TASK GROUP ON THE SI (TG-SI) REPORT TO CCT

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Terms of reference: The Terms of Reference follow closely the Recommendation 1 of the 94th meeting of the CIPM in 2005, (CI-2005), "Preparative steps towards new definitions of the kilogram, the ampere, the kelvin and the mole in terms of fundamental constants". The TG-SI is presently tasked with the following two terms:

- monitor closely the results of new experiments relevant to the possible new definition of the kelvin, and to identify necessary conditions to be met before proceeding with changing the definition;

- solicit input from the wider scientific and technical community on this important matter.

Since CCT-27 TG-SI met twice:
The CODATA task group on fundamental constants (TGFC) organized from 1 to 6 February 2015 the Fundamental Constants Meeting 2015 in Eltville, Germany. Connected to this meeting CCT TG-SI met on Friday, 6 February 2015 in the conference venue, Hotel Frankenbach, from 8:30 to 12:30. In the meeting TG-SI concentrated on open questions and decisions in order to support the 2014 CODATA adjustment.

The TG-SI members, and a few additional experts (Livio Gianfrani (Univ. Naples), Christof Gaiser (PTB), Christophe Daussy (Univ. Paris North), Bo Gao (TIPC), Dolores del Campo (CEM)) met together with WG-CTh to review the final state of the Boltzmann constant determinations at BIPM on 30 May 2017, right before CCT-28, from 14:00 to 18:00. This was the closing meeting of TG-SI as its tasks have been successfully completed.

In 2016, TG-SI produced a two-page document entitled “Redefinition of the kelvin” to increase awareness and understanding of the new definition and posted it on the CCT homepage under the new entry “Future redefinition of the SI”: www.bipm.org/en/committees/cc/cct/publications-cc.html

Similarly, in 2017 TG-SI contributed to the activities of the CIPM Task Group for Promotion of the SI with the following 100-words-statement:
“The redefinition of the kelvin will have no immediate effect on temperature measurement practice or on the traceability of temperature measurements, and for most users, it will pass un-noticed.
The redefinition lays the foundation for future improvements. A definition free of material and technological constraints enables the development of new and more accurate techniques for measuring temperature, especially at extremes of temperature.
After the redefinition, the Mise en Pratique of the definition of the kelvin will guide world-wide dissemination of the kelvin by describing primary methods for measurement of thermodynamic temperature and equally through the defined scales ITS-90 and PLTS-2000.”

Based on the comprehensive review of recent determinations of the Boltzmann constant k TG-SI drafted recommendation T 1 (2017). This recommendation is endorsing the new definition of the kelvin by fixing the numerical value of k as now all conditions set by CCT are completely fulfilled.

In the following, a brief review of the determinations of the Boltzmann constant k important for the new definition of the kelvin and performed in the years from 2008 to 2017 is given. A summary paper on the determination of the Boltzmannn constant will be prepared by the TG-SI members. The leading authors are Michael de Podesta for AGT, Christof Gaiser for DCGT, Jifeng Qu for Johnson noise thermometry, and Christophe Daussy for Doppler broadening thermometry.

The starting point for determinations of the Boltzmann constant leading to a new definition of the kelvin was an iMERAPlus research project. Between 2008 and early 2011 this project [1] was coordinating the European activities to determine *k* in Denmark (Danish Fundamental Metrology, DFM), France (Laboratoire National de Métrologie et d'Essais, LNE-CNAM and Laboratoire de Physique des Lasers at University Paris North, LPL), Italy (Istituto Nazionale di Ricerca Metrologica, INRiM and Universities of Naples and Milan), Spain (Universidad de Valladolid and Centro Español de Metrología, CEM), United Kingdom (National Physical Laboratory, NPL) and Germany (Physikalisch-Technische Bundesanstalt, PTB). This large research collaboration project resulted in a major progress and overall in essential developments for acoustic gas thermometry (AGT). The AGT measurements of LNE-CNAM [2, 3], NPL [4], and INRiM [5] all used resonators jointly developed within the iMERAPlus project and achieved the smallest uncertainties of all methods achieved so far. All results were highly consistent and agreed very well with the CODATA value of 2006 [6] based mainly on [7]. These four new determinations were exploited by the CODATA TGFC in its 2010 adjustment together with the fundamental AGT results [8] and [7]. The CODATA TGFC recommended a value for *k* with a relative standard uncertainty of 9.1×10^{-7} [9].

