MHFORCE Morehouse
THE FORCE IN CALIBRATION SINCE 1925

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

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

Deadweight Primary Standards: Best Practices and Their Associated Risks for Stability Determination in Compliance with ISO/IEC 17025

Abstract

This paper explores the hierarchy, standards, and long-term stability of deadweight primary standard force machines used in load cell calibration. While many understand the basic principles of load cell calibration, fewer fully grasp the distinctions and implications between force standards, such as ASTM International's E74 Practices for Calibration and Verification for Force-Measuring Instruments (ASTM E74) [1] and the International Standard ISO 376 Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines (ISO 376) [2]. Despite differing classification and methodology, these standards emphasize the critical role of traceability and uncertainty in force calibration.

Deadweight primary standards represent the highest level of accuracy, achieving expanded uncertainties below 0.002 % of applied force. The paper discusses the construction, materials, and performance characteristics contributing to their exceptional stability. It cites studies by the National Institute of Standards and Technology (NIST) and the United Kingdom's National Physical Laboratory (NPL), demonstrating negligible mass drift over decades. This paper further outlines the best practices for maintenance, interlaboratory comparisons, and statistical process control, arguing against frequent disassembly of deadweight systems due to the associated risks and costs.

Through historical context, technical evolution, and real-world data, this paper concludes that with proper design, environmental control, adequate maintenance, and verification procedures, deadweight primary standards can maintain their accuracy and traceability for intervals of 20–30 years or more, reinforcing their role as the gold standard in force calibration.

Preliminaries

Although many people understand the basic principles of load cell calibration, fewer are familiar with the various standards used to calibrate load cells and their specific requirements and implications. Without a doubt, the two most used and referenced standards for load calibration are ASTM E74 and ISO 376. While they may differ on calculated results, one key thing that they share is an understanding of a hierarchy of load cells and what is required to calibrate them.

The machines used to calibrate load cells also have a hierarchy based on the amount of **measurement uncertainty** they can maintain. The techniques employed to apply load vary by loading capacity and **measurement uncertainty** limitations. This hierarchy of machines, starting with the most accurate and lowest overall uncertainty, begins with deadweights, such as the Morehouse deadweight force standard shown below, followed by standards such as lever deadweights, hydraulic amplification machines, and hydraulic Universal Calibrating Machines, or mechanical machines, with multiple transducers. At the lowest end of the spectrum, some labs may use a Universal Testing Machine or a homemade press to calibrate load cells.

This paper examines deadweight standards' stability, the foundation for achieving the highest classification levels defined by ASTM and ISO. Due to their unmatched precision and long-term reliability, deadweight primary standards represent the ideal starting point in the calibration hierarchy. Subsequently, methods are selected based on each application's specific uncertainty and traceability requirements.

Note: All units and quantities not directly quoted in this paper are presented following the International System of Units (SI) guidance in NIST Special Publication 811 (2008 Edition). The use of "parts per million" (ppm) appears in this paper to maintain consistency with terminology found in key reference standards and source materials. Where used, "ppm" should be interpreted as 1×10^{-6}, consistent with SI guidance outlined in NIST SP 811, even though "ppm" is not formally an SI unit.

Figure 1: Morehouse Automated Deadweight Machine

What is a Deadweight Machine?

Deadweight primary standards, also called **deadweight force machines**, represent the pinnacle of accuracy in force measurement calibration, achieving Calibration and Measurement Capabilities Uncertainty Parameters (CMCs) as low as 0.0008–0.0010 % of applied force. These machines apply force through precisely calibrated weights whose mass is traceable to the International System of Units (SI) and adjusted for local gravity, air buoyancy, and material density.

ASTM E74 in section 3.1.2 defines 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.” [1]

The weights are corrected for the effects of local gravity where the machine is used, air buoyancy, and material density.

Deadweight Machine Evolution.

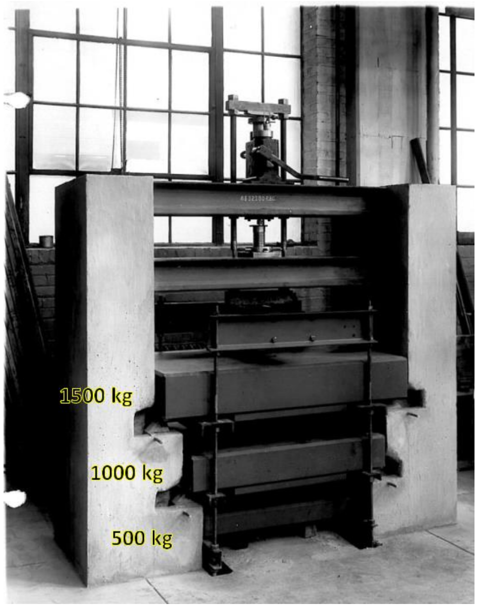


Figure 2: NBS 3000 kgf Brinell Hardness Machine - Image Courtesy of NIST

The National Bureau of Standards (NBS), which later became the National Institute of Standards and Technology (NIST), began its force calibration work with 3000 kgf **deadweight force machines** in the 1920s. These early machines were limited to weights in 500 kgf increments, with a maximum of 3000 kgf.

