TECHNISCHE UNIVERSITÄT
ILMENAU

50. Internationales
Wissenschaftliches Kolloquium

September, 19-23, 2005

Maschinenbau von Makro bis Nano /

Mechanical Engineering from Macro to Nano

Proceedings

Fakultät für Maschinenbau /
Faculty of Mechanical Engineering

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Andrea Schneider

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Redaktionsschluss: 31. August 2005
(CD-Rom-Ausgabe)

Technische Realisierung: Institut für Medientechnik an der TU Ilmenau
(CD-Rom-Ausgabe) Dipl.-Ing. Christian Weigel
Dipl.-Ing. Helge Drumm
Dipl.-Ing. Marco Albrecht

Technische Realisierung: Universitätsbibliothek Ilmenau
(Online-Ausgabe) ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

ISBN (Druckausgabe): 3-932633-98-9 (978-3-932633-98-0)
ISBN (CD-Rom-Ausgabe): 3-932633-99-7 (978-3-932633-99-7)

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=15745

50. Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
19.-23. September 2005

T. Fehling / T. Fröhlich / D. Heydenbluth

The new Sartorius 1Kg-Prototype Balance for High Precision Mass Determination and Research Applications

ABSTRACT

The 1kg-prototype balance is a result of the technical collaboration between the Sartorius AG and the BIPM. Construction and functionality of the 8-position load alternator are based on the known BIPM FB2-technology. The 1kg-Prototype balance is constructed for highly accurate mass determination and is developed to create and maintain the national mass scale as well as the use for research and development. It permits the weighing of Pt-Ir or stainless steel masses from 100g to 1 kg as well as 1kg silicon spheres or buoyancy artifacts. The complete measurement device is installed inside an enclosed airtight aluminum chamber which can be evacuated to primary vacuum. The load alternator can be loaded comfortably through a quick load-lock device. Additional standard vacuum flanges are freely available for measuring sensors, control purposes and electronic or other connectors. The control unit running the control software allows flexible and easy programming of the required measuring sequences. Routine matter mass calibration as well as complex weighing series could be done. A detailed description of the technical and metrological parameters and possible applications are given.

INTRODUCTION

The development of the 1kg-prototype balance is a collaboration between BIPM/France and Sartorius AG/Germany. When signing the contract Sartorius intended to include its collaboration partner of many years in the field of basic research in weighing technology, the Technical University of Ilmenau/Germany (TUI). This was a good choice, due to the fact that necessary tasks in research works, in construction and design and even the provision of a suitable mass laboratory have taken place in Ilmenau/Thuringia.

When starting the project in 2000 the main task was to reproduce the FB2 prototype balance from the mass section of BIPM [1][2]. Different NMI´s from all over the world would like to use a prototype balance for their own high accuracy mass determination and research applications similar or equal the well known FB2 which is unique. But what does a reproduction mean, what are the main difficulties, what should be complemented and what did Sartorius expect to do in a different way than the people from BIPM? When discussing all details in the mass lab at BIPM two things quickly became clear. First this was the realization that the 8-position loading device was designed perfectly to get the expected performance, but needed to be expanded for the application of measuring 1kg silicon spheres as used for example in the

Avogadro experiment. Second, Sartorius as a seller and manufacturer for analytical balances and high accuracy mass comparators should face the challenge to insert an own weighing system specified for the task of a prototype balance like FB2.

The new 1kg-prototype balance is build for use in the following applications:

- Use as a prototype mass comparator for connection of primary standards of national metrology institutes (called NMIs for short in the following) to national mass standards (kilogram prototype) of the various countries
- Dissemination of the mass scale of NMIs in the range from 1 kg to 100 g
- Measurement of mass (100 g to 1 kg) within the scope of international comparison measurements (key comparisons) and calibrations for government institutes, calibration laboratories and industry according to the attainable uncertainties of measurement given in the CMC tables of the BIPM
- Experimental determination of the air density by comparative weighing of special buoyancy artefacts in air and under vacuum
- Measurement of the mass of 1-kg silicon spheres (also within the scope of the Avogadro project to determine the Avogadro constant and redefine the kilogram as a unit of mass)
- Experiments to study the influence of cleaning procedures and of the effects of sorption and convection on the measurement of mass and to study the long-term stability of mass standards

The construction of the whole unit is a modular one. The 1kg-prototype balance consists of 3 main parts:

1. Enclosure with integrated load alternator and mass comparator
2. Control unit with PC and drive unit
3. Vacuum pumping unit with turbo-molecular pump.

