BIPM Capacity Building & Knowledge Transfer Program
2022 BIPM - TÜBİTAK UME Project Placement

REPORT

Project Name	CALIBRATION OF MASS STANDARD AND DETERMINATION OF DENSITY OF THE MATERIALS USED AS MASS STANDARD.
Description	The project aim at improving the participant capability in the calibration of mass standard and determination of density of the materials used as mass standard so as to lender reliable metrological traceability to underpin scientific activities on health, research and industries.
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Motivation & Introduction
Mass Measurement at primary level should be precise and reliable. This was the main reason why this project was chosen, so that it can help the National Metrology Institute of Tanzania for continuous improvement of their measurement processes and capabilities at primary level in Mass Metrology Laboratory.
Tanzania Bureau of Standard is the National Metrology Institute of Tanzania with the core objective of the realization, maintenance and dissemination of SI units. The need for this project came from the desire to increase knowledge and expertise in the area of mass metrology, to support regional and international metrological equivalence in providing accurate metrological traceability to align with the sustainable development goals.
The main objective of this project were:-

- Accurate Calibration of Mass Standards.
- Accurate determination of densities of materials used for mass standards.
- Quantification of uncertainty of measurements in mass standard and densities of the materials used.
- Calculation of the True mass and Conventional Mass.
- Dissemination of the SI unit of mass from the National Prototype of Kilogram (NPK).
- Basics of Kibble balance project developed in UME.

Research
My research was based on theory and practical approach. The following were the important things considered prior the calibration of mass standards.

- Validated Calibration method i.e Laboratory developed method or Standard method.
- Traceable reference mass standard i.e with high OIML accuracy class.
- Mass standard to be calibrated i.e with lower OIML accuracy class compared to reference standard.
- Stable mass comparator i.e be chosen depending on the capacity of the mass to be calibrated. It shall have a documented history on performance test.
- Controlled Environmental Condition i.e the facility shall have suitable equipment for environmental control for example Thermo-hygrometer and Barometer.
- Trained personnel for performing the activities.

Equipment used during the project

- Automatic Mass Comparator.
- Manual Mass Comparator
- Vacuum Comparator
- Density Hydrostatic System
- Magnetic Susceptibility Meter
- Thermo-hygrometer and barometer





Performance Evaluation of the Mass Comparators
The following test are performed periodically to check a proper functionality of a mass comparator to ensure reliability of measurements results. The history of performance test is well documented for traceability and decision making.

- Linearity (Weighing performance) test
- Discrimination test

For better performance of the mass comparator the resolution shall be less than or equal to three-quarter of the repeatability.

a) Selection of Weighing Format

There are several weighing format that are employed during mass standard calibration i.e ABA format, ABBA format and Subdivision/Multiplication format.

In primary level calibration process we normally use the ABBA weighing format because it can provide a small standard deviation of the comparison with less number of cycles as well as weighing difference between test and reference weight.

b) Determination of True Mass (under normal air conditions and under vacuum), Conventional Mass

- **True Mass under normal air conditions (m_T)**

  Is the air buoyancy corrected Mass. It is given by the following formula.

$$m_T = m_{TR} + \rho_a (V_T - V_R) + \Delta m$$

where:

m_T = True Mass

m_{TR} = True Reference Mass (From the Calibration Certificate)

ρ_a = Density of air

V_T = Volume of Test Mass

V_R = Volume of Reference Mass

Δm = Mass Difference (average from the weighing cycles ABBA)

- **Conventional Mass (m_{ct})**

  For a weight taken at a reference temperature (tref) of 20 °C, the conventional mass is the mass of a reference weight of a density (ρref) of 8 000 kg m^{-3} which it balances in air of a reference density (ρ_0) of 1.2 kg m^{-3}.

