CCM WG Strategy 14.01.2013 (latest revision: 28.06.2018)

Strategy 2017-2027
Consultative Committee for Mass and Related Quantities (CCM)

The audience for this strategy is mainly the CCM, the NMI Directors, the government representatives, the BIPM director and the CIPM.

Major topics (and actions) for the CCM

- Coordinate the transition to the revised definition of the kilogram according to the Recommendation G 1 (2017) and the CCM Roadmap 2018 (Appendix 2);
- Guarantee uniform dissemination of the mass unit from multiple primary realizations after the redefinition (2018) according to the *mise en pratique*;
- Encourage the BIPM and a sufficient number of National Metrology Institutes to continue to develop, operate and improve facilities for the primary realization of the mass unit at the level of one kilogram and other nominal values;
- Improve the CCM operating efficiency, mainly by defining clear action plans and structured reporting;
- Address the key recommendations of the CIPM MRA Review.

0 Management summary

The CCM has 9 Working Groups. During the period from 1999 to 2016, 87 Key Comparisons were completed. Currently 10 are in progress and 4 planned. The total number of Calibration and Measurement Capabilities is 2771.

The agreed repeat interval for key comparisons at the CCM level is generally 10 years. The CCM seems to have a sufficient number of KCs to cover the declared CMCs.

The strategy presents the status of activities and achievements of each Working Group as well as future vision of the landscape and anticipated requirements and measurement challenges. The redefinition of the kilogram will dominate the scene for the next few years, involving new challenges and commitments. The role of the BIPM will be mainly driven by this issue. Most of the other activities traditionally covered by the CCM will continue largely unchanged. Legal metrology and accreditation bodies, as well as mechanical industry, will continue to be important stakeholders. Dynamic measurement of quantities derived from mass, like torque and pressure, is becoming an important topic. The CIPM MRA is a big cost factor for the NMIs but the benefits for global trade are probably higher.

1 General information on the CCM

1.1 Administrative information

Date Established: 1980
President: Philippe Richard, METAS since October 19, 2012
Number of Members: 22 (+ 6 observers)
Number of Participants at last meeting (2017): 56 (10 guests and 4 BIPM staff members)
Periodicity of Meetings: 1 to 3 years (2017, 2015, 2013, 2011, 2010, 2008, 2007, 2005…)
Date of last/next meeting: 16th meeting in May 2017 / 17th meeting planned for May 2019

1.2 Working Groups

The CCM has established the following 8 technical WGs and a WG on Strategy and MRA coordination:

- WG on Density and Viscosity (WGDV)
- WG on Fluid Flow (WGFF)
- WG on Force and Torque (WGFT)
- WG on Gravimetry (WGG)
- WG on Hardness (WGH)
- WG on Pressure and Vacuum (WGPV)
- WG on Dissemination of the kilogram (WGD-kg)
- WG on Realization of the kilogram (WGR-kg)
- WG on Strategy and MRA coordination (WGS)

A table with detailed information on each WG is given in Appendix 1.

1.3 Key Comparisons

Number of Key Comparisons (KCs) organized (from 1999 up to and including 2016): 87 completed, 10 in progress and 4 planned.
Number of Pilot studies organized (from 1999 up to and including 2016): Total: 10; 4 (WGG), 3 (WGH), 1 (WGR-kg), 1 (WGFF), 1 (WGPV)
Number of CMCs published in KCDB supported by CC body activities (up to and including 2016):
Total CMCs[1]: 2771 (WGD-kg: 818, WGDV: 586, WGPV: 480, WGFT: 238, WGH: 135, WGG: 5, WGFF: 509)

The reader should be aware that the significance of the total number of CMC entries and KCs is limited.

Detailed KCs information is given in sections 7 and 8.

1.4 Common issues across all CCM WGs

- Expand stakeholders awareness of CCM efforts and the KCDB. Presently, public knowledge of the work and results of the CCM, including the use of KCDB is too limited.
- Web meetings. Increase participation in WGs by NMIs of smaller economies by using web meetings or video conference.
- Directives for technical work. The approach to be followed during review of documents, *mise en pratique*, KCs and CMCs should be documented with structured, consequent actions. The procedures for receiving comments and communicating responses should be clear. WGs should consider using the BIPM discussion forum[2] for more transparent communication.

[1] http://www.bipm.org/utils/common/pdf/KCDB_CMCs.pdf
[2] http://www.bipm.org/jforum/forums/list.page

- Dynamic calibrations, digitalization and industry 4.0. Dynamic (rather than static) calibration is key to future development in a number of technology areas (pressure, force, vacuum). Possible impact of digitalization and industry 4.0 in the fields related to CCM needs to be analyzed.
- CMCs. In some measurement areas, the existing structure of service categories should be improved (e.g. combine categories for mass flow and volume flow to decrease the number of CMC entries). Service categories should be added to accommodate new calibration capabilities in the area of dynamic (non-steady state) measurements (see results of the BIPM Dynamic Measurements Workshop of November, 2012).

  A general extension of the CMC range has to be considered (and therefore the KCs required) for example for ultra-high pressure, nano-force, micro-hardness, micro-mass, vacuum leak rate and liquid micro-flow.
- KC efficiency and funding. The mean time for completion of a CCM KC is >5 years. For the pilot laboratory, the labour is >100 man-days and equipment and transport costs are > Euro 25,000. This cost demonstrably decreases when KCs are repeated, especially as we learn which transfer standards offer the best performance. Further efficiency can be gained by developing and using common validated data reduction spreadsheets, protocol and report templates and best available uncertainty analysis and recommended papers for calibration of various types of reference standards, by increasing time between recurring KCs, by reducing the total duration of KCs and by covering more CMCs with less KCs.

  For many measurands, it is difficult to find NMIs to volunteer as pilot laboratory. Generally, the larger NMIs are repeatedly serving as pilot laboratory because small NMIs cannot afford the cost. Some KCs have successfully shared shipping costs. Others have benefited from having a small group running the comparison to share the burden across several NMIs. Mechanisms for cost sharing to better distribute the cost of transfer standard equipment should be considered, perhaps via a general fund administered by the BIPM. The WGFF has several recent examples of serious shipping and customs difficulties. The CCM.FF-K4.2011 was held in Brazilian customs for 8 months, the CCM.FF-K3-2011 transfer standard was lost in Dubai (not a participant in the KC) for 6 months. WGFF attempts to share shipping expenses between participants have been unsuccessful or terribly cumbersome. Too much technical staff time is being spent on these administrative issues.

2 Terms of reference

Present activities concern matters related to considerations affecting the definition and realization of the unit of mass, establishment of international equivalence between national laboratories for mass and a number of related quantities (density, pressure, force, fluid flow, viscosity, hardness, gravitational acceleration) and advice to the CIPM on these matters.

The terms of reference of all CCM WGs are available on the BIPM web site. They are regularly reviewed at CCM meetings.

3 Baseline
(status of activities and achievements up to and including 2016)

The number of *completed KCs* (first number) and *KCs in progress* (second number) below is related to the period 1999-2016. The number of CMCs is the status at the end of 2016. A table with detailed KCs information is given in section 8. The agreed repeat frequency at the CCM level is generally 10 years (15 years for WGFT).
The CCM seems to have a sufficient number of KCs to cover the declared CMCs. The CIPM MRA is a big cost factor for the NMIs but the benefits for global trade are probably higher.