The design of load alternator and measuring system allows easy exchange of the installed weighing system. This has a favorable affect in case of service or scientific research.

The different parts of the 1kg-prototype balance will be presented in detail in the following sections.

ENCLOSURE FOR AIRTIGHT AND VACUUM CONDITIONS

Designing the enclosure, several things had to be taken into accounts which are in contrast to the enclosure of the FB2. First of all the whole equipment of load alternator, weighing cell and special loading device had to be included. The diameter of the designed turntable of the load alternator increased to 555mm due to the fact that silicone spheres of about 94mm diameter have to be carried. If we follow the design of a usual vacuum enclosure which is typical a cylindrical one, we would get an unacceptable outer diameter of the whole bell. This leads to the chosen square of 840 to 940mm.

The enclosure exists of four main parts, which are the bottom plate, the base chamber in the middle, the top cover plate and the cover (tower) for the weighing cell. The four parts are connected each by another HV-compliant with a vacuum seal made of Viton. These parts of the whole enclosure don't need to be dismounted during normal work after first installation. The special kind of upper tower is equipped with a 160mm square quick-lock door to add or remove substitution weights on the upper weighing pan of the balance. The base chamber in the middle is equipped with the same 160mm square quick-lock device, for loading the weights onto the turntable. For this purpose a special external quick load device has been designed (figure 1.). This construction allows easy loading of weights for fast performance of mass comparisons under airtight and especially vacuum conditions. A sensitive handling of expensive and valuable weights during loading procedure without any risk of damage is obtained.

The quick load device is equipped with 3 strain gauge systems set up to take the weight after manual loading on the main carrier. The center of gravity of the weight in relation to a centric position on the carousel can be determined with the 3 mass values from the strain gauge systems. During automatic loading procedure the eccentricity of the weight will be adjusted in x-axis by the movement of the carrier in direction to the carousel, in y-axis by the rotation of the carousel itself. The effect is a pre-centred weight on the carousel ready for mass comparison procedure.

The enclosure is equipped with several standard vacuum flanges on the base chamber for any kind of electrical or mechanical feed through. This allows to implement additional sensors for measuring temperature or pressure for instance. Furthermore the enclosure is equipped with a DN100 vacuum flange for connecting the turbo molecular pump in case of evacuation.

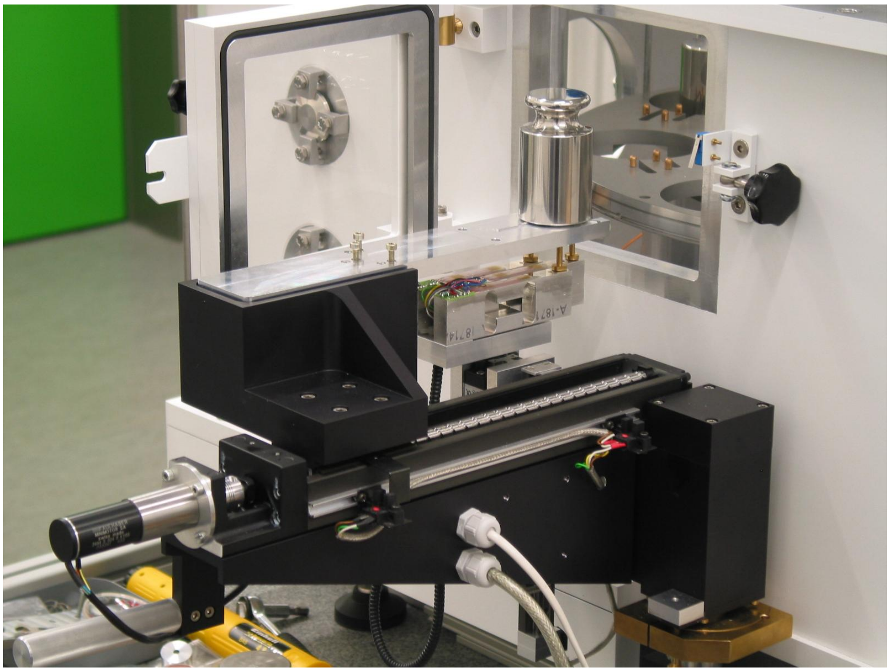


Figure 1: Quick load device with 1kg-weight in front of the vacuum chamber

The complete enclosure was tested from the manufacturer for high vacuum application. The Helium leakage rate is ≤ 10^{-7} (mbar * l) / s. The chosen material for the enclosure is aluminum. This material has the advantage of being absolutely non magnetic and having better thermal conductivity as stainless steel. For having a stable mechanic setup inside the enclosure even under vacuum conditions we needed to calculate the thickness of the base plate accurate. To approve all calculations and being sure that no influence due to deflection could cause difficulties during measurement a finite elements analysis (FEA) calculation has been proceeded at the TUI.

