Strategy 2022-2032

Consultative Committee for Mass and Related Quantities (CCM)

Version 1.8

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1. EXECUTIVE SUMMARY

The document was prepared in 2021 by the Consultative Committee on Mass and Related Quantities (CCM) Working Group on Strategy and MRA Coordination (WGS). Its intended audience are mainly the CCM, NMI Directors, CGPM delegates and the CIPM. The strategy was approved by the CCM by correspondence in March 2022 and will be periodically updated.

The strategy document presents an overview of major scientific, economic and social challenges which can be addressed by measurements of mass and related quantities for five sectorial (Climate change and Environment, Health and Life Sciences, Food Safety, Energy and Advanced Manufacturing) and two cross-cutting (Digital Transformation and "New" Metrology) challenges identified by the CIPM in response to evolving needs in metrology. The revision of the SI in May 2019 enables realizing the unit of mass and some related quantities directly from fundamental constants. Measurements directly traceable to the SI, dynamic measurements and measurements with a wider range and under wider condition are the main topics for the next decade.

The CCM set three strategic aims for the 2022-2032 period. The strategy foresees contributions to progressing measurement science across all technical areas covered by the CCM. Progress is expected from improvement on density standards, kilogram realization experiments, absolute gravimeters and pressure standards, to the extension of measurement ranges in flow, force and torque. To support global comparability of measurements, managing the transition from an internationally coordinated kilogram dissemination to the use of individual sovereign realizations remains the main focus. The CCM will continue to implement the CIPM-MRA by efficiently organizing key comparisons and coordinating RMO key and supplementary comparisons. It is proposed to develop specific guidance for CMC review and to revise about 300 CMC uncertainty equations in the KCDB. The CCM aims to facilitate stakeholder engagement and knowledge transfer by continuing the organization of workshops and initiating webinars and to seek extended collaborations with other Consultative Committees and involvement of external bodies.

The CCM oversees the work programme of the BIPM mass laboratories. The BIPM supports the implementation of the CCM strategy by organizing the comparisons of realizations of the kilogram as well as artefact based kilogram standard, disseminating the kilogram using an internally coordinated value and providing knowledge transfer of the realization and the dissemination of the kilogram.

2. SCIENTIFIC, ECONOMIC AND SOCIAL CHALLENGES

The Consultive Committee for Mass and Related Quantities covers a very diverse range of measurements which include: Mass, Vacuum, Barometry, High Pressure, Force, Torque, Hardness, Liquid Flow, Gas Flow, Solid Density, Liquid Density, Volume of Liquid, Hydrometry, Liquid Refractive Index, Surface Tension, Gravimetry.

The technologies applied to the measurements in these areas vary greatly, as do the scientific and industrial areas which rely on these measurements. Adding the diversity of mass related measurement area to the fact that the measurement of dynamic quantities is becoming increasingly important in a number of these areas (force, torque and pressure for example) means that the scope for end-user benefit can potentially be very wide and a strategy to maximize the impact will need to focus on areas where the benefits can be most effectively exploited.

The revision of the SI and the associated redefinition of the kilogram in May 2019 represented a step change in the way the SI unit of mass is defined, maintained and disseminated at NMI level. More widely, the redefinition of the kilogram enables new methods of traceability to fundamental constants. These will initially be developed at NMI level but, within a few years, will lead to measurements at the point of need, providing improved accuracy and reliability by direct realization of the SI.

For clarity the major activities and strategy of the CCM are discussed based on how they relate to the seven “grand challenges” identified by the CIPM.

Climate change and Environment

The assessment of the extent of long-term climate change and the dependable measurement of short-term trends relies on the reliability and equivalence of sensor measurements. For mass related quantities, major requirements in this area are for air speed and pressure measurements. The traceability chain for the calibration of sensors and instruments in these areas can be very long and use of the revised definition of the kilogram, together with the implementation of new technologies such as optical cavity pressure sensors, will enable the reduction of the traceability chain length and provide an improvement in the reliability and uncertainty of environmental measurements. The density of water also needs to be measured accurately and repeatably to assess salinity (a key marker for changes in ocean current patterns) and pollution. Robust field sensors which provide direct traceability to the SI using, for example, resonant technology should be developed. Gravimetry also has a role to play in tracking climate change, for example in determining (changes in) local hydrology and demonstration of the equivalence of gravity values measured using different instruments is crucial.