Many of the activities of the CCM WG on Strategy and MRA coordination over the period 2012-2016 have focused on providing the inputs to a full review of the CIPM MRA, and on identifying the needs and developing guidelines and templates to improve the efficiency of the KCs within CCM. They include the CCM Guidelines for approval and publication of the final reports of key and supplementary comparisons which went into force on August 2013 and revised on June 2016. A draft template for key comparisons reports was produced and is being tried in the WGs. A review of all CCM comparisons was conducted. 33 CCM KCs were surveyed. The maximum of participants is 19 in a KC with a mean of 9 participants. Median and weighted mean are the methods most used to calculate reference value. The survey revealed that uncertainty of transfer standard is a problem. Inconsistency is often found between CMCs and KC uncertainty claims. Guidance is needed on: appropriate KCRV calculation methods, flow chart or software template for KCRV calculations, how to handle unstable transfer standard effects, and how to assess results for multiple set points. The WG1 of JCGM (Joint Committee for Guides in Metrology) has offered professional help to work out guidelines for best practice of KC data analysis.

3.1 Realization and Dissemination of the kilogram (KCs: -, CMCs: -)/(KCs: 8 *completed* / 0 *in progress*, CMCs: 818)

The international prototype of the kilogram was used in an “extraordinary calibration” to calibrate the working standards of BIPM. Calibrations of mass standards and artefacts of the watt (or Kibble) balance and XRCD experiments were completed at BIPM in February 2015.

The EMRP Joint Research Project (JRP) kNOW “Realization of the awaited definition of the kilogram - resolving the discrepancies” was finished in August 2015. In this project, most of the institutes working on the XRCD method cooperated with the European watt (or Kibble) balance projects in order to improve the methods and resolve discrepancies.
The International Avogadro Coordination published in 2015 an Avogadro constant with a relative standard uncertainty of 2.0 x 10^{-8}. Using the CODATA value of the molar Planck constant, a value of the Planck constant can be calculated with the same relative uncertainty.
The NIST (USA) calculated a final Planck constant value with a relative standard uncertainty of 5.7 x 10^{-8} using all measurements of the NIST-3 watt (or Kibble) balance. Additionally NIST measured a Planck constant value with the new NIST-4 watt (or Kibble) balance with a relative standard uncertainty of 1.3 x 10^{-8}. The NRC (Canada) published a new value of the Planck constant with a relative standard uncertainty of 0.9 x 10^{-8}. The LNE (France) measured the Planck constant with a watt (or Kibble) balance in air achieving a relative standard uncertainty of 5.7 x 10^{-8}.
The International Avogadro Coordination measured the Avogadro constant with a relative standard uncertainty of 1.2 x 10^{-8} using a new Si28 single crystal and two spheres manufactured from this crystal. PTB received a further single crystal of isotopically enriched silicon which is used for manufacturing two new 1 kg spheres and for the determination of the Avogadro and Planck constants and - after redefinition - for realizing the new kilogram. Three other Si28 single crystals are in preparation.

In 2016, the CCM Pilot Study was carried out. The objectives are to test the consistency of future primary realizations and the continuity with the present definition. Three NMIs participate with watt (or Kibble) balances and two with Avogadro spheres. Draft A was distributed in December 2016, the final report in June 2017.

The conclusions of the results presented above are included in the CCM Recommendation G1 (2017).

The WGD-kg deals with the dissemination of mass standards. This is currently from the IPK but in future will be from primary realizations. WGD-kg also addresses other issues related to mass standards (like material, magnetic properties, stability, cleaning and sorption effects). Currently, the main range of interest is 1 mg to 10,000 kg. There is also interest in smaller masses and supplementary comparisons have been registered for sub-mg weights.
With a national prototype of the kilogram calibrated against the IPK, the present dissemination of the mass scale is highly decentralised and reasonably robust. However, the variability

in the mass scale maintained by the BIPM during the last decade may present some challenges for linking recent key comparisons.
The major issues are closely related to the preparation work towards the new definition of the kilogram. Good progress has been made on cleaning methods for mass standards, on the study of new materials for mass standards, on mass comparisons under vacuum, on transfer from vacuum to atmosphere and on uncertainty related to the traceability to the IPK.
The new definition of the kilogram is stimulating a lot of scientific work related to the future *mise en pratique* of the definition. Many scientific papers were published during the last ten years. The EMRP JRP NewKILO was completed in May 2015. The project aimed to put in place the infrastructure and procedures necessary to link the primary realization experiments to the IPK and subsequently to disseminate the mass scale from these primary realizations. The outcomes included the evaluation of materials for new mass standards (compatible with the redefinition requirements), protocols for the (air-vacuum) transfer, cleaning and storage of mass standards validated gravimetrically and by surface analysis and the uncertainty budgets associated with the mass dissemination following the new definition.

3.2 Density and Viscosity (KCs: 5 *completed* / 2 *in progress*, CMCs: 586)

In 2014, the Working Groups on Density (WGD, established in 1981) and the Working Group on Viscosity (WGV, established in 2005) were merged into WGDV.

On density, the major achievements created through the technical discussions and research works are:

- recommended table for the density of water between 0 °C and 40 °C based on recent experimental reports[3],
- revised CIPM formulation for the density of air[4],
- clarifying roles of the CIPM and IAPWS[5] formulations for the density of water[6].

As a result of these achievements, most of the NMIs are now using a silicon sphere as their density standard instead of the liquid density standard based on the density of water.
Because water is still important for most calibration work, redetermination of its density was reported by PTB and discussed to improve the precision of the liquid density reference for the use in density calibration, volume determination of mass standard artefacts, and general volumetry.

On viscosity, methods for the absolute measurement of viscosity and for the calibration of viscometers, and related issues like reference liquids in a broad viscosity and temperature range have been discussed. The covered viscosity range is from 1 mm²/s to 1’000’000 mm²/s, the covered temperature range is from -40 °C to +150 °C.
The technical discussions were related to:

- Viscosity, temperature and pressure range to be covered,
- Reduction of the number of CMC entries,
- Absolute measurement of viscosity at intermediate viscosities,
- Use of viscometers other than glass capillaries.

3.3 Force and Torque (KCs: 8 *completed* / 6 *in progress*, CMCs: 238)

The technical discussions were related to force standards and focused on the improvement in the stability and reproducibility of force transducers, torque measurement standards.
The discussion on the repeat frequency of KCs has shown that KCs will never cover all ranges. But many CMC entries are supported by other measurements or results of special investigations or knowledge and by supplementary comparisons.

[3] Metrologia Vol. 38, 2001, pp. 301–309
[4] Metrologia Vol. 45, 2008, pp. 149–155
[5] International Association for the Properties of Water and Steam
[6] Metrologia Vol. 46, 2009, pp. 196–198

3.4 Fluid Flow (KCs: 14 *completed* / 3 *in progress*, CMCs: 509)

The WGFF covers liquid flow (i.e. water, hydrocarbon liquid, cryogenic nitrogen), gas flow (air, nitrogen, natural gas, etc.), liquid volume (from microliters to thousands of litres), and the speed of fluids (air speed and water speed).

A global update of flow CMCs occurred during 2014 and 2015. NMIs were encouraged to use either mass flow or volume flow service categories (not both) in order to reduce the number of flow CMCs. This merging of entries reduced the total number of flow CMCs from 585 in 2012 to 511 in 2016, despite the addition of 105 CMCs for new NMIs or measurands.

The WGFF *Guideline on CMC Uncertainty and Calibration Report Uncertainty* was completed and posted to the BIPM/WGFF web page in 2013. The guideline results in better consistency NMI uncertainty statements by explaining how to quantify and include uncertainty due to the device under test. The WGFF has publicized the guideline to accrediting bodies in an effort to coordinate the uncertainty policies used by the NMIs and by commercial calibration labs. A WGFF sub-group completed the *Review Protocol for Fluid Flow Calibration and Measurement Capabilities* in August, 2014.

