Morehouse
THE FORCE IN CALIBRATION SINCE 1925

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Mass to Force Guidance

Using mass weights not adjusted for Force can result in a large measurement error. The two major measurement parameters typically affected are Force and torque. Any measurement involving Force should use Force. There are acceptable formulas for correcting mass weights to force to enable companies who use Mass for these applications to apply known forces.

Saying one has accounted for the differences between Mass and Force in their uncertainty budget cannot be trusted unless they are using a relatively large number such as 0.539%. Why 0.539%, we cover that later in this document.

We created this guidance document to help reduce measurement errors associated with using mass weights for applications involving Force.

Please feel free to share it with anyone. The information is not proprietary and is given in the hope that, as a metrology community, we can stop bad practices and start making better measurements.

Mass to Force Guidance

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Introduction

Using mass weights not adjusted for Force can result in a large measurement error. The two major measurement parameters typically affected are Force and torque.

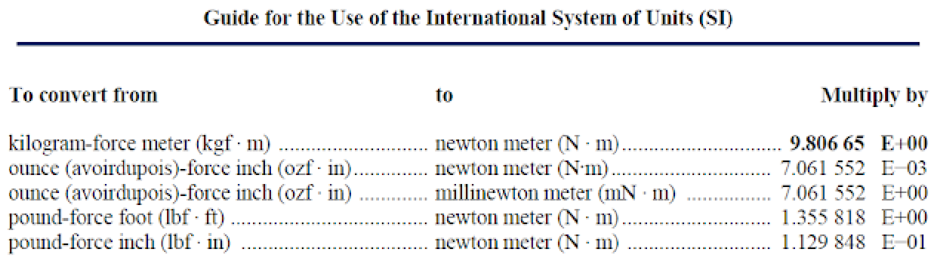
When a device is calibrated using weights corrected for Force, the device will measure Force without additional error for gravity correction, air density correction, and so on. Meaning if your device was calibrated using force units such as lbf, kgf, kN, N, and gf, then it can be used anywhere in the world to measure forces.

Both Force and torque share the same SI base units. These are Mass, time, and length.

According to the CIPM Resolution 2, the unit of Force [in the MKS (metre, kilogram, second) system] is the Force that gives to a mass of 1 kilogram an acceleration of 1 metre per second, per second. [1]

The definition of torque found in the SI-Brochure-9-EN is the cross-product of a position vector and a force vector. The SI unit is newton metre. Even though torque has the same dimension as energy (SI unit joule), the joule is never used for expressing torque. [2]

Thus, our definition of torque is force times length. It is not mass times length. In discussions with many professionals and manufacturers of torque equipment, we have found that some labs use mass weights at the end of a torque arm and claim they are applying torque.



Guide for the Use of the International System of Units (SI)

To convert from	to	Multiply by	
kilogram-force meter (kgf · m)	newton meter (N · m)	**9.806 65**	**E+00**
ounce (avoirdupois)-force inch (ozf · in)	newton meter (N·m)	7.061 552	E−03
ounce (avoirdupois)-force inch (ozf · in)	millinewton meter (mN · m)	7.061 552	E+00
pound-force foot (lbf · ft)	newton meter (N · m)	1.355 818	E+00
pound-force inch (lbf · in)	newton meter (N · m)	1.129 848	E−01

Figure 1 SI Brochure Conversion Showing Torque is Force times Length.

The Reason Not Correcting Mass for Force Matters

Because using mass weights not adjusted for Force can result in a large measurement error should be reason enough to correct it, right?

Well, you would hope so as labs should not want to understate their uncertainties.

If someone is using Mass for force applications, they are not only likely understating their uncertainty, but also, it’s likely they have a lot of bias that is being ignored.

This matters because when a known bias is ignored (i.e., not corrected), measurement traceability may not be fully achieved, and all subsequent measurements will be suspect.

When this happens, it’s highly likely that several deficiencies will need to be cited.

These might include:

- Equipment and reference measurement standards that must be calibrated do not have calibration records for the parameter using Force. (They likely have mass certificates, which then would require them to know the uncertainty due to material density, air buoyancy, and gravity.) All of which could then be cited separately. (7.5.1)
- When calibration and reference material data include reference values or correction factors, the laboratory shall ensure the reference values and correction factors are updated and implemented, as appropriate, to meet specified requirements. (6.4.11)
- The CMC uncertainty will not properly account for all contributors, specifically significant contributors that apply to the measurement. (ILAC P-14)
- Possible citation of procedures if the lab does not have criteria for evaluating the necessary corrections. (7.10.1)
- Communication with the customer about statements of conformity, specifically getting agreement on the potential risk of using Mass instead of Force. (7.1.1 d)
- Metrological traceability is not evaluated properly as the measurement uncertainty for each step in the traceability chain is evaluated according to agreed methods. (6.4.6)
- The systematic measurement error (sometimes called "bias") of the calibrated equipment is not taken into account when disseminating metrological traceability. (7.2.2.3)

Conformity Assessment Using Mass and Not Force

Making a conformity assessment of "in tolerance" is all about location, location, and location of the measurement. It's also about the uncertainty of the measurement because anything other than a nominal measurement will significantly raise the risk associated with the probability of false accept (PFA).

The probability of a false accept is the likelihood of a lab calling a measurement "in tolerance" when it is not. PFA is also commonly referred to as consumers risk (β: Type II Error).

The measurement location we are referring to is how close the measurement is to the nominal value. If the nominal value is 10 000.0 lbf and the reference lab uses lb, a correction would need to be applied to convert the mass value to force. This is further complicated in that Mass used for a measurement in one location, would need to be corrected at the location of actual use.

The higher the measurement bias is from the nominal, the higher the measurement uncertainty of subsequent measurements unless the measurement bias is corrected. If the unit under test becomes the reference standard, and the measurement bias is not corrected, future measurements made with that reference standard will introduce additional measurement risk not accounted for in the reported measurement uncertainty.

It gets worse when a decision rule involving TUR is agreed upon with the customer because using mass weights for force applications always introduces biases. And when biases are not corrected, the reference lab's reported values will not be centered. Not only will metrological traceability not be achieved, but the reference laboratory will also introduce additional biases, causing the conformity assessment to be made incorrectly.