These FEA calculations have been done to ensure the mechanical stability of the enclosure under vacuum conditions a well as the temperature gradients inside the chamber under some different thermal disturbances. The bending of the base plate under vacuum conditions is shown in figure 2. Suppose an ambient temperature gradient of 1K, a case which should normally not occur in a mass laboratory, then the temperature distribution on the outer surface is as shown in figure 3. Inside of the chamber gradients are not grater than some mK in this case.

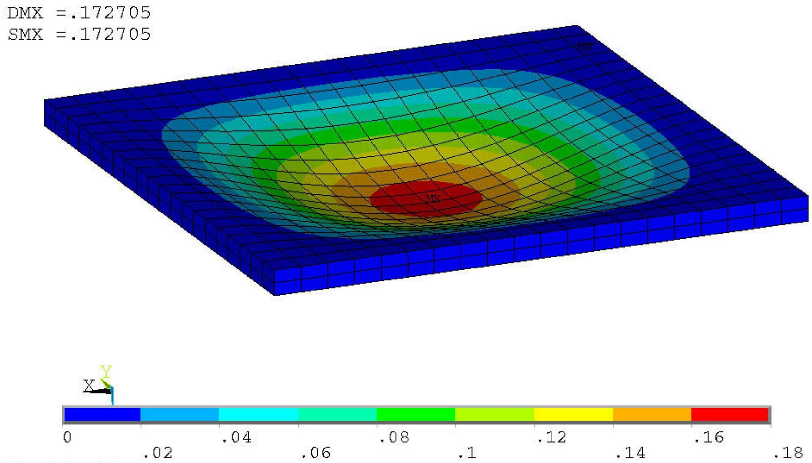


Figure 2: Bending of the base plate of the chamber under vacuum conditions

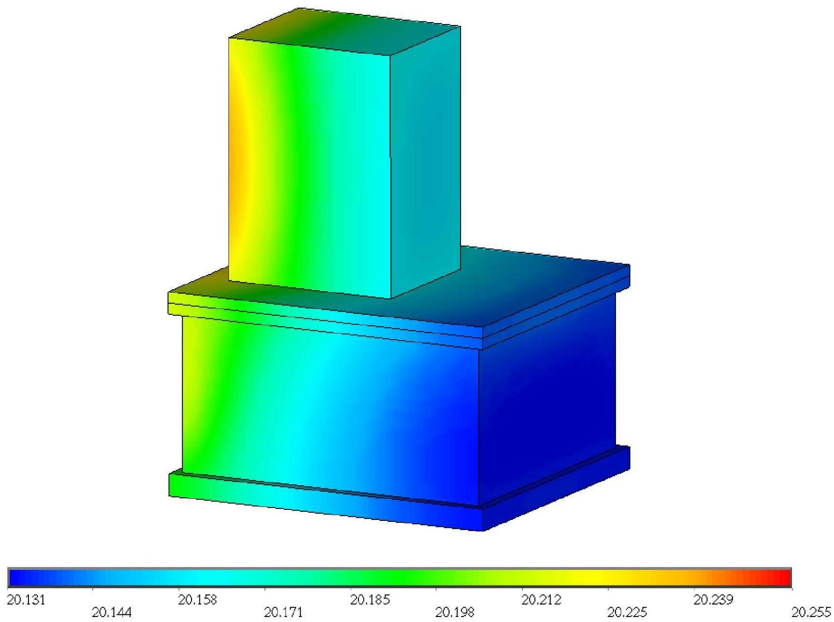


Figure 3: Temperature distribution on the outer surface at a supposed ambient temperature gradient of 1K

THE LOAD ALTERNATOR

The load alternator (figure 4.) is designed similar to the original FB2 one with the main difference in diameter of the turntable. This important increase up to 555mm is necessary to fulfill the made stipulations to carry spherical weights up to 100mm diameter on each position. The demand on providing place for 2 reference weights, 2 buoyancy artifacts and at least 4 test weights is fulfilled with the 8 positions on the turntable. All electrical heat sourcing driving mechanism of the load alternator are located outside the enclosure. The movement of the turntable is done by a thin tungsten wire with a diameter of 0.125mm which is winded up the end face of the turntable 4 times. This is sufficient for all necessary movements during mass comparison between each of the 8 positions.

