The Kelvin Redefinition and Mise en Pratique of the Definition of Kelvin (*MeP*-K)

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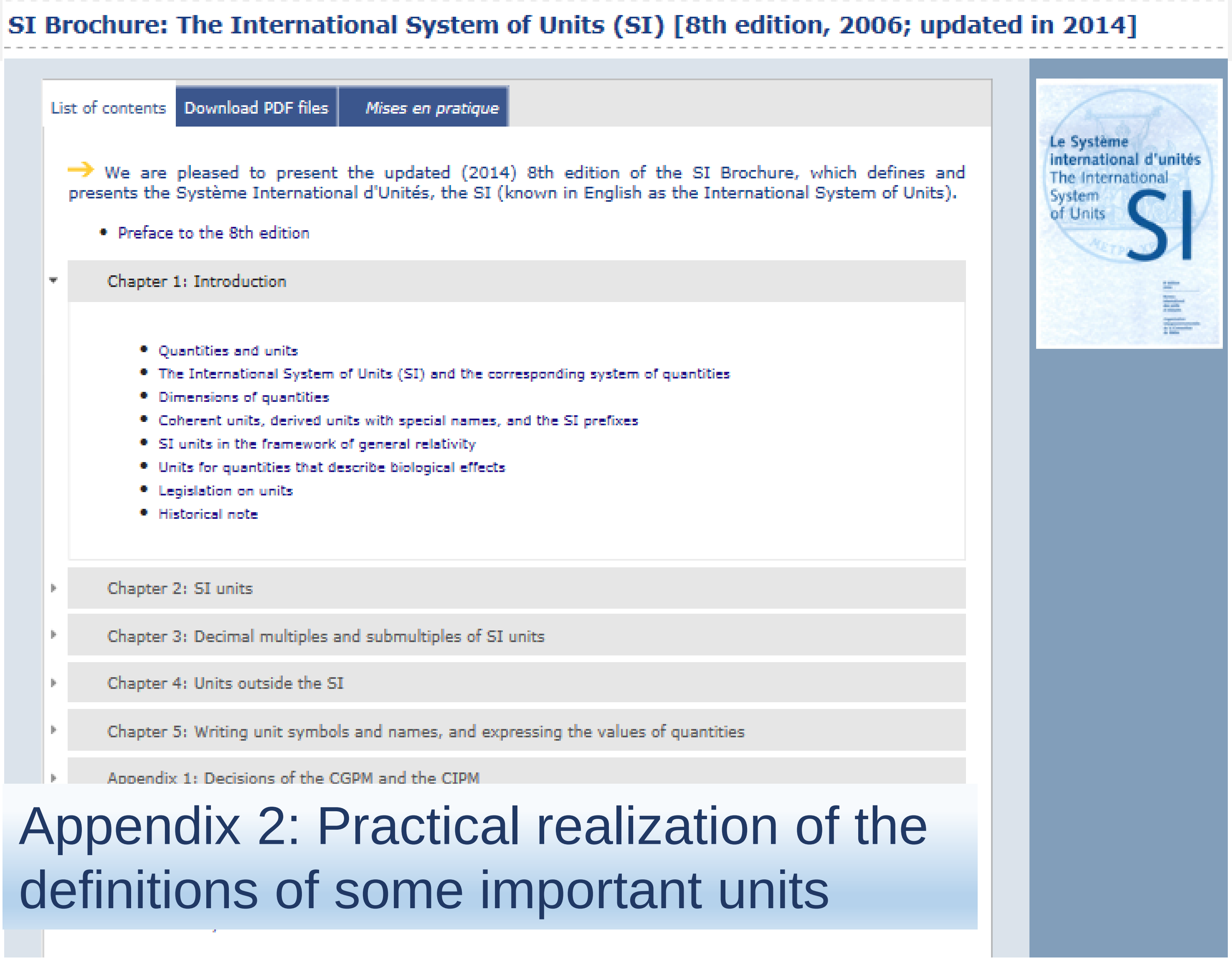
1. Background and role of the MeP-K

Mise en Pratique (MeP):
Practical realisation

The CIPM foresaw desirability of the MeP for each base unit on redefinition of the SI

MeP should include only top-level realisation methods

MeP-K > > flexible path for expanding the range of thermometric methods


SI Brochure: The International System of Units (SI) [8th edition, 2006; updated in 2014]

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We are pleased to present the updated (2014) 8th edition of the SI Brochure, which defines and presents the Système International d'Unités, the SI (known in English as the International System of Units).

