output at a specific load and the corresponding point on the straight line drawn between the outputs at minimum load and maximum load. Normally it is expressed in units of % of full scale. It is normally calculated between 40 - 60 % of full scale.[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. There will be additional errors in almost all cases if the end user fails to have the force-measuring instrument calibrated with the same adapters being used in their application. Other errors may include temperature change under no-load conditions. Errors from loading equipment not being level, square and rigid can have significant contributions.

Primary Standard: Per ASTM E74, a deadweight force is applied directly without intervening mechanisms such as levers, hydraulic multipliers, or the like whose mass has been determined by comparison with reference standards traceable to the International System of Units (SI) of mass. NOTE: Weights used for force measurement require the correction for the effects of local gravity and air buoyancy and must be adjusted to within 0.005 % of nominal force value. The uncertainty budget for primary standards also needs to consider possible force-generating mechanisms other than gravity and air buoyancy, including magnetic, electrostatic, and aerodynamic effects.

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

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

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

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

Measurement repeatability, Repeatability (JCGM 200:2012, VIM 2.21): Measurement precision under a set of repeatability conditions of measurement.

> 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. The purpose of this test is to determine the uncertainty of force generation in a force calibrating machine or test frame. For laboratories testing multiple ranges, it is recommended that the measurement sequence takes a point for every 10% of the ranges they calibrate.
>
> Example: A laboratory performing calibrations from 10 N through 10,000 N. The ranges calibrated may be 10 N - 100 N, 100 N - 1,000 N, and 1,000 N – 10,000 N. Recommended practice would be to take test points at 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, and 10,000 N.
>
> For this application, zero should never be considered as a first test point. A force-measuring instrument should not be used to calibrate other force-measuring instruments outside the range it was calibrated over. A force-measuring instrument calibrated from 10 % through 100 % of its range may not be capable of calibrating force-measuring instruments outside of this range.

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

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

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

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

> 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 from a best fit line through zero OUTPUT. It includes the effects of NON-LINEARITY, HYSTERESIS, and non-return to MINIMUM LOAD. Normally expressed in units of %FS.

30. Additional Information

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

Your time is valuable. Morehouse, thanks you for taking the time to read this document. We wish you the absolute best and are always here to help!

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

Subscribe to our YouTube Channel

Follow us on social media.

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

31. References

---

[1] Reprinted courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States.
[2] ISO 376, Annex A.4.1 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[3] ASTM E74-18 https://www.astm.org/Standards/E74.htm
[4] ASTM E74-18, Note 4 https://www.astm.org/Standards/E74.htm
[5] ISO 376 Section 7.4.3 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[6] EURAMET cg-4 section 6.2 Note https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-4__v_2.0_Uncertainty_of_Force_Measurements.pdf
[7] ASTM E74-18, section 11.2.2 https://www.astm.org/Standards/E74.htm
[8] ISO 376 Section 8.3.2 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[9] ASTM E74-18, section 13 https://www.astm.org/Standards/E74.htm
[10] ISO 376 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[11] ISO 376, Annex A.4.1 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[12] ISO 376 Section C.2.11 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[13] ISO 376, Annex A.4.1 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[14] VIM: International vocabulary of metrology 2.24 (3.7, Note 2) https://jcgm.bipm.org/vim/en/2.13.html
[15] ASTM E691 3.1.10 https://www.astm.org/Standards/E691
[16] ASTM E177 3.1.11 https://www.astm.org/Standards/E177.htm
[17] ASTM E177 3.1.12 https://www.astm.org/Standards/E177.htm
[18] ASTM E177 3.1.13 https://www.astm.org/Standards/E177.htm
[19] NASA-HDBK-8739.19-4 https://standards.nasa.gov/standard/nasa/nasa-hdbk-873919-4
[20] NASA-HDBK-8739.19-4 https://standards.nasa.gov/standard/nasa/nasa-hdbk-873919-4
[21] MSA 4th Edition https://www.aiag.org/store/publications/details?ProductCode=MSA-4
[22] MSA 4th Edition https://www.aiag.org/store/publications/details?ProductCode=MSA-4
[23] MSA 4th Edition https://www.aiag.org/store/publications/details?ProductCode=MSA-4
[24] VIM: International vocabulary of metrology https://jcgm.bipm.org/vim/en/2.13.html
[25] JCGM 200:2012 Section 4.2 https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf
[26] ISO/IEC 17025 Section 7.7.1 https://www.iso.org/standard/66912.html
[27] NCSLI RP-12, section 12.3 https://ncsli.org/store/viewproduct.aspx?id=16960491
[28] ASTM E74-18 section 13.1.12 https://www.astm.org/Standards/E74.htm
[29] ASTM E74-18 Section 7.1.2https://www.astm.org/Standards/E74.htm
[30] ISO 376 Section C.2.11 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[31] ISO 376 Section 3.1 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en
[32] ASTM E74-18 section 12.1.1 https://www.astm.org/Standards/E74.htm
[33] ASTM E74-18 section 12.1.3 https://www.astm.org/Standards/E74.htm
[34] NCSLI RP-12, section 12.3 https://ncsli.org/store/viewproduct.aspx?id=16960491
[35] ISO 17025:2017 https://www.iso.org/standard/66912.html
[36] ILAC P14:01/2013 https://ilac.org/publications-and-resources/ilac-policy-series/
[37] A2LA R205 https://a2la.qualtraxcloud.com/ShowDocument.aspx?ID=10221

[38] NPL Guide 102 https://www.npl.co.uk/resources/gpgs/all-gpgs
[39] ISO "Guide to the Expression of Uncertainty in Measurement" (GUM). https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6
[40] ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) section 4.3 https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6
[41] A2LA R205 https://a2la.qualtraxcloud.com/ShowDocument.aspx?ID=10221
[42] EURAMET-cg-04 https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-4__v_2.0_Uncertainty_of_Force_Measurements.pdf
[43] VIM, https://jcgm.bipm.org/vim/en/2.13.html
[44] VIM, https://jcgm.bipm.org/vim/en/2.13.html
[45] ISO/IEC 17025:2017, https://www.iso.org/standard/66912.html