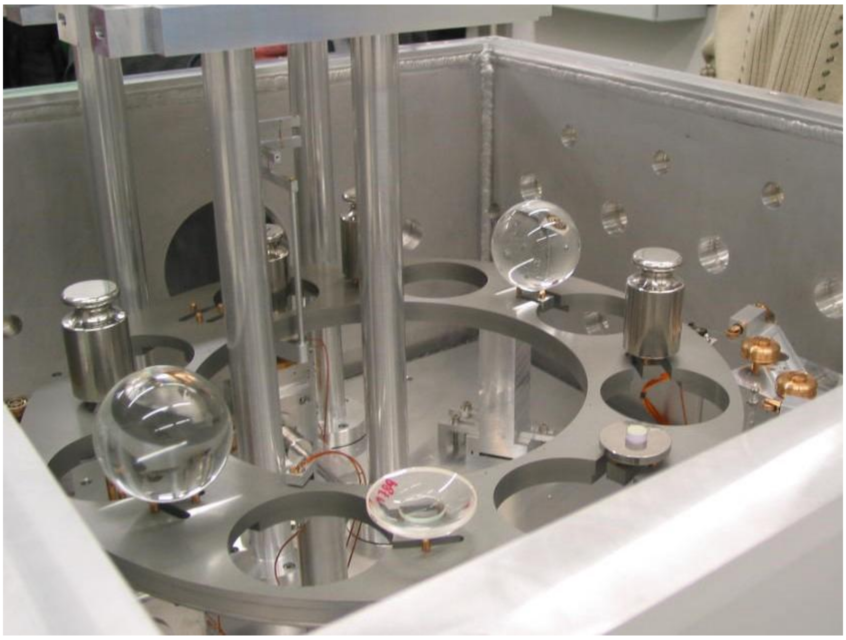
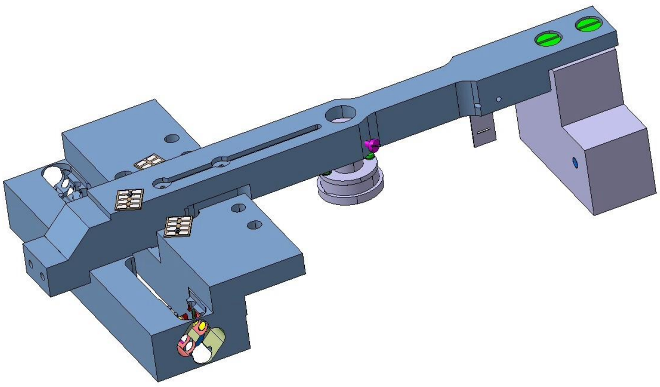


Figure 4: opened base chamber with turntable

THE USED BALANCE

For the required specifications for mass comparison as described in section 6 we need a balance for 1kg maximum load with a readability of 0.1µg. The used balance which has to be developed is based on the commercial 1kg Sartorius Mass Comparator CC1000S-L. This instrument gives us already a readability of 1µg with a reproducibility of less than 1µg (Std.-deviation from 6ABBA-cycles). Several things had to be modified for using this electromagnetic force compensation system for the prototype balance. The weighing cell had to be changed for more sensitivity at the electronic sampling device, given by the optical position sensor of the beam. This has been realized by decreasing the spring constant of the used flexures in the universal joint (figure 6.). A special lever (figure 5.) was designed using the knowledge of Sartorius monolithic manufacturing process. This leads to a minimum of movement of the lever caused by material tension with the result of a reproducible positioning after load change.



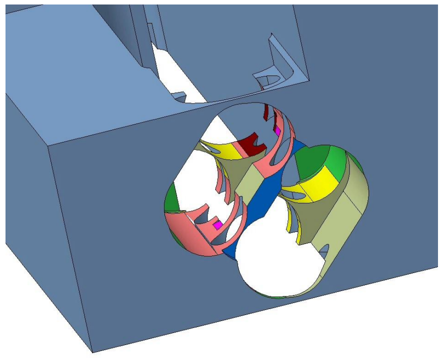


Figure 5: Lever with coil and counterweight **Figure 6:** monolithic universal joint (fixed)

Also the weighing cell had to be modified for use under vacuum conditions. This means for example that no blind holes are allowed and any kind of electric wire has to be changed into a suitable one with special isolation made of PTFE or Kapton.