Following the war, many early deadweight machines underwent significant upgrades, and in the 1960s, NBS would ultimately build a 4.45 MN machine. This machine is still the world's largest deadweight machine today. **Deadweight force machines** can be built in many capacities, from smaller ones with 1 N or less weights to larger machines with 200 kN weights. Common capacity machines are built with weights ranging from 5 kN to 50 kN. It is not uncommon for National Metrology Institutes (NMIs) to have 500 kN or larger machines. Many early **deadweight force machines** after World War II underwent significant upgrades or rebuilds following technological advancements.

Significant technological and methodological advancements have been made over several decades involving primary standards. NIST documentation shows that their **deadweight force machines** have had several enhancements since their installation in the mid-1960s [3]. Initially, the machine's accuracy was fundamentally limited by uncertainties related to gravitational acceleration, mass determination, and air buoyancy effects. However, progressive improvements in sensor technology, computational algorithms, and environmental controls have significantly reduced these uncertainties. Other key milestones include automating weight-changing mechanisms in 1989 and incorporating advanced data acquisition systems that improved measurement precision and reduced human error.

Today, our knowledge of measurements associated with maintaining environmental conditions, calculating material density, air density, and building machines whose frames strictly follow the plumb, level, square, and rigid guidelines has all contributed to an overall decrease in **measurement uncertainty**. Another significant contribution to **measurement uncertainty** is the alignment of the loading axis and having the correct adapters to improve the alignment of the unit under test, which helps minimize **measurement uncertainty**.

Understanding how weights might wear over time and designing systems with the appropriate lifting mechanisms is paramount in deadweight machine design. Gone are the days of worrying about a more frequent calibration schedule of the deadweight force machine, as our current understanding and collective experience tells us there is more risk in disassembling large weight stacks than there is benefit.

The design of a calibration laboratory should incorporate overhead cranes to facilitate the safe assembly and potential disassembly of **deadweight force machines**. An optimal deadweight primary standards lab often features a multi-level configuration, supported by a robust foundation, carefully planned layout, and strict environmental controls. For example, the photo below shows a two-story setup at the United States Air Force (USAF) facility, where the weight stacks are positioned beneath the main testing floor. This design supports precise force generation and provides ample clearance and rear access behind the machines, allowing for easier maintenance or disassembly if required.

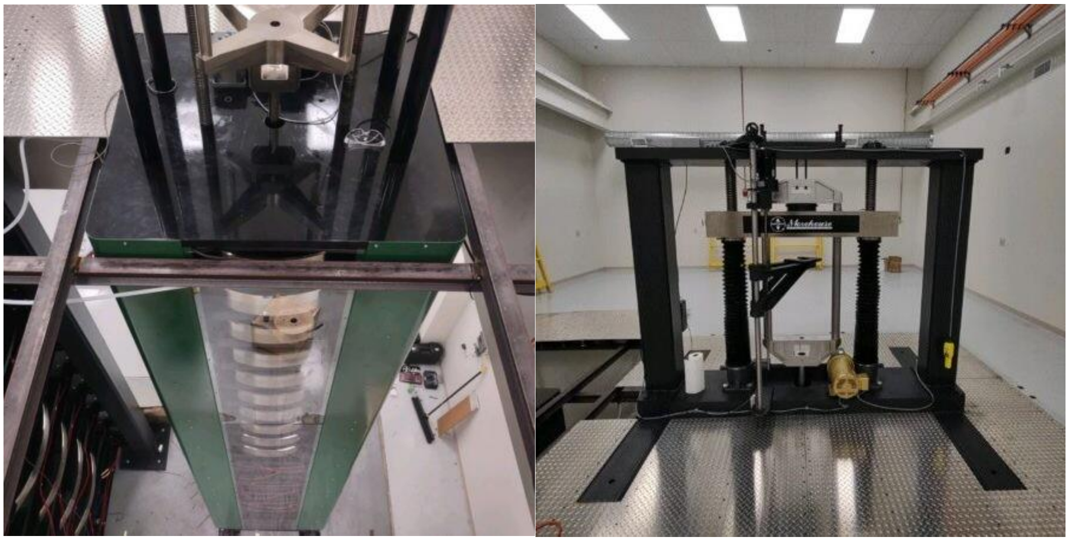


Figure 3: Early Image of the USAF Top Floor Showing Morehouse Machines

When multiple **deadweight force machines** are available, a load cell may be used for intra-laboratory comparisons and cross-checks between systems. Additionally, the load cell can function as a high-precision mass comparator in situ and across machines to monitor and verify the long-term stability of the deadweight standards. In this role, the load cell operates by performing substitution weighing, where known weights are applied, removed, and re-applied while monitoring the load cell's electrical output. By comparing the output differences corresponding to known mass changes, any deviation from expected behavior can be detected, allowing subtle shifts in mass or applied force to be identified. This highly sensitive method enables mass differences to be resolved at the parts-per-million (ppm) level, provided environmental and loading conditions are tightly controlled.