- Preface to the 8th edition

Chapter 1: Introduction

- Quantities and units
- The International System of Units (SI) and the corresponding system of quantities
- Dimensions of quantities
- Coherent units, derived units with special names, and the SI prefixes
- SI units in the framework of general relativity
- Units for quantities that describe biological effects
- Legislation on units
- Historical note

Chapter 2: SI units

Chapter 3: Decimal multiples and submultiples of SI units

Chapter 4: Units outside the SI

Chapter 5: Writing unit symbols and names, and expressing the values of quantities

Appendix 1: Decisions of the CGPM and the CIPM

Appendix 2: Practical realization of the definitions of some important units

2. First version of the *MeP*-K (approved in 2011)

Text of the defined ITSs

- International Temperature Scale of 1990 (ITS-90)
- Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000)

Technical Annex for the ITS-90 (Progress!)

- Prescription of the isotopic composition for H_2, Ne, and H_2O
- Correction equations for samples having other isotopic compositions

Guides for the realisation of the ITS-90 and PLTS-2000

$T - T_{90}$ and $u(T - T_{90}) \rightarrow$ conversion of values (Progress!)

Technical Annex for the ITS-90

Isotopic composition and corrections for the TPW

- Vienna Standard Mean Ocean Water (V-SMOW)
- $T_{meas} = T_{90}(\text{TPW}) + A(\text{D})\ \delta\text{D} + A(^{17}\text{O})\ \delta^{17}\text{O} + A(^{18}\text{O})\ \delta^{18}\text{O}$
- $u_{max}(T_{meas} - T_{90}) < 5\ \mu\text{K}$

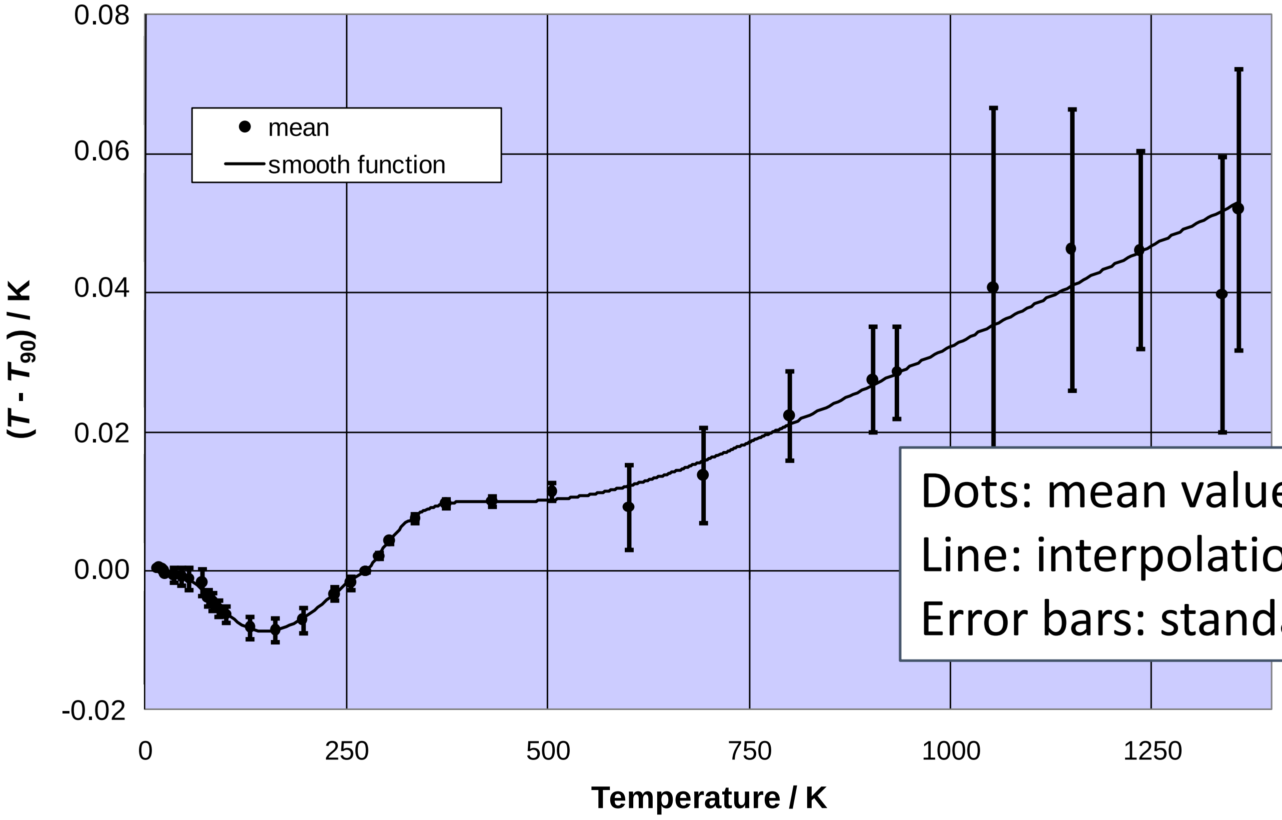
Isotopic composition and corrections for Neon