Knowing the perfect performance of the FB2 equal arm balance which is more or less depending on a constant load device based on the piezoelectric effect we decided to install such a constant load device into the Sartorius weighing cell, too. The piezoelectric transducer (figure 7.) is directly connected to the vertical weighing axis of the balance coupling device. A location where any force due to stressing by weights is been guided to the balance beam. When changing the weights by the load alternator, the feedback loop of the balance controls the installed piezoelectric transducer in between a small range of the electronic weighing range which is shown in figure 8. As the desired result the beam is under the same mechanical stress each time. This causes less creeping effects of the material shown by unstable mass values after load change.

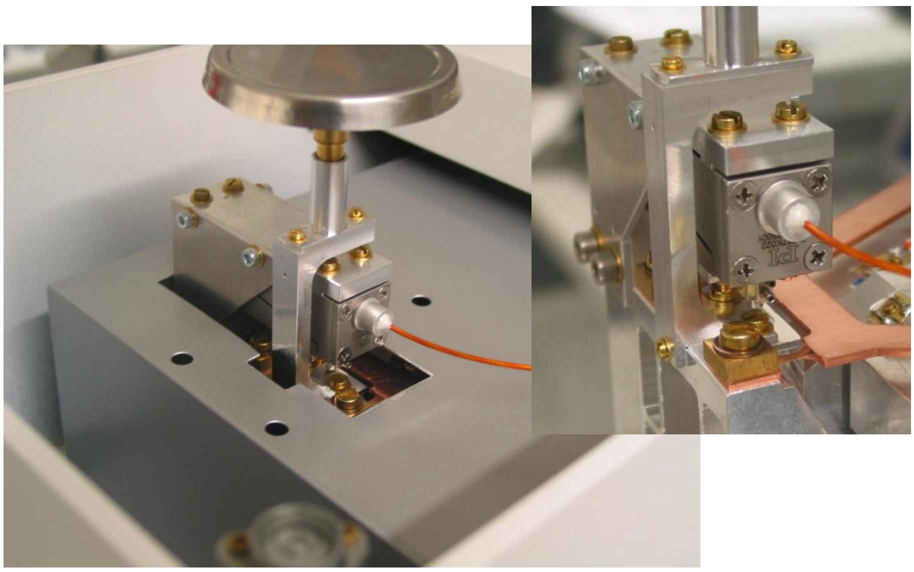


Figure 7: PZT-transducer mounted on the weighing system (detail zoom-in)