Deadweight Force Machines, Measurement Uncertainty, and Stability

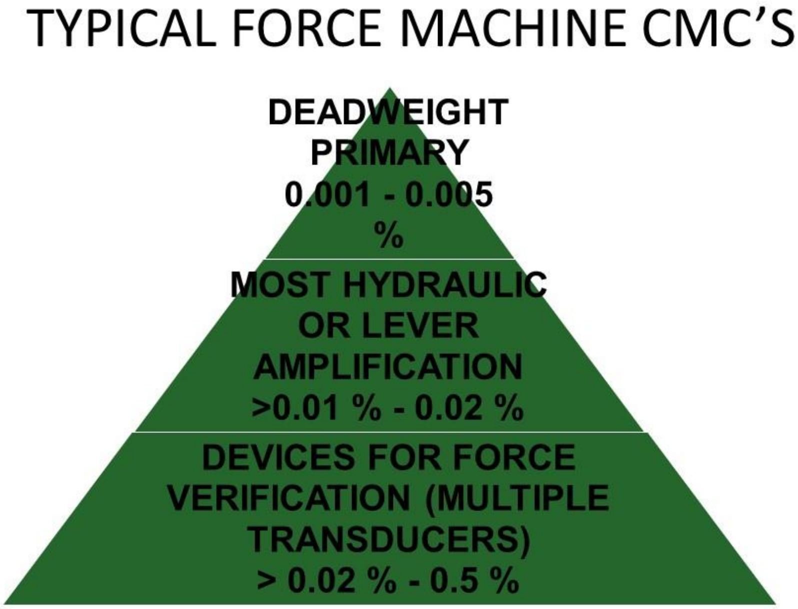


Figure 4: Typical Force CMCs in % of Applied Force.

Deadweight force machines represent the most accurate method available for calibrating load cells. When overall measurement accuracy is critical, it is strongly recommended that deadweight standards be used. These systems are capable of calibrating force-measuring instruments to the highest classifications, including ISO 376 Class 00 [2], ASTM E74-18 Class AA verified range of forces [1], and Australian Standard AS 2193 Class AA [4], as well as other devices requiring exceptional precision.

Note: If ASTM Class AA is required, a deadweight machine is the only standard suitable to calibrate the ASTM E74 Class AA verified range of forces. Expanded Uncertainty must be better than 50 ppm to assign a Class AA loading. (See ASTM E74 [1].) Deadweight makes classifying a force-proving instrument to Class 00 of ISO 376 easier, though it is not necessarily needed.

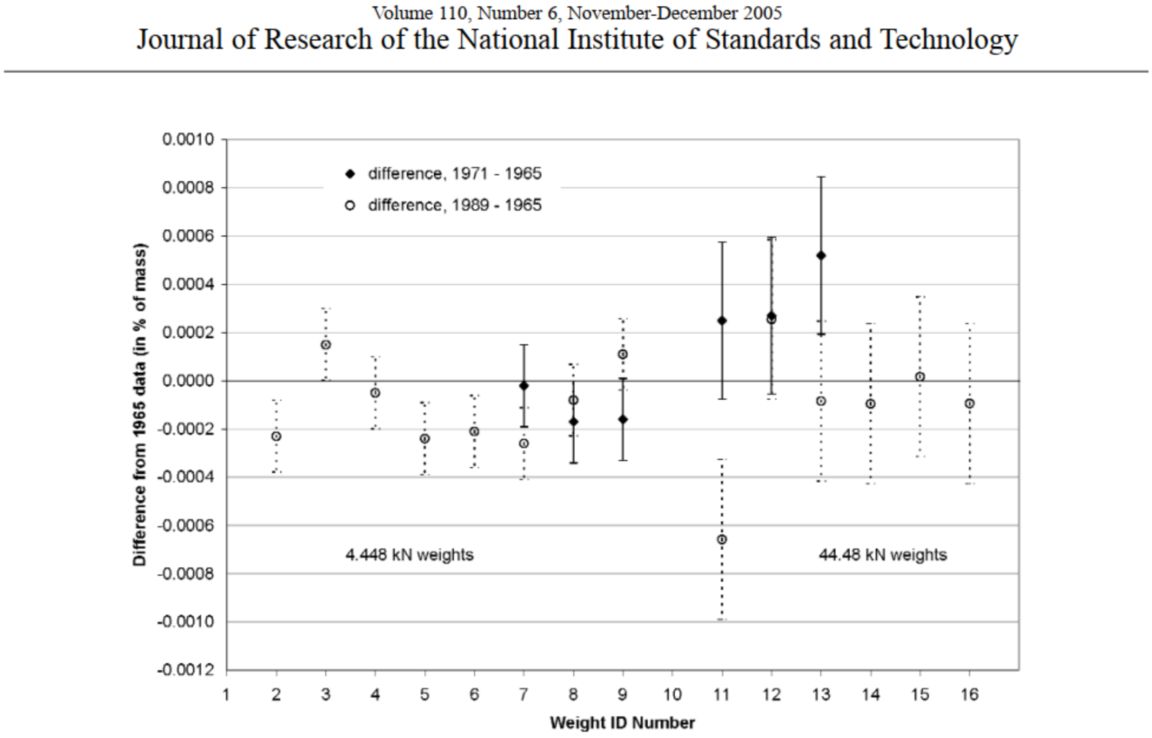
All Morehouse automatic **deadweight force machines** have expanded uncertainties better than 0.002 % of the applied force. Designing these machines requires careful consideration of many factors, including a robust and rigid structure, a weight hanger that minimizes sway, and precisely machined weights to achieve the target mass needed for accurate force generation.

