Conditions, Methods, and Systems that Impact Force Calibration

Force Calibration Guidance for Technicians and Quality Managers

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1. Introduction

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 1: 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.

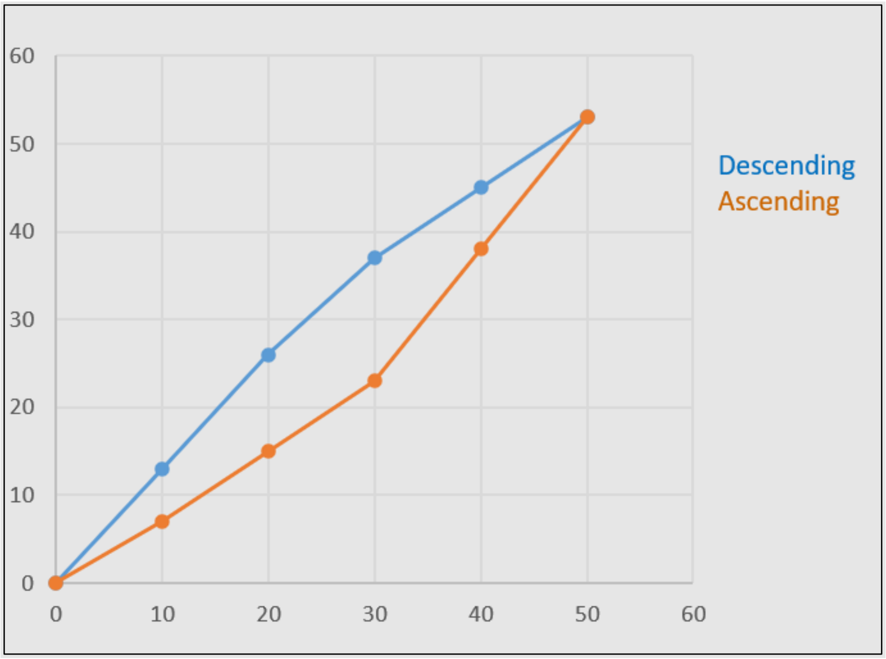


Figure 2: Descending Versus Ascending Calibration Curves

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 3: 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.[1]

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.”[2]

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

ASTM E74 Versus ISO 376

Morehouse has been performing ASTM E74 and ISO 376 calibrations for decades. We have followed the ASTM E74 standard since its 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." [3]

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.

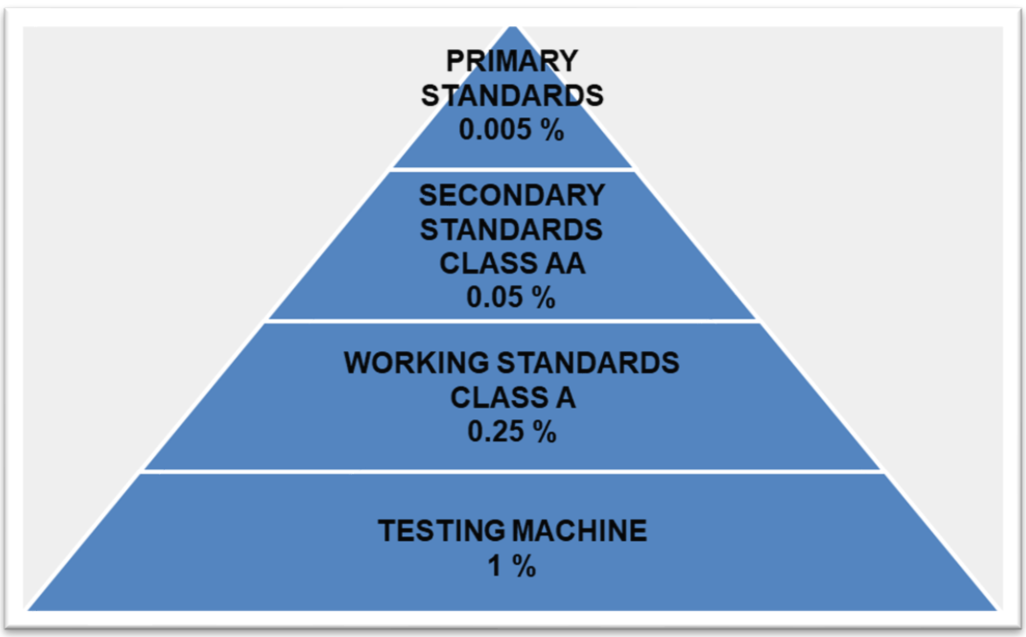


Figure 5: ASTM E74 Test Accuracy Ratio Pyramid

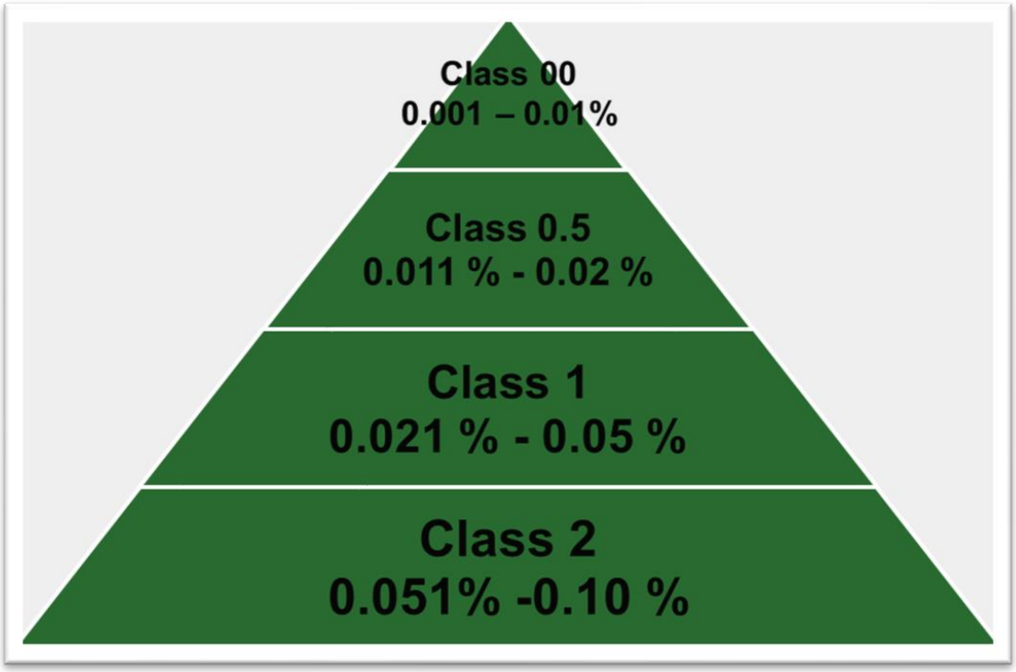


Figure 6: ISO 376 Expanded Uncertainty of Applied Calibration Force

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.