  Assumptions:

  - Air Density = 1.2 kg/m^3
  - Density of reference mass = 8000 kg/ m^3

An approximate formula for conventional mass

$$m_{ct} = m_{cr} + (\rho_a - 1.2)*(V_T - V_R) + \Delta m$$

Where:

m_{ct} = Conventional Mass

m_{cr} = Conventional Reference Mass (From the Calibration Certificate)

ρ_a = Air Density

V_T = Volume of Test Mass

V_R = Volume of Reference Mass

Δm = Mass Difference (average from the weighing cycles ABBA)

Conventional Mass from the True Mass, Exact formula from the definition

$$m_{ct} = (m_n + \delta m_T)*\frac{(1- \rho_a/\rho_T)}{(1-\rho_a/\rho_R)} - m_n = (m_n + \delta m_T)*\frac{(1- 1.2/\rho_T)}{0.99985} - m_n$$

Where:

m_{ct} = Conventional Mass

δm_T = The error in true Reference Mass (From the Calibration Certificate)

ρ_a = Air Density

ρ_T = Density of Test Mass

ρ_R = Density of Reference Mass

m_n = Nominal Mass under test

- **Mass in Vacuum Formula**

$$m_{mc} = m_{NPK} + \Delta m$$

Where:

m_{mc} = mass in vacuum

m_{RNPK} = Reference mass of the NPK (National Prototype of Kilogram)

Δm = Mass Difference (average from the weighing cycles ABBA)

c) Air Density

In primary level laboratory and high OIML class calibration of weights, it is recommended to use the revised formula for density of moist air (CIPM – 2007) which depends on the following measured parameters, Temperature, Relative Humidity Air Pressure and Mole fraction of carbon dioxide in air.

CIPM 2007 air density formula

$$\rho_a = \frac{PM_a}{ZRT} [\ 1 - Xv\ (1 - M_v/M_a)]$$

An approximate formula for calculating density of air can be used in low OIML class calibration of weights, its given by:-

$$\rho_a = \frac{0.34848\ P - 0.009\ (hr) * EXP^{(0.061t)}}{(273.15 + t)}$$

d) Buoyancy Correction

Buoyancy correction for True Mass (m_T), it is given by

$$BC_T = \rho_a\ (V_T - V_R)$$

Buoyancy correction for Convectional Mass (m_{ct}), it is given by

$$BC_{ct} = (\rho_a - 1.2)*(V_T - V_R)$$

e) Correction Factor due to difference in Temperature of Reference and Test Weights

Volume of the materials are always reported at 20 ^{0}C, so at different temperature we should find the effect of rise in temperature. It is given by:-

$$C_t = \rho_a\ (t - t_0)*(V_{T0}\gamma_T - V_{R0}\gamma_R)$$

Where:

t_0=20^{0}C

t = average temperature during calibration

ρ_a = Air Density

V_{T0} = Volume of Test mass at 20 ^{0}C

V_{R0} = Volume of reference mass at 20 ^{0}C

γ_T = Volume Expansion of Test mass

γ_R = Volume Expansion of Reference Weight

Note:

Volume Expansion (γ) = 3* Linear Expansion (α)

f) Correction due to difference in center of mass position between the reference and test weights

In every one meter when you move upward, acceleration due to gravity decreases by -3* 10^-7/m. The difference in the center of mass positions of the reference and test weights affect the measurement results during calibration so that it is better to account its contribution.

Formula

$$C_{\Delta h} = (m_n - \rho_a * V_R) * \partial * (Z_R - Z_T)$$

Where:

m_n = Nominal mass

V_R = Volume of reference mass

Z_R = Height of standard mass from the center of mass position

Z_T = Height of test mass from the center of mass position

∂ = -3* 10^-7/m

g) Uncertainty Calculation in Mass Standard Calibration

- **True Mass Uncertainty Components**

$$uc_{mT} = \sqrt{\ u^2 m_{TR}/k^2 + u^2{}_d + u^2 BC_T + u^2 \Delta m + u^2 res}$$

where

$$uBC_T = \sqrt{\ (V_T - V_R)^2 * u^2\rho_a + \rho^2{}_a * (u^2{}_{VT} - u^2{}_{VR})}$$ - Uncertainty of buoyancy correction under True mass.