Properly machined weights with enough adjustment cavities to fine-tune their mass are essential for any deadweight machine. If the weights are poorly machined, such as imperfect surface finishes, become even slightly corroded, or are constructed from cast iron, maintaining uncertainties below 0.005 % becomes challenging. These issues and other potential sources of error can alter the actual mass of weights, resulting in higher measurement uncertainties.

The stability of weights can also be an issue, as certain materials may lead to significant measurement errors over time. It has been proven that austenitic stainless-steel masses remain stable to better than 0.2 ppm over ten years, so stability becomes a minimal concern when stainless steel is chosen as the material for manufacturing calibration weights. *Note: When fabricated correctly, plated weights are also stable; the key is to avoid using porous material.*

Several authoritative studies have demonstrated the stability of **deadweight force machines**:

1. ***National Institute of Standards and Technology (NIST):***



Volume 110, Number 6, November-December 2005
Journal of Research of the National Institute of Standards and Technology

Figure 5: Comparison of mass values determined in 1965, 1971, and 1989 for the NIST 498 kN deadweight machine[3]

NIST has conducted several internal studies to assess the long-term stability of mass standards. In these efforts, they reweighed various machines after 30 to over 40 years and found minimal changes in the mass values. As reported in Bartel's study on NIST force measurements [3], the average difference across twenty data points was less than 0.0001 % (1 part per million), which is too small to indicate any significant change. The paper also notes that, with only two exceptions, the measured relative mass differences between the 1989 and 1965 data sets fell within the expected uncertainty range of ±0.0003 %, supporting the conclusion that the masses remained stable over time.

A review of weight measurements taken over several decades at NIST showed only slight variations, all generally within the expected measurement uncertainties, highlighting the excellent long-term stability of the masses. More recent mass determinations, when compared with earlier data, revealed minimal increases within the combined uncertainty range, further confirming the consistent stability of these standards over time [3].

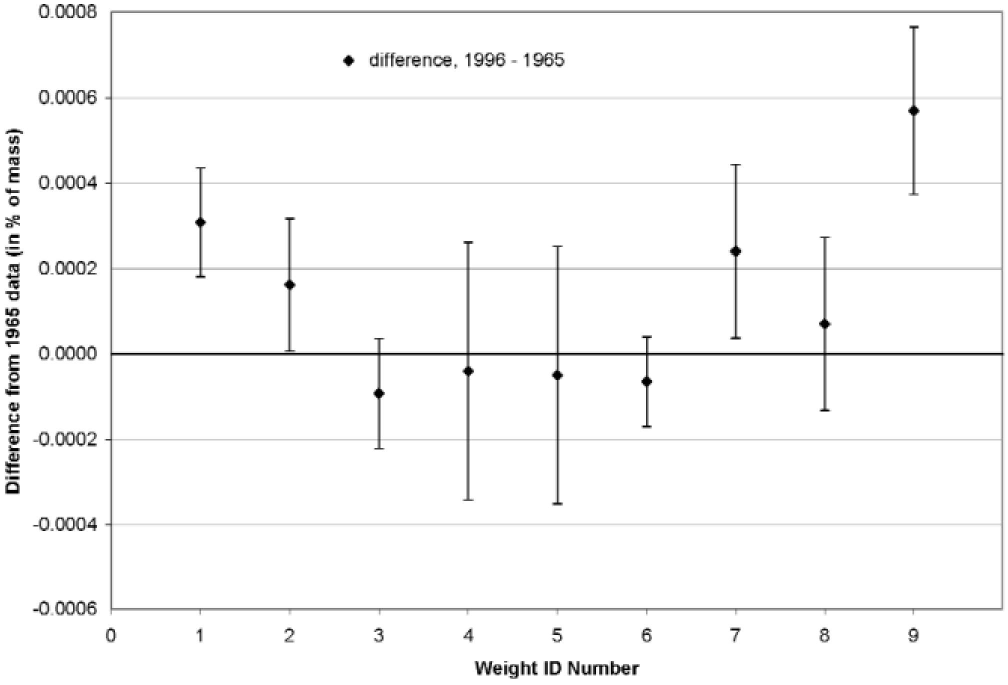


Figure 6: Comparison of mass values determined in 1965 and 1996 for the NIST 2.2 kN deadweight machine[3]

The error bars for the 1996 and 1965 mass measurements reflect the combined standard uncertainties, expressed as a percentage of each mass. These uncertainty ranges vary in length because each is explicitly calculated from the data associated with that weight. While one data point falls slightly outside the ±0.0003 % threshold, considered the upper limit for standard uncertainty in mass determination, most values stay within this range. Four out of nine measurements show uncertainty intervals that extend beyond the baseline, and two exceed their expanded uncertainties, assuming a coverage factor of *k* = 2. However, the average difference of +0.0001 % is too small to suggest any meaningful or systematic change in mass. Given that larger **deadweight force machines** are expected to experience even smaller relative mass variations than the 2.2 kN system, the findings support the conclusion that no significant long-term mass changes have occurred within NIST's force laboratory equipment [3].

National Physical Laboratory (NPL) Studies:

ASTM E74 quotes an NPL study in Section X1.5, which states, "The National Physical Laboratory in England reports experience with austenitic stainless-steel masses shows the mass is likely to be stable to better than 0.2 ppm over a period of ten years. For the purpose of this example, a stability of 0.2 ppm (0.00002 %) for ten years will be used [5]."