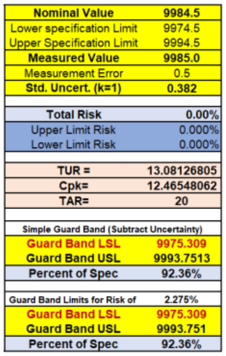
Introduction to Statistics in Metrology addresses bias (measurement bias) in section 5.2 by stating, "There are important assumptions associated with using TUR as a metric and the requirement of a TUR of 4 or 10. Using a TUR assumes that all measurement biases have been removed from the measurement process and the measurements involved follow a normal distribution. If there are significant biases that cannot be removed, the TUR will not account for the increased risk." [1]

When the process distribution is centered between the specification limits and does not overstate or understate the nominal value of the measurement, higher TURs produce wider acceptance limits. In comparison, lower TURs, such as 1:1, will reduce acceptance limits.

JCGM 106 references that when a measuring system is used in conformity assessment, the measuring system has been corrected for all recognized significant systematic errors (bias). [2]

When we do not correct for bias, measurement uncertainty might be underestimated, and therefore may not align with the definition of metrological traceability, undermining measurement confidence.

Metrological traceability is defined in JCGM 200:2012 as "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty." [3]



Nominal Value	**9984.5**
Lower specification Limit	9974.5
Upper Specification Limit	9994.5
Measured Value	**9985.0**
Measurement Error	0.5
Std. Uncert. (k=1)	**0.382**
Total Risk	**0.00%**
Upper Limit Risk	0.000%
Lower Limit Risk	0.000%
TUR =	**13.08126805**
Cpk=	**12.46548062**
TAR=	**20**
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	**9975.309**
Guard Band USL	**9993.7513**
Percent of Spec	**92.36%**
Guard Band Limits for Risk of	**2.275%**
Guard Band LSL	**9975.309**
Guard Band USL	**9993.751**
Percent of Spec	**92.36%**

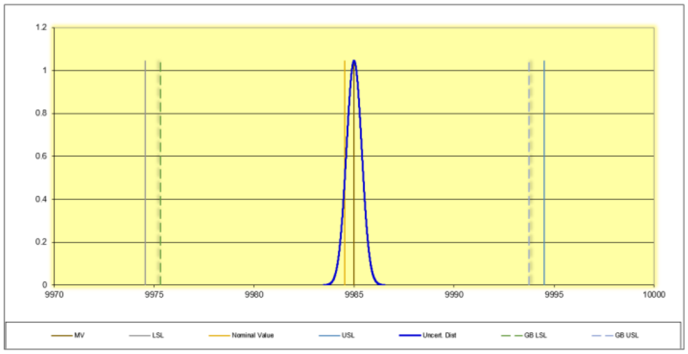
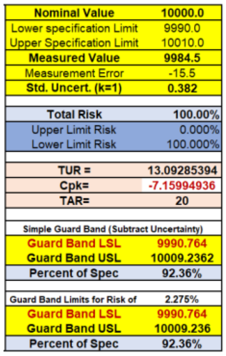


Figure 2 10 000 lbf calibration on a 0.1 % device with Mass converted to **Force** correctly.



Nominal Value	**10000.0**
Lower specification Limit	9990.0
Upper Specification Limit	10010.0
Measured Value	**9984.5**
Measurement Error	-15.5
Std. Uncert. (k=1)	**0.382**
Total Risk	**100.00%**
Upper Limit Risk	0.000%
Lower Limit Risk	100.000%
TUR =	**13.09285394**
Cpk=	**-7.15994936**
TAR=	**20**
Simple Guard Band (Subtract Uncertainty)	
Guard Band LSL	**9990.764**
Guard Band USL	**10009.2362**
Percent of Spec	**92.36%**
Guard Band Limits for Risk of	**2.275%**
Guard Band LSL	**9990.764**
Guard Band USL	**10009.236**
Percent of Spec	**92.36%**

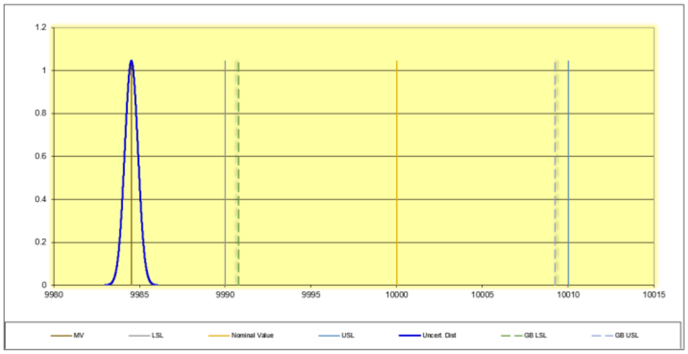


Figure 3 10 000 lbf calibration when 10 000 lb of **Mass** is used and not Force.

Figures 2 & 3 demonstrate what happens when Mass is used instead of Force. When we key in a gravity of 9.792980 m/s^2, air density of 0.001225 g/cm^3, and a material density for the masses of 8.0000 g/cm^3, we can show that 10 000 lb of Mass at this location equates to a force value of 9984.5314 lbf. Figure 2 shows what happens when 9984.5314 lbf is applied to our 0.1% accuracy device. The measurement risk is insignificant. However, when Mass is applied, and the lab claims 10 000 lbf, and not 9 984.5314 lbf, the risk jumps to 100% as the **measurement error in this scenario is above 15 lbf on a device with a tolerance of ± 10 lbf. The risk passed to the end-user is 100%, and the submitted device was likely found out of tolerance (OOT) and adjusted to the wrong value.**

The Difference Between Force and Mass

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. The effect of gravity can produce significant errors when comparing mass and force measurements.

Gravity is not constant over the surface of the Earth. The most extreme difference is 0.539% between the poles and the equator (983.2 cm/s2 at the former compared to 978.0 cm/s2 at the latter). A force or torque measuring device calibrated in one location using mass weights and then deployed somewhere else will produce different physical elements, and the resulting measurement errors can be significant.

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). At Morehouse in York, Pennsylvania, the gravitational constant is 9.801158 m/s2. The gravity of Houston, TX, is 9.79298 m/s2. If we compare the difference in gravity, ((9.79298 m/s2 - 9.801158 m/s2) / 9.79298 m/s2); we get a percentage difference of -0.084%.

So, if a lab in Houston calibrated a force or torque measuring device with mass weights for use at a different location, say York, PA, we could expect anything we weigh to be heavier by 0.084%. Not correcting for the differences between gravity can have many consequences. If we were shipping steel by tonnage, we would ship less steel, reducing our cost and upsetting our customers. If a steel supplier in Houston uses a scale calibrated in York with mass weights without correction, they will ship more steel per ton.