- IUPAC (International Union of Pure and Applied Chemistry) Composition
- $T_{meas} = T_{90}(\text{Ne TP}) + k_0 + k_1\ (^{22}x + {}^{21}x/2) + k_2\ (^{22}x + {}^{21}x/2)^2$
- $u_{max}(T_{meas} - T_{90}) < 5\ \mu\text{K}$

Isotopic composition and corrections for Hydrogen

- Standard Light Antarctic Precipitation (SLAP)
- $T_{meas} = T_{90}(\text{e-H}_2\ \text{TP}) + k_D\ (x - x_0)$
- $u_{max}(T_{meas} - T_{90}) < 20\ \mu\text{K}$

$T - T_{90}$ and $u(T - T_{90})$

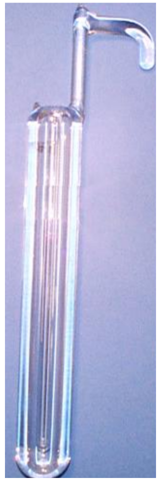


Dots: mean values
Line: interpolation with polynomials
Error bars: standard uncertainty

References:
Fischer et al.: Int. J. Thermophys. **32,** 12-25 (2011)
Engert et al.: Metrologia **44**, 40-52 (2007)

3. Redefinition of the SI base unit kelvin in 2018

Actual definition:
1/273.16 of the temperature of the triple point of water



Weakness in the actual definition:
Dependence on the properties of the water sample, especially the isotopic composition

Planned explicit-constant definition:
The kelvin, symbol K, is the SI unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly $1.380\,649 \times 10^{-23}$ when it is expressed in the SI unit $s^{-2}\ m^{2}\ kg\ K^{-1}$, which is equal to $J\ K^{-1}$.

$$k = 1.380\,649 \times 10^{-23}\ J/K$$

This means, the kelvin will be defined in terms of the SI derived unit of energy, the joule.

Progress on the determination of the Boltzmann constant

2002:

Study on *k* determination with DCGT
$u_r(k) \approx 2$ ppm

2004:

TEMPMEKO: Lecture with first idea for new definition

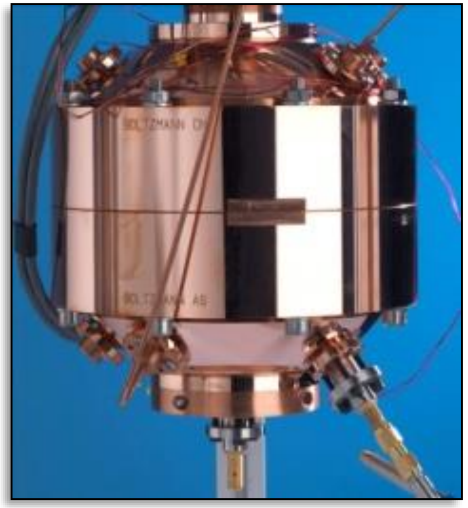
2005:

CCT TG-SI formed

2006:

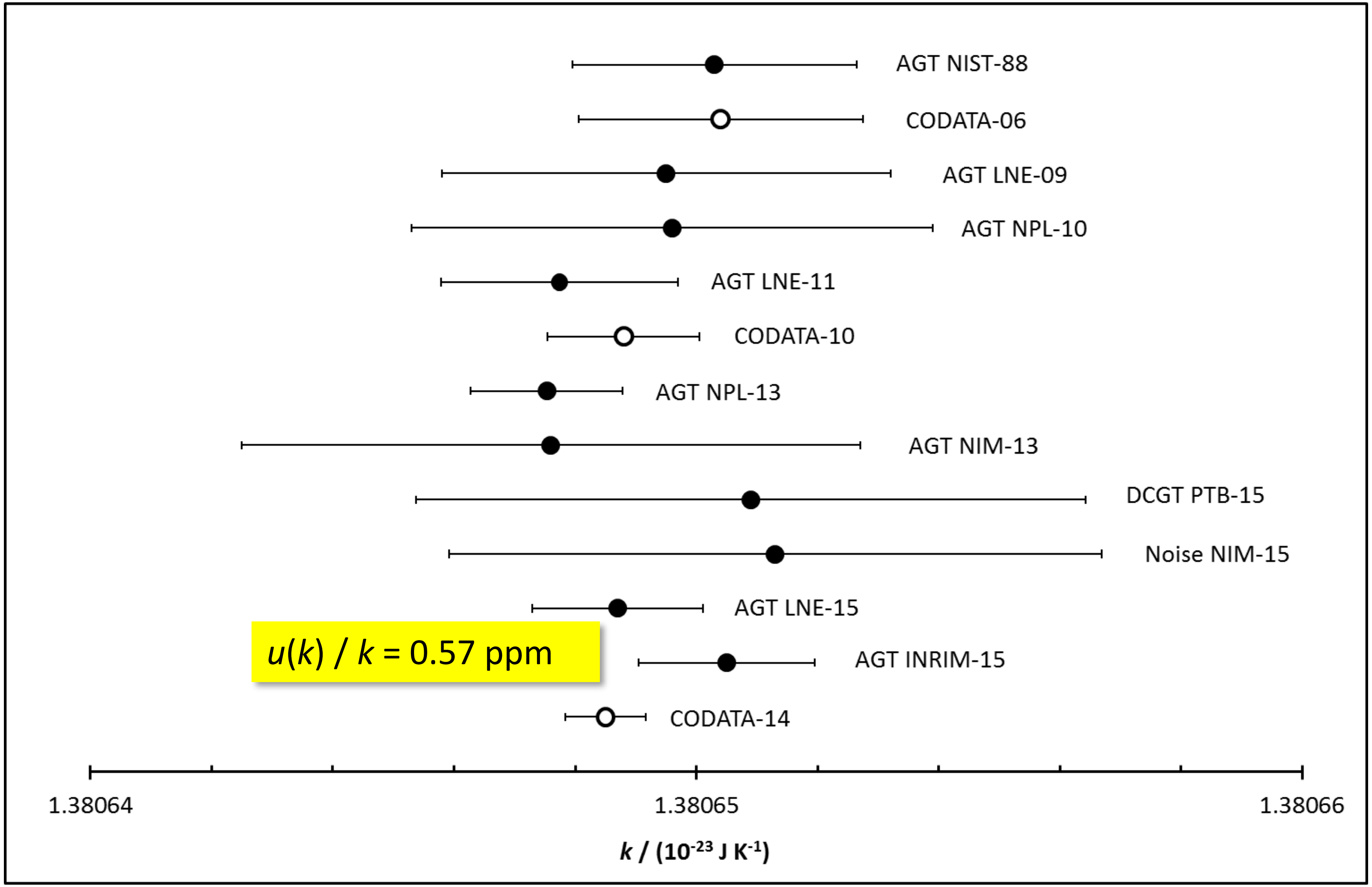
EURAMET-Project 885: “Determinations of the Boltzmann Constant“