In 2013 **NPL** published high-precision **AGT** measurements using argon gas in a 1.0 liter volume (62 mm radius) quasi-sphere with a relative standard uncertainty of 0.71×10^{-6}, [10]. The NPL estimate of *k* was 2.7×10^{-6} higher than the LNE-CNAM estimate with argon in 2011 [3] and this difference was inconsistent with the combined relative uncertainty of both determinations of 1.4×10^{-6}. Examination of the contributions to the measurement uncertainty in *k* showed that the largest single component (24%) is the uncertainty of the molar mass of atmospheric argon determined by Lee *et al*. at the Korea Research Institute of Standards and Science (KRISS) [11]. The NPL estimate was based on a comparison at the Scottish Universities Environmental Research Centre (SUERC) of the isotopic composition of the experimental gas with the isotopic composition of argon from atmospheric air, and referenced to the KRISS 2006 estimate for the isotopic composition of atmospheric argon [11]. In contrast, the LNE-CNAM Boltzmann value was based on the molar mass determinations of the Institute for Reference Materials and Measurements, Belgium (IRMM). Important studies were performed during the period October to December 2014 to resolve the issue [12]. Based on the measurements at KRISS the value of *k* determined in the NPL 2013 experiment was corrected by $\Delta k/k = -2.73\times10^{-6}$, resolving the discrepancy between both results [13]. For the CODATA adjustment of 2014, both the LNE-CNAM 2011 and the NPL 2013 results are considered to rely on the KRISS molar mass determinations and no longer on the IRMM and SUERC results, introducing a strong correlation between the 2011 LNE-CNAM and the 2013 NPL results [14]. Taking into account the uncertainty of the KRISS measurement increases the 2011 LNE-CNAM and the 2013 NPL total relative standard uncertainties of *k*, now estimated at 1.41×10^{-6} and 0.90×10^{-6}, respectively [14]. In 2017, NPL published a revised relative uncertainty for the 2013 measurement of 0.702×10^{-6}. The reason of the error made in the 2013 measurement was found to be contamination of the argon gas by atmospheric air during sampling for the molar mass determination [15].

LNE-CNAM published in 2015 the series of measurements of May 2012 and January 2013 using helium gas with the 0.5 liter copper quasi-sphere BCU3 (50 mm radius) [16]. The value of *k* is in good agreement with the earlier measurements in argon and has a relative standard uncertainty of 1.01×10^{-6}. The values of the uncertainty contributions are nearly equally spread over the measurements of acoustic frequency, resonator volume, molar mass, and temperature, the latter being the lowest. For the results with the large 3.1 liter quasi-sphere BCU4 and 90 mm radius operated with helium they claim a (preliminary) relative standard uncertainty of *k* of 0.60×10^{-6} [17]. This is the lowest uncertainty in the determination of the Boltzmann constant achieved.

INRiM has pursued an accurate determination of the speed of sound in helium at 273.16 K with a 3-liter volume copper sphere assembled in 2013. Acoustic and microwave results indicate that the performance of the experiment has significantly improved with respect to previous INRiM achievements [5]. Also, temperature measurement and thermal gradients across the resonator are now satisfactory. A cross-check of the current estimate of helium impurities was made by using the mass spectrometry facilities made available by PTB. Thus, for all the four major uncertainty contributions significant progress has been obtained. INRiM published in 2015 a new value for the Boltzmann constant with a large reduction of the relative standard uncertainty to 1.06×10^{-6} [18]. The uncertainty contributions are 9.0×10^{-7} for the square of the speed of sound, 3.7×10^{-7} for the molar mass of the helium gas, and 4.2×10^{-7} for the temperature measurement.