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

Figure 7: 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 8: 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."[4]

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.[5]

- ISO 376 allows for a maximum validity of the calibration certificate to not exceed 26 months (about 2 years).[6]

Reporting Criteria

ASTM E74 requires:[7]

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:[8]

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

Figure 10: 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 11: 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 12: 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.

Force Versus Mass

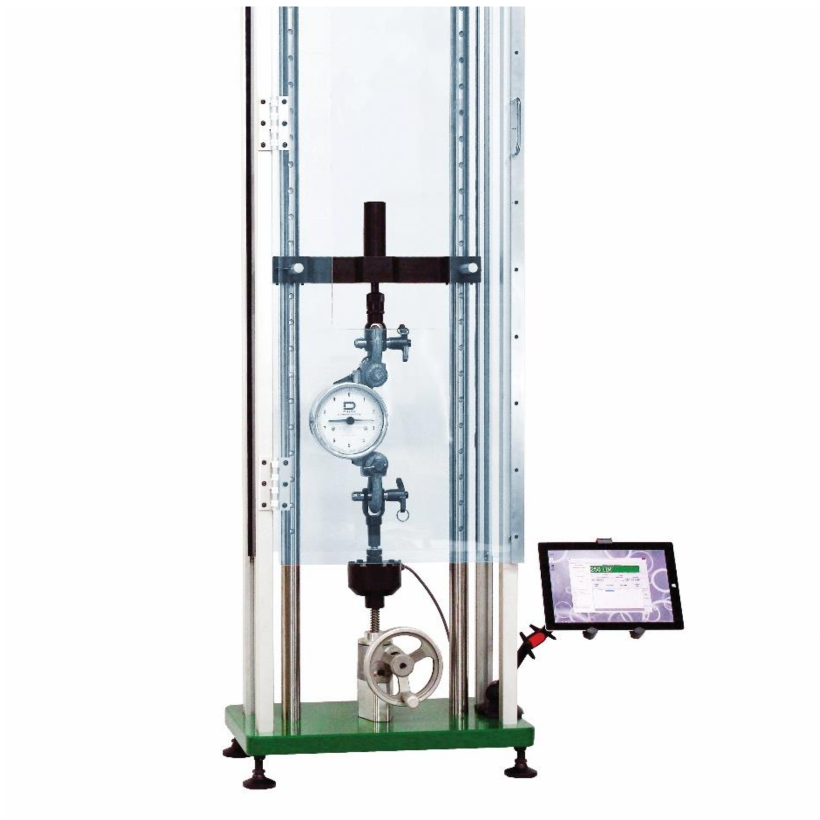


Figure 13: Morehouse Tensiometer

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 14: 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

2. 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 15 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).

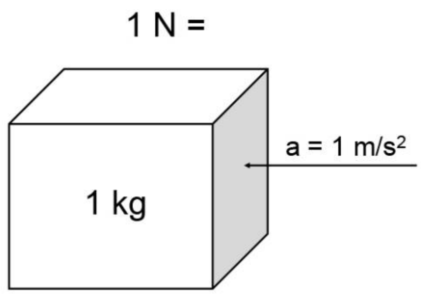


Figure 16 Force Units

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.

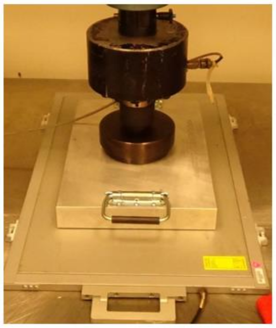
   Mass, under almost every terrestrial circumstance, is the measure of matter in an object. Measuring force takes additional factors into account: air density, material density, and gravity. It is the effect of gravity that can produce significant errors when comparing mass and force measurements. Gravity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

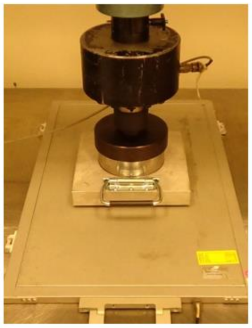
   A force measuring device calibrated in one location using mass weights then deployed somewhere else will produce different strains on the physical element. The resulting measurement errors can be significant. Correcting the difference in force and mass measurements is possible. When a device is adjusted 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 17 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.

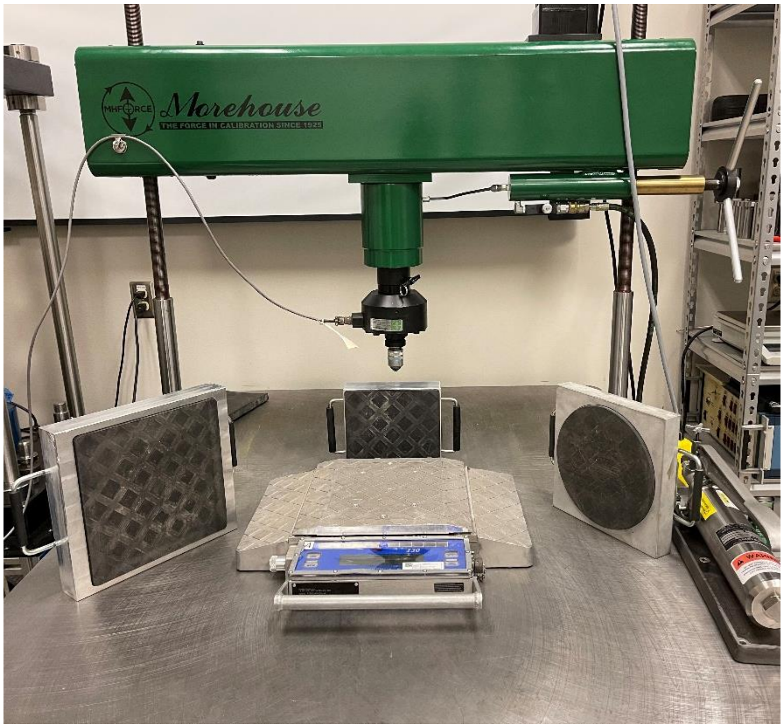


Figure 18 A Truck Scale Tested with 3 Different Size Adapters

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 19 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.