Another WGFF sub-group led to the 2016 Metrologia paper *Transfer Standard Uncertainty Can Cause Inconclusive Inter-Laboratory Comparisons*, highlighting the importance of quantifying transfer standard uncertainty using preliminary tests made by the pilot lab. The CCM.FF-K2.2011.2 comparison for liquid hydrocarbon flow (published in 2016) demonstrates best practices for assessing the sensitivity of the transfer standard to external influences like temperature, pressure, and fluid properties. The transfer standard contributed extraordinarily small uncertainty to the comparison results, less than 0.01 %.

The CCM.FF-K2.2011.1 (presently in Draft A) demonstrated that it is practical to use a coriolis meter transfer standard for both water and hydrocarbon liquid flow measurements, making it possible to combine what are traditionally two KCs into one.

The CCM.FF-K3.2011 comparison for air speed (presently in Draft A) used two transfer standards to demonstrate that the effects of the instrument under test on the velocity field in a wind tunnel are often underestimated in NMI calibration reports. This result will lead to a review of “blockage effects” in air speed calibrations and more realistic uncertainty statements in customer calibration reports.

A survey of existing CMCs from 47 countries and 12 past KCs was conducted in 2016 to assess whether prior comparisons adequately covered the range of values measured by the NMIs (a “Gap Analysis”). The results are available in one of the presentations of the 2016 WGFF meeting (see WGFF web page). The Gap Analysis shows that measurands are generally well covered, but that future comparisons should be directed towards larger liquid volumes, smaller gas flows, and micro-flows of liquid. KCs for smaller gas and liquid flows are in the planning stage now.

In November 2016, the WGFF (with the Executive Secretariat’s support) posted an uncertainty analysis template for a commonly used liquid flow standard on the WGFF members only web page.

3.5 Gravimetry (KCs: 2 *completed* / 1 *in progress*, CMCs: 5)

From simple estimations of the offsets between the participating gravimeters in 1980s the WGG in collaboration with geodetic community developed procedures for the organization of Key Comparison of Absolute gravimeters and evaluation of the results of comparisons in conformity with the MRA rules.

The results of investigations of different kinds of the sources of systematic uncertainties, as well as different procedures and documents related to the organization of comparisons are still under discussion. The interest of absolute gravimeter users in the determination of metrological characteristics of absolute gravimeter and insufficient traditional metrological service in absolute gravimetry are other issues.

Currently there are only four NMIs and DIs with declared CMCs. The specificity of situation in absolute gravimetry is that 90 % of more than one hundred absolute gravimeters in use are fabricated by the same company. These gravimeters are not calibrated by the producer.

For the first time in 2009 the CCM.G-K1consisted of simultaneous KC and Pilot Study parts with the participation of a new type of absolute gravimeter based on cold atom interferometry.

An important joint strategy document has been agreed between the CCM and Commission 2 “Gravity Field” of the International Association for Geodesy (IAG). The principal objective of this document, initiated by the CCM President, is to coordinate and harmonize activities carried out by the two bodies. This will help to ensure traceability to the International System of Units (SI) for gravity measurements at the highest level of accuracy, for the purposes of both metrology and geodesy, within the framework of the CIPM Mutual Recognition Arrangement (CIPM MRA).

3.6 Hardness (KCs: 1 *completed* / 1 *in progress*, CMCs: 135)

The WGH deals with hardness standards and promotes the international cooperation among NMIs, DIs, RMO members and international organization like ISO, ASTM, OIML, VAMAS and others, for improving traceability and standardization in the field. The most important activities and goals are the following:

- International primary definition of hardness scales (Rockwell C approved; Rockwell B, Rockwell N and Brinell under development),
- Organization of Key comparisons on the most used hardness scales (Vickers, Brinell and Rockwell) and on others under development (Martens, Leeb, Shore).

Organization of Pilot Studies to understand the problems and needs of future Key Comparisons (Rockwell Diamond Indenter Geometrical Parameters, Leeb completed; Rockwell B and Brinell under development).

3.7 Pressure and Vacuum (KCs: 16 *completed* / 0 *in progress*, CMCs: 480)

In 2014, the Working Groups on High Pressure (WGHP, established in 1981) and the Working Group on Low Pressure (WGLP, established in 1981)) were merged into WGPV.
The first KC for leak rates (small molar gas flows) was completed in 2012 and, as a result, first CMCs under category fluid flow/gas flow rate/molar flow rate were registered. This ensures international traceability for accredited laboratories in this field which did not exist before.
Near 7 MPa, in the framework of the determination of Boltzmann constant, an uncertainty reduction to about 1 ppm was achieved.
The WG PV published recommendations on recommended practices for the use of spinning rotor gauges in inter-laboratory comparisons in 2015 as a result of WG PV workshop held in 2014.
Measurements of gas density, related to pressure from 1 Pa to 100 kPa, by optical methods are tested for their applicability as fundamental standards since 2012. Calibration standards for partial pressures were established. There is a continuing close cooperation with ISO TC 112 (Vacuum Technology).

4 Stakeholders / end users
(who they are and their level of involvement)

Looking at the broad scope of the CCM, its work will remain of significant importance for a large variety of different stakeholders, be it “external” ones, such as industry, legal metrology bodies, research institutes, standardization bodies, or “internal” ones, i.e. the various organizations and institutes being directly involved in metrology issues.

4.1 Identification of general stakeholders

The following stakeholders are considered to be important, regardless of any specific CCM working group.

a) The “metrology community” itself
- The committees of the meter convention: CIPM, CGPM, BIPM, CCM itself and other CCs, (Example: work in XRCD and watt (or Kibble) balance projects in the frame of the redefinition of the kilogram),
- NMIs, VAMAS.

b) Stakeholders from outside the "metrology community"

b1) Industry

- Industry from different economic sectors such as process control (sensors), transportation, energy measurement, safety, health, environment, automotive, aeronautic, petrochemical, aviation, …
- Manufacturers to control their production or rendering calibration services, also those manufacturers that have global manufacturing and calibration facilities requiring uniform application of accreditation requirements and equivalence between the measurements made in NMIs.
- Accredited calibration laboratories using standards with traceability to NMIs.

b2) Legal metrology: OIML, verification offices, inspection services, …

b3) Standards and conformance bodies (conformity assessment bodies).

b4) Research field: Universities, research institutes / facilities, academic foundations including CODATA Task Group on Fundamental Constants, …

4.2 Identification of specific stakeholders

In the following, some specific stakeholders are identified that are related to some CCM working groups.

Density and viscosity:

Traditional users of density standards are the oil industry, the liquor and alcohol industries, where hydrometers (covered by CCM.D-K4) have been calibrated for legal metrology and taxation at each country. However, more precise, automatized and conventional instruments, such as vibrating-tube density meters, have recently been introduced in those industries. This stimulated a new calibration service using density standard liquids (covered by CCM.D-K2). Silicon density standards (covered by CCM.D-K1) are now used by most of the NMIs as density standards for calibrating the density of solid, liquids, and even gases. In the 201 CMCs on density, many of them are for the density and volume of stainless steel weights. This is the reason why CCM.D-K3 is necessary for evaluating the density and volume measurements of the stainless steel weights.