At Universidad de Valladolid in collaboration with **CEM** a stainless steel misaligned spherical resonator with a radius of 40 mm was developed to determine the Boltzmann constant. Due to the material, small size and surface quality of the cavity the relative uncertainty was limited to 20×10^{-6} [19]. Further, a new quasi-spherical gold-coated resonator has been developed. They plan to submit the results with a relative standard uncertainty of 7.5×10^{-6} for the Boltzmann constant in time for the redefinition of the kelvin.

The National Metrology Institute of China (**NIM**) compensated for the disadvantages of cylindrical resonators by developing a special two cylinder regime. As proof of concept a single 130 mm long cylindrical cavity was used [20]. In 2013 advanced results were obtained with the single resonator with a relative standard uncertainty of 3.7×10^{-6} [21], where the shape was closer to that of a perfect cylinder and also the thermometry was improved. The largest component of the uncertainty resulted from inconsistent values of k determined with the various acoustic modes and is 2.9×10^{-6}. Then, NIM applied the two-cylinder regime by developing a special virtual resonator approach. The main advantage of measuring the acoustic resonances in the new regime with two cylindrical cavities of identical diameters and lengths l and $2l$ is the removal of some major perturbations causing otherwise large corrections. NIM used two cavities of lengths 80 mm and 160 mm for a test of the virtual regime for the determination of k. An undesired resonant coupling between the two cavities or the pressure vessel was limiting the performance of the experiment [22]. Therefore, NIM returned finally to the single-cylinder regime and performed measurements in spring 2017. They published a weighted mean of all determinations with a relative standard uncertainty of 2.0×10^{-6} [23] considering carefully the correlations.

Dielectric-constant gas thermometry (**DCGT**) was developed by **PTB** and an experimental setup operated at 273.16 K has been constructed [24] consisting of a large-volume thermostat, a vacuum-isolated measuring system, stainless-steel 10 pF cylindrical capacitors, an autotransformer ratio capacitance bridge, and a high-purity gas-handling system including a mass spectrometer. The pressure was generated by special pressure balances with traceably calibrated piston-cylinder assemblies having effective areas of 2 cm^2. In the pressure range from about 1 MPa to 7 MPa, helium isotherms have been measured and a value has been determined for k with a relative standard uncertainty of 9.2×10^{-6}. Earlier low-temperature DCGT experiments yielded a value with a relative standard uncertainty of 15.9×10^{-6} [25]. The weighted mean of the two values has a relative standard uncertainty of 7.9×10^{-6} [24].

A significant reduction of uncertainties was achieved in 2013 by the use of tungsten-carbide cylindrical capacitors featuring at least a factor of two lower effective compressibility. Another essential progress was the determination of their effective compressibility, the sensitivity of the capacitance bridge, the influence of stray capacitances, the purity of the measuring gas, the pressure measurement, and the scattering and evaluation of the data. The resulting new value has a relative standard uncertainty of 4.3×10^{-6} [26]. Activities to decrease the uncertainty of the pressure measurement to a level of 1×10^{-6} were successfully completed in 2014 [27]. This included extensive cross-float comparisons between six independent primary piston–cylinder assemblies to improve the consistency of their effective areas and pressure-distortion coefficients. The resulting new relative standard uncertainty for the Boltzmann constant amounts to 4.0×10^{-6} [28].

Since 2013, further progress has been achieved concerning the design and the assembling of the capacitors, the determination of their effective compressibility, the sensitivity of the capacitance bridge, and the scattering and the evaluation of the data. Based on a huge amount of data, two new k values have been obtained applying two different capacitors. The combination of these two values with the 2013 one considering fully correlations yielded the final result of DCGT with a relative standard uncertainty of 1.94×10^{-6} [29]. The largest uncertainty contributions are the type A estimate and the determination of the effective compressibility.