For environmental monitoring in the form of particulates, true SI traceability is achieved by laboratory based gravimetric measurements. These are therefore not real-time measurements and since they are based on aggregated particulate accumulation over a period of time, do not give a true reflection of peak values. Mass and pressure measurements also provide the SI traceability basis for gas standards which are in turn used to calibrate environmental monitoring equipment. In future, new sensors based on (micro-)Kibble balance and optical cavity pressure sensor technology could provide direct SI traceability for environmental (gas) and particulate monitoring. Beside this, the on-site production of reference materials with high flexibility in composition based on flow measurement is another issue. This is driven by needs to investigate, for example, the dynamic response characteristic of chromatograph equipment or to react in a fast way to end-user demand.

Health and Life Sciences

The measurement of mass and related quantities plays a critical part in the diagnosis and treatment of a range of clinical conditions and in research into and production and delivery of drugs, pharmaceutical products and medical implants.

True SI traceability for diagnostic measurements of blood pressure, intraocular pressure and for continuous cardiac output instruments needs to be developed in order to improve the reliability and comparability of these measurements as the basis of diagnoses.

The development of micro- and nano- force, mass, flow and surface tension measurement technologies will be important for pharmaceutical research and production and for personalised medicines and medical devices. High accuracy surface tension and density measurements will be crucial in improving production processes and assessing the quality of medical implants and prosthetics, particularly those produced by additive manufacturing and where coating processes are used.

In both the above areas new measurement technologies are being or have been developed and the key is applying the technologies to specific measurands and to achieving acceptance by the end-user medical communities. The latter is an area where collaboration between CCs will be important.

Food safety

High-pressure processing for food preservation uses pressure rather than heat to effect pasteurization and is becoming more common. This underpins a new requirement for accurate and traceable ultra-high-pressure measurements and sensors. Density measurements are key to food (and drink) processing and product characterisation and are often manual and off-line. With a drive towards digitization new, on-line, automated measurement techniques will need to be developed. Similarly, the measurement of and standards for the refractive index of liquids are required to meet the demands from the food industry such as calibrating sugar content using the Brix scale.

Energy

Density and viscosity are key parameters for the evaluation of energy-related materials such as oil, biofuels and gas. Various measurements under a wide range of conditions are needed in the energy chain from production to end-use. Current density tables are based on old data and known to be relatively inaccurate. Implementing new measurement techniques, for example density based on the density of a silicon sphere or related to the velocity of sound, will enhance accuracy and reliability for density measurements needed in this area and also enable the accurate measurement of properties under wide pressure and temperature ranges to enhance improvement of thermal efficiency in industrial processes such as heat pump system using alternative refrigerants. Improved in-line flow, density and pressure measurements are also required for new energy areas such as hydrogen production, distribution and consumption. With the establishment of a hydrogen-based energy supply, more new synthetic fuels will appear on the market and this will lead to new requirements for fluid flow to maintain the traceability chains to the SI units. Due to higher diversity of fluid characteristics, the sensors' behaviour dependency on fluid properties will have a higher impact on the overall achievable uncertainty. Therefore, intensified research work on modelling of sensor behaviour will be necessary to compensate this impact.

Alternative carbon neutral energy sources like wind and tidal energy require the development of dynamic measurement capability in the areas of force and torque and an extension of the range of traceable torque measurements. Real-time dynamic torque measurements are also key to the development of efficient drive-trains for electric vehicles. Given the continuing use of nuclear energy remote self-calibrating sensors for pressure, mass and density measurements will improve monitoring and safety.

Advanced Manufacturing

Advanced manufacturing process control and inspection requires a range of mass related measurements. The dynamic nature of the manufacturing processes and the trend towards miniaturisation presents challenges and opportunities for the measurement of mass and related quantities. In particular sensors based on Kibble balance technology will allow direct traceability to the SI for a number of process-based measurements. These sensors will be self-calibrating so are suitable for embedding in process measurements, for use in harsh environments and where dynamic real-time mass and force measurements are required. Advanced manufacturing needs a control of the acting forces and moments in the machine which will lead to an increase in the need for multicomponent force and torque calibration for the sensors used.

For the characterization of manufactured components, in particular those produced by additive manufacturing, a range of new measurement techniques needs to be developed. Density determination by gas pyknometry, traceable to the density of pure silicon, can be used to (non-destructively) assess the integrity and surface and bulk porosity of components. New hardness test methods for in-process evaluation or for product acceptance also need to be developed. The development of real time density and micro-flow sensors to look at feedstock and melt pool characteristics respectively, will improve the quality and reproducibility of additively manufactured components. Improved, in-process measurements of surface tension and wetting will be needed to optimise additive manufacturing and coating processes.

Digital transformation

Digital transformation is something that impacts all aspects of metrology and a coordinated response across all CIPM Consultative Committees is required. Similarly, digital transformation in metrology needs to be integrated with the wider digitization of society and needs, to a large extent, to be driven by the requirements of the end users in the individual technical areas.