3. 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 20 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

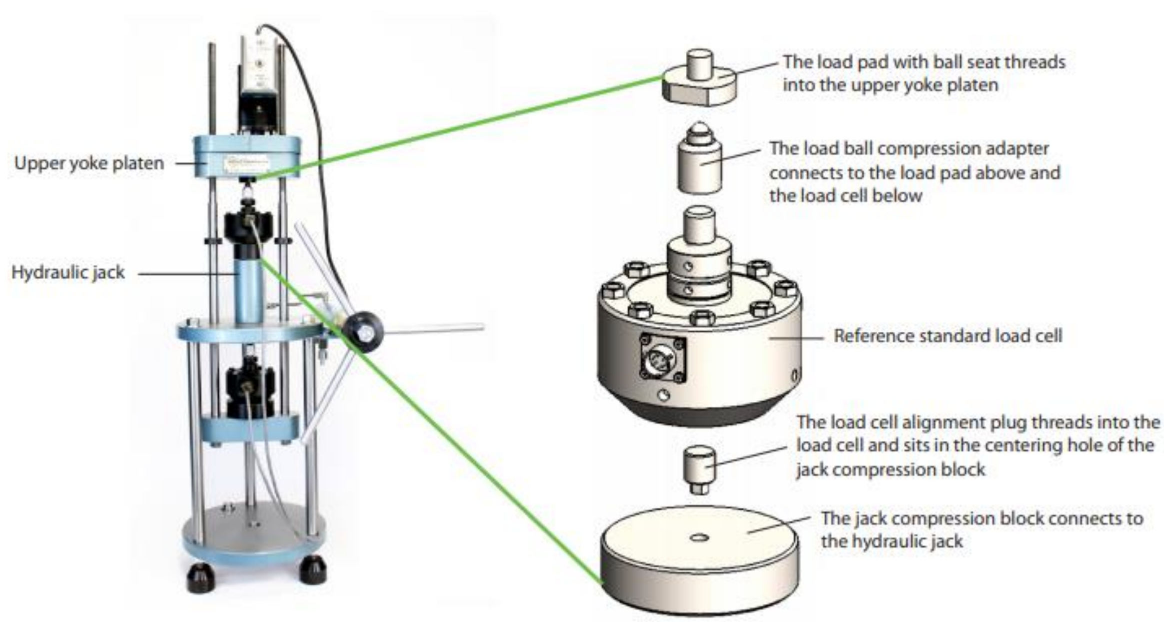


Figure 21 Morehouse Universal Calibrating Machine with a Compression Setup for the Unit Under Test

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 22 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 23 Morehouse Tension Adapters Designed Using Recommendations from ISO 376 [10]

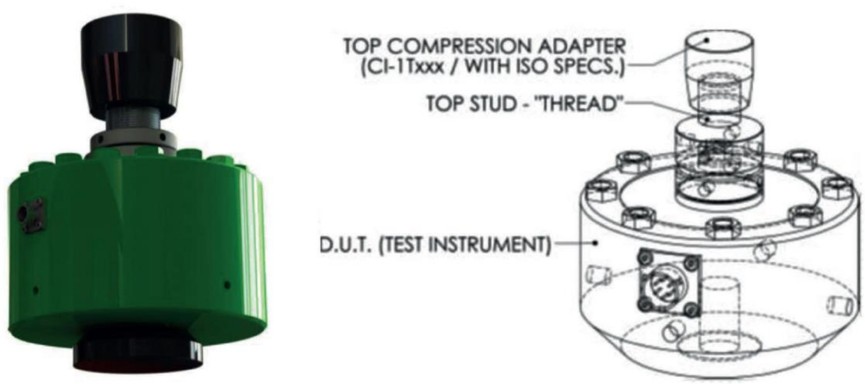


Figure 24 Morehouse Compression Adapters Designed Using Recommendations from ISO 376

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.”[9]

Figure 25 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."[10]

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:

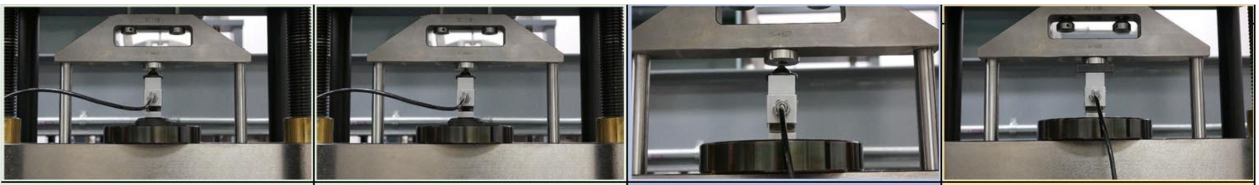
- The calibration laboratory should not perform compression and tension calibration in the same setup. This is a common practice because it is much quicker.
- They should use the customer's top blocks and use separate compression setups.
- In compression, the calibration laboratory should require a baseplate 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.

4. 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 26: 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.

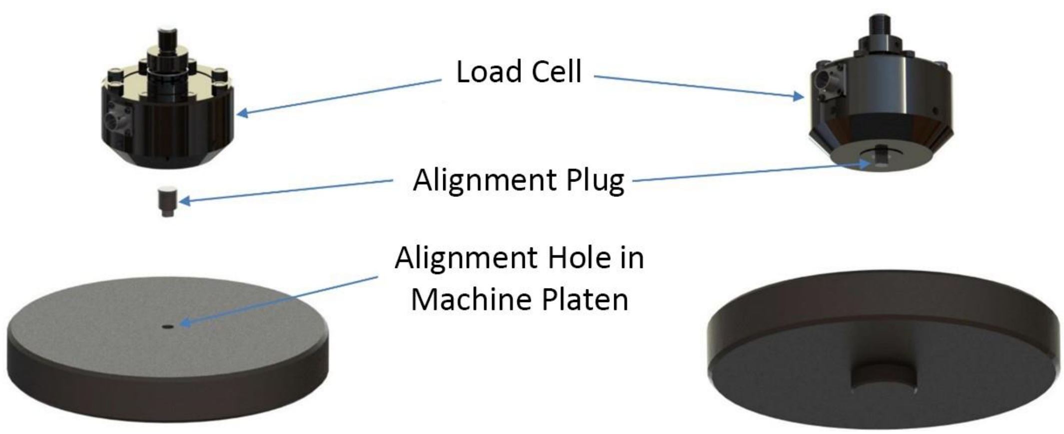


Figure 27: Morehouse Alignment Plug

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 28: 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 29: 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 30: 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.