With **Johnson noise thermometry NIST** achieved a relative standard uncertainty of 12 parts in 10^6 [30] for the Boltzmann constant. NIST has developed an advanced system for a more efficient measurement: The 2 channel-system is replaced by a 4 channel-system in a very compact setting with a 4-channel ADC-readout. The bandwidth of the system was increased by switching to amplifiers with increased bandwidth, with lower or comparable noise and higher linearity. In the most recent experiment, NIST used a 200 Ω sense resistor that reduced the statistical uncertainty by 25 % in the same measurement period compared to that of a 100 Ω sense resistor [31]. This system is different from systems that generated previous determinations, including the 2011 determination at NIST and both 2015 and 2017 determinations at NIM, in particular in the input circuit approach for matching the frequency response of the two noise sources. They plan to submit the final result in time for the redefinition of the kelvin.

A completely new noise thermometer was developed at the **NIM** in cooperation with the NIST [32]. It measures *k* by comparing the thermal noise across a 100 Ω resistor with the noise synthesized with a bipolar pulse-driven quantum-voltage-noise source. The flat ratio between the thermal noise and the calculated quantum voltage noise up to 800 kHz, and self-consistent fitting results with different bandwidths, indicate that the systematic uncertainties are greatly reduced. NIM compared the thermal noise power of a 200 Ω sensing resistor directly immersed in a triple-point-of-water cell to the noise power of a quantum-voltage noise source of nominally equal noise power. Measurements integrated over a wide bandwidth of 575 kHz and a total integration time of 33 days gave a relative standard uncertainty of 3.9×10^{-6} [33]. In the course of this determination very accurate measurements of the non-linearity of the detection system have been performed contributing only 0.1×10^{-6} to the relative uncertainty. In 2017, the consortium published the final value for the Boltzmann constant with a relative standard uncertainty of 2.71×10^{-6} [34]. The dominating uncertainty of 2.68×10^{-6} arises from the ratio of thermal and quantum voltage noise powers including a 2.37×10^{-6} statistical uncertainty. In total 120 measurements having each an integration period of 20 hours contributed, such that 100 days of integration time were accumulated.

As shown in table 1 there are several determinations of *k* with AGT featuring a relative uncertainty around 1×10^{-6}. Because of these and because the discrepancy between LNE-11 and NPL-13 experiments is resolved, the relative standard uncertainty of the *adjusted* value of *k* was in the 2014 CODATA calculation only 5.7×10^{-7} [35]. This uncertainty is securely below 1.0×10^{-6} thus fulfilling the first CCT condition for the new definition of the kelvin. The uncertainties of all determinations taken into account in the 2014 CODATA adjustment are marked in bold. For a complete list of determinations as of the 2016 state see [36]. In addition, the more recent low-uncertainty determinations INRiM-15 [18], PTB-17 [29], NIM/NIST-17 [34], NPL-17 [15], and LNE-17 [17] are listed in table 1 with (preliminary) uncertainty values in italics. With the results DCGT PTB-17 [29] and noise NIM/NIST-17 [34] the second CCT condition, demanding an independent method with a relative standard uncertainty below 3×10^{-6}, is fulfilled. Thus, the way for the new definition of the kelvin is free. In figure 1 apart from the determinations listed in table 1 also the CODATA adjusted values of 2010 [9] and 2014 [35] are shown for comparison.

Table 1 Development of the relative standard uncertainties $u(k)/k$ of high-accuracy determinations of the Boltzmann constant. Applied method and gas are specified. The uncertainties of the determinations contributed to the 2014 CODATA adjustment are marked in bold. For all AGT measurements up to 2015 uncertainties with correlations considered [14]. New determinations after the CODATA 2014 adjustment with uncertainties in italics (preliminary values marked by *).

determination	method	gas	$u(k)/k$ / 10^{-6}			
			up to 2011	2013	2015	2017
NIST-88	AGT	Ar	**1.77**	-	-	-
INRiM-10, -15	AGT	He	7.49	-	*1.06*	-
LNE-09, -15, -17	AGT	He	**2.73**	-	**1.01**	*0.60**
LNE-11	AGT	Ar	**1.41**	-	-	-
NPL-10, -13, -17	AGT	Ar	**3.19**	**0.90**	-	*0.70*
NIM-11, -13, -17	c-AGT	Ar	7.9	**3.70**	-	*2.0*
PTB-11, -13, -15, -17	DCGT	He	7.9	4.3	**4.0**	*1.94*
NIM/NIST-15, -17	Noise	-	-	-	**3.9**	*2.71**
NIST-11, -17	Noise	-	12.1	-	-	*?*