Note that dynamometers, crane scales, tension links, handheld force gauges, and 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 one ton through 300 tons, so having the mass weights necessary to calibrate on-site is impractical. Therefore, calibrating using Force may be the only practical method to certify these types of devices.

Mass Definitions and Conversions

M = True mass of the artifact. The term "mass" is always used in the strict Newtonian sense as a property intrinsic to matter. This property is sometimes referred to as "true mass" or "mass in a vacuum" to distinguish it from the conventional (apparent) mass.

CM = Conventional mass of the artifact. The conventional mass is defined as the mass of material of a specified density that would exactly balance the unknown object if the weighing were carried out at a temperature of 20°C in air of density 0.0012 g/cm3.

Density, Conversions, & Gravity

Air Density is typically in the range of 0.0011 g/cm3 to 0.0012 g/cm3.

Equal Conversions: 0.0012 g/cm3 = 1.2 kg/m3 = 1.2 mg/cm3

Stainless steel weights (mass reference standards) typically have a material density in the range of 7.85 g/cm3 to 8.03 g/cm3.

Equal Conversions: 8.0 g/cm3 = 8000 kg/m3 = 8000 mg/cm3

Cast iron weights (mass reference standards) typically have a material density close to 7.2 g/cm3.

Equal Conversions: 7.2 g/cm3 = 7200 kg/m3 = 7200 mg/cm3

By international convention (recommendation), weight calibration certificates typically report conventional mass values and/or conventional mass corrections.

Formulas for Converting Mass to True Mass and True Mass to Conventional Mass

Generic Mass Equations

The formula for CM is:

$$CM_x = \frac{M_x\left(1 - \dfrac{0.0012\ {}^{g}\!/_{cm^3}}{\rho_x}\right)}{\left(1 - \dfrac{0.0012\ {}^{g}\!/_{cm^3}}{8.0\ {}^{g}\!/_{cm^3}}\right)}$$

The formula for true Mass is:

$$M_x = \frac{CM_x\left(1 - \dfrac{0.0012\ {}^{g}\!/_{cm^3}}{8.0\ {}^{g}\!/_{cm^3}}\right)}{\left(1 - \dfrac{0.0012\ {}^{g}\!/_{cm^3}}{\rho_x}\right)}$$

Converting Mass to Force

The Mass of a body relates to the amount of material it contains.

Forces are defined by Newton's second law of motion as expressed in the equation:

force = mass x acceleration, or F = ma

"Since it is impractical to make an accurate determination of force directly from this equation — at least as a routine procedure — it is customary to establish force standards directly from the attraction of the earth on known masses." - D.R. Tate, a scientist at NIST

The formula to determine the Mass needed to obtain the required Force is as follows:

$$M = \left(\frac{9.80665}{g}\right) \times \left(\frac{D}{D-d}\right) \times F$$

Where:

m = Mass of the weight (true Mass)

g = gravity at a fixed location, m/s2. The Force that attracts a body toward the center of the Earth, or toward any other physical body having Mass. Newton's laws of gravity apply for most purposes, with minor modifications to consider the general theory of relativity.

It’s very important to establish the gravity value for the location where the weight is to be used.

Note: Not using the correct gravity for the location will result in significant errors.

d = air density – mass per unit volume of air (kg/m^3)
D = material density – A quantitative expression of the amount of mass contained per unit volume. The standard unit is the kilogram per meter cubed (kg/m^3).
F= force
Note: Air buoyancy – an upward force exerted by pressure in air that opposes the weight of an object.

Basic Calculation Example

1 newton = Use the N to kgf the formula per NIST SP811 which is 1 / 9.80665 = 0.101 kgf

0.101 kgf covert to gf by multiplying by 1000 = 101.971621 grams-force

mass = (9.80665/g) (D/ (D-d) * F

g = local gravity in m/s^2

d = air density = 0.0012 g/cm^3

D = density of weight material = 7.9 g/cm^3

F= force

9.79957 m/s2 local gravity from http://geodesy.noaa.gov/cgi-bin/grav_pdx.prl

mass = (9.80665/9.79957) (7.9/(7.9-0.0012) * 101.971621 = 102.060796432 grams

Note: This example calculation used a standard value for air density and typical stainless steel material density. If one wants to minimize uncertainty, the actual value of the air density at the place of use and the density of the material should be used.

ASTM E74 & E2428 Equation to Calculate Force

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

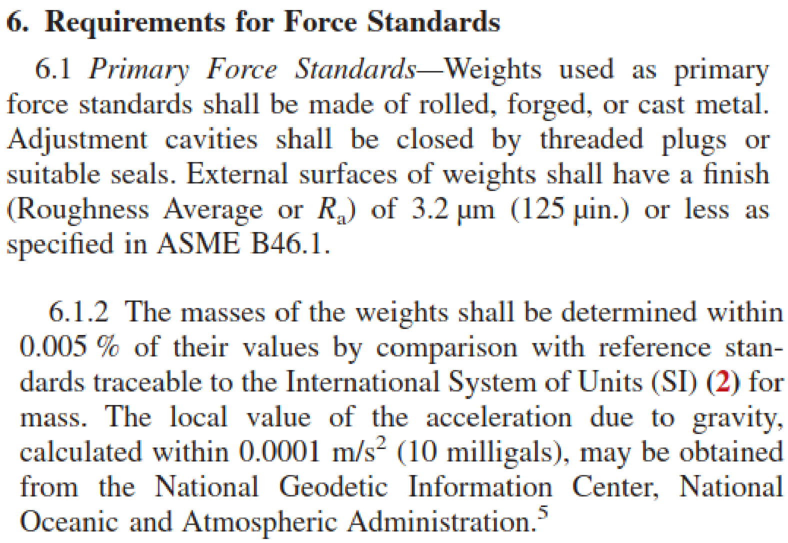
m = true Mass of the weight (not to be confused with conventional Mass)

g = local acceleration due to gravity, m/s2

d = air density (approximately 0.0012 g/cm3)

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

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



6. Requirements for Force Standards

6.1 *Primary Force Standards*—Weights used as primary force standards shall be made of rolled, forged, or cast metal. Adjustment cavities shall be closed by threaded plugs or suitable seals. External surfaces of weights shall have a finish (Roughness Average or R_a) of 3.2 µm (125 µin.) or less as specified in ASME B46.1.