2017: *Ready for determination of k and redefinition*

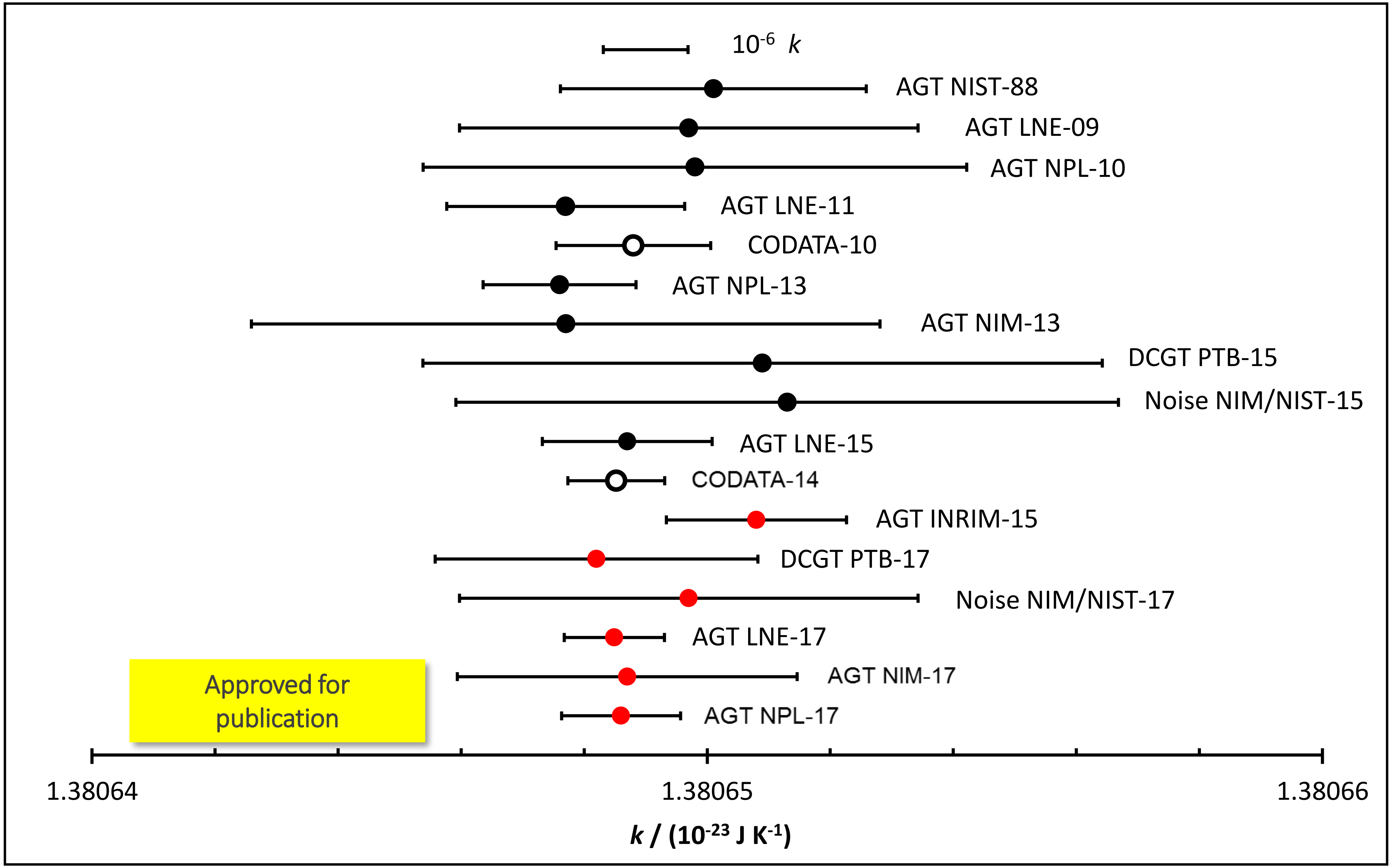


CCT TG-SI chaired by Dr Joachim Fischer (PTB)

