IMEKO 24th TC3, 14th TC5, 6th TC16 and 5th TC22 International Conference
11 – 13 October 2022, Cavtat-Dubrovnik, Croatia

DISSEMINATING FROM THE KIBBLE BALANCE TO INDUSTRY

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Abstract:

The SI unit of mass, the kilogram, was redefined on 20 May 2019. The new definition is made in terms of the fixed numerical value of the Planck constant, *h*. The kilogram no longer takes traceability from the International Prototype of the kilogram and therefore a new system of traceability and dissemination must now be established to ensure reliable and repeatable measurements for industry. Two methods of dissemination will be compared and evaluated.

Keywords: traceability; Kibble balance; SI; consensus value; mass standards

1. INTRODUCTION

The new definition of the kilogram has created an exciting opportunity for National measurement laboratories around the world to contribute to a “consensus value” currently being used to maintain and disseminate the kilogram. It also brings about the need to re-establish and redesign the traceability chain.

From 1889 the kilogram was defined as the mass of the International Prototype of the kilogram (IPK) maintained by the Bureau International des Poids et Mesures (BIPM) in Sèvres, France [1]. Following the ratification of the revision of the SI at the 26th General Conference on Weights and Measures (CGPM), the kilogram was officially redefined in terms of the Planck constant, *h*. This new definition can be realised via two different methods, one being the X-ray crystal density technique (XRCD) [2] the other the Kibble balance [3]. Prior to the redefinition, traceability was established to the IPK via platinum-iridium kilogram standards, the UK’s standard kilogram being copy no. 18 of the IPK. Traceability in the UK was established via a hierarchical system of measurements starting with kilogram 18.

The National Physical Laboratory (NPL) is developing a next generation Kibble balance. Due to the nature of the new definition and the kilogram realisation experiments, it is possible to access the SI unit of mass at any value. The NPL next generation Kibble balance will operate at around 200 g. Given the current hierarchical approach starting at one kilogram and working down, we need to develop a new system that works from 200 g upwards (and downwards), whilst maintaining an appropriate level of uncertainty for our customers.

2. DISSEMINATING FROM THE KIBBLE BALANCE

There is a need to optimise the process of dissemination whilst minimising uncertainty and there are multiple ways of disseminating. Each method must be individually evaluated and compared, two of the proposed methods are shown below.

The Kibble balance will primarily operate using 200 g tungsten masses. The material of these masses adds an extra element of difficulty as it is necessary to compare them to stainless steel equivalent masses in vacuum. The two proposed dissemination methods, Method A and Method B, are shown in Figure 1 and Figure 2 respectively.

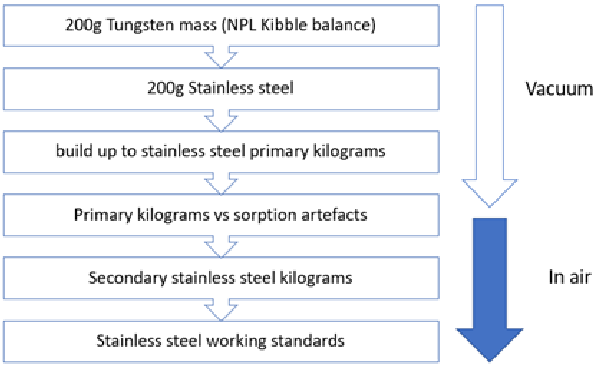

Figure 1: Conventional Method A

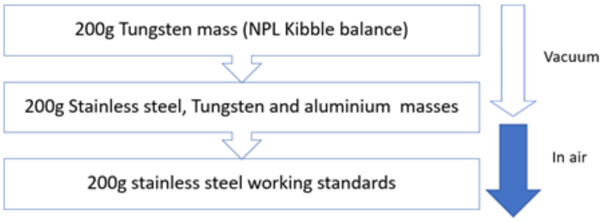

Figure 2: Simplified Method B

For conventional Method A shown in Figure 1, it is necessary to use sorption artefacts to establish the correction needed when moving from air to vacuum. The sorption artefacts have the same mass as their equivalent stainless-steel artefacts but have a significantly larger surface area, meaning we can use the surface area difference to calculate a sorption correction which can then be applied to the stainless-steel kilograms when moving from vacuum to air or vice versa [4].

NPL proposes using a simplified method, Method B as shown in Figure 2. This method disseminates directly to 200 g without the need to build up to kilogram standards in vacuum. By using simplified Method B over conventional Method A we can reduce the number of weighings needed to be done in vacuum which saves a significant amount of time as the artefacts need longer to stabilise. The fewer steps needed to get from the Kibble balance to our working standards could reduce the uncertainty of the traceability chain. When completing customer jobs of 200 g or less it will no longer be necessary to sub-divide from 1 kg, it will now be possible to sub-divide from lower down the traceability chain reducing the number of measurements, uncertainty and time needed to complete customer jobs. The majority of our high accuracy customers require calibrations below one kilogram.

For simplified Method B, 200 g tungsten masses will be directly compared to other 200 g masses of different materials, namely stainless steel and aluminium. By cycling between vacuum and air it is possible to calculate a sorption correction relative to stainless steel. The volumes of the tungsten, stainless steel and aluminium will need to be measured to a low uncertainty. Berry and Davidson [4] have shown that metallic masses have similar sorption corrections. Both vacuum-air methods will be evaluated and compared.