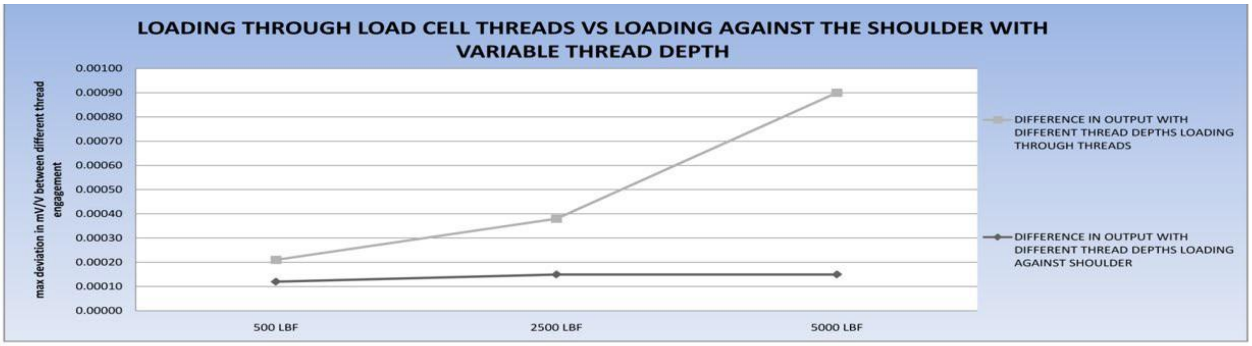


Figure 31: Graph Showing the Errors of Using Adapters with Different Thread Depths

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

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 33: 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.

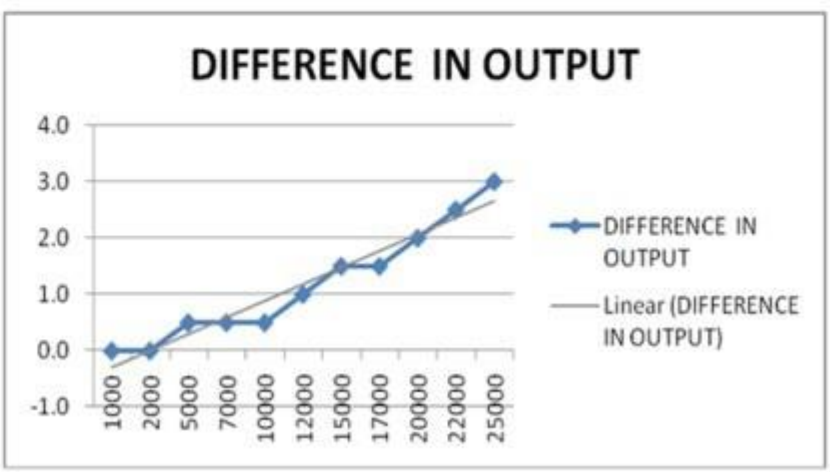


Figure 34: Graph Showing a 0.012 % by Varying the Loading Conditions

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.

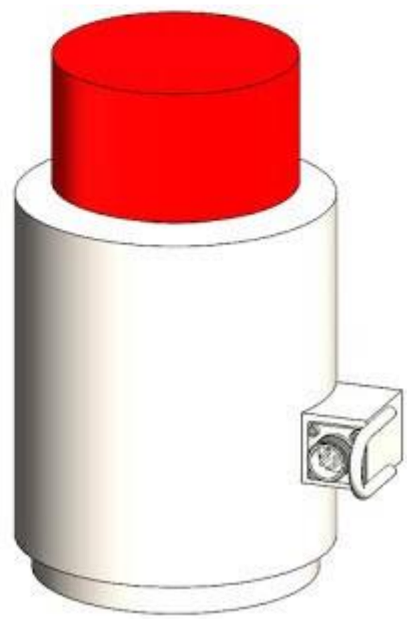


Figure 35: Multi-Column Load Cell

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.

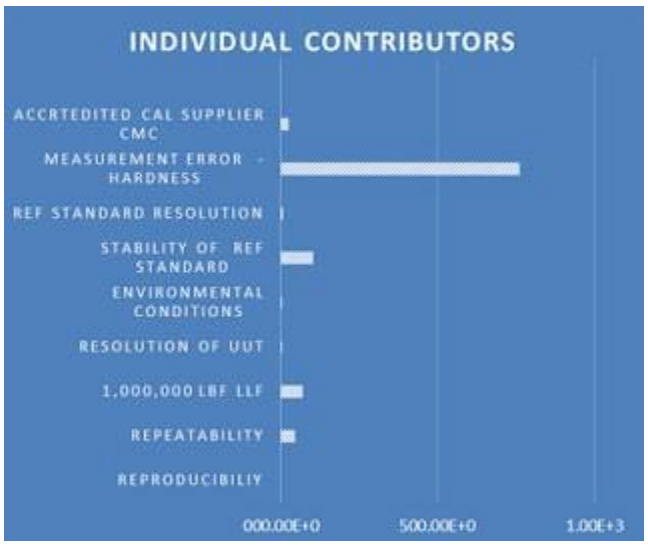


Figure 36: Individual Uncertainty Contributors

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.