6.1.2 The masses of the weights shall be determined within 0.005 % of their values by comparison with reference standards traceable to the International System of Units (SI) (2) for mass. The local value of the acceleration due to gravity, calculated within 0.0001 m/s^2 (10 milligals), may be obtained from the National Geodetic Information Center, National Oceanic and Atmospheric Administration.[5]

Figure 4 Sections from ASTM E74-18 on Gravity and Requirements for Force Weights

Finding the Gravity of Your Location

The actual value of gravity varies over the surface of the Earth from around 983.2 cm/s2 over the poles to 978.0 cm/s2 at the equator.

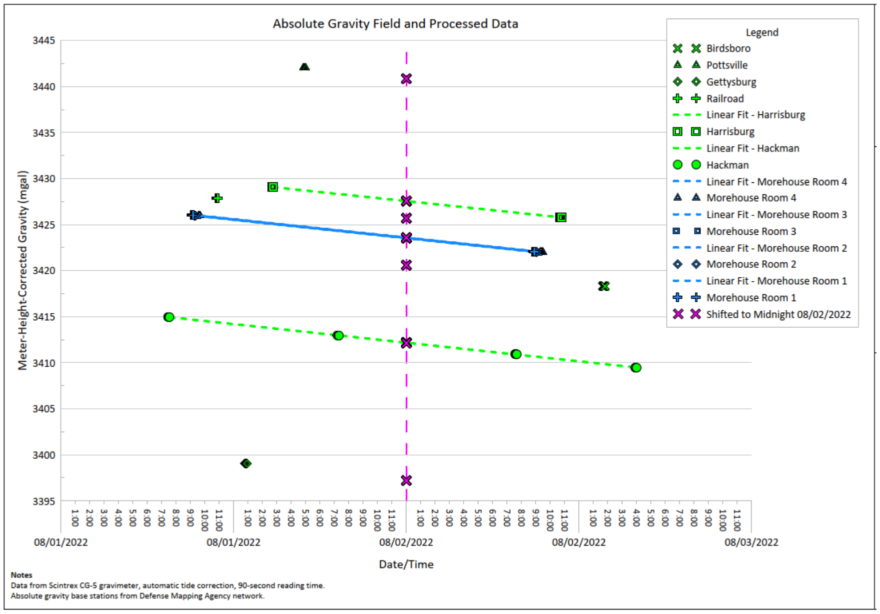
To find gravity for a fixed location, firms or universities can be hired to come to your location to measure gravity. Typically, this will result in a measurement of g accurate to ± 0.5 mgals. Alternatively, gravity for your location can be calculated free of charge using online resources.

Steps To Find Gravity Using Online Resources:

1. Find your longitude, latitude, and elevation: geoplaner.com

2. Calculate your local gravity: geodesy.noaa.gov/cgi-bin/grav_pdx.prl

Note: The expanded uncertainty from this calculation is likely to be within 5 ppm anywhere in the U.S. This uncertainty value (as a maximum), or the actual reported value, belongs in any uncertainty budget for Force, etc. Of course, the mean value reported must also be applied to the actual measurement data as a correction.



Notes
Data from Scintrex CG-5 gravimeter, automatic tide correction, 90-second reading time.
Absolute gravity base stations from Defense Mapping Agency network.

Station	Value (mgal)	Est. Error (mgal +/-)
Morehouse Room 1	980115.698	0.0548
Morehouse Room 2	980115.678	0.0550
Morehouse Room 3	980115.698	0.0551
Morehouse Room 4	980115.734	0.0553

Figure 5 Gravity Determination at Morehouse

At Morehouse, we've calculated our actual gravity, and the results vary slightly from NOAA's.

Morehouse Information from Gravity Determination On-Site Versus NOAA

Elevation: 126.2

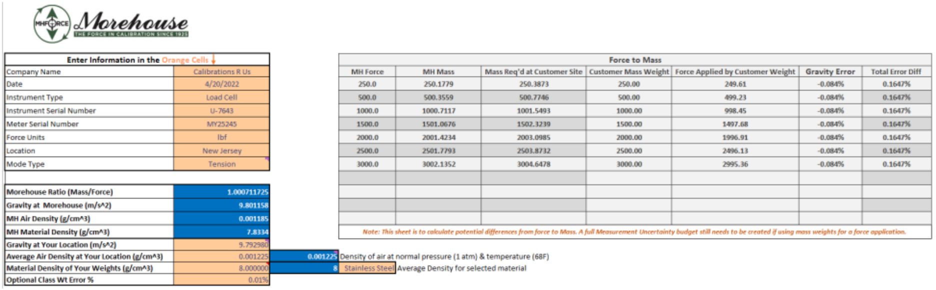
From NOAA 9.80117 m/s2

From Morehouse determination on-site 9.801157 m/s2 Difference of 1.3 ppm or 0.00013%

Morehouse Spreadsheet to Convert Mass to Force

Because these formulas may seem overwhelming, we have simplified things as much as possible.

Morehouse has a free spreadsheet tool to help with conversions from Force to Mass and Mass to force. The spreadsheet will allow load cells to be converted from Force to Mass and provides formulas to correct mass weights properly for Force.



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

Force to Mass						
MH Force	MH Mass	Mass Req'd at Customer Site	Customer Mass Weight	Force Applied by Customer Weight	Gravity Error	Total Error Diff
250.0	250.1779	250.3873	250.00	249.61	-0.084%	0.1647%
500.0	500.3559	500.7746	500.00	499.23	-0.084%	0.1647%
1000.0	1000.7117	1001.5493	1000.00	998.45	-0.084%	0.1647%
1500.0	1501.0676	1502.3239	1500.00	1497.68	-0.084%	0.1647%
2000.0	2001.4234	2003.0985	2000.00	1996.91	-0.084%	0.1647%
2500.0	2501.7793	2503.8732	2500.00	2496.13	-0.084%	0.1647%
3000.0	3002.1352	3004.6478	3000.00	2995.36	-0.084%	0.1647%

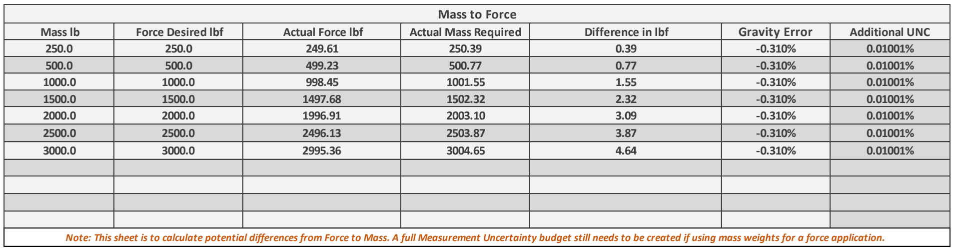
Note: This sheet is to calculate potential differences from force to Mass. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.