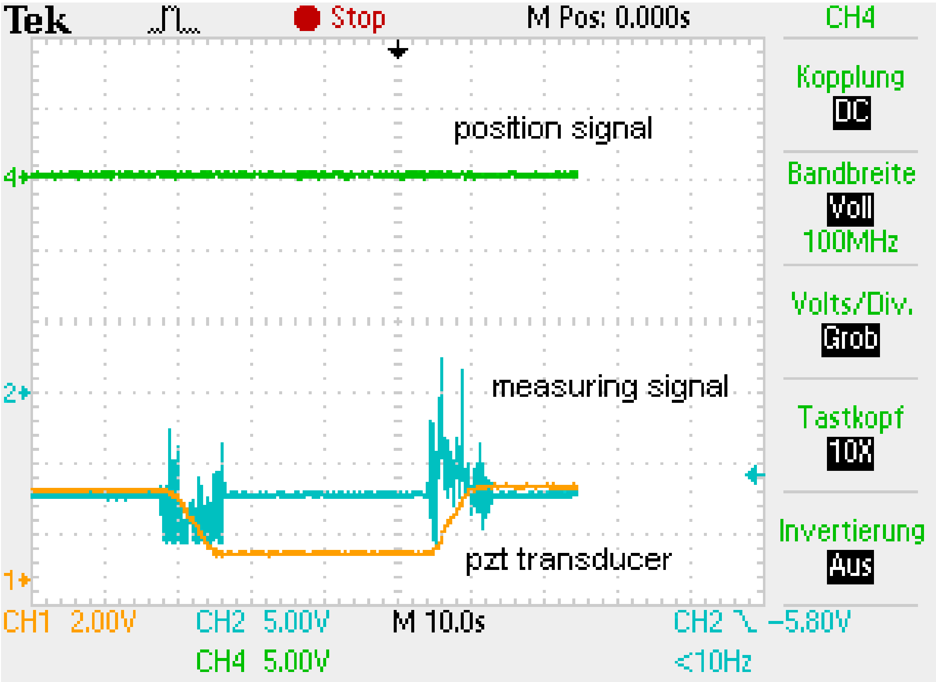


Figure 8: PZT-transducer signal

Another important difference to the commercial mass comparator is the change from a top loading balance back to traditional suspension device. The used Centermatic pan from the CC1000S-L was no more necessary. The centring of the weights is done by the suspension device designed like a pendulum. Special efforts had to be done to design a pendulum suspension which works nearly in absence of feedback caused by eccentric loads, otherwise needs to be damped for getting stable weighing results. A special conical coupling device with a flexion spring was designed.

THE CONTROL UNIT WITH APPLICATION SOFTWARE

The control unit exists of 3 main parts, which are installed in a separate rack. These are the driver motors for all necessary movements of the turntable and the lifting device of the load changer, the high voltage driver unit for the piezo transducer, and the PC equipped with the operating software. The design of the rack can be extended for customer-specific applications so that it is possible to integrate further modules. The operating software of the prototype mass comparator consists of software for controlling the sequence of mass comparisons and of evaluation software for calculating the measurement results using all the features necessary for this. The structure of the evaluation software is essentially comprised of the following modules:

- Determination of the conventional mass by substitution weighing
- Highly accurate mass determination by substitution weighing
- Dissemination of the mass scale

SPECIFICATIONS

- The prototype mass comparator is equipped with a fully automatic load alternator with 8 alternating positions. All 8 alternating positions are suitable without further modification for mass standards, buoyancy artefacts or spherical test objects (e.g., silicon spheres).
- The maximum diameter of the weights is 95 mm for cylindrical and for spherical objects on each alternating position. It is possible to position spherical objects with a maximum diameter of 110 mm in each 2nd alternating position if the spherical objects with a diameter ≤ 80mm are used in the remaining positions on the load alternator.
- The maximum height of the weights is 110 mm (also in the form of combinations).
- It is possible to load platinum-iridium kilogram prototypes or steel kilogram standards (according to OIML R 111) without tilting or turning them. A novel, integrated loading device on the vacuum chamber makes this possible.
- The mechanical effect of the load alternator on the surface of platinum iridium kilogram prototypes, steel kilogram standards and 1-kg silicon spheres is metrological negligible.
- The vacuum systems consists of a vacuum housing and an oil-free pump stand (consisting of a turbo-molecular pump, fore-pump, valves, power supplies and control electronics/control unit). It is suitable for a pressure range of 0.1 Pa to standard barometric pressure (10^5 Pa).
- The pressure stability of the vacuum system in the entire pressure range is better than 2 Pa in 24 h (with the vacuum pump shut off and all valves closed), disregarding desorption processes within the vacuum chamber.

The metrological requirements and specifications are as follows:

- The allowable pressure range in the vacuum housing for maintaining specifications is between 0.1 Pa and standard barometric pressure (10^3 hPa).
- The maximum capacity of the prototype mass comparator is 1,011 g.
- The use of external substitution weights enables the mass of any values to be determined in a range from 1 g up to the mass comparator’s maximum capacity.
- The electrical weighing range is 2 g.
- The readability is 0.1 μg.

- The repeatability is ≤ 0.3 μg.
- The linearity in the electrical weighing range is ≤ 1.5 μ.
- The stabilization time is ≤ 60 s.
- The sensitivity drift is ≤ 2 ppm/°C.

SUMMARY

The new Sartorius 1kg-prototype balance is designed to fulfil high accuracy mass determination between the Pt-Ir reference weight and standard steel weights as well as silicone spheres. The measurements can be carried out under airtight or vacuum conditions. The chosen material of aluminium guarantees a maximum of insensitiveness against magnetic influence on the measurement caused by the enclosure. The enclosure is designed to allow fast measurement procedures after load changes due to small load-lock ports. A special load device takes care of the expensive and valuable weights during the loading procedure.

ACKNOWLEDGEMENTS

The authors thank the colleagues from BIPM Dr. Richard Davis and Mr. Alain Picard for their support and assistance during the long way of development of a new kind of prototype balance like presented. As our cooperation partner these colleagues helped us in a very efficient and successful way to solve all arising mechanical or electronically problems during valuable discussions in Sévres or at the object in the TUI laboratory in Ilmenau with all their excellent knowledge in mass metrology.

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