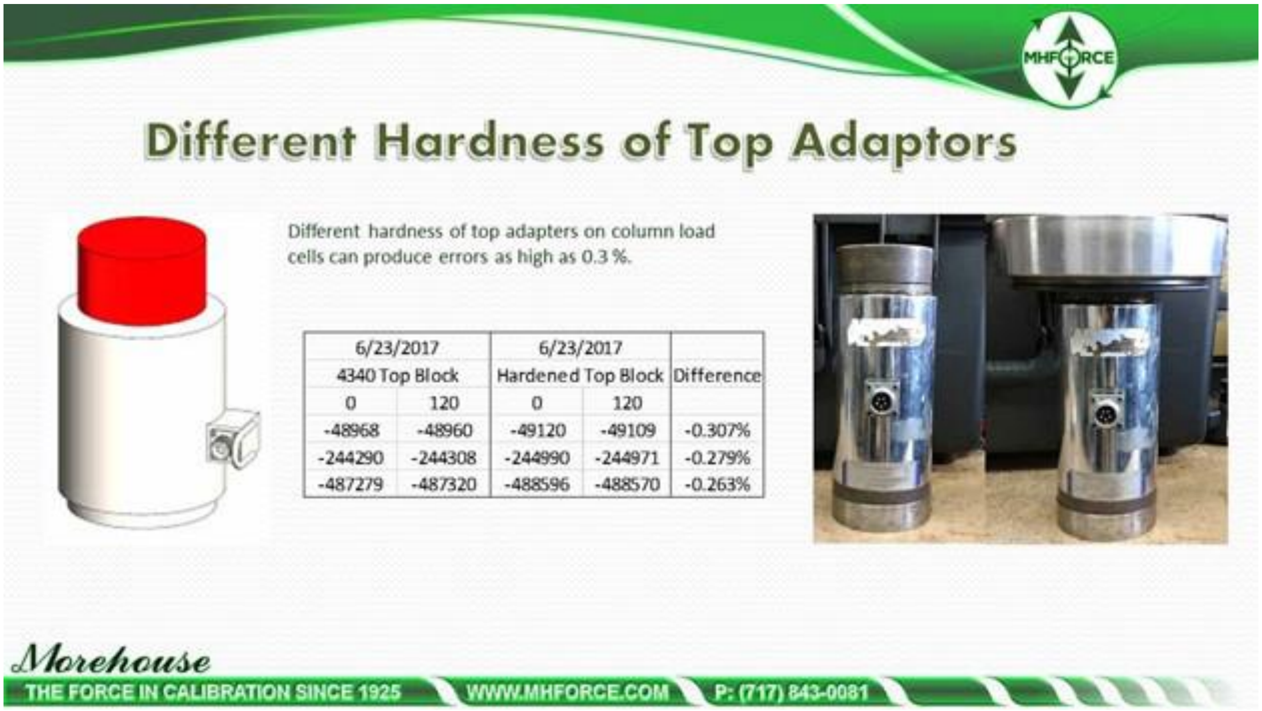


Figure 37: Different Hardness of Top Adapters

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.

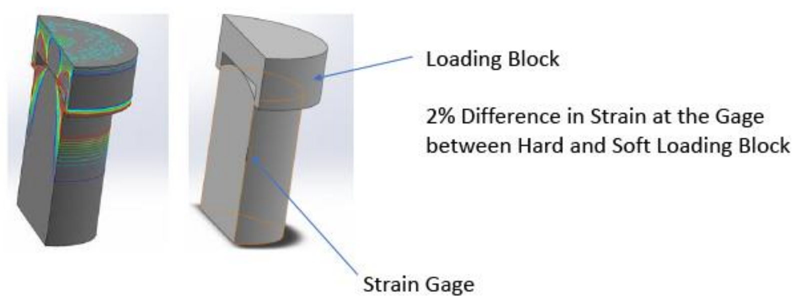


Figure 38: Effect of Loading Block on Column Type Load Cell

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 39: 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 40: 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 41: Multi-Column 300K Load Cell with a Non-Ground Base

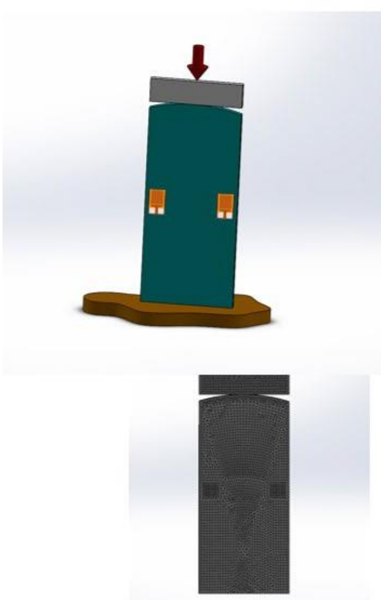
Installing a non-flat base on a multi-column cell can cause an error. The actual test results we observed on a multi-column cell are shown below. We received the load cell and tested it with the non-ground base attached to it. We set up the load cell in our 2,250,000 lbf force machine and exercised it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

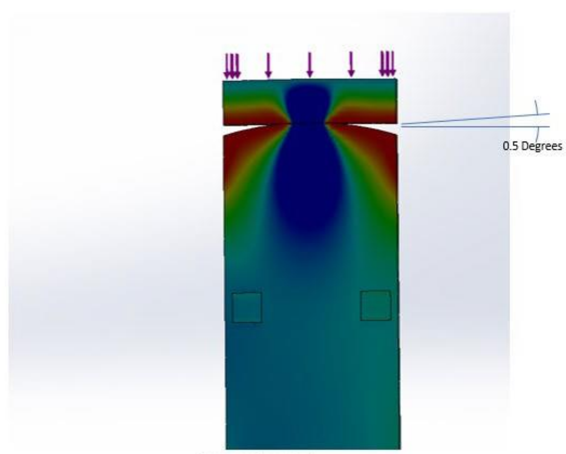
Figure 42: Shows Five Times the Measurement Error with a Non-Flat Base

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



Compress Stress (psi)

	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 43: 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.

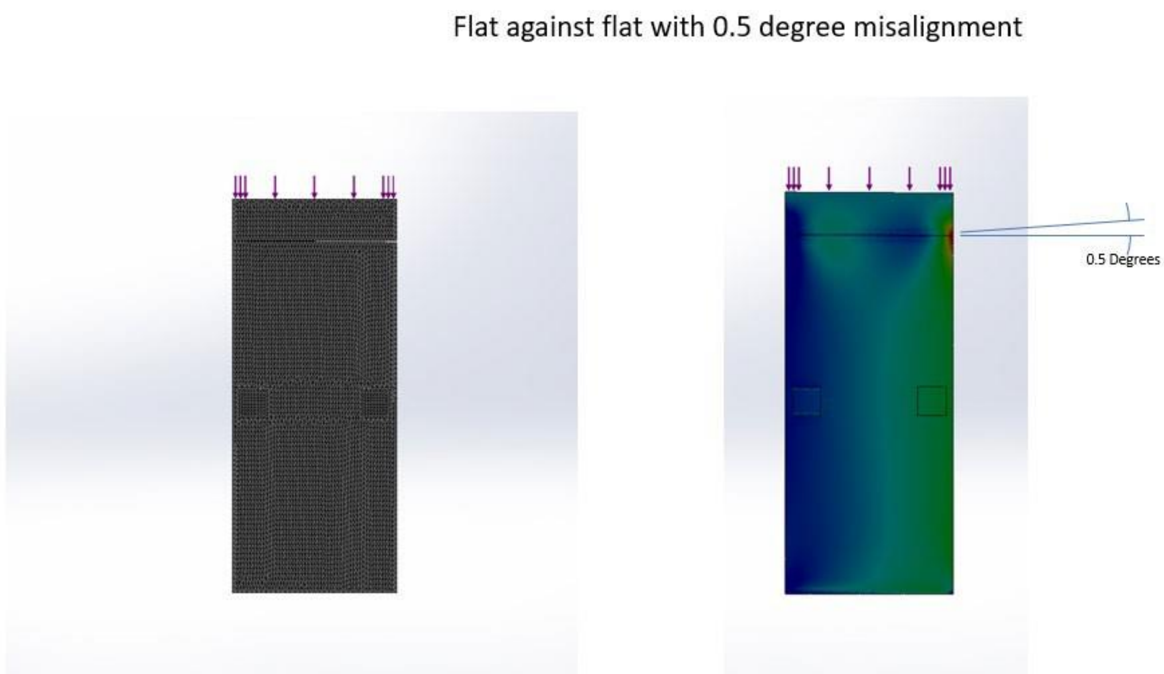


Figure 44: Stress Analysis with Flat Surface 0.5 Degree from Level

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.