The reason for the negative sign of the term $\rho^2_a\, u^2VR$ is that usually the volume of a mass standard is determined only once, so that the air buoyancy corrections of consecutive comparisons are correlated.

- **Conventional Mass Uncertainty Components**

$$uc_{mct} = \sqrt{u^2m_{cr}/k^2 + u^2_d + u^2BC_{ct} + u^2\Delta m + u^2res}$$

where

$$uBC_{ct} = \sqrt{(V_T - V_R)^2 * u^2\rho_a + (\rho_a - 1.2)^2 * (u^2_{VT} - u^2_{VR})}$$ – Uncertainty of buoyancy correction under Conventional mass

- **Conventional mass from True Mass Uncertainty Component**

$$uc_{mct} = 1/0.99985\sqrt{u^2c_{mT} + u^2_d + 1.2^2 * u^2_{VT}}$$

- **Mass in Vacuum uncertainty components**

$$uc_{mv} = \sqrt{u^2m_{TR}/k^2 + u^2_d + u^2\Delta m + u^2res}$$

h) Density of materials used as mass standard

Hydrostatic comparison method using distilled water, the system developed at TUBITAK – UME.

Formula

$$V_T = \frac{(m_{TR} - \rho_a V_R) - (\rho_{al} V_r - m_r) + (\Delta m_a - \Delta m_l)}{\rho_l - \rho_a}$$

Where:
m_{TR} = True Reference Mass
ρ_a = Air Density
ρ_{al} = Air Density in water comparison
Vr = Volume of reference weight used during comparative measurements with the test in water and reference in air
m_{tr} = True Reference Mass used during comparative measurements with the test in water and reference in air
Δm_a = Mass difference in air
Δm_l = Mass difference in water and air comparison
ρ_l = Water Density
V_T = Volume of Test Mass

Uncertainty Formula

$$uc_{VT} = 1/(\rho_l - \rho_a)\sqrt{u^2m_R + (-V_R + V_T)^2 * u^2\rho_a + \rho^2_a * u^2_{VR} + V^2_r * u^2\rho_{al} + \rho^2_{al} * u^2_{Vr} + u^2\Delta m_a + u^2\Delta m_l}$$

For Weight class E0, E1 & E2 it is better to report the True Mass, Conventional Mass and Volume of the materials used as mass standard in one calibration certificate so as to be able to reduce the measurement uncertainty as well as to have reliable results.

Volume calculation using conventional mass (m_{ct})

Formula

$$V_T = \frac{(m_{cr} - m_{ct}) * 0.99985 + 1.2 * V_R - \rho_l * V_R) + \Delta m_l}{(1.2 - \rho_l)}$$

Results

True Mass Value

Nominal Mass	True Mass	Uncertainty (±)
10 kg	10kg +13,5 mg	1,1 mg

Conventional Mass Value

Nominal Mass	Conventional Mass	Uncertainty (±)	MPE (±) E2
10 kg	10kg + 3,2 mg	1,0 mg	8,0 mg

Volume and Density Value

Nominal Mass	Volume (cm^3)	Uncertainty (±) (cm^3)	Density (kg/m^3)	Uncertainty (±) (kg/m^3)
10 kg	1258,6	0,2	7946,0	1,5

Conclusions and Future Work

My project placement at TUBITAK UME help myself to develop in-depth understanding about mass metrology practices at primary level laboratory. The knowledge I gained while doing my project will share with my colleagues for continuous improvement of mass metrology laboratory in our institute. This knowledge will also facilitate the following objective to be achieve timely and consistently, (i) Improvement of our measurement capability in mass metrology (CMC's), (ii) Involvement in Key and Supplementary comparisons (iii) Publishing our CMCs in the BIPM KCDB and (iv)To become a full member in the CIPM MRA.

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References

1. OIML R 111-1 2004 (E).
2. Comprehensive Mass Metrology, Manfred Kochsiek & Michael Glaser book.
3. Precision Mass Measurement – Report on Progress in Physics, M Glaser & M Borys 2009.
4. JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement.
5. VC1005 manual.
6. Revised Formula for the density of moist air (CIPM – 2007).