Figure 6: Morehouse Force to Mass Spreadsheet

Download the Mass to Force spreadsheet, which can also be used to convert Force to Mass.

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

When converting mass weights to force, the weights are likely to be strange, not nominal values. If this is an issue, we recommend purchasing weights or equipment capable of generating forces correctly. Morehouse can supply such equipment. If the decision is made to convert the mass weights to force, an uncertainty analysis will need to be performed. That analysis should take into account gravity, material density, and air buoyancy, as well as any other uncertainties and known biases from the reference laboratory who calibrated the weights. A complete list of uncertainty components is found in a later section.



Mass to Force

Mass lb	Force Desired lbf	Actual Force lbf	Actual Mass Required	Difference in lbf	Gravity Error	Additional UNC
250.0	250.0	249.61	250.39	0.39	-0.310%	0.01001%
500.0	500.0	499.23	500.77	0.77	-0.310%	0.01001%
1000.0	1000.0	998.45	1001.55	1.55	-0.310%	0.01001%
1500.0	1500.0	1497.68	1502.32	2.32	-0.310%	0.01001%
2000.0	2000.0	1996.91	2003.10	3.09	-0.310%	0.01001%
2500.0	2500.0	2496.13	2503.87	3.87	-0.310%	0.01001%
3000.0	3000.0	2995.36	3004.65	4.64	-0.310%	0.01001%

Note: This sheet is to calculate potential differences from Force to Mass. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.

Figure 7: Morehouse Mass to Force Tab

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

Common Issues with Measurement Uncertainty Using Mass Weights for Force Applications

ISO/IEC 17025:2017 states, "Laboratories shall identify the contributions to measurement uncertainty. When evaluating measurement uncertainty, all contributions that are of significance, including those arising from sampling, shall be taken into account using appropriate methods of analysis." And the standard goes on to further state, "A laboratory performing calibrations, including of its equipment, shall evaluate the measurement uncertainty for all calibrations." [4]

When Mass is used in place of Force, the likelihood of identifying the contributions to measurement uncertainty decreases greatly. Many labs may say they considered it; they might even provide calculations on the additional errors from their gravity calculation that compares their gravity against standard gravity.

The common other missed items are the uncertainty from air buoyancy and material density.

Buoyant Force

Buoyant forces equal to the weight of the air displaced are exerted on the weights. This Force varies with atmospheric pressure and humidity. The correction factor is $(1 - d/D)$ where d = air density and D = weight density. [7]

Air Buoyancy

Air density varies with fluctuations in barometric pressure, humidity, and temperature. According to NBS Monograph 133, at a constant temperature of 23 °C, barometric pressure and humidity changes may cause the actual air density to vary as much as 3 % in either direction from the average air density at a given time and place. [8] If the environment is maintained at 23 °C ± 2 °C, the variation will typically cause a change in the Mass of less than 6 ppm.

Material Density

Density is the substance's Mass per unit of volume. The density of a material varies with temperature and pressure.

Metal Density Chart

Various Metals	Density, g/cm3	Density, kg/m3	Density, lb/in3	Density, lb/ft3
Mild Steel	7.85	7,850	0.284	490
Medium carbon steel	7.83	7,830	0.283	489
High carbon steel	7.81	7,810	0.282	488
Stainless steel	7.7-8.0	7,700-8,000	0.278-0.289	481-499
Aluminum	2.7	2,700	0.098	169

The density of the material may be determined by actual measurement or handbook values may be used. Actual measurement often involves sending a coupon from the material lot used to manufacture the weights. The coupon is calibrated, and a report is issued. Note: Using this value typically yields very low contributions to the overall measurement uncertainty.

Even if the uncertainties of gravity, material density, and air buoyancy are considered, there is almost always missing reporting of the values used. This matters because if the MT & E end-user is at a location with different gravity, that end-user will have the burden of correcting the data for the difference in gravity and air buoyancy at the location where they are using it. As demonstrated earlier, when Force is used, the end-user does not need to worry about these additional corrections for the MT & E, as any mass would need to be corrected for Force at the location of use.

Additional Information on Uncertainty

The VIM in section 2.26 defines measurement uncertainty as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. [9]

Measurement uncertainty simplified is the value assigned to "doubt" about the validity of an assigned calibration value.

Documented measurement uncertainties are required on a calibration certificate to support metrological traceability. Uncertainty is more than any accuracy statement. Measurement uncertainty will be broken down into several contributors per the section heading of this document. Of these contributors, uncertainty is often broken down into two types: Type A and Type B evaluations.

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

Type A Uncertainty Contributions

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

- Repeatability (required by the GUM, Accreditation bodies, and UKAS M3003)
- Reproducibility
- Stability / Drift
- Others (These would include ASTM E74 llf, non-linearity, hysteresis, or SEB for commercial calibrations)

Note: Stability can be treated as Type B if values are taken over a range using previous measurement data. Stability data may be treated as Type A if an evaluation is made using statistical methods over several calibration data sets.

Type B Uncertainty Contributions

Per section 4.3 of the GUM Type B, evaluation of standard uncertainty may include:

- Previous measurement data
- Experience with or general knowledge of the behavior and properties of relevant materials and instruments
- Manufacturer's specifications
- Data provided in calibration and other certificates
- Uncertainties assigned to reference data taken from handbooks
- Bias (systemic error) if not corrected*

Additional Type B considerations provided below.

- Resolution of the reference standard
- Resolution of the best existing force-measuring instrument or the force-measuring instrument used for repeatability studies
- Reference standard uncertainty
- Reference standard stability
- Environmental factors
- Other error sources

*Note on bias: The GUM requires that corrections be applied for all recognized and significant systematic effects and potential errors. Where a correction is applied based on a bias, an estimate of the associated.