5. 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 45: 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.

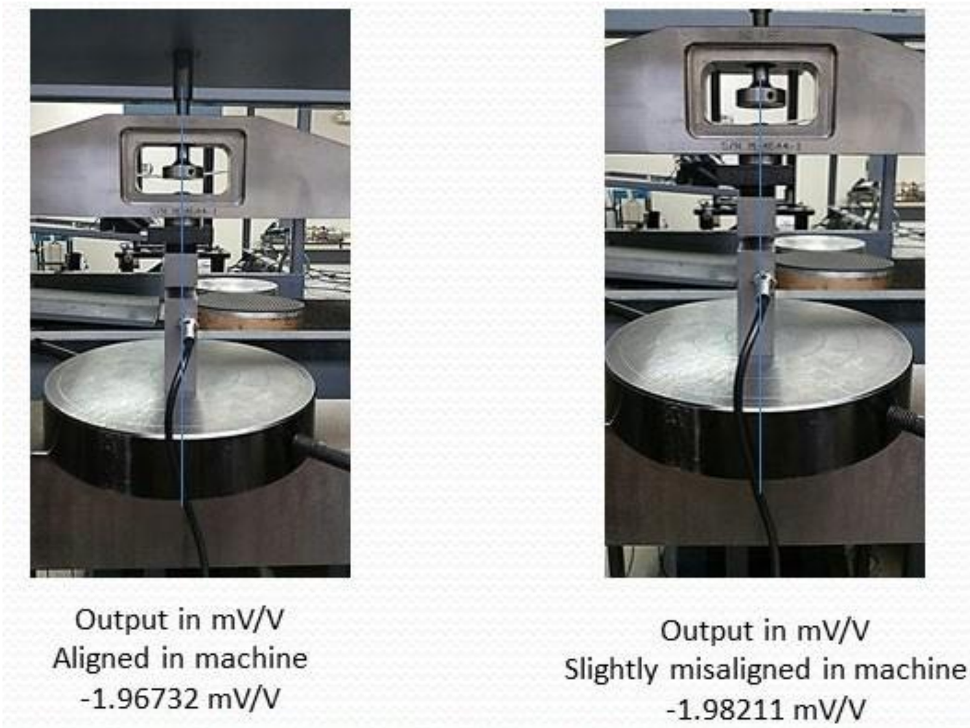


Figure 46: S-beam load cell with slight misalignment producing a 0.752 % error.

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.

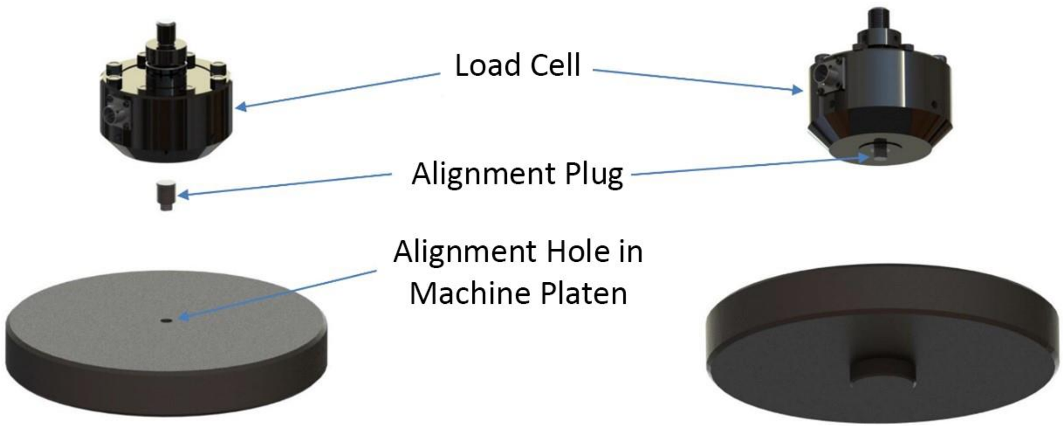


Figure 47: Morehouse Alignment Plug

Figure 48: Proper Way to Thread an Alignment Plug: Thread is Past Flush and Into Cell

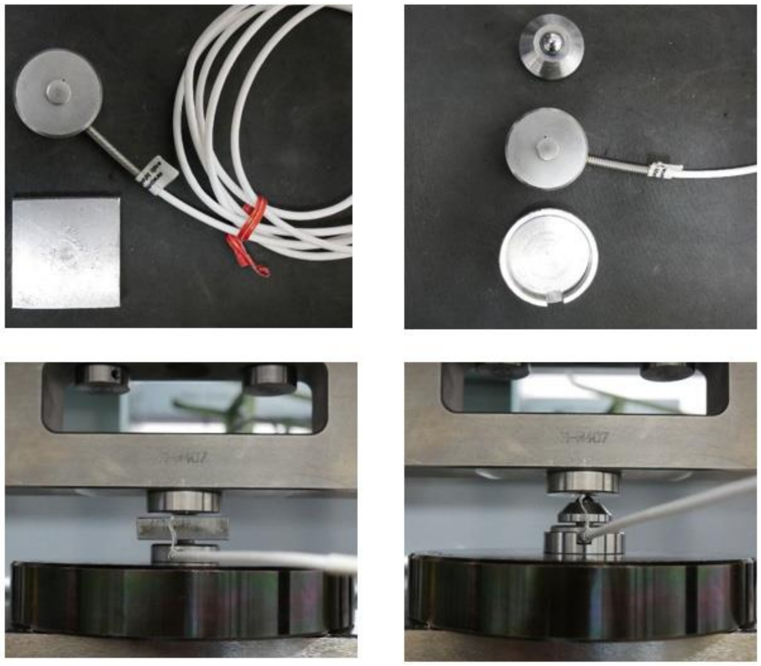
When using alignment plugs that thread into the bottom of your load cells, make sure they are threaded flush to the load cell's bottom. Once they are flush, thread the adapter an extra turn into the cell. Make sure that none of the threads are exposed below the load cell base. If one or more threads 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 49: Improper Way to Thread an Alignment Plug: Thread is Not Engaged Enough into the Load Cell

Figure 50: 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 51: 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 52: 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".[11]

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.