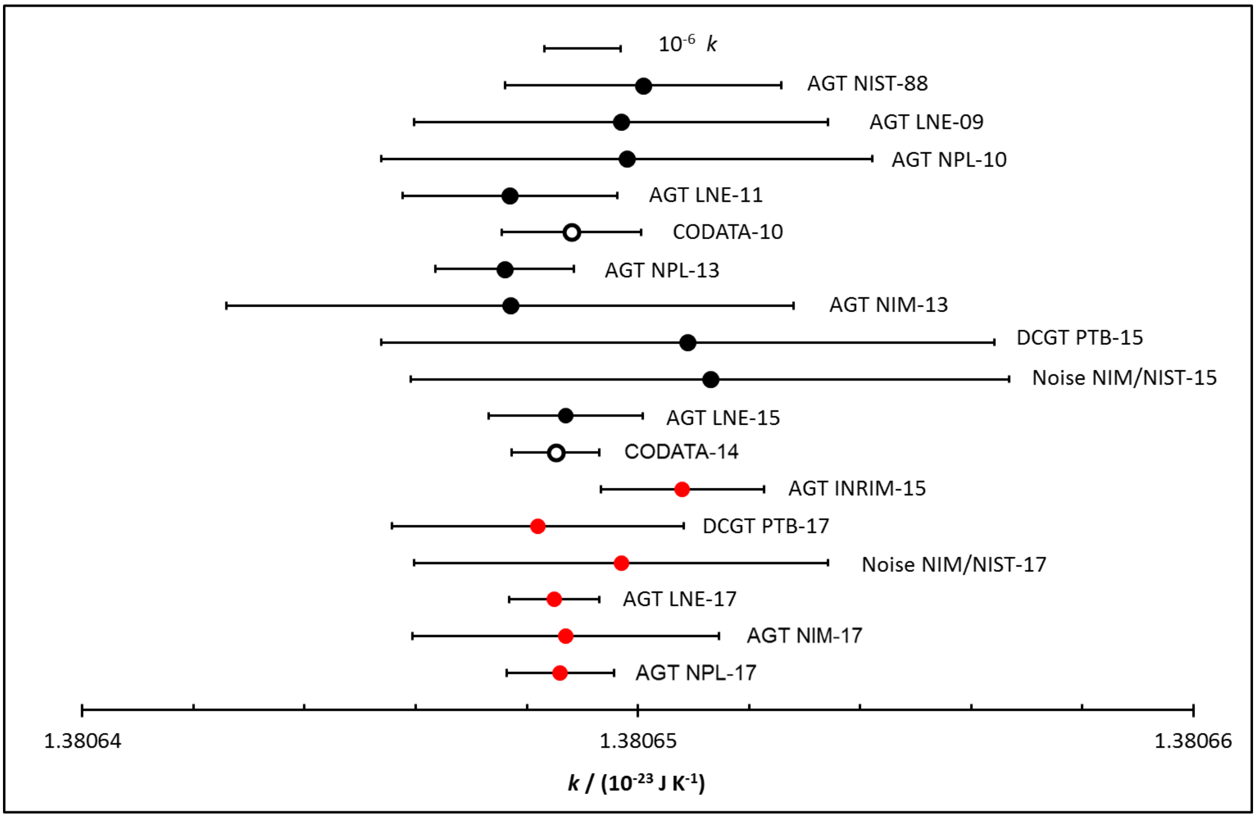

Figure 1 High-accuracy determinations of the Boltzmann constant in chronological order. Black dots: all contributions to the adjusted CODATA value of 2014. Red dots: new measurements after the CODATA 2014 adjustment. In addition, the CODATA adjusted values of 2010 and 2014 are shown as open circles. All error bars denote standard uncertainties. Uncertainties of NIM/NIST-17 and LNE-17 are preliminary.

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