On viscosity standards, the end-users who need characterization of materials are fuel, oil, lubricant, paint, furnish, and food industries. A direct contact between users/stakeholders and the WGDV does not exist up to now. There are more personal contacts between members of the WGDV and standardization bodies and calibration laboratories. The capabilities of NMIs are restricted to Newtonian liquids measured by glass capillaries and serves for basic calibrations. The users are often focused on non-Newtonian liquids and are measuring using rotational viscometers.

Force and Torque:

- Producers of force and torque equipment and transfer standards,
- Users of force and torque.

Fluid flow:

Flow measurements are critical to nearly every economic sector: transportation, energy, safety, manufacturing, etc. Petroleum, natural gas, and alternative fuel providers are notably important stake holders. A few specific examples are: air speed measurements for wind turbines, the quantity of fuel dispensed to vehicles, and the flow of gases used in manufacturing semiconductors. All sectors are connected to WGFF activities via RMO flow technical committees, NMIs, instrument manufacturers, and commercial calibration laboratories.

Gravimetry:

The end users of traceable absolute gravity measurements are the NMIs for watt (or Kibble) balance experiments, for the calibration of absolute gravimeters and sometimes for in-the-field measurements, DIs, IUGG, IAG, geodetic, geophysics, geological and other services for the engineering geology, hydrology, for the geological exploration, for the monitoring of mineral reserves including the hydrocarbons and water, volcanology, for the support (calibrations) of international, national and local gravimetry networks.

Hardness:
- Producers of hardness equipment and reference standards,
- Users of hardness testers.

Pressure:
- Gauge manufacturers,
- Industries: semiconductor, coating, photovoltaic, lightning, metallurgical, chemical, pharmaceutical, food, automotive, aerospace, process, petrochemical, aviation,
- Research facilities: high-energy accelerators, synchrotrons, fusion, and surface science.
- Secondary calibration laboratories and instruments manufacturing companies.

Mass standards:
- Weighing instrument manufacturers, manufacturers of weights,
- Key end users in other fields of metrology, in material testing, in surface coating industry and in pharmaceutical industry.

5 Future Scan

5.1 General issues

The redefinition of the kilogram will dominate the scene for the next few years, involving new challenges and commitments. Nonetheless, most of the activities traditionally covered by the CCM will continue largely unchanged, as they will be only marginally affected by the redefinition. This is especially true for most derived units. Legal metrology and accreditation bodies, as well as mechanical industry, will continue to be important stakeholders. In this respect, dynamic measurement of quantities derived from mass, like torque and pressure, is becoming an important topic.

5.2 Sector specific

5.2.1 Density and Viscosity

On density standards, the strategic planning to serve industry and society has been discussed at its meetings on the following subjects:

- comparison of the capabilities in calibrating vibrating-tube density meters,
- refractive index of liquids for food industry and agriculture,
- density measurements under high pressures and high temperatures (*pρT* properties) for energy saving and environment technology.

As the vibrating-tube density meters are widely used in industries, the importance of evaluating the equivalence of their calibrations was recognized. The *pρT* properties of fluids are of importance for energy savings and energy transportations, especially for heat pump technologies using refrigerants. The standards for the refractive index of liquids are necessary especially for calibrating sugar content of the Brix scale. As the density of liquid is closely related to the refractive index of liquids, a few NMIs already possess such calibration services. Consequently, a new key comparison for the vibrating-tube density meter (CCM.D-K5) was approved in 2015. Refractive index of liquid (CCM.D-K6) was also approved as a new key comparison in 2015. This is included also as a new service category for density.

On viscosity standards, following items were discussed in its meeting:

- Implementing measurements under pressure,
- Implementing non-Newtonian liquids,
- Implementing viscometers other than glass capillaries,
- Implementation of industrial measuring devices into CMCs,
- Increasing industrial/research requirement for density determination on porous materials, powders and particulates (which involves techniques such as gas pyknometry).

5.2.2 Force and Torque

Some new metrological challenges for big forces up to 50 MN are expected due to the testing of new materials and constructions in the of civil engineering and oil industry and in the very high torque range (1 MN·m up to 20 MN·m) due to new power generators (wind energy, improvement of turbines) and better control of ship propulsion, etc.

As future subjects, the working group will consider small force measurement, multi-component force measurement, and comparisons under consideration of parasitical components and dynamic force metrology. In the field of force and torque it is planned to continue the force and torque KCs in the range below 5 kN and 500 N·m, especially for the force steps of 200 N and 500 N and for the torque steps of 20 N·m and 50 N·m.

5.2.3 Fluid Flow

- The WGFF is focused on comparisons and relies on Pilot labs to perform R&D to improve the stability of transfer standards,
- Existing comparisons are likely to be repeated on an approximately 10 year cycle. Some comparisons will occur on a shorter cycle because they are simpler and cheaper to perform or because there is an economic justification (e.g. natural gas flow or liquid volume [petroleum]),
- New comparisons will arise as NMIs fulfil their customer’s measurement needs,
- Some possibilities are:
    - Cryogenic flows (to support liquefied natural gas transactions),
    - Micro-flows, both gas and liquid (for manufacturing and medical applications). A EURAMET liquid micro-flow pilot study was completed in 2015 and a WGFF liquid micro-flow comparison is in the planning stages,
    - Dynamic or transient flows (for gaseous vehicle refuelling, better process control),
    - The WGFF will continue working on guidelines and templates to assist with conducting, analyzing, and reporting comparisons, estimating uncertainty for commonly used types of flow references, submitting CMCs, and other core WG activities. Future products are: 1) a guideline on what changes are permitted between Draft A and Draft B of a KC report and 2) a document on methods for establishing linkage between KCs and regional comparisons.

5.2.4 Gravimetry

Taking into account the growing needs for absolute gravimetry in metrology, geodesy, geophysics, geology and the growing number of absolute gravimeters worldwide, including those based on new technologies (cold atom gravimetry), it can be anticipated that the needs for calibrations will increase. The required uncertainty in absolute gravity measurements will be at the level from one to a few 10^{-8} $m \cdot s^{-2}$. Smaller uncertainties than those currently declared in the CMCs of NMIs and DIs are already required for calibration of absolute gravimeters. This also will require realization of the corresponding R&D projects aimed at improving the existing absolute gravimeters and investigating sources of systematic errors.

5.2.5 Hardness

Hardness fields in which it is foreseen to have further activities to improve the measurement traceability through development of primary definitions and organization of KCs and pilot Studies are the following:

- Instrumented indentation test,
- nano-indentations,
- dynamic hardness,
- portable hardness testers,
- hardness of elastomers,
- Martens hardness,
- Leeb hardness.

It is already decided to carry on:

- Activity in the development of international primary definitions for Brinell, Vickers and Rockwell scales,
- KCs in different hardness scales (HRB, HRN, HBW, HSD, HL).

Plans are currently underway for conducting Key Comparisons in Brinell hardness (HBW) [the scales and hardness levels to be determined], and Rockwell B scale hardness (HRBW) Other likely Key Comparisons to be conducted following these are for the Rockwell HR15N, HR30N, HR45N hardness scales and Leeb hardness.

5.2.6 Pressure and Vacuum

Pressure:

- Replacement of primary mercury manometers by alternative standards – special pressure balances, oil manometers or optical standards,
- Low differential pressures with high accuracy and low line pressure,
- Standards for industrial high pressure technologies (above 1 GPa).

Vacuum:

- Leak reference and transfer standards,
- Standards for outgassing, outgassing reference probes, special materials with low outgassing rate,
- Standards for partial pressure measurements.

Pressure and vacuum:

- Optically based standards for pressure,
- Dynamic pressure measurements.