The revision of the SI and the redefinition of the kilogram will help to facilitate the digitization of the measurement process particularly for mass and force measurements. Other step changes such as the implementation of optical (cavity) pressure standards and atom trap UHV standards will also be key to achieving a “digital NMI” which is not based at a single laboratory site. It will also allow the implementation of the on-site calibration of instruments minimizing disruption to research and production processes.

The provision of digital certificates to end-users is already being implemented in the area of mass and related quantities and user requirements for the dynamic calibration of sensors and instruments will increase the amount and complexity of data which needs to be transferred. The implementation of digital twins for calibration instruments will increase knowledge of performance and inform the need for recalibration. Digital twins will also be useful in the development of complex instruments such as the Kibble balance.

"New" metrology

The redefinition of the kilogram in terms of a fixed value for the Planck constant opens the possibility for a wide range of "new" metrology within the scope of mass and related quantities. Kibble and micro-Kibble instruments can provide mass, force and potentially torque measurements traceable to the SI at point of need. Similarly, optical cavity and trapped atom sensors could be used to cover the entire pressure range from high pressure to ultra-high vacuum giving direct SI traceability. Implementation of such sensors is a significant step towards providing SI traceability at point of need and therefore improving the reliability and uncertainty of measurements made by end-users. However, care needs to be taken in the implementation and validation of such measurements and this will be a key role for NMIs in the future. The development of remote calibration to check these instruments will be critical in the ongoing maintenance of global equivalence for the measurement of mass and related quantities.

3. Vision and mission

CCM Vision

A world in which all measurements of mass and related quantities are traceable at the required level of accuracy to meet the needs of society.

CCM Mission

To promote the global comparability of mass and related quantities measurement standards and capabilities, enabling Member States and Associates to make and use measurements with confidence.

4. Strategy

To implement the CCM's vision and mission, the CCM strategy has three main aims:

- **Progressing the state of the art** for issues identified by NMIs/DIs and the BIPM, by providing leadership and coordination and encouraging the organization of joint research projects.
- **Promoting global measurement comparability** by making comparisons more accessible and quicker, increasing the scope to cover emerging measurement areas and technologies, using a risk-based approach for deciding comparison scope and CMC review exercises and supporting the work of the BIPM. A particular focus is to ensure world-wide equivalence of the dissemination of the mass unit following the redefinition of the kilogram.
- **Improving stakeholder engagement** by organizing workshops and webinars and encouraging collaboration inside and outside the CCM community.

5. Activities to support the strategy

The CCM and BIPM activities are aligned to meet the CCM strategy.

5.1. Progressing measurement science

Most of the research and development for the advancement of metrology of mass and related quantities is carried out by individual NMIs and DIs together with, and coordinated by, the RMOs. The CCM has a guiding and coordinating role by defining measurement challenges for NMIs/DIs through CCM strategy and the work plans of the CCM Working Groups. Measurement science is progressed through the execution of pilot studies to investigate new methods or measurement areas and workshops focusing on new measurement challenges and technologies (see also 5.3).

The developments in mass and related quantities focus on activities for improving and standardizing measurement of high importance to stakeholders and research projects related to scientific, economic and social grand challenges. The following summarizes such activities in the CCM technical Working Groups.

- Density and Viscosity: For the determination of the Planck constant to redefine the kilogram, the uncertainty in the density measurement of silicon spheres was significantly reduced by improving optical interferometers for the sphere volume measurement. It is expected that this would be reflected in the results of scheduled key comparison on density measurements of silicon spheres and also in the future evolution of a variety of comparative measurements based on silicon density standards. A new key comparison for refractive index of liquids is scheduled, which includes recently developed method with optical interferometry. Supplying traceable standard liquids being ensured reliability by this comparison is expected.
- Fluid Flow: there is now a backbone of key comparisons established which covers the range of industrial needs in mass flow rate from mg/min to tonnes/s. Within this the main conventional fluids like water, hydrocarbons, air, nitrogen, and natural gas are involved. For the key comparisons, a set of commercially available transfer meters have been identified to ease the effort of preparing and performing similar comparisons in future. For air speed measurements, comparability was significantly enhanced by introducing non-intrusive optical sensors (LDV) and the equivalence of national realizations for fluid speed was demonstrated at a new lower level of uncertainty. In the field of volume of liquids, especially micro-pipette measurements, the activities to address standardization and liaisons with ISO TC28 and TC48 as well as OIML TC8 were established.
- Force and Torque: the established key comparisons cover the force range from 10 N to 20 MN and the torque range from 100 N·m to 100 kN·m and an extension to lower ranges down to 1 N·m is decided. The force and torque transfer standards are improved in the past years but the long-term stability is the limiting factor to verify lowest uncertainties of $\leq$ 0.002%. Pilot studies are performed to cover, for example, lower force ranges down to 1 µN. In lower force and torque ranges there is the need for the development of suitable transfer standards, but it is expected that, based on the new SI, this range can be improved by Kibble balances. Dynamic investigations of force and torque sensors are at the research level and are topics for future pilot studies.