Values of *k* ---- CODATA 2014



Values of *k* ---- CODATA 2017



Recent data

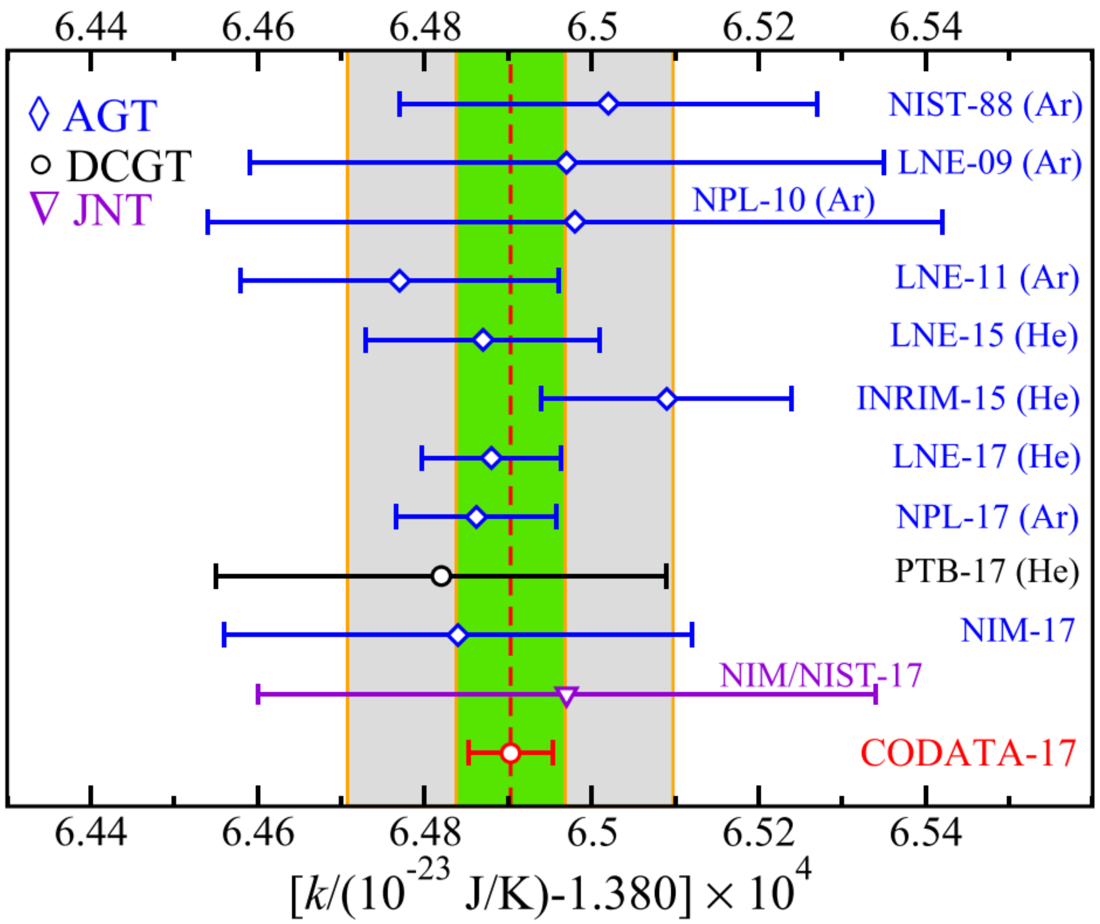
relative standard uncertainties in ppm

Method	gas	up to 2011	2013	2015	2017	institute
AGT	Ar	1.8	-	-	-	NIST
AGT	He	7.5	-	1.1	-	INRiM
AGT	He	2.7	-	1.0	0.6*	LNE-CNAM
AGT	Ar	1.4	-	-	-	LNE-CNAM
AGT	Ar	3.2	0.9	-	0.7*	NPL
AGT	Ar	-	-	20	7.5	UniVal+CEM
c-AGT	Ar	7.9	3.7	-	2.0	NIM/NIST
DCGT	He	7.9	4.3	4.0	1.9	PTB
JNT	-	-	-	3.9	2.7	NIM/NIST
JNT	-	12	-	-	< 3 ?	NIST
DBT	NH_3	50	-	-	-	LPL+LNE-CNAM
DBT	CO_2, H_2O	160	24	-	**10 ?**	UniNA+INRiM

Redefinition of the kelvin

- Set criteria on redefinition achieved
- Codata 2017 Special adjustment

k = 1.380 649 × 10^{-23} J/K



Redefinition of the kelvin

- Main text of *Mise en Pratique* now adapted to new format and style

  [Drs Bernd Fellmuth (PTB) and Christoph Gaiser (PTB)]

- MeP-K is based on a main text, supported by a set of Appendices:

  - 2 published in referred journals (Acoustic GT, Dielectric Constant GT)
  - 2 published on the BIPM web (Radiation T)
  - 1 submitted for publication (Refractice Index GT)
  - 2 almost completed (Johnson Noise T)

The MeP-K can hence easily be extended.

CCT Recommendation 2014

RECOMMENDATION T1 (2014)
<u>On a new definition of the kelvin</u>

The Consultative Committee for Thermometry (CCT)

recalling

- the CCT Report to the CIPM in 2007, “Report to the CIPM on the implications of changing the definition of the base unit kelvin”;
- the CCT Recommendation to the CIPM in 2010, “Considerations for a new definition of the Kelvin”, CCT T 2 (2010);

welcoming

- the Resolution 1 (2011) of the CGPM, “On the possible future revision of the International System of

The CCU Recommendation to the CIPM, “Revision of the International System of Units, the SI”, CCU U 1 (2013)

the need to confirm and clarify Recommendation CCT T 2 (2010) in the light of Resolution CCU U 1 (2013);

noting that

- experiments such as acoustic gas thermometry, dielectric constant gas thermometry, Johnson noise

the CODATA recommend a value for *k* with a relative standard uncertainty equal to 9.1 parts in 10^7 in its 2010 adjustment of fundamental constants, however based on only one experimental method.