5.2.7 Mass standards (realization and dissemination)

In connection with the planned redefinition of the kilogram and in agreement with the *mise en pratique* for the definition of the kilogram, the following activities would be necessary:

- Realization and dissemination of the redefined kilogram based on appropriate primary methods and primary mass standards to be developed, improved to relative uncertainties below 2×10^{-8} and adequately maintained, both at the BIPM and at NMIs,
- The role of the BIPM in the context of the SI unit of mass to be defined and practically implemented to continue to guarantee, in collaboration with WGR-kg, the continuity, traceability, accuracy and acceptance of mass measurements worldwide for the immediate future. This is likely to include maintaining ensembles of appropriate mass standards (at NMIs as well as at the BIPM), including ^{28}Si and natural Si spheres, organisation of key comparisons for primary methods, and continuation and improvement of the BIPM watt (or Kibble) balance. Also see section 6.4,
- New realizations of the mass unit in terms of the Planck constant, alternative to watt (or Kibble) balance and XRCD routes, thus based on different ideas,
- Further independent watt (or Kibble) balances,
- Further independent XRCD experiments,
- Development of commercial instruments for the realization of the unit of mass at the kilogram and at other mass value both for use at NMIs and longer term by a wide range of end users,
- Establishment of criteria for accepting new experiments as realizations,
- Establish experiments for the direct realization for small masses and forces,
- Continue the classical KCs for the dissemination of the kilogram, extending the range to mass values below 1 mg as required,
- Monitor the mass of the IPK (after the redefinition).

6 Rationale for various activities

6.1 Overview

Research and development activities, measurement services and key comparisons under the scope of the CCM are driven by international needs for metrology in spheres of activity including industry, science, health, society and the environment. Examples of these needs are given below that will require metrological developments during the next decade.

The CCM has a sufficient set of comparisons that covers the current scope of the CCM's activities (see section 7). The light shines wide enough to cover most of the CMCs. There is a small room for improvement in defining the right set of KCs for each field (see section 7). It is anticipated that this set will be only slightly expanded with time to complement new measurement capabilities. The CCM will further improve the efficiency and effectiveness of the KCs and CMC review by addressing the key recommendation of the CIPM MRA Review. In particular, the CCM will continue to develop common toolkits and best practice in order to encourage the NMIs to share the roles involving in coordinating KCs. Guidance will be useful to improve the consistency in the expression of CMCs and improve the efficiency of the CMC review process.

6.1.1 Density and viscosity

- More accurate and precise $p\rho T$ properties of refrigerants are needed in IEA (International Energy Agency) for efficiency improvement of heat pump systems. Development of a new ozone-depletion free and low GWP (Global Warming Potential) fluid is an urgent task for environment. Standards for the thermodynamic properties of those fluids are needed for developing their equation of state (EOS),
- Producers of instruments measuring the refractive index of liquids are now requiring a traceable standard liquid. Supplying the refractive index standard liquids, which are similar to the density standard liquids, would introduce a good impact for food industry and agriculture,
- Measure of the pressure dependence of fuels and of heat transfer liquids.

6.1.2 Force and Torque

Efficient and sustainable energy production (e.g. wind energy as renewable energy source) and protection of the environment (e.g. more efficiency and less pollution of engines)

6.1.3 Fluid Flow

- CMC versus KC Gap Analysis is directing the WGFF to comparisons of smaller gas and liquid flows,
- Improve the procedures and uncertainty estimates for blockage effects in air speed calibrations. The uncertainty needs for air speed instrumentation are getting more rigorous due to applications related to wind turbine siting and operation. Instruments under test alter the flow field in wind tunnels, especially large instruments in small wind tunnels. The procedures followed to correct for blockage effects are not documented and the uncertainty due to blockage effects is often underestimated.

Some flow CMCs registered in the MRA KCDB are not yet covered by key comparisons.

6.1.4 Gravimetry

- Organize sufficient calibration service in gravimetry, like calibration of absolute and relative gravimeters (the present CMCs are related only to the absolute on-site measurements) (more calibrations than participation to a KC),
- Decrease uncertainty (CMCs),
- Increase number of CMCs entries (more participants).

6.1.5 Hardness

All activities are devoted to improve traceability and equivalency among NMIs as requested by stakeholders.

6.1.6 Pressure

Research and development activities are required in the fields of:

- Optical methods for total pressure (possibly a new realization of the Pascal) and partial pressure measurement,
- Low differential pressure with high accuracy and low line pressure (10 to 120 kPa absolute mode),
- High hydraulic pressures (above 1 GPa),
- Dynamic pressures (in all modes and ranges, starting with relative hydraulic pressure in medium pressure, 100 MPa),
- Requirements relating to the refrigerant greenhouse, specifications of tightness of refrigerant equipment and refrigerants' limit leak detection, improved leak testing of nuclear power stations and nuclear waste storage containers,
- Fusion experiments, high energy research facilities, innovative industrial processes such as e.g. semiconductors, coatings, displays production or EUV-lithography have very strict requirements for vacuum properties, i.e. very low outgassing, traceable outgassing rate measurement,
- Measurements of partial pressure performed in industry using residual gas analysers (RGAs) are very important to control many kinds of processes (e.g. physical and chemical vapour deposition),
- More reliable reference and transfer standards for UHV,
- High pressure technologies such as high pressure processing of food, innovative diesel engineering, autofrettage, hydroforming and isostatic pressing, vessel production for the petrochemical and pharmaceutical industry, manufacturing of water cutting machines and new material fabrication require traceable pressure measurement above 1 GPa.

Some pressure CMCs registered in the MRA KCDB are not yet fully covered by KCs.

6.1.7 Mass standards (realization and dissemination)

- The standard uncertainty likely to be achieved for mass standards realized in terms of the Planck constant immediately after the redefinition is within 20 parts in 10^9 (20 µg at 1 kg) at best. This is larger than the uncertainty currently available via traceability to the IPK. There will be a need to manage any consequences of this larger uncertainty,
- In the short and middle term, there is some benefit in the BIPM maintaining an ensemble of mass standards as a means of averaging the values from primary mass realizations world-wide and using this ensemble as the reference for a mass calibration service for NMIs,
- In the longer term, there is a need for additional independent mass realizations and for different approaches to their use. For example, primary realizations such as watt (or Kibble) balance, may be used directly in NMIs as the basis for the mass unit. In this way, the mass hierarchy can be shortened and the required accuracy of the primary realization reduced. A primary realization at 1 kg with a relative standard uncertainty of about 1 part in 10^7 is sufficient to calibrate an OIML R111-1 Class E_1 kilogram and would be sufficient as the basis for routine mass calibrations in many NMIs,
- Do the utmost to ensure continuity, traceability, accuracy and acceptance of mass measurements worldwide, i.e. avoid or at least minimize possible discrepancies between different (“national”) realizations for mass metrology,
- To develop a more cost-effective approach to the primary realization with the final objective to make a (commercial) realization widely available (over a range of mass values).

6.2 Visions

The CCM WG on Strategy and MRA coordination wants to:

- Simplify and increase the operational efficiency of the CCM,
- Managing the level of participation in KCs more effectively,
- Simplify, standardise and accelerate all steps of KCs (from the protocol to the publication of results),

- Encourage common views across the CCs to analyse KC data and aim at an improved coordination work across the CCs,
- Improving the efficiency of the CMC review processes,
- Review or create directives for the technical work.