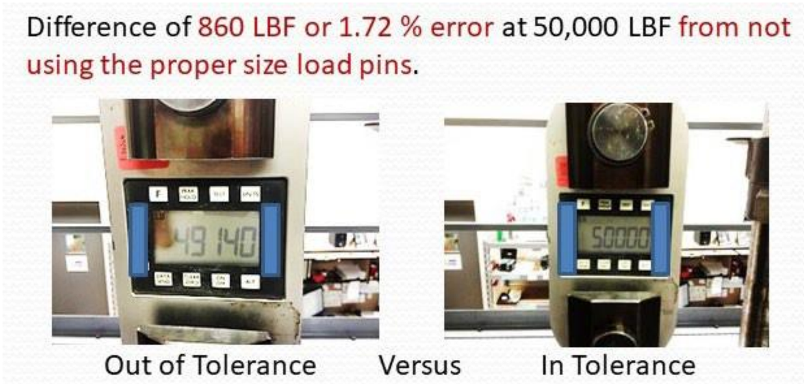


Figure 53: Tension Link Difference in Output with Pin Size

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 54: 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

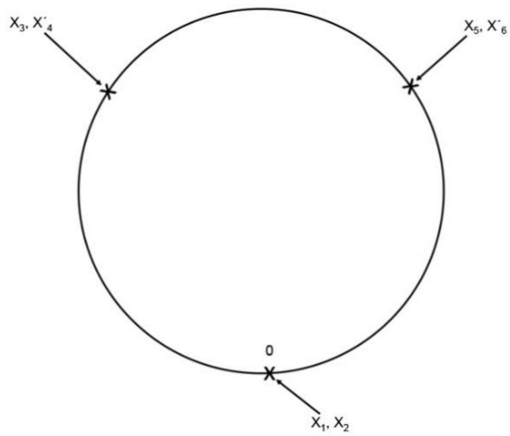


Figure 55: Diagram of Different Positional Tests at 120 Degrees Rotation

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 56: 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 [12]

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. [13]

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. [14]

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 %). [15]

Reproducibility standard deviation (sR), n—the standard deviation of test results obtained under reproducibility conditions. [16]

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. [17]

Then under error sources lists.

- Operator Bias (Reproducibility) - Error due to quasi-persistent bias in operator perception and/or technique. [18]

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. [19]

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.[20]

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.[21]

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 57: 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 58: 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 59: 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." [22]

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.

6. 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 60: 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.

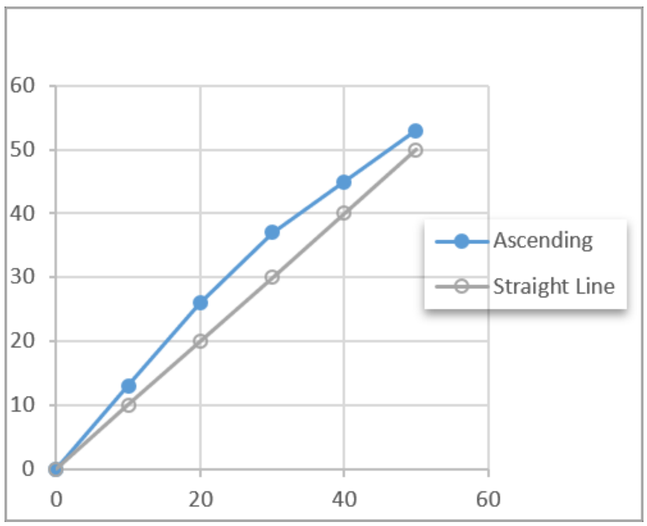


Figure 61: Load Cell Curve Versus a Straight Line

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 62: 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. [23]

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 63: Graph of a 3rd Order Least Squares Fit

Instead of using the equation for a straight line (y=mx+b), we have two formulas to solve for both force and response. These are:

Response (mV/V) = $A_0 + A_1(\text{Force}) + A_2(\text{Force})^2 + A_3(\text{Force})^{3,}$ and
Force (lbf) = $B_0 + B_1(\text{Response}) + B_2(\text{Response})_2 + B_3(\text{Response})^3$

When substituting these values with that in the equation shown on the line above, we are solving for Force when we know the Response; we would use $B_0 = 0.0614$, $B_1 = 2415$, $B_2 = -1.4436$, $B_3 = 0.17379$, so the formula becomes:

Force(lbf) = $0.0614 + 2415(\text{Response}) +-1.4436(\text{Response})^2 + 0.1379\ (\text{Response})^3$.

These are often called coefficients and are labeled as A0, A1, etc., and B0, B1, etc.; A0 or BO would determine the point at which the equation crosses the Y-intercept, while the other coefficients determine the curve.

Many force standards allow curve fitting of a 3rd degree and limit the maximum degree fit to a 5th degree. The most recognized legal metrology standards for using Coefficients are ASTM E74, primarily used in North America, and ISO 376, 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 64: 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%

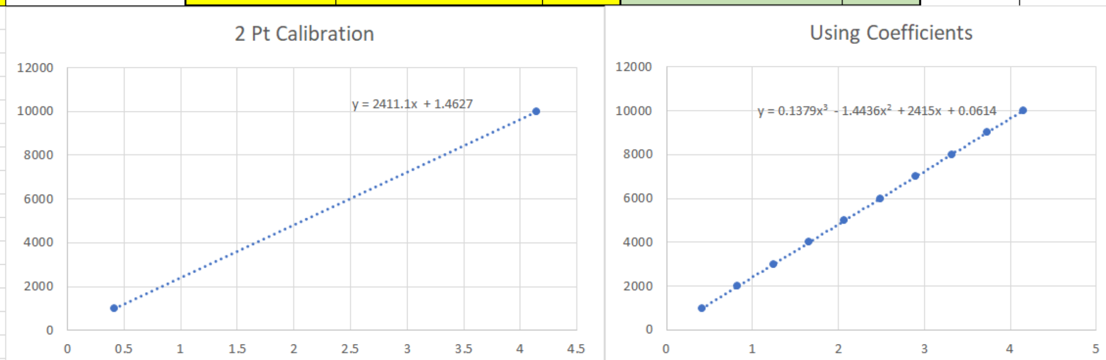


Figure 65: Difference Between 2-pt Span and Coefficients on the Same Load Cell

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 66: 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 67: 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 68: 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.”[24]

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.

Figure 69: 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."[25] 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

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 70 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 71 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 72 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 73 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 74: 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

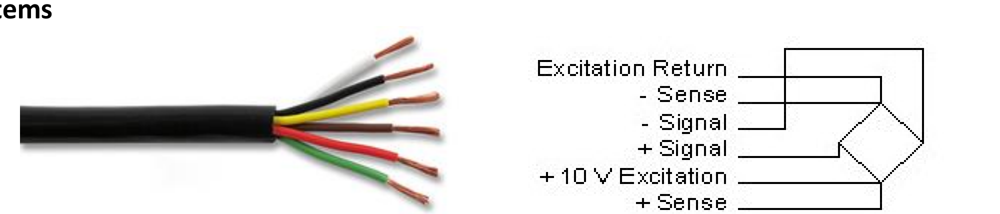


Figure 75: 6-Wire Cable and Diagram

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.