CCT Recommendation 2014

considering

- the discussions held at the 26th and 27th meetings of the CCT in 2012 and 2014;
- the considerable progress recently achieved in experimental determinations of the Boltzmann constant to improve confidence in the 2010 value, as reported at the CCT "Task Group on the SI" meetings held in 2013 and 2014;
- that additional results are anticipated before the end of 2015;
- that experimental progress has allowed the development of a *mise en pratique* for the new definition of the kelvin, which has been extended to cover direct measurement of thermodynamic temperature after

recom

2 conditions:

1. the relative standard uncertainty of the adjusted value of k is less than one part in 10^6
2. the determination of k is based on at least two fundamentally different methods, of which at least one result for each shall have a relative standard uncertainty less than 3 parts in 10^6

Both conditions are fulfilled now.

CCT Recommendation 2017

CCT drafted a recommendation on the redefinition of the kelvin:

recommends

- that the CIPM finalises the unit redefinitions through agreeing to fix the values of the fundamental physical constants, from which a fixed numerical value of the Boltzmann constant with 8 digits will be adopted for the redefinition of the kelvin,
- that member state NMIs take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *mise en pratique* for the definition of the kelvin.

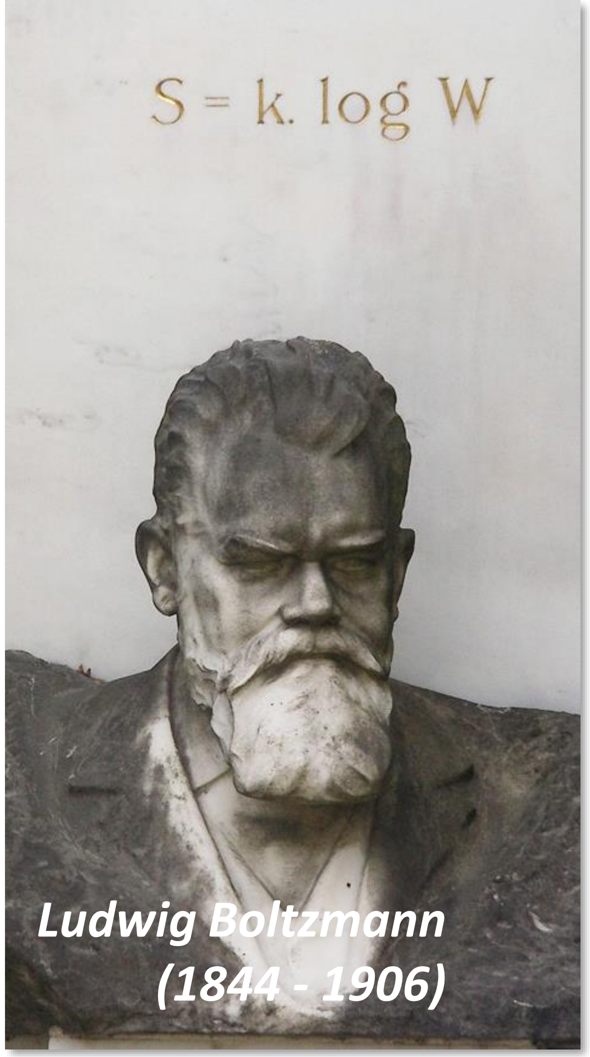
Impact of redefinition of the kelvin

Short term:

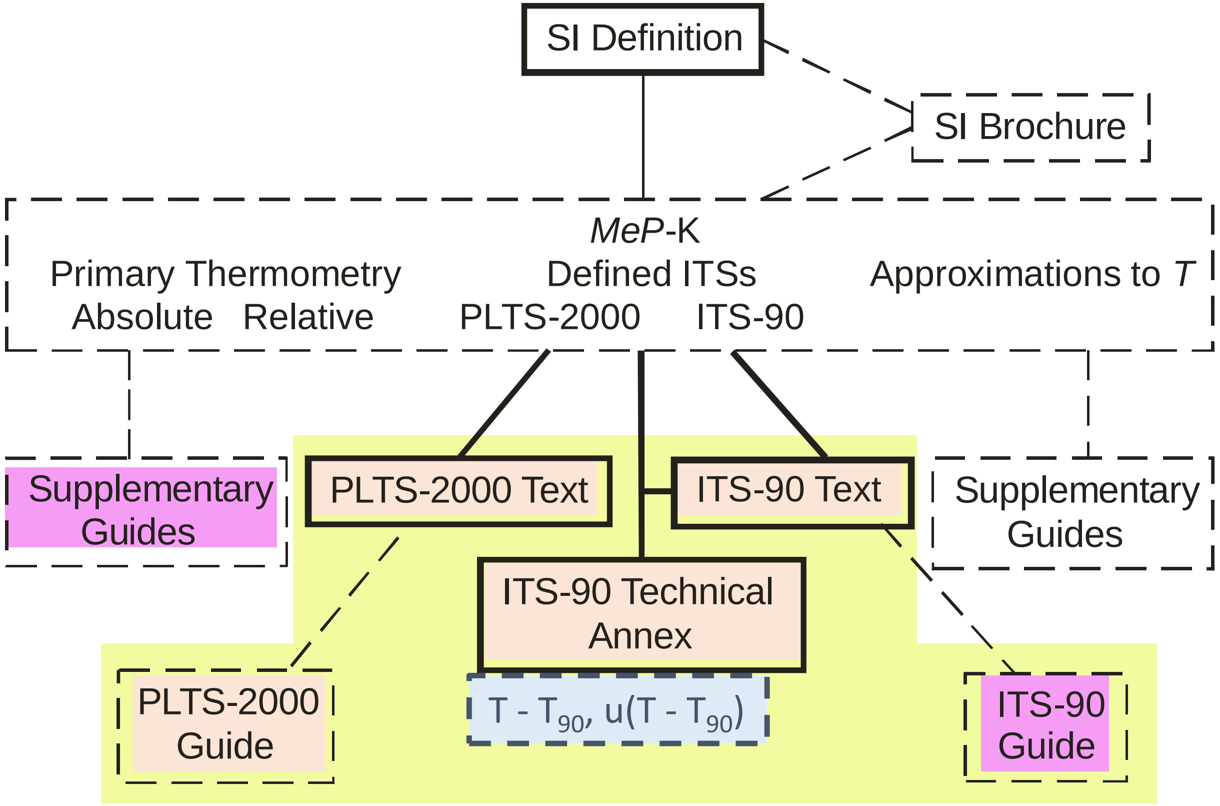
- the kelvin definition is independent of any material
- no favoured fixed point
- no favoured measurement method
- no error propagation from TPW
- thermodynamic measurements and ITS-90 are coexisting
- < 20 K and > 1300 K thermodynamics are superior

Long term:

- With improvement of primary thermometry thermodynamic measurements may replace ITS-90



Schematic representation of relationship between *MeP*-K and other documents



Solid border: prescriptive document
Dashed border: non-prescriptive guidance

MeP-K 2011

on CCT webpage

under preparation

4. Second version of the *MeP*-K (after redefinition of K)

Nomenclature: Primary Thermometry

Thermometers based on well-understood physical systems, for which the equation of state describing the relation between T and other independent quantities can be written down explicitly without unknown constants

Absolute ↔ relative primary thermometry

- Absolute primary thermometry: Measurement directly in terms of the definition using the value of k, no reference to any fixed point.
- Relative primary thermometry: Use of fixed points, for which values of T and their uncertainties are known from previous primary thermometry

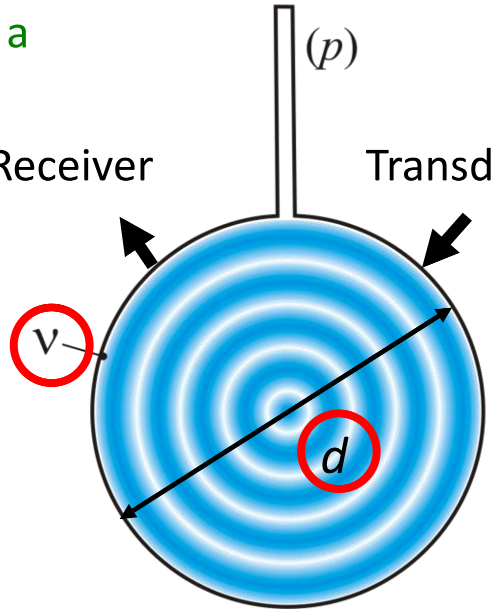
Brief descriptions for AGT, RT, PGT (DCGT, RIGT), JNT

Appendices/references for AGT, RT, PGT (DCGT, RIGT), JNT

Primary-thermometry methods: AGT

Acoustic Gas Thermometry

Standing waves in a resonator



To be measured:

- frequency ν_a
- dimensions via microwaves ν_m, pyknometry, or CMM

❖ **Absolute AGT: u(T) / T of order 1 ppm**
❖ **Relative AGT: measurement of u ratios**
❖ **Review paper: Metrologia 2014**

Equation of state for an ideal gas

$$u^2 = \frac{\gamma k T}{m}$$