These authoritative references consistently affirm the remarkable stability of meticulously maintained and well-engineered deadweight primary standards.

These studies conclude that deadweight force calibration machines are the most accurate means for calibrating other force-measuring devices. They are recognized for their exceptional stability and long calibration intervals.

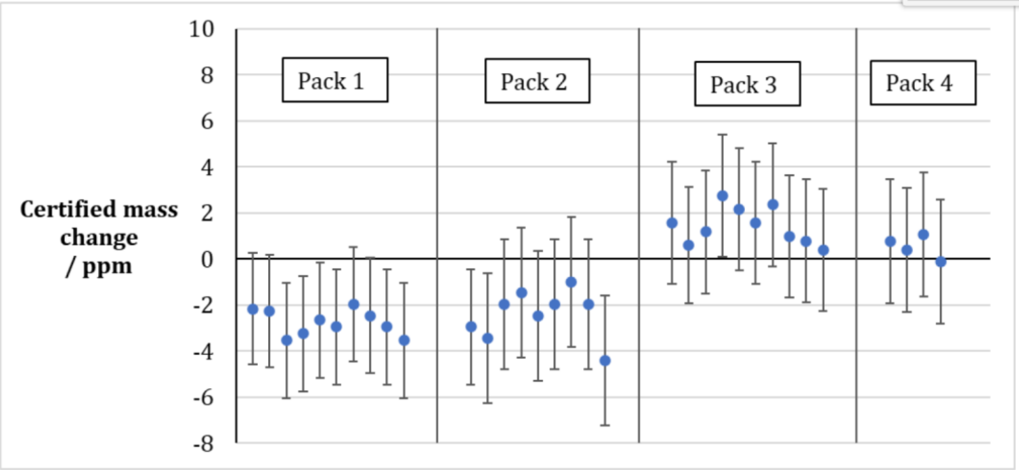


Figure 7: NPL Evidence Supporting the Stability of NPL UK's kN Deadweight masses[6]

The above figure is data taken from the NPL Validity Extension Justification internal document, which shows the change in the measured value of weights in 1992 and their recalibration in 2001/2002. Each data point represents the individual weights. Pack 1 weights are designed to generate a nominal force of 10 kN, Pack 2 weights 20 kN, and Packs 3 and 4 each 25 kN per individual weight. The error bars represent the quadrature sum of the expanded uncertainties from the two calibration events.

This data concludes that "These calibration results demonstrate no significant systematic change in mass value for any of the weights over an extended period of time. It can also be concluded that there is no reason to suspect that there will be any significant systematic change in mass value for any of the weights over future time periods, assuming that they are maintained in the same environmental conditions [6]." It is important to note that deadweight primary standards have consistently demonstrated exceptional stability and reliability over extended periods, substantiating extended calibration intervals. NPL UK conducted a thorough internal analysis, documented in their Validity Extension Justification, highlighting negligible systematic mass changes in precision-calibrated stainless-steel weights across decades. Additionally, regular cross-checks and intercomparisons by respected institutions, such as NPL and NIST, further support these findings, indicating insignificant deviations and maintaining high confidence in the sustained accuracy of **deadweight force machines**. Systematic monitoring of other parameters, including local gravity, air density, and weight density, has also reinforced this long-term stability.

These studies suggest that the risks of dismantling **deadweight force machines** for recalibration, such as potential mechanical damage, contamination, and unnecessary handling errors, significantly outweigh the benefits. Empirical evidence and rigorous verification practices strongly advocate for recalibration intervals of twenty to thirty years or more, minimizing unnecessary disruptions to these high-precision instruments.

Best Practices: Compliance with ILAC G24 and ISO/IEC 17025

Laboratories using **deadweight force machines** should implement robust measures to maintain measurement confidence. **These measures include participation in proficiency tests, intra- and inter-laboratory comparisons, and establishing a comprehensive Statistical Process Control (SPC) system, all aligned with ISO/IEC 17025, International Laboratory Accreditation Cooperation (ILAC) Guidance Document ILAC-G24, and other relevant International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standards.** With these practices in place, frequent calibrations at intervals of ten years or less pose more significant risks than advantages.

Figure 8: Multiple Load Cells that Can be Used for Various Checks

In-situ checks offer significant advantages because the load cell is tested under identical mechanical conditions, preserving critical factors such as machine rigidity, levelness, plumbness, squareness, and torsional characteristics. By contrast, these conditions can vary when comparing results between different machines, potentially introducing additional mechanical errors and affecting measurement consistency. Regular use of one or more load cells in this manner provides an effective means to verify machine stability and detect changes in applied forces without requiring full disassembly or recalibration.

Note: *Intra-laboratory comparisons, cross-checks, and in-situ weight checks are valuable tools for monitoring the performance of* ***deadweight force machines****; however, they are not a substitute for the initial calibration of the weights by National Metrology Institutes (NMIs) or accredited laboratories, which is necessary to achieve low measurement uncertainties and maintain traceability to the International System of Units (SI).*

While in-situ weight checks and cross-machine comparisons provide valuable point-in-time monitoring, broader statistical tools such as control charts offer continuous oversight of machine stability over time.