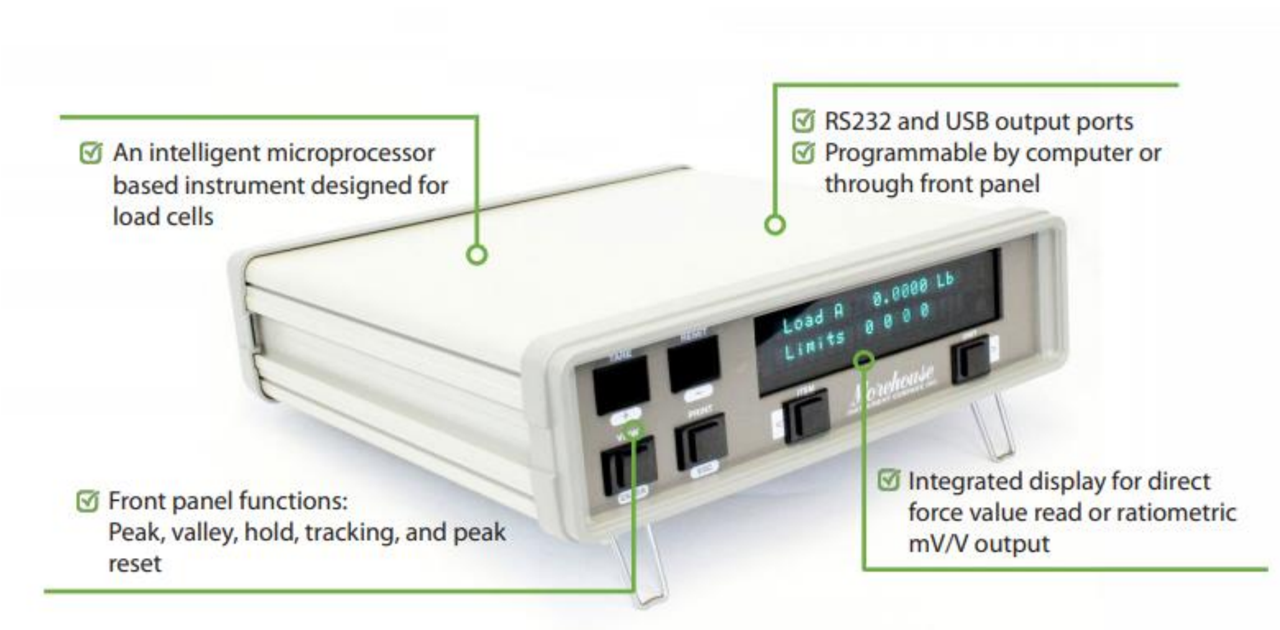


Figure 76: Morehouse 4215 Meter is a 6-Wire Sensing Indicator

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

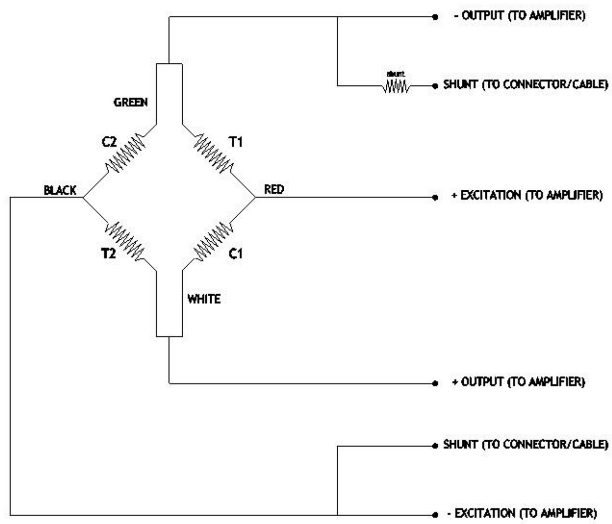


Figure 77: Load Cell Bridge with a Shunt Calibration

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."[26] 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 78: 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.

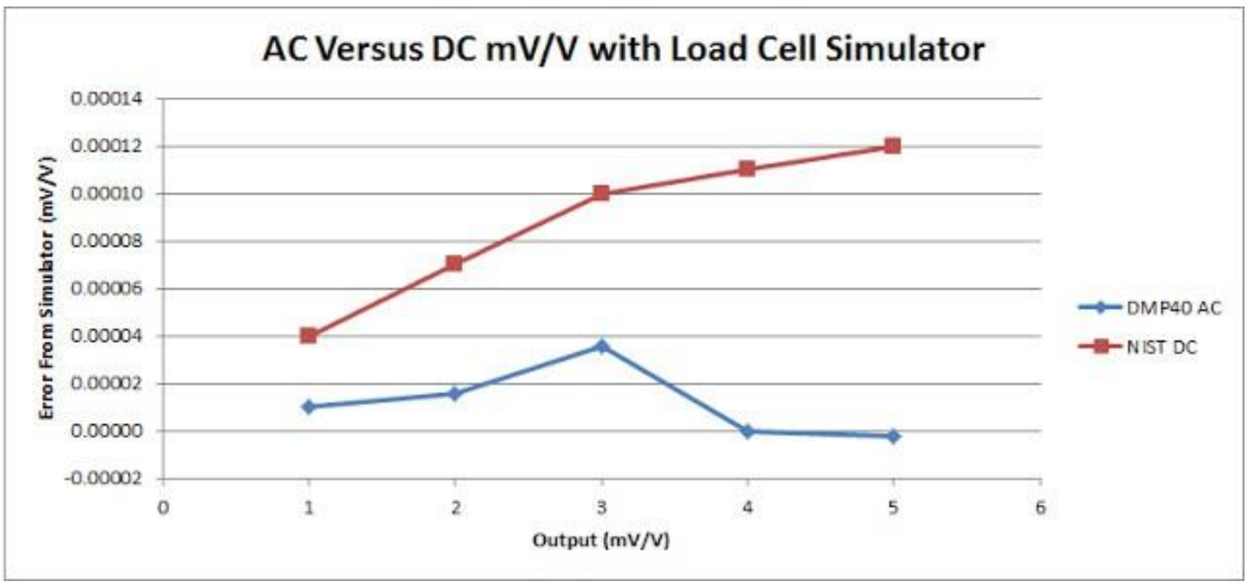


Figure 79: Graph of AC versus DC Indicator Data

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.

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.

7. 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).[27]

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.”[28]

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.”[29]

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."[30]

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:[31]
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.[32] 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:[33]

- 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:[34]

- 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:[35]

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.

8. 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.

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.

9. 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.

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