Uncertainty must then be included in the uncertainty analysis. If corrections are not applied, bias must be added to the expanded uncertainty (U + bias)

Sources of Measurement Uncertainty

All relevant sources of uncertainty should be evaluated. The example presented is a recommendation and may not include all potentially significant uncertainties for the user's calibration process, apparatus, and personnel. The user should evaluate and identify any other uncertainties significant to the calibration result and incorporate them into the measurement uncertainty analysis.

Additional Information on Uncertainty for Deadweight Primary Standards Using Weights Adjusted for Force

Uncertainty of the Applied Force of Primary Force Standards

Type A Uncertainty Contributions

1) Uncertainty of the Mass of the weights

2) Uncertainty of the determination of local gravity

3) Repeatability conducted with the best existing Force measuring instrument

4) Repeatability and reproducibility between technicians

Note: 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) Uncertainty of the gravity correction for the height of the weight stack

3) Uncertainty due to variation of the buoyant Force

4) Uncertainty of the air density

5) Uncertainty in the determination of the density of the material from which weights are made

6) Uncertainty due to the stability of mass values with time

7) Bias or systemic errors (Use SOP 29 U + bias information)

8) Other error sources – Uncertainty due to misalignment, lack of rigidity, torsion, unlevel conditions, and weight swing.

Note: ASTM E74 provides additional guidance on measurement uncertainty for primary standard force machines. Both the ASTM E74 document and A2LA Guidance G126 on Uncertainty Budgets for Force Measuring Devices (which has additional guidance on calculating MU for Force) are highly recommended reading.

Examples

Example 1 Calibration of a 1000 lb. Scale

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

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 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 120,000 lbf primary standard deadweight machine, we used the following values.

force = M x g / 9.80665 (1 – d/ D)

These values become ((mass * 9.801158 m/s2)/9.80665 m/s2) * (1 –(0.001185/7.8334)

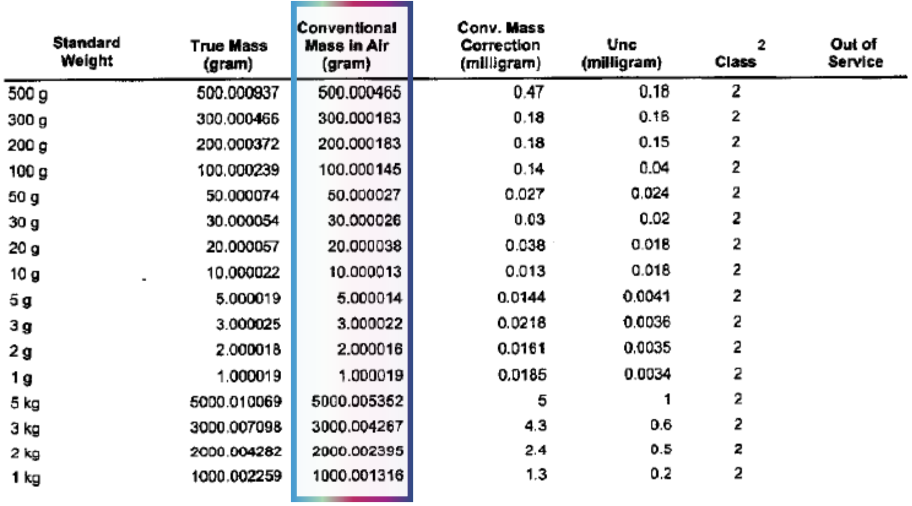
Force = mass x 0.999288781

or

mass = force x 1.000711725

Example 2. Converting Conventional Mass to True Mass

Table 1 – Example weight certificate



Standard Weight	True Mass (gram)	Conventional Mass in Air (gram)	Conv. Mass Correction (milligram)	Unc (milligram)	Class 2	Out of Service
500 g	500.000937	500.000465	0.47	0.18	2	
300 g	300.000466	300.000183	0.18	0.16	2	
200 g	200.000372	200.000183	0.18	0.15	2	
100 g	100.000239	100.000145	0.14	0.04	2	
50 g	50.000074	50.000027	0.027	0.024	2	
30 g	30.000054	30.000026	0.03	0.02	2	
20 g	20.000057	20.000038	0.038	0.018	2	
10 g	10.000022	10.000013	0.013	0.018	2	
5 g	5.000019	5.000014	0.0144	0.0041	2	
3 g	3.000025	3.000022	0.0218	0.0036	2	
2 g	2.000018	2.000016	0.0161	0.0035	2	
1 g	1.000019	1.000019	0.0185	0.0034	2	
5 kg	5000.010069	5000.005352	5	1	2	
3 kg	3000.007098	3000.004267	4.3	0.6	2	
2 kg	2000.004282	2000.002395	2.4	0.5	2	
1 kg	1000.002259	1000.001316	1.3	0.2	2	

To convert to true mass, we take the conventional mass values and calculate the ratio between air density and material density vs the standard density and standard material density using equation 1.

$$M_x = \frac{CM_x \left(1 - \dfrac{0.0012\ {}^{g}/_{cm^3}}{8.0\ {}^{g}/_{cm^3}}\right)}{\left(1 - \dfrac{0.0012\ {}^{g}/_{cm^3}}{\rho_x}\right)}$$

For example:

Number in table for conventional mass * (1-((0.0012/8.0)) / (1-((0.0012 /Material Density))

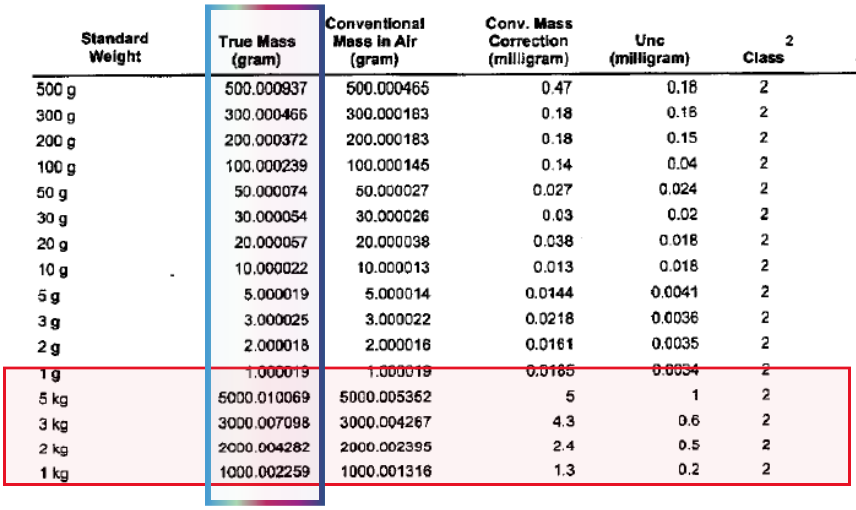
1000.001316 * (1-((0.0012/8.0)) = 999.8513158 divided by