Figure 9: A Control Chart Comparing the mV/V Output of One Load Cell in Three Different Deadweight Force Machines Over Time

Control charts are vital tools for ensuring measurement assurance and maintaining metrological traceability. These statistical instruments provide real-time insights into process performance. They allow organizations to monitor measurement variability, identify abnormal patterns or trends, sustain process stability, and build confidence in their measurement systems.

By visualizing process behavior, control charts help distinguish between inherent process variation and significant anomalies that require corrective action. They function as an early warning system, alerting users when measurements exceed established control limits.

Figure 9 illustrates a control chart created using one load cell and multiple **deadweight force machines**, verifying that each machine yields consistent results. This chart represents an intra-laboratory comparison at Morehouse, specifically force intercomparisons between machines. In addition to intra-laboratory checks, cross-checking can be a helpful tool, as a technician may do a quick, undocumented check or verification check to ensure machine agreement.

Cross-checking between machines involves comparing the forces generated by two or more deadweight systems at specific points to ensure consistency within their combined uncertainties. It might occur if a technician questions a load cell's behavior in one machine and then uses another machine at the same force point to see if the results match.

Intra-laboratory comparisons are formal, documented exercises to validate internal consistency and competence; cross-checks are simpler, and routine or sporadic checks between machines confirm agreement and detect problems quickly.

Both tools allow internal consistency monitoring, help ensure measurement integrity, and support compliance with international quality standards.

According to ILAC-G24:2022, laboratories must justify and periodically review equipment recalibration intervals through one or more structured approaches (Section 6). While deadweight primary standards have repeatedly demonstrated exceptional long-term mass stability through studies by NIST, NPL, and other NMIs, reliance solely on historical data is insufficient to meet the complete requirements of ILAC-G24. **Laboratories must supplement this evidence with a documented methodology, such as control charting, in-use time monitoring, or statistical analysis, as outlined in Sections 6.1 through 6.7 of ILAC-G24 [7].**

The selection of this method, per Section 4.8, must be justified and maintained as part of the laboratory's quality documentation. ILAC-G24 also emphasizes the implementation of intermediate checks (Sections 4.9 & 4.10) to ensure equipment remains within performance specifications throughout extended intervals [7].

These checks may include force intercomparisons between machines, as mentioned earlier, replication of measurements with control instruments, and routine monitoring of environmental factors. When correctly implemented, such practices satisfy the intent of ILAC-G24 while preserving the integrity of highly stable systems like **deadweight force machines**.

These practices align directly with ISO/IEC 17025:2017, particularly in equipment control and performance verification. Clause 6.4.7 of ISO/IEC 17025:2017 requires laboratories to establish and maintain a calibration program that maintains confidence in the calibration status; meanwhile, Clause 6.4.10 mandates intermediate checks when necessary to confirm ongoing performance. Moreover, Clause 7.7.1 requires statistical techniques and routine monitoring to ensure the validity of results, including interlaboratory comparisons and proficiency testing (Clause 7.7.2). Clause 6.5 further mandates metrological traceability of all measurement results, including those produced by in-house calibration systems such as **deadweight force machines** [8].

To fully meet ILAC-G24 and ISO/IEC 17025 requirements, laboratories utilizing deadweight primary standards should **maintain control charts**, **participate in proficiency and/or interlaboratory comparisons**, and **document internal verification processes**. These actions confirm that measurement performance remains within acceptable bounds, reduce the risk of undetected drift, and validate extended calibration intervals without unnecessary and potentially harmful teardown of the system.

To adhere to this ISO/IEC 17025, Section 7.7 requirement, while maintaining the integrity of deadweight primary standards, laboratories likely should follow best practices such as:

1. Implement automated systems to apply and remove weights individually, reducing handling errors and enhancing repeatability.
2. Maintain rigorous environmental control (temperature, humidity, air density) to minimize variability in air buoyancy corrections.
3. Schedule periodic internal verifications and interlaboratory comparisons to ensure ongoing validation of measurement performance.
4. Setup Statistical Process Control Monitoring using various statistical tools.
5. Employ data acquisition systems capable of capturing multiple readings to provide representative average values over a specified and controlled timing profile, enhancing measurement reliability.
6. Ensure transparent documentation and record-keeping of environmental conditions, calibration procedures, and equipment performance checks to demonstrate continuous compliance and traceability.

Note: Morehouse automated ***deadweight force machines*** *are either already capable of implementing all these practices or allowing end-users to implement all these practices by purchasing the appropriate tools. While several manufacturers of environmental logging equipment exist, we use and recommend Vaisala.*

Some other manufacturers have built all types of machines that may be inadequate or have shortcomings in the overall machine design, so we have compiled a list of recommended attributes necessary for meticulous and robust deadweight force calibration machines:

1. Use corrosion-resistant materials, particularly stainless steel, to prevent deterioration and maintain weight accuracy. Plated weights are also acceptable, as stainless steel can be more costly.
2. Automated individual weight application and removal to prevent shock loading and operator-induced variability.
3. Flat lifting surfaces might be needed for weights if conical lifting surfaces cannot overcome the friction required for self-alignment and can induce swaying. Weights can even see-saw on conical surfaces if the center of gravity is too high and the diameter is large.