3. VACUUM STABILITY

To ensure dissemination Method B works, it is important to ensure that the proposed spherical weights remain stable whilst in vacuum and demonstrate repeatable behaviour when cycling between air and vacuum. Examples of tungsten and aluminium spherical masses are shown in Figure 3.

Tests were carried out to establish how stable tungsten masses were in vacuum compared with equivalent stainless steel masses. The measurements were carried out on a Mettler-Toledo M_one mass comparator with six weighing stations within a vacuum chamber that can be varied in pressure as shown in Figure 4. A vacuum was obtained within the chamber through the use of an oil-free pumping system comprising a Leybold EcoDry M15 piston pump and a Leybold HY.CONE 60 turbomolecular pump [5].


Figure 3: Tungsten and aluminium masses


Figure 4: M_one mass comparator

The chamber was pumped to vacuum, and comparison measurements made over a period of fourteen days. At this point the vacuum pumps were switched off and the vacuum chamber was allowed to return to air at standard laboratory pressure by filling the chamber with filtered laboratory air. The weights were then returned to vacuum and the comparison measurements repeated over a ten-day period. The pressure during the measurements was read using a calibrated MKS Instruments series 900 Micro Pirani vacuum gauge with measured values in the range of 0.007 Pa to 0.01 Pa. The results are shown in Table 1.

Table 1: Results of weight comparisons for different material combinations

Run	**Days in vacuum**	**Tungsten (200 g) vs stainless steel (200DD)**	**Stainless steel (200DD) vs stainless steel (200TD)**
		Linear fit / (µg/day)	**Linear fit / (µg/day)**
1	14	-0.71	0.51
2	10	-0.31	0.25
	Average	-0.51	0.38

The relative vacuum stability of stainless steel against stainless steel and tungsten against stainless steel is shown in Figure 5 and Figure 6 respectively. Comparing tungsten against stainless steel over both runs shows an average relative linear change of 0.51 µg/day for tungsten. In Run 1 the first four measurements were removed from the averages due to balance instability. The mass changes have been deemed acceptable and will be a negligible addition to the overall uncertainty budget.

The repeat measurement Run 2, performed after taking the steel and tungsten weights to air and back to vacuum again, showed that the tungsten weights demonstrate excellent stability when cycled between air and vacuum. The measurements of the mass differences at the end of Run 1 agreed with the mass differences at the start of Run 2 within the weighing uncertainty of 1 µg.

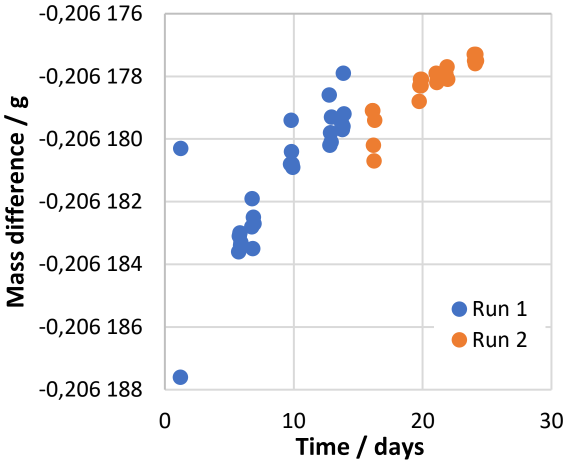

Figure 5: Vacuum stability: stainless steel vs stainless steel

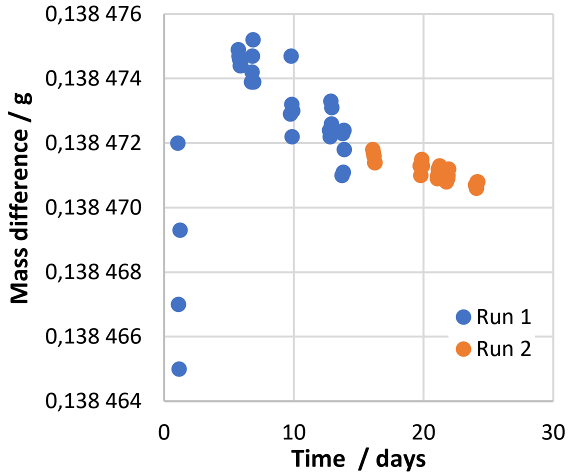

Figure 6: Vacuum stability: tungsten vs stainless steel

4. MAGNETIC PERMEABILITY

It is important to establish the effects of magnetic permeability on the Kibble balance mass standards due to the high magnetic field generated by the balance. NPL's mass department will measure the magnetic properties of the mass standards in collaboration with NPL's magnetics department.

The magnetic susceptibility of spherical stainless steel masses will be measured, and these will be used to evaluate the effects of the magnetic field from the Kibble balance magnets on a material of relatively high magnetic susceptibility. Using this data, we can assess whether tungsten or aluminium, or indeed stainless steel, would be suitable mass standards for use on the Kibble balance.

5. SUMMARY

The SI unit of mass, the kilogram, was redefined on 20 May 2019. The new definition gives NPL the ability to contribute to a consensus value of the kilogram whilst removing the need to realise and disseminate the SI unit of mass from one kilogram downwards. NPL must implement a new measurement hierarchy taking into consideration the challenges of using a new standard. NPL will compare two methods of disseminating the kilogram and decide on the optimum method. Based on the results from Section 3 it is reasonable to suggest that in terms of vacuum stability, tungsten masses would be suitable standards for use on the Kibble balance. Further tests will be carried out to evaluate the stability and repeatability of aluminium and other possible spherical masses.

6. REFERENCES

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