- Gravimetry: Key comparisons of absolute gravimeters are beneficial not only to the gravimetry community but also to the Kibble balance community for the realization of the redefinition of the kilogram. Moreover, absolute gravimeters with cold-atom sensors have made huge progress. The best instruments have uncertainty of about 2 μGal (2E-8 m/s2). The AQG (Absolute Quantum Gravimeter) commercial gravimeter shows repeatability of 1-2 μGal, however, the uncertainty has not been validated yet. The increasing number of absolute gravimeters with cold-atom sensors are expected to participate in all levels of comparisons. A set of newly determined or updated corrections were evaluated for FG5/FG5X absolute gravimeters based on laser interferometry. The associated instrumental uncertainty of FG5/FG5X absolute gravimeter could be reduced slightly below 2 μGal. Finally, the excellent cooperation with the Geodesy Community for the International Gravity Reference System and Frame (IGRS/IGRF) following the CCM – IAG Strategy for Metrology in Absolute Gravimetry will allow greater progress in the future.
- Hardness: Hardness is an ordinal quantity measurement, or a measurement where the result is dependent on the test method used. There are no other independent measurements that can be made to obtain the same hardness result. While the test method procedures specified by Standards Development Organizations, such as ISO and ASTM, are adequate for industrial applications, they allow test parameters to vary within ranges of values. To maintain equivalent hardness national standards between nations, more specific test method definitions are required with single-value test parameters. Consequently, one ongoing effort of the WGH is to develop specific definitions for use by NMIs to reduce global measurement differences at the highest level. As these definitions are developed and approved by the Working Group members, key comparisons are then initiated to determine measurement equivalency among nations and to confirm that the definitions have reduced measurement differences between NMIs.
- Mass: For Mass metrology the revision of the SI and the redefinition of the kilogram represents a major step change in the way the SI unit of mass is defined and also in the way it will be realised and disseminated. While the development of the realization experiments reached a level of uncertainty and equivalence which was acceptable to allow the redefinition of the unit of mass in 2019 work is still ongoing to improve the number and reliability of the experiments and the degree of equivalence. To this end a series of (biennial) comparisons has been established which allows NMIs with realization experiments to validate their evolving levels of uncertainty and equivalence. In addition to the primary realization experiments NMIs are also applying Kibble balance and XRCD technology towards the goal of a distributed SI system. Results of the XRCD experiment have been used to establish direct SI traceability for nanoscale dimensional standards and Kibble and micro-Kibble balances are being developed which will provide direct SI traceability for end-users for a wide range of applications from dynamic monitoring in production process to developing the next generation of personalised medicines.
- Pressure and Vacuum: The revision of the SI has promoted changes to the realization and dissemination of pressure. New measurement techniques that quantify molecular number density of a gas can be used to realize the Pascal directly from the Boltzmann constant and temperature and have been shown to be as accurate or better than existing pressure standards. These methods rely on quantum-based measurements and molecular interactions to determine the density of molecules. Many NMIs are developing new standards utilising these methods and the first international comparisons are planned. At higher pressures,

determination using mass standards retains a lower uncertainty and these standards will remain. In the future, ensuring fundamental standards agree irrespective of the method used to obtain SI traceability will be the task.
Establishing gas pressure standards and providing measurement capabilities up to 100 MPa to support new hydrogen-based technologies and applications are new challenges. Comparisons of 100 MPa gas pressure standards need to be organised to support new measurement capabilities. In the field of vacuum pressure there is close collaboration with ISO TC 112 so that new developments, such as recent work on new ionisation vacuum gauges, progress quickly into the industrial community.

The CCM will continue to provide a global forum to exchange information about the state of the art and best practice by organizing workshops and selected technical presentations at the time of CCM meetings. The focus of these events will evolve from an emphasis on topics in mass metrology to examine other quantities greatly influenced by the kilogram redefinition and to topics connected to the grand challenges.

The CCM will actively promote collaboration among CCM Working Groups and participate in cross-disciplinary projects with other Consultative Committees especially in responding to evolving needs in metrology.