4. Air bladder systems are used to gently lower weights and mitigate shock effects. The Morehouse proprietary lift system eliminates all pneumatic/hydraulic cylinders and requires no scheduled maintenance for the machine's life.
5. A robust yoke design, allowing for multiple force-measuring instrument sizes and capacities, engineered to prevent fatigue and mechanical failure.
6. The strategic arrangement of weights, typically with the largest at the top, to maintain stability and accuracy.
7. Eliminate the use of all hydraulics. Any leaks onto the weights will require complete dismantling to clean the machine properly. Even a few drops of oil can significantly impact the **measurement uncertainty**.
8. The machine's frame should not be built based on strength. Instead, it should be overbuilt to reduce deflection throughout. As the weights are added or removed, any machine movement will cause swaying or touching of the weights. High deflection can also cause parts of the machine to act like a spring and bounce up and down.
9. Advanced automated controls enable precise timing profiles and loading sequences, conforming to industry standards like ISO 376, which require uniform intervals between successive loadings. Such automation enhances repeatability, minimizes human error, and provides consistent data acquisition.

When **deadweight force machines** are thoughtfully designed with these attributes and maintained under controlled conditions, they provide unmatched accuracy and long-term stability in force measurement. However, even the most meticulously engineered systems are vulnerable to disruption when subjected to unnecessary handling or disassembly. Despite the precision and durability built into high-end machines like those from Morehouse, removing weights introduces many potential risks that can compromise performance. It is, therefore, essential to understand the implications of weight removal and why minimizing such interventions is necessary.

Risks Associated with Removing Weights:

Frequent removal of weights from **deadweight force machines** for external calibration can introduce unnecessary risks, potentially compromising the machine's accuracy and stability. Mechanical disturbances, damage, or contamination occurring during transport or handling may lead to shifts in mass values or surface damage, affecting the accuracy of subsequent calibrations. The integrity of the deadweight system is best preserved by minimizing weight handling, thereby reducing calibration drift and enhancing long-term stability.

The National Institute of Standards and Technology in the USA (NIST) performed periodic maintenance and teardowns of their **deadweight force machines**, notably their 498 kN machine. These teardowns, conducted in 1971 and again in 1989, provided valuable insights into the system's long-term stability. Upon disassembly, NIST conducted detailed mass determinations of the individual weights removed; comparative analyses of these weights across years revealed minimal mass variations, typically within measurement uncertainties, demonstrating outstanding long-term stability. A Euramet comparison (EURAMET.M.M-S7) for 500 kg Mass Standards showed better stability than 0.000278 % over several years [9].

The precise engineering, robust materials, and careful handling contributed significantly to the observed minimal wear and negligible mass changes. Such findings underscore the importance of maintaining the integrity of these highly precise systems.

Beyond the technical risks of removing and recalibrating weights, a substantial financial and logistical burden is also tied to full-scale teardowns of **deadweight force machines**. Even when performed by highly experienced national laboratories, the process requires significant planning, heavy lifting equipment, specialized refurbishment, and considerable downtime. To illustrate the extent of this undertaking—and why it should be avoided unless necessary, it is helpful to examine a high-profile example from NIST, where one of the world's largest and most precise **deadweight force machines** underwent a full restoration.

Expensive Teardown and What Is at Risk

In 2014, NIST initiated a significant teardown and restoration of its 4.45 MN (1 million pounds-force) deadweight machine, the largest in the world. This process was completed in 2016 and marked the first significant overhaul since the machine's construction in 1965. Their key findings and repairs performed can be summarized as follows:

1. **Material Galling**: The primary reason for the teardown was to address material galling in key structural components within the stainless-steel weight stack. Galling is a form of wear caused by friction, leading to the fusion of surfaces, which can cause mechanical failures.
2. **Disassembly and Inspection**: The weight stack, consisting of 19 nearly identical stainless-steel discs, was disassembled, with each disc weighing 50,000 pounds (about 22,696 kg). During the disassembly, previously suspected damage in conical contact joints was confirmed, particularly on the bottom hub plates and pick-up studs of some weights.
3. **Repair and Refurbishment**: The damaged components were remachined and treated with a solid lubricant to prevent future galling. The weights were recalibrated to ensure precision in force generation.
4. **Reassembly and Testing**: The machine was reassembled and tested after refurbishment. This process involved massive equipment, including 30-ton cranes and large air hammers.
5. **Calibration and Accuracy (No Change in Forces Realized)**: Previous measurements made with the machine were unaffected despite the damage. The restoration ensured that the machine could continue to provide precise force calibrations for load cells used in various industries, such as aerospace and construction.
6. **Validation and Comparisons**: The machine's accuracy was validated through repeated measurements and international comparisons, which demonstrated agreement with other standards and reinforced confidence in the integrity of the forces realized by the machine.

This teardown was a massive effort involving years of planning, heavy machinery, and expert-level work to repair and reassemble the system. In the end, even with signs of wear, the machine’s accuracy hadn’t changed—a powerful reminder that these systems are built for the long haul. When designed and maintained properly, **deadweight force machines** can stay reliable for decades without needing disruptive or costly overhauls.

Considering the decades of demonstrated stability, the significant risks introduced by unnecessary weight handling, and the substantial cost of dismantling these machines, it is clear that deadweight systems do not require frequent recalibration absent specific evidence of instability.