6.3 Action plan at the technical level

- Strategic actions and management actions decided at the 15th and 16th CCM meetings,
- Advise the BIPM on its next Program of Work,
- Address the key recommendations of the CIPM MRA Review, in particular:
    - continue to use common resource for KCs and streamlining (protocols, data analysis, reporting) at least within each WGs
    - continue to develop and share validated calculation tools
    - continue to encourage NMIs to share the roles involved in coordinating KCs (e.g. through mentorship, sharing toolkits and best practice)
    - limit participation in CC KCs that use sequentially travelling standards
    - progress towards better consistency in the expression of CMCs (e.g. units, uncertainty ranges)
    - interpret the results of KCs and SCs as widely as reasonably applicable to indicate coverage of CMCs
    - cover CMCs as many services as is technically justified and use uncertainty equations and matrices to reduce the number of CMCs where possible
    - develop and implement a “risk-based” approach to CMC review
- Review the chairmanship of the CCM WG,
- Review the CCM membership.

6.4 Role of the BIPM

6.4.1 Rationale for activity at the BIPM

The following rationale applies to the quantity: mass.

- The unique artefact (IPK) providing global traceability requires central, neutral laboratory for long-term maintenance and global dissemination,
- After redefinition: traceability to multiple primary realizations based on new and complex primary methods will require comparisons to maintain worldwide mass uniformity,
- The potential small number of future national primary realizations in the short term and medium terms (current realizations are complex and expensive) requires an international programme to guarantee access to primary realizations (Ensemble of reference mass standards together with the set of Pt-Ir working standards and potentially a watt (or Kibble) balance).

There are no other activities at the BIPM concerning other related quantities of the CCM.

6.4.2 Rationale for a specific activity at the BIPM Physical Metrology department

Traditional mass metrology

Rationale: All mass measurements are currently traceable to an artefact, the IPK. BIPM currently has the responsibility for disseminating the mass unit (mandated activity):

- Provision of calibrations of Pt-Ir prototypes and 1 kg stainless steel mass standards against the IPK,
- Provision of Pt-Ir prototypes,
- Investigation of cleaning techniques.

These needs must be carefully monitored as the new kg definition comes into effect.

Support for the new kg definition

Rationale: As the custodian of the IPK, BIPM has special responsibility for dissemination of the mass unit. This responsibility will remain with the BIPM in the short and medium terms with a focus on:

- Ensuring the continuity between the present and the new kg definition at the highest accuracy level (Extraordinary Calibrations),
- Achieving worldwide uniformity of multiple primary realizations based on new and complex primary methods by organizing comparisons at the level of 1 kg,
- Guaranteeing the reliability of the new *mise en pratique* by ensuring access to primary realizations.

6.4.3 BIPM activities

The main activities in the mass area are:

- Organization of future ongoing comparison,
- Watt (or Kibble) balance,
- Ensemble of reference mass standards (establishment, characterization and link to primary realizations),
- Fabrication of Pt-Ir mass prototypes for member states and calibration (at present wrt to IPK, after redefinition wrt primary realizations by using the Ensemble of reference mass standards together with the set of Pt-Ir working standards),
- Investigation of air-vacuum mass transfer, storage and cleaning of mass standards,
- Reinforce collaboration with WGD-kg, WGR-kg and NMIs in order to avoid duplication of efforts.

The Ensemble of reference mass standards together with the set of Pt-Ir working standards will serve as a flywheel for KCs of primary realizations and will allow the dissemination of the kg unit over a limited time, even if a sufficient number of primary realizations would be unavailable by this period. The total number of operating watt (or Kibble) balances is expected to be small and fluctuating, depending on national policies. The same is true for the realizations by the XRCD method. The BIPM watt (or Kibble) balance is developed on a cost-shared basis and shall be maintained for an extended time.

7 Required key comparisons and pilot studies with indicative repeat frequency

The CCM general philosophy when deciding to make a comparison is to be close to industry and to the customer needs. Where travelling standards are used sequentially, participation in CIPM KCs should be limited to the minimum number of institutes necessary to provide effective linkage in each region (no more than three institutes per RMO).

A short description and a timetable of the required KCs in each WG are given here. The list of ongoing and planned KCs is presented under section 8. Without further indication, the repeat frequency for a KC is 10 years.

7.1 Density and viscosity

- In general, completed and planned KCs covers almost all of the CMCs on density. No frequent KCs are necessary. A period of 10 to 15 years is considered to be adequate for density,
- As the gas density measurements will be of importance for energy savings and energy transportations, such a CMC may be covered by a new KC on the $p\rho T$ properties of fluids,
- As the food industry and agriculture need a traceable standard of the refractive index of liquids for sugar content measurements, supplying the refractive index standard liquids, which are similar to the density standard liquids, are necessary. Such a comparison is covered by CCM.D-K6,
- The current situation on viscosity is to perform one key comparison every 6 years, alternating between broad viscosity range at moderate temperatures and moderate viscosities in a broad temperature range.

year 20XX KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.D-K1					X									
CCM.D-K2							X							
CCM.D-K3		X												
CCM.D-K4											X			
CCM.D-K5			X											
CCM.D-K6				X										
CCM.V-K1														
CCM.V-K2														
CCM.V-K3					X						X			
CCM.V-K4		X						X						X

Table 1: Timetable of the required KCs in density and viscosity.

7.2 Force and Torque

- In general, for dead-weight force and torque facilities, no frequent KCs are necessary, a period of 15 to 20 years is considered to be adequate,
- At the moment, there are no results available as a basis for estimating an appropriate repeat frequency of comparisons with non-dead weight machines being involved,
- KCs are especially necessary in the ranges not yet covered by comparisons, e.g. in force below 5 kN and in torque below 100 N·m or above 20 kN·m,
- A comparison of 200 N and 500 N in force and a comparison of 20 N·m and 50 N·m in torque is planned to be carried out in the next years. The pilot for 200 N and 500 N will be METAS and details will be decided in 2017 and it is planned to start with this comparison in 2018,
- A comparison up to 200 kN·m is foreseen without concrete planning yet,
- To cover the development of force standards with forces in the mN, µN and nN range pilot studies are recommended,
- Also in the new field of dynamic force measurement pilot studies can be performed.

year 20XX KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.F-K1					X									
CCM.F-K2											X			
CCM.F-K3														X
CCM.F-K4								X						
CCM.F-K23 new (200N, 500N		X												

CCM.T-K1						X								
CCM.T-K2									X					

Table 2: Timetable of the required KCs in force and torque.

7.3 Fluid Flow

- WGFF KCs are presently organized into 6 measurands: 1) water flow, 2) hydrocarbon liquid flow, 3) air speed, 4) liquid volume, 5) high pressure gas (and natural gas) flow, and 6) low pressure gas flow,
- A 10 year cycle is not a serious burden for the flow community. Lengthening the period could probably be tolerated, but is not recommended. If KCs were not organized by the WGFF, comparisons would continue (informally organized between NMIs as they were before the WGFF was formed in 2000), but they would be poorly organized, selectively documented, etc. (as they were before 2000). Progress in the study of transfer standards and protocols for KCs and the corresponding improvements in proficiency testing for commercial lab accreditation would suffer,
- The WGFF is near completion of the second round of KCs in our 6 general measurands: we recently completed or are in Draft A stage for 6 KCs and one in the testing stage. Three KCs are in the planning stage, including 2 directed at the small gas and liquid flow ranges indicated by our Gap Analysis.

year 20XX / KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.FF-K1 CCM.FF-K6	X													
CCM.FF-K2					X									
CCM.FF-K3					X									
CCM.FF-K4					X									
CCM.FF-K5										X				

Table 3: Timetable of the required KCs in fluid and flow.