5.2. Promoting global comparability

The CCM will continue to manage the practical realization and dissemination of the kilogram in the transition period from an internationally coordinated maintenance and dissemination to individual sovereign realizations. The CCM will produce additional/revised guidance as necessary.

The CCM will continue to work with RMOs in the context of the CIPM MRA to efficiently plan, execute and monitor key and supplementary comparisons. The CCM will investigate more efficient, timely and robust comparison schemes such as star-type comparisons in force and torque, co-sharing piloting responsibilities, etc. This will help overcome challenges such as finding pilots for comparisons, staff resourcing/continuity at pilot laboratories and failure of transfer standards. The CCM will keep under review the existing arrangements for 'how far the light shines' statements on the results from comparisons. The strategy for comparisons will also be kept under review. It will end up in best practise guidance to ensure knowledge transfer and to support improvement in the delivery of proficiency testing under ILAC.

To support and simplify the process of CMC review, specific guidance on criteria for a risk-based approach in each mass related quantity will be established by the relevant CCM Working Group. The CCM will continue to work with the RMOs and NMIs on reducing the number of CMCs following the recommendations of the CIPM MRA review. The CCM will revise about 300 CMC uncertainty equations to implement quantity-based equation for the KCDB 2.0.

The CCM will support the introduction of the SI digital framework in mass related metrology, working with BIPM and other consultative committees. That includes digitalization of services such as the use of digital calibration certificates, making comparison data machine-readable and actionable, and providing support for NMIs/Dis in implementing digital ways of working.

The CCM will continue to support the BIPM in organizing the comparison of realizations of the kilogram and in disseminating the kilogram using a Consensus Value during the transition to the use of individual sovereign realizations.

5.3. IMPROVING STAKEHOLDER INVOLVEMENT

The CCM will continue to provide workshops and initiate webinars, both at CCM and CCM WG levels, to facilitate stakeholder engagement and enable knowledge transfer to and from the stakeholder communities.

The CCM aims to achieve a greater involvement of external bodies by inviting their representatives for a talk at CCM meetings or strategic discussions of the CCM Working Groups. This aim can be more easily achieved by the increasing use of videoconference meetings.

The CCM will encourage WGs to include in meeting agenda, points on feedback about individual interaction with stakeholder groups of interest to the wider community, for example, WG on Force and Torque, WG on Hardness and WG on Fluid Flow about the ISO technical committee activities. The CCM also will encourage the direct relationships, e.g. via liaisons, with relevant ISO TCs, ILAC and OIML.

The CCM will also seek contributions from other Consultative Committees as well as key manufacturing and supply industries, accreditation organizations and universities. The CCM will create an appropriate structure to communicate and provide input into any CIPM sector specific structure or other Consultative Committees that would benefit from CCM engagement.

In support of smaller NMIs/DIs, the CCM together with RMOs will increase knowledge transfer activities closely linked to the BIPM Capacity Building & Knowledge Transfer Programme.

5.4. WORK PROGRAM OF THE BIPM LABORATORIES

The work programme of the BIPM Laboratories is closely aligned to the work of the CCM[1].

As the past custodian of the international prototype of the kilogram and as the pilot laboratory for the key comparisons of realization experiments, the BIPM has special responsibility for dissemination of the mass unit. Until satisfactory agreement between independent realizations has been reached, internationally coordinated dissemination through the Consensus Value approach is being used during Phase 2 of the kilogram dissemination, which came into force in February 2021[2]. The BIPM reference mass standards serve as a "flywheel" to link successive KCs of the kilogram realizations and to maintain the Consensus Value during the Phase 2.

[1] Details are available on https://www.bipm.org/documents/20126/17315032/BIPM-strategic-plan-2018.pdf/92359f3e-85e8-c160-988d-ddc2dfcf2347

[2] Details are available on the CCM detailed note on the dissemination process after the redefinition of the kilogram, https://www.bipm.org/documents/20126/28432674/working-document-ID-11291/cf8f685d-fc3d-1883-9a42-0678a2c34453

The main activities in the mass area are:

- Organization and coordination of periodic key comparisons of primary realizations of the kilogram CCM.M-K8 and of secondary mass standards,
- Contribution to the calculation of the Consensus Value of the kilogram after each CCM.M-K8 comparison during the Phase 2 of the dissemination,
- Maintenance of an ensemble of reference mass standards as a means of providing traceability for BIPM kilogram calibrations and as reference to link successive CCM.M-K8 comparisons,
- Completion and maintenance of the BIPM Kibble balance for realizing the kilogram, participation in the CCM.M-K8,
- Calibration of Pt-Ir and stainless steel kilogram mass standards for member states,
- Implementation of digital calibration certificates,
- Providing knowledge transfer in the fields of the realization (Kibble balance) and dissemination of the kilogram,
- Collaboration with CCM-WGM and NMIs in order to avoid duplication of effort.