Common Sense Preventative Maintenance Practices for Deadweight Systems

While the exceptional stability of deadweight primary standards minimizes frequent disassembly or recalibration, it does not eliminate the need for routine maintenance.

Routine preventative maintenance is essential to preserving the accuracy and longevity of these critical systems. ISO/IEC 17025:2017, specifically Clause 6.4.13.g, requires laboratories to maintain equipment to ensure its functionality and integrity [8].

In practice, this means keeping deadweight force machines clean, ensuring they remain level, verifying proper environmental controls, and periodically checking for any signs of corrosion, mechanical wear, or contamination. Surfaces must be kept free of excess dust and debris, which can introduce friction or alter mass distribution.

All structural loading elements should be inspected regularly to confirm that they are level and properly aligned. The air lines should be checked for leaks if the machine is pneumatic. Gears, screws, or drive mechanisms should be lubricated at appropriate intervals according to the manufacturer's recommendations. Visual inspection of loading surfaces and the surrounding area should occur with every calibration. Environmental monitoring devices (**temperature**, humidity, and air density) should be calibrated appropriately to ensure accurate air buoyancy corrections.

Note: The need to monitor humidity and air density can be eliminated if the ***measurement uncertainty*** *budget includes allowances for variations and provides supporting evidence of these variations.*

It is considered best practice to perform these maintenance checks at defined intervals, to document findings, and to address any anomalies immediately. If anomalies could impact measurement results, additional SPC checks should be performed to confirm continued system performance.

Skipping or overlooking these seemingly simple tasks can lead to cumulative errors over time, undermining the system's exceptional performance and risking nonconformities during audits. Proper maintenance complements long-term stability studies and is vital to any force laboratory's quality assurance system.

Conclusion:

Calibration intervals for deadweight force standard machines should be determined by empirical stability data rather than arbitrary timeframes like every four or five years. Leading metrological agencies emphasize that no one-size-fits-all schedule exists; calibration frequency should reflect each machine's performance history and long-term stability.

Relying on measured data, such as historical drift, control charts, and interlaboratory comparisons, allows laboratories to make informed, evidence-based decisions. This approach meets the intent of ISO/IEC 17025 and ILAC G24. It helps avoid the unnecessary risks, costs, and disruptions associated with frequent recalibration or teardown. By basing recalibration decisions on observed performance over time, laboratories can maintain confidence in results while minimizing avoidable downtime and expenses.

Empirical evidence from multiple NMIs supports the exceptional long-term stability of well-engineered deadweight force machines. Adopting automated systems, ensuring proper handling, and maintaining robust environmental controls further enhance stability, reliability, and compliance. As confirmed by NIST's teardown analysis, these practices also help safeguard against errors introduced by unnecessary manual interventions.

Numerous scientific community references support ongoing internal checks, comparison results, and statistical process control programs in place of repeated disassembly or recalibration of the masses. As one experienced United Kingdom Accreditation Service (UKAS) assessor aptly said, *"The worst thing you can do to a working deadweight machine is take it apart."* With proper design, maintenance, and monitoring, these machines remain the most accurate and dependable force calibration standards.

References

[1] ASTM International, *ASTM E74-18: Standard Practices for Calibration and Verification for Force-Measuring Instruments*, West Conshohocken, PA, 2018.
Available: https://www.astm.org/e0074-18.html

[2] International Organization for Standardization, *ISO 376:2011 – Metallic Materials — Calibration of Force-Proving Instruments Used for the Verification of Uniaxial Testing Machines*, Geneva, Switzerland, 2011.
Available: https://www.iso.org/standard/44668.html

[3] R. J. Bartel, "Uncertainty in NIST Force Measurements," *Journal of Research of the National Institute of Standards and Technology*, vol. 110, pp. 1–16, 2005.
https://nvlpubs.nist.gov/nistpubs/jres/110/6/j110-6bar.pdf

[4] Standards Australia, *Calibration and Classification of Force-Measuring Systems*, AS 2193-2005 (R2017), Sydney, Australia, 2005.
Available: https://www.standards.org.au/search-results?query=AS%202193

[5] ASTM International, *ASTM E74-18*, Appendix X1.5, citing National Physical Laboratory (NPL), United Kingdom.
Available: https://www.astm.org/e0074-18.html

[6] A. Knott, *Validity Extension Justification*, Internal Document, National Physical Laboratory (NPL), UK, Aug. 2023. [Unpublished].

[7] ILAC and OIML, *ILAC-G24:2022 / OIML D 10:2022 – Guidelines for the Determination of Recalibration Intervals of Measuring Equipment*, 2022.
Available: https://ilac.org/publications-and-resources/ilac-guidance-series/

[8] International Organization for Standardization, *ISO/IEC 17025:2017 – General Requirements for the Competence of Testing and Calibration Laboratories*, Geneva, Switzerland, 2017.
Available: https://www.iso.org/standard/66912.html

[9] EURAMET, "Comparison of 500 kg Mass Standard," *EURAMET.M.M-S7*, July 2021.
Available: https://www.bipm.org/documents/20126/48150857/EURAMET.M.M-S7.pdf/

Formal Acknowledgements

The author sincerely appreciates Andy Knott, Klaus Jaeger, Mark Jones, and Wayne Hayward for their constructive feedback and technical guidance, which greatly enhanced the quality of this paper.