(1-((Air Density at time of use / Material Density)) = 0.999846

Thus 999.8513158 / 0.999849057= 1000.002259

Example 3. Computing Force of Class 2 Weight

Table 2 – Example weight certificate



Standard Weight	True Mass (gram)	Conventional Mass in Air (gram)	Conv. Mass Correction (milligram)	Unc (milligram)	Class 2	Out of Service
500 g	500.000937	500.000465	0.47	0.18	2	
300 g	300.000466	300.000183	0.18	0.16	2	
200 g	200.000372	200.000183	0.18	0.15	2	
100 g	100.000239	100.000145	0.14	0.04	2	
50 g	50.000074	50.000027	0.027	0.024	2	
30 g	30.000054	30.000026	0.03	0.02	2	
20 g	20.000057	20.000038	0.038	0.018	2	
10 g	10.000022	10.000013	0.013	0.018	2	
5 g	5.000019	5.000014	0.0144	0.0041	2	
3 g	3.000025	3.000022	0.0218	0.0036	2	
2 g	2.000018	2.000016	0.0161	0.0035	2	
1 g	1.000019	1.000019	0.0165	0.0034	2	
5 kg	5000.010069	5000.005352	5	1	2	
3 kg	3000.007098	3000.004267	4.3	0.6	2	
2 kg	2000.004282	2000.002395	2.4	0.5	2	
1 kg	1000.002259	1000.001316	1.3	0.2	2	

A customer sent in a 10 kgf force gauge, and the lab has Class 2 mass weights shown above.

Note: Most labs will supply both conventional mass values. Many of these labs can report true mass as well, though that likely needs to be requested in the request for tender stage.

To apply 10 kgf, we need to use a combination of the weights above. We will use the True Mass values.

The weights are all Class 2 weights with a material density of **7.95g.cm**^{3}

1. To Find your gravity

Put the address into www.iTouchMap.com to get their facility's latitude and longitude coordinates.

For York, PA 17403, we get 39.96542 and -76.69149

Then, put the latitude, longitude, and elevation values into https://www.ngs.noaa.gov/cgi-bin/grav_pdx.prl.

The value will be in gals, which must be converted to m/s^^{2}. The predicted gravity will include a +/- value that should be considered in your uncertainty analysis.

NOAA will give a value of 9801158 milligals. 1 gal = 1 cm/s^{2}. We will convert by dividing 100,000 by **9.801158 m/s^{2}**.

2. Find the Air Density if not known.

An accurate method to determine air density is to measure the temperature, humidity, and barometric pressure. You can then apply the formula(s) found in:

> NIST SOP 2 Recommended Standard Operating Procedure for Applying Air Buoyancy Corrections. Paragraph 5, Assignment of Uncertainty, explains the standards' accuracy requirements for determining air density based on how accurate the air density must be.[4]

Weather sites that list barometric pressure are all corrected back to sea level. If you use weather information, your air density will appear very near standard density (0.0012 g/cm^3) because they correct those values back to sea level. NOAA's term for barometric pressure at the location is called "station pressure." If you can find the "station pressure," you can use that value. Altimeter setting information from airports can be used to determine the barometric pressure at the airport location. To convert altimeter setting information from an airport to the location barometric pressure using the following formula, you need the altimeter setting in inHg and the altitude in meters. This link has Station Pressure Calculator and additional information about air pressure.
https://www.weather.gov/epz/wxcalc_stationpressure

$$Station\ Pressure\ (inHg) = Altimeter\ Setting(inHg) \times \left(\frac{(288 - 0.0065 \times Elevation(meters))}{288}\right)^{5.2561}$$

0.001225 g/cm^3

– This is optional, though recommended, as not knowing could yield higher errors. If your temperature is controlled, the values should be within about 3 % per NBS Monograph 133

Commented [GB1]: I keep going back and forth on this one. You're making a correction d/D, d really is a variable (can be measured) where D is closer to a consensus standard. Air density change between Miami and Denver causes a 30 ppm change in the force applied. The guidance should be anytime you use standard air (0.0012) AND your CMC is 0.06 % or smaller, then the CAB must document how they determined their air density change from standard was negligible (less than 5 % of the CMC). Using "weather" data should be a fail;(
The back and forth is whether if you're CMC is less than 0.06 % you have to show an accredited barometer measurement in your lab.... And your field locations where you'd do force to 0.06 % or better.

Note: It is a strong recommendation that anytime the value of 0.0012 (standard air) is used for air density, a lab should document how they determined their air density change from standard was negligible

$$Force = \frac{Mg}{9.80665}\left(1 - \frac{d}{D}\right) \qquad \text{(Equation 5)}$$

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

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

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

D = density of the weight in the same units as d (approximately 8.0 g/cm3) **7. 95g.cm^3**

For the 1 kg weight

Force = (**1.000002259 * 9.801158) / 9.80665 = 0.9994422296**

(1 – (0.001225 / 7.95)) = 1 - 0.00015409 = 0.999845912

0.9994422296*0.999845912 = 0.999288227 kgf.

Thus, when force is computed, our 1 kg class 2 weight equals **0.999288227 kgf or 999.28822749 gf.**

We continue to apply this formula to all weights to compute the force for each weight in our set at the location of use.

Note: If our location changed, so would the gravity value and, possibly, the air density value. The forces must be recomputed with the new local gravity and air density.

Air Density	0.001225
Material Density	7.95

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

Table 1: True Mass from a calibration certificate converted to kgf.

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

We would use this method for the remaining weights to find combinations to apply the needed force.