7.4 Gravimetry

CCM.G-K2, CCM.G-K2.2017, regional comparison of AGs (EURAMET, APMP, SIM, COOMET) – periodicity of six to eight years.

year 20XX / KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.G-K2	X						X						X	

Table 4: Timetable of the required KCs in gravimetry.

7.5 Hardness

- Vickers (every 10 years changing partially the scales),

- Brinell (every 10 years changing partially the scales),
- Rockwell C (every 10 years),
- Rockwell (other scales) (every 10 years),
- Shore (10 years),
- Leeb (10 years).

year 20XX KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.H-K3	X													
CCM.H Brinell hard-ness (HBW)		X												
CCM.H Rockwell N scale (HR15N, HR30N and HR45N)		X												

Table 5: Timetable of the required KCs in hardness.

7.6 Pressure

List of next key comparisons in order of proposed priorities is available in the WGPV webpage. The suggested repetition period is 15 years. A KC for a new quantity, leak rate against atmosphere, is planned. Also first pilot comparisons for dynamic pressures are planned.

year 20XX KC identifier	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.P-K1.b CCM.P-K1.c CCM.P-K2	X													
CCM.P-K3		X												
CCM.P-K4							X			(X)				
CCM.P C-Poil; C-Neg; C-Diff				X										
CCM.P C-HPoil							X							
CCM.P-K12				X										
CCM.P-K15													X	

Table 6: Timetable of the required KCs in pressure and vacuum.

7.7 Mass standards (realization and dissemination)

- On-going key comparisons of realizations of the revised definition of the kilogram (the first immediately after redefinition, the second at the latest after 5 years, further comparisons approx. every 10 years if the results of the previous comparisons are acceptable considering the CCM recommendation G1 (2017),

- Traditional comparisons of mass standards should continue following the current plan,
- Comparisons below 100 mg (at least once) should be considered.

KC identifier \ year 20XX	17	18	19	20	21	22	23	24	25	26	27	28	29	30
CCM.M-K1 CCM.M-K4 (1 kg)						X								
CCM.M-K2 CCM.M-K5 CCM.M-K7 ((sub-)multiples)										X				
CCM.M-K3 CCM.M-K6 (50 kg)								X						
BIPM.M-K1			X					X						

Table 7: Timetable of the required KCs in mass standards.

8 Summary table of comparisons

The following table lists the ongoing and future CCM KCs.

Branch	Reference number	Description	Repeat cycle	Start date	How far does the light shine
Density	CCM.D-K3	Density of stainless steel weight	10-15	2018	Mass range 100 g to 1 kg
Density	CCM.D-K5	Liquid density measurement by oscillation-type density meter	10-15	2019	0.8 kg/m^3 to 1.5 kg/m^3
Density	CCM.D-K6	Refractive index of liquid	10-15	2020	1.3 to 1.7
Density	CCM.D-K1	Density of silicon crystal	10-15	2021	Mass range 100 g to 1 kg
Viscosity	CCM.V-K3	Measurement of viscosity standard liquids in a wide viscosity range	6	Ongoing	5 mm^2/s to 160000 mm^2/s
Viscosity	CCM.V-K4	Measurement of viscosity standard liquids in a wide temperature range	6	2018	10 °C to 100 °C
Fluid Flow	CCM.FF-K5.2016	High pressure gas flow	10	2016	10 m^3/h to 10^6 m^3/h
Fluid Flow	CCM.FF-K1.2017	Water flow	10	2017	1 m^3/h to 10^3 m^3/h
Fluid Flow	CCM.FF-K6.2017	Low pressure gas flow	10	2017	10^{-4} m^3/h to 10^3 m^3/h
Fluid Flow	CCM.FF-K1.2018	Water micro flow	10	2018	10^{-8} m^3/h to 10^{-3} m^3/h
Fluid Flow	CCM.FF-K2.2021	Hydrocarbon liquid flow	10	2021	1 m^3/h to 10^3 m^3/h

Fluid Flow	CCM.FF-K3.2021	Air speed	10	2021	10^{-1} m/s to 10^{2} m/s
Fluid Flow	CCM.FF-K4.2021	Liquid volume	10	2021	10^{-6} L to 10^{6} L
Force	CCM.F-K23	Force Measurements at 200 N, 500 N	15-20	2018	Force Range: 10 N – 1000 N
Force	CCM.F-K1	Force Measurements at 5 kN, 10 kN	15-20	2021	Force Range: 1 kN – 20 kN
Force	CCM.F-K2	Force Measurements at 50 kN, 100 kN	15-20	2027	Force Range: 20 kN – 200 kN
Force	CCM.F-K3	Force Measurements at 500 kN, 1000 kN	15-20	Ongoing	Force Range: 200 kN – 1000 kN
Force	CCM.F-K4	Force Measurements at 2 MN, 4 MN	15-20	2024	Force Range: 1 MN – 20 MN
Torque	CCM.T-K1	Torque Measurements at 500 N·m, 1000 N·m	15-20	2022	100 N·m to 2 kN·m proposal
Torque	CCM.T-K2	Torque Measurements at 10 kN·m, 20 kN·m	15-20	2025	2 kN·m to 100 kN·m proposal
Gravity	CCM.G-K2.2017	Free-fall acceleration	6	2017	All gravity ranges
Hardness	CCM.H-K3	Rockwell C scale (HRC)	10	2017	20 HRC, 30 HRC, 45 HRC, 60 HRC and 64/65 HRC
Hardness	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
Hardness	CCM.H-K5	Rockwell HR15N scale (HR15N)	10	2021	72 HR15N, 78 HR15N, 83 HR15N, 90 HR15N, 94 HR15N proposal
Hardness	CCM.H-K6	Rockwell HR30N scale (HR30N)	10	2022	46 HR30N, 55 HR30N, 64 HR30N, 78 HR30N, 86 HR30N proposal
Hardness	CCM.H-K7	Rockwell HR45N scale (HR45N)	10	2023	22 HR45N, 37 HR45N, 49 HR45N, 67 HR45N, 78 HR45N proposal
Pressure	CCM.P-K3	Type C-IG, range $3 \cdot 10^{-9}$ Pa … $9 \cdot 10^{-5}$ Pa	15	2018	Pressure range 10^{-9} Pa ... 10^{-4} Pa
Pressure	CCM.P-K1.b	Type C-BarG, 25 kPa to 175 kPa (gauge mode)	15	2017	Pressure range 10^{5} Pa ... 10^{6} Pa gauge
Pressure	CCM.P-K1.c	Type C-HPgas, 1 MPa to 7 MPa (gauge mode)	15	2017	Pressure range 10^{6} Pa ... 10^{7} Pa gauge
Pressure	CCM.P-K2	Type C-BarA, 25 kPa to 175 kPa (absolute mode)	15	2017	Pressure range 10^{5} Pa ... 10^{6} Pa gauge
Pressure		Type C-ATL, $2 \cdot 10^{-9}$ mol/s	15	2018	Molar flow (leak) rate 10^{-10} mol/s ... 10^{-7} mol/s

9 Document Revision Schedule

1 year for exceptions
2 year updating of all lists
4 year major revision with extension of period covered by rolling programme

Versions:
14 January 2013: First version (version 0.7)
01 March 2013: Update (including appendix) after the 14th CCM (version 1.0)
3 October 2013: Update (including the major topics for the CCM, the comments from the NMI directors, the CCM roadmap 2018 and the main BIPM activities) after the CIPM meeting of June 2013 (version 2.0 for 2014 - 2024).
October 2017: Version 3.0 for 2017-2027 (major revision of the document, extension of period covered by rolling programme)