ANNEX

1. GENERAL INFORMATION

CC Name: Consultative Committee for Mass and Related Quantities

Date established: 1980

CC President: Dr Philippe RICHARD

CC Executive Secretary: Dr Hao FANG

Number of CC Members: 25 (plus 4 Observers)

Periodicity between Meetings and date of last/next Meeting: 2-3 years (1981...2019, 2021, 2023)

Working Groups:

WG	Technical area covered
WGDV	Working Group on Density and Viscosity
WGFF	Working Group on Fluid and Flow
WGFT	Working Group on Force and Torque
WGG	Working Group on Gravimetry
WGH	Working Group on Hardness
WGM	Working Group on Mass
WGPV	Working Group on Pressure and Vacuum
WGS	Working Group on Strategy and MRA Coordination

TGPfD-kg	Task Group on the Phases for the Dissemination of the kilogram following redefinition

2. LIST OF KEY AND SUPPLEMENTARY COMPARISONS

The key and supplementary comparisons organized by the CCM and the RMOs are listed on the KCDB. The Final Reports of the comparisons as well as those of the Pilot Studies are also available on the CCM web site. The following table lists the ongoing and future CCM KCs.

Comparison	Description	Repeat cycle	Start date	How far does the light shine
Density and viscosity				
CCM.D-K3	Density of stainless steel weight	10-15	2018	Mass range 100 g to 1 kg
CCM.D-K5	Liquid density measurement by oscillation-type density meter	10-15	2019	0.8 kg/m³ to 1.5 kg/m³
CCM.D-K6	Refractive index of liquid	10-15	2020	1.3 to 1.7
CCM.D-K1	Density of silicon crystal	10-15	2021	Mass range 100 g to 1 kg
CCM.V-K3	Measurement of viscosity standard liquids in a wide viscosity range	12	2024	5 mm²/s to 160000 mm²/s
CCM.V-K4	Measurement of viscosity standard liquids in a wide temperature range	12	2018	10 °C to 100 °C
Fluid flow				
CCM.FF-K5.2016	High pressure gas flow	10	2016	10 m³/h to 10^6 m³/h
CCM.FF-K1.2017	Water flow	10	2017	1 m³/h to 10^3 m³/h

CCM.FF-K6.2017	Low pressure gas flow	10	2017	10^{-4} m^3/h to 10^3 m^3/h
CCM.FF-K1.2018	Water micro flow	10	2018	10^{-8} m^3/h to 10^{-3} m^3/h
CCM.FF-K2.2021	Hydrocarbon liquid flow	10	2021	1 m^3/h to 10^3 m^3/h
CCM.FF-K3.2021	Air speed	10	2021	10^{-1} m/s to 10^2 m/s
CCM.FF-K4.2021	Liquid volume	10	2021	10^{-6} L to 10^6 L
Force and torque				
CCM.F-K23	Force Measurements at 200 N, 500 N	15-20	2019	Force Range: 10 N – 1000 N
CCM.F-K1	Force Measurements at 5 kN, 10 kN	15-20	2021	Force Range: 1 kN – 20 kN
CCM.F-K2	Force Measurements at 50 kN, 100 kN	15-20	2027	Force Range: 20 kN – 200 kN
CCM.F-K3	Force Measurements at 500 kN, 1000 kN	15-20	2030	Force Range: 200 kN – 1000 kN
CCM.F-K4	Force Measurements at 2 MN, 4 MN	15-20	2024	Force Range: 1 MN – 20 MN
CCM.T-K1	Torque Measurements at 500 N·m, 1000 N·m	15-20	2022	100 N·m to 5 kN·m proposal
CCM.T-K2	Torque Measurements at 10 kN·m, 20 kN·m	15-20	2025	5 kN·m to 100 kN·m proposal
CCM.T-K3	Torque Measurements at 20 N·m, 50 N·m	15-20	2022	1 N·m to 100 N·m
Gravimetry				
CCM.G-K2.2023	Gravity acceleration	6	2023	9.75 m/s^2 to 9.85 m/s^2
Hardness				
CCM.H-K3	Rockwell C scale (HRC)	10	2017	20 HRC, 30 HRC, 45 HRC, 60 HRC and 64/65 HRC
CCM.H-K4	Brinell hardness (HBW)	10	2019	HBW hardness levels 250, 350, 450 HBW scales HBW1/30, HBW2.5/187.5, HBW5/750, HBW10/3000 proposal
CCM.H-K5	Rockwell HR15N scale (HR15N)	10	2021	72 HR15N, 78 HR15N, 83 HR15N, 90 HR15N, 94 HR15N proposal
CCM.H-K6	Rockwell HR30N scale (HR30N)	10	2022	46 HR30N, 55 HR30N, 64 HR30N, 78 HR30N, 86 HR30N proposal
CCM.H-K7	Rockwell HR45N scale (HR45N)	10	2023	22 HR45N, 37 HR45N, 49 HR45N, 67 HR45N, 78 HR45N proposal
Mass				
CCM.M-K1	1 kilogram stainless steel	10	1998	1 kg
CCM.M-K4	1 kilogram stainless steel	10	2012	1 kg
CCM.M-K2	(Sub-)multiples of the kilogram	10	1999	1 mg to 10 kg
CCM.M-K5	(Sub-)multiples of the kilogram	10	2003	1 mg to 10 kg
CCM.M-K7	(Sub-)multiples of the kilogram	10	2015	1 mg to 10 kg