For 10 kgf, we might use a 5 kg, 3kg, 2 kg, 10g, which would convert to 10.002905477 kgf

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

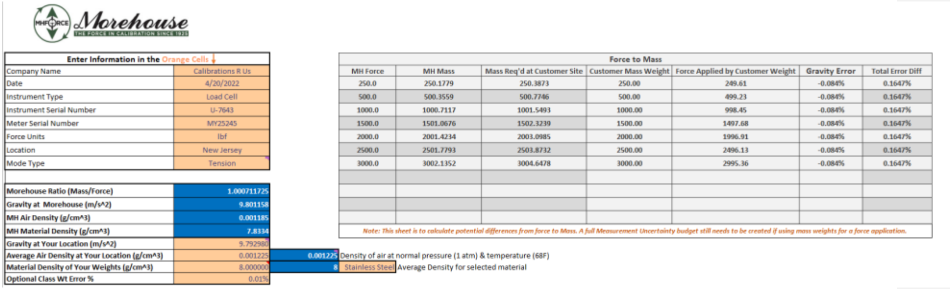
Morehouse Solutions

Figure 8: Morehouse 2,000 lbf Portable Calibrating Machine

1. Morehouse manufactures force-calibrating machines with varying degrees of mobility, including highlyconvenient 1-ton capacity portable calibrating machines (pictured above). These machines eliminate the need to stack mass weights. The advantage is that these machines calibrate their reference load cells in Force. They eliminate stacking weights which can pose safety hazards, and they often result in calibration that is better known as the machines are plumb, level, square, rigid, and have low torsions, while stacking weights often introduces misalignment errors as it is hard to balance the weights on the unit under test.

Figure 9 Morehouse Supplemental Weights

2. Morehouse can make weights with adjustment cavities so they can be corrected for Force at almost any location in the world.



Enter Information in the Orange Cells	
Company Name	Calibrations R Us
Date	4/20/2022
Instrument Type	Load Cell
Instrument Serial Number	U-7643
Meter Serial Number	MY25245
Force Units	lbf
Location	New Jersey
Mode Type	Tension

Morehouse Ratio (Mass/Force)	1.000711725		
Gravity at Morehouse (m/s^2)	9.801158		
MH Air Density (g/cm^3)	0.001185		
MH Material Density (g/cm^3)	7.8334		
Gravity at Your Location (m/s^2)	9.792980		
Average Air Density at Your Location (g/cm^3)	0.001225	0.001225	Density of air at normal pressure (1 atm) & temperature (68F)
Material Density of Your Weights (g/cm^3)	8.000000	8	Stainless Steel Average Density for selected material
Optional Class Wt Error %	0.01%		

Force to Mass						
MH Force	MH Mass	Mass Req'd at Customer Site	Customer Mass Weight	Force Applied by Customer Weight	Gravity Error	Total Error Diff
250.0	250.1779	250.3873	250.00	249.61	-0.084%	0.1647%
500.0	500.3559	500.7746	500.00	499.23	-0.084%	0.1647%
1000.0	1000.7117	1001.5493	1000.00	998.45	-0.084%	0.1647%
1500.0	1501.0676	1502.3239	1500.00	1497.68	-0.084%	0.1647%
2000.0	2001.4234	2003.0985	2000.00	1996.91	-0.084%	0.1647%
2500.0	2501.7793	2503.8732	2500.00	2496.13	-0.084%	0.1647%
3000.0	3002.1352	3004.6478	3000.00	2995.36	-0.084%	0.1647%

Note: This sheet is to calculate potential differences from force to Mass. A full Measurement Uncertainty budget still needs to be created if using mass weights for a force application.

Figure 10 Morehouse Free Online Spreadsheet

3. To calculate the correction, a lab can continue using its existing mass weights and the free Morehouse spreadsheet. The lab can then use the corrected values and report the actual forces applied, like 999.485 lbf.

Figure 11 Morehouse 1,000 lbf automated deadweight machine

4. Morehouse makes deadweight primary force machines. Deadweight force machines or primary force standard (CMCs as low as 0.001% of applied Force) — a deadweight force applied directly

without intervening mechanisms such as levers, hydraulic multipliers, or the like, whose Mass has been determined by comparison with reference standards traceable to the International System of Units (SI) of Mass (Section 3.1.2 of ASTM E74). The weights are corrected for the effects of local gravity where the machine is to be used, air buoyancy, and material density.

Deadweight machines are the most accurate method for calibrating force-measuring devices. When the overall accuracy of the load cell matters, it is highly recommended that deadweight standards perform calibration.

The deadweight primary standard machine's expanded uncertainty is typically broken down into two main components: 1) the uncertainty of the individual weights, and 2) the uncertainty of several weights when applied together in the deadweight machine to achieve a certain test point.

1 Page Summary

Why is it important to do the conversion in lieu of accounting for the differences in the measurement uncertainty budget?

- Saying one has accounted for the differences between Mass and Force in their uncertainty budget cannot be trusted — unless they are using a relatively large number such as 0.539%, which is the maximum variation in gravity on the Earth. Unless the calibration laboratory knows specifically where the equipment, they are calibrating with mass weights — not Force — is being used, additional errors could be as high as 0.539%.

Top Audit Deficiencies to Cite

- When calibration ***and reference material*** data include reference values or correction factors, the laboratory shall ensure the reference values and correction factors are updated and implemented, as appropriate, to meet specified requirements. (**6.4.11)**
- Possible citation of procedures if the lab does not have criteria for evaluating the necessary corrections. (7.10.1)

The calculation for force weights is as follows:

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

- m = true Mass of the weight (not to be confused with conventional Mass)
- g = local acceleration due to gravity, m/s2
- d = air density (approximately 0.0012 g/cm3)
- D = density of the weight in the same units as d (approximately 8.0 g/cm3)

Excel sheet to verify calculations and help with conversions:

Download the Mass to Force spreadsheet, which can also be used to convert Force to Mass.

Conclusion

Morehouse has been manufacturing force products for 100 years. During this time frame, the accuracy of the equipment used to measure forces and torques has improved exponentially. Using mass weights instead of weights adjusted for Force creates values for uncertainty that are often larger than the accuracy specification of the equipment. The best measurement systems are not only having the weights adjusted for Force, they have a calibrated barometer, air temp probe and humidity indicator to constantly monitor the environment as well.

We have noticed various equipment manufacturers do not provide weights adjusted for Force nor instructions for converting them. We hope this guidance document will improve measurements involving Force. When corrections are applied or the proper equipment is purchased for the measurement, the measurement risk is drastically reduced, and the world becomes safer.

Please feel free to contact Morehouse at sales@mhforce.com if you have any questions.

References

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6. ISO/IEC 17025:2017 "General requirements for the competence of testing and calibration laboratories."
7. ASTM E74-18 Standard Practices for Calibration and Verification for Force-Measuring Instruments Appendix
8. NBS Monograph 133 "Mass and Mass Values"
9. International Vocabulary of Metrology – Basic and general concepts and associated terms (VIM)