10 Appendix 1: Details of CCM Working Groups

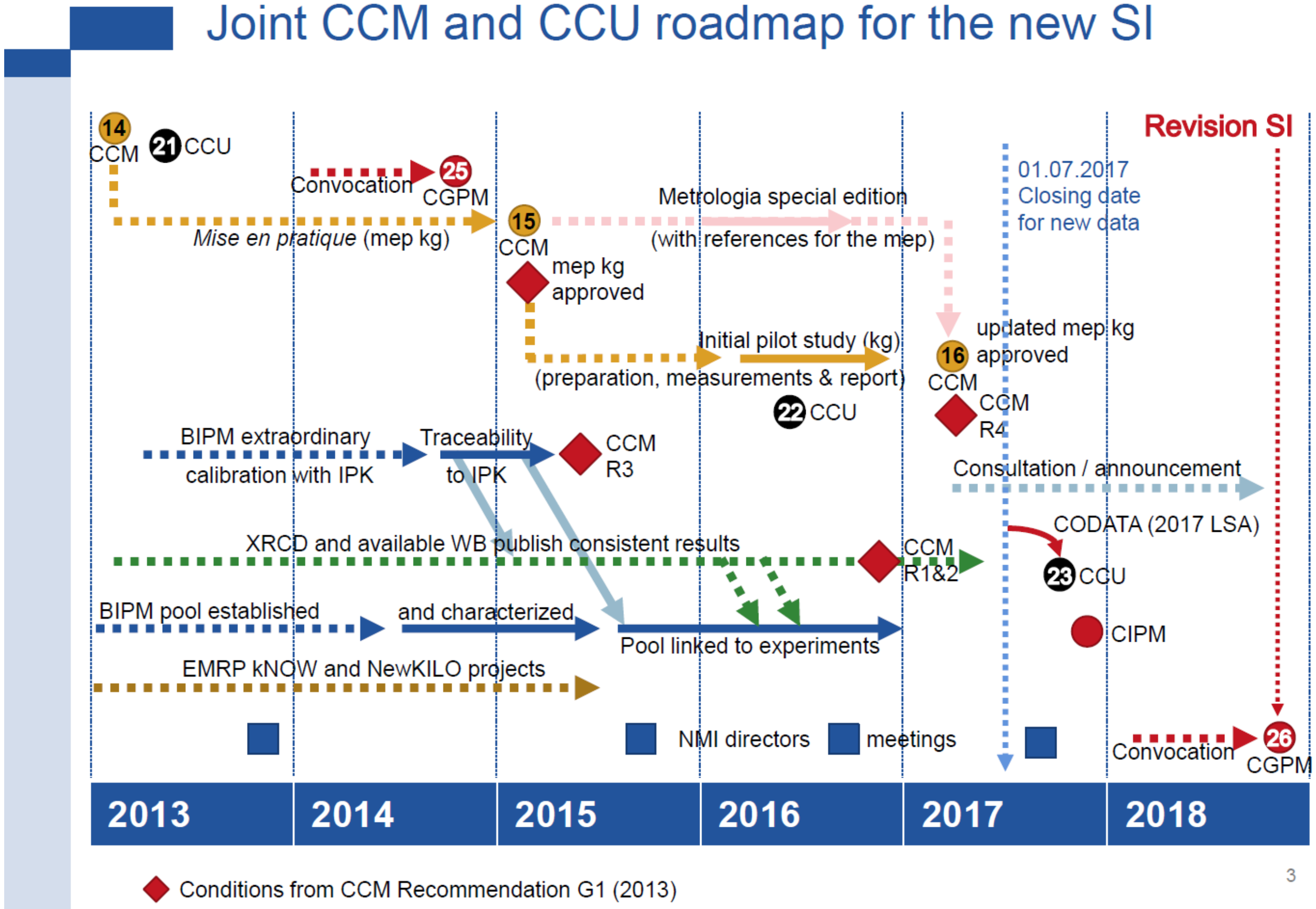
CCM WG	Date estab-lished	Chair (vice chair)	Institute	Years in post[7]	Number of members (ob-servers)	Participants at the last meeting (members/guests)	Date last meeting	Periodici-ty (years)
WGDV	2014	K. Fujii (H. Wolf)	NMIJ (PTB)	3	27 NMIs + BIPM	36/ 2	May 2017	2-3
WGFT	1981	R. Kumme	PTB	9	30	18/2	June 2017	3
WGFF	2000	J. Wright (B. Mickan)	NIST (PTB)	7	25	27	March 2018	1
WGG	2003	A. Germak	INRIM	2	20	12/2	February 2016	1 - 2
WGH	1998	S. Low (F. Menelao)	NIST (PTB)	2	20 NIMs	11 Delegates or Tech. Experts from 10 NMIs / 4 Visitors	September 2017	1
WGPV	2014	K. Jousten (J. Torres)	PTB (CENAM)	2	20 (3)	21	May 2017	3
WGD-kg	2013	C. Sutton (S. Davidson)	MSL (NPL)	3	22(2)	25/2	May 2017	1 - 3
WGR-kg	2013	H. Bettin	PTB	3	15	10/19	May 2017	1 - 2
WGS	2012	P. Richard as CCM President	METAS	4	15	12+ RMO TC chairs	May 2017	1 - 2

Working Group on Density and Viscosity (WGDV)
Working Group on Fluid Flow (WGFF)
Working Group on Force and Torque (WGFT)
Working Group on Gravimetry (WGG)
Working Group on Hardness (WGH)
Working Group on Pressure Vacuum (WGPV)
Working Group on Strategy and MRA coordination (WGS)

[7] All WG chairpersons (except for the WGS) were appointed or re-appointed by the CCM President with the agreement of the CM members at the 13th CCM meeting in 2011 for four years and implicitly reappointed at the 14th CCM meeting in 2015. According to the document CIPM-D-01, section 6.3, all WG chairs must be reappointed at the latest in 2019.

Working Group on the Dissemination of the Kilogram (WGD-kg)
Working Group on the Realization of the Kilogram (WGR-kg)

11 Appendix 2: CCM Roadmap 2018



12 List of abbreviations

The abbreviations of the working groups are given in Appendix 1.

AG	Absolute gravimeter
APMP	Asia pacific metrology program
ASTM	American Society for Testing and Materials
BIPM	Bureau international des poids et mesures
CC	Consultative Committee
CCEM	Consultative committee on electricity and magnetism
CCM	Consultative Committee for Mass and related quantities
CGPM	Conférence générale des poids et mesures
CIPM	Comité international de poids et mesures
CMC	Calibration and measurement capabilities
DI	Designated institute
EMRP	European Metrology Research Programme
EOS	Equation of state
EURAMET	European association of metrology institutes
EUV	Extreme ultraviolet
GWP	Global Warming Potential
IEA	International Energy Agency
IUGG	International Union of Geodesy and Geophysics
IAG	International Association of Geodesy
IAPWS	International Association for the Properties of Water and Steam
ISO	International Organization for Standardization
IPK	International prototype of the kilogram
KC	Key comparison
KCDB	Key comparison data base
METAS	Federal institute of metrology (Switzerland)
MoU	Memorandum of Understanding
MRA	Mutual recognition arrangement
NMI	National metrology institute
NMIJ	National metrology institute of Japan
OIML	Organisation internationale de métrologie légale
PTB	Physikalisch- Technische Bundesanstalt (National metrology institute of Germany)
R&D	Research and development
RGA	Residual gas analyser
RMO	Regional metrology organization
TC	Technical committee
VAMAS	Versailles Project on Advanced Materials and Standards
WG	Working group
XRCD	X-ray-Crystal-Density