CCM.M-K3	50 kg stainless steel	15	2002	10 kg to 100 kg
CCM.M-K3.1	50 kg stainless steel	15	2009	10 kg to 100 kg
CCM.M-K6	50 kg stainless steel	15	2013	10 kg to 100 kg
CCM.M-K8	Kilogram realizations at 1 kg	Initially 2	2021	1 kg realization
Pressure and vacuum				
CCM.P-K3	Type C-IG, range $3{\cdot}10^{-9}$ Pa … $9{\cdot}10^{-5}$ Pa	15	2019	Pressure range 10^{-9} Pa ... 10^{-4} Pa
CCM.P-K1.b	Type C-BarG, 25 kPa to 175 kPa (gauge mode)	15	2019	Pressure range 10^{5} Pa ... 10^{6} Pa gauge
CCM.P-K1.c	Type C-HPgas, 1 MPa to 7 MPa (gauge mode)	15	2019	Pressure range 10^{6} Pa ... 10^{7} Pa gauge
CCM.P-K2	Type C-BarA, 25 kPa to 175 kPa (absolute mode)	15	2019	Pressure range 10^{5} Pa ... 10^{6} Pa gauge
	Type C-ATL, $2{\cdot}10^{-9}$ mol/s	15	2020	Molar flow (leak) rate 10^{-10} mol/s … 10^{-7} mol/s
CCM.P-K4.2019	C-CDG/RSG (P-K4), 1 Pa to 10 kPa	15	2019	Pressure range 1 Pa ... 10^{4} Pa

3. Summary of work accomplished

The key actions accomplished by the CCM have been the following since 2017.

Strategy and action plans: undertaking a major revision of the CCM Strategy and establishing the Strategy 2017-2027; defining and following-up of annual CCM actions plans

Meetings: organization of the CCM meetings and a workshop on new activities and developments in mass and related quantities

Enabling and managing the redefinition of the kilogram

- follow-up of a joint CCM-CCU roadmap
- development of the *mise-en-pratique* and a *Metrologia* Focus Issue on Realization, Maintenance and Dissemination of the kilogram
- drafting Information for users about the redefinition of the kilogram
- set-up of the Task Group TGPfD-kg
- elaboration of a detailed note on the dissemination process after the redefinition of the kilogram and a note on the impact of the redefinition of the kilogram on BIPM mass calibration uncertainties
- completion of the Pilot Study of future realizations and the first comparison of realizations of the kilogram
- calculation of the first Consensus Value and coordinating the update of the CMCs

CIPM MRA Review: providing inputs to the CIPM MRA Review and addressing the key Recommendations from the WG on the Implementation and Operation of the CIPM MRA

Guidance documents: producing the KC report template, Guidelines for the approval of comparison reports and CMC submission and review protocol based on a risk-based approach

KCs and CMCs: completion of a large number of CCM and RMO comparisons and CMC reviews

The main achievements of the CCM technical WGs are summarized as follows.

- Density and Viscosity: key comparisons covering possible CMCs for a variety of density measurements mainly based on silicon density standards and also for viscosity measurements under wide viscosity and temperature ranges have been implemented. In the hydrometer calibration, degrees of equivalences for 36 NMIs were covered by key comparison CCM.D-K4 and its linkage to several RMO key comparisons. This is the first example of the global evaluation in the field of density. Refractive index of liquid was newly added in the CCM service category in 2016, and the work toward implementing key comparison is underway in liaison with the CCPR.
- Fluid Flow: As the quantity of fluid in flow measurement is always compared indirectly via the indication of flow sensors, the performance of the sensors depending on time and on fluid properties is essential for the correct evaluation of comparison results, the related uncertainties, and statements on equivalence between different realizations of units. The development and publication of statistically based criteria to judge the impact of the transfer standard characteristics on the outcome of comparisons was done in 2016. With this, there are now criteria and tools available to evaluate the applicability of transfer standards a priori to a comparison. Parallel to this, WGFF clarified essential terms and released a guide on the declaration of uncertainties in CMCs and calibration reports. For time efficiency in the review CMC claims, all reports of comparisons now provide a final chapter explicitly stating the success for each participant with respects to its published CMCs. Together with a review protocol for CMCs under WGFF, the consistency of CMC claims among all RMOs will be achieved.
- Force and Torque: key comparisons in force and torque are regular performed with selected force and torque transfer measuring devices and defined measurement procedures. The transfer standards have been improved in the past years, but the stability is still the main influence to be considered in the key comparison evaluation. To consider the drift effect of the sensors, the star type formation was used which results in a lot of work for the pilot and long duration of the comparisons. To reduce the time and to reduce the work for the pilot in these comparisons, instead of circulating the transfer standards from the pilot, each participant sends own transfer standards to the pilot.
- Gravimetry: The key comparison CCM.G-K2.2017 and the linked EURAMET.M.G-K3 have been performed and the results had already been published in the BIPM KCDB. For CCM.G-K2.2017, it was the first time that such a comparison was organized outside of the European continent and established a new global gravity comparison site in China. For the next CIPM key comparison of absolute gravimeters in 2023, NIST, USA have already been accepted by CCM as the piloted lab and site. Up to now, 8 CMCs on gravity acceleration have already been approved which includes 4 new CMCs from 2017 to 2020. The contribution of absolute "*g*" measurement (covered by CMC) to Kibble balance experiments was significantly reduced and the relative expanded uncertainty decreased from 8.0×10^{-9} to 4.4×10^{-9} in 2020. In addition, "CCM – IAG Strategy for Metrology in Absolute Gravimetry" has been discussed with the geodesy community to ensure traceability to the SI for gravimetric measurements in the International Gravity Reference System.
- Hardness: In 2021, improved new definitions for the Rockwell hardness 15N, 30N and 45N scales were developed and approved for use by NMIs. In addition, an improved revision of the Rockwell HRC scale definition was also approved. A key comparison of the Rockwell HRC scale is now underway, with plans moving forward for key comparisons of the Rockwell 15N, 30N and 45N scales. In recent years, two Pilot Studies for the Geometrical Measurement of

the Rockwell Diamond Indenter and for Leeb Hardness Measurement were conducted. Both Pilot Studies demonstrated problematic comparison issues that need to be addressed before conducting key comparisons of these measurements.

- Mass: Progress on developing the XRCD and Kibble balance realization experiments continues, either to reduce uncertainties or to make the measurements more reliable and easier to perform. The first key comparison of realization experiments was completed in 2019 and the results of this, together with those of a previous Pilot Study, were used to calculate the first Consensus Value for the kilogram. The Consensus Value, based on the values of all the realization experiments with uncertainties less than 2 in 10^7, will be reviewed every 2-years based on the results of repeats of the key comparison CCM.M-K8. Once an acceptable number of realizations have demonstrated equivalence at a suitable level of uncertainty, direct dissemination of the SI unit of mass from these experiments will commence. Key comparisons of artefact mass standards at the kilogram and at a range of other nominal values are being repeated on a regular basis to ensure continued global equivalence of measurements.
- Pressure and Vacuum: Several NMIs have picked up the new fundamental method of realising the Pascal by measuring gas density via refractive index. Others improved the method of absorption spectroscopy to determine gas density and pressure. So, there is a general trend towards optical methods for pressure and vacuum standards. The Working Group for Pressure and Vacuum served as an advisory committee for several research projects developing a novel, highly stable ionisation vacuum gauges suitable as transfer and reference gauges, and new optical methods for the realization and dissemination of the pressure scale. The first digital certificates have been issued in this community. The list of key comparisons has been revised to adequately address the changing demands in pressure calibrations as well as the new measurement capabilities of NMIs' standards. An analysis of best units-under-calibrations (UUCs) was performed and a list of best UUCs provided, which should facilitate a realistic evaluation of NMIs' CMCs in the field of pressure and vacuum. A task group was established, and the first work performed to establish an objective and efficient risk-oriented process for the evaluation of new CMC submissions.

4. Document revision schedule

1 year for exceptions
2 years for updating numbers and dates
4 years for general revision

Document	Type of revision	Date of revision
CCM Strategy 2022-2032	4-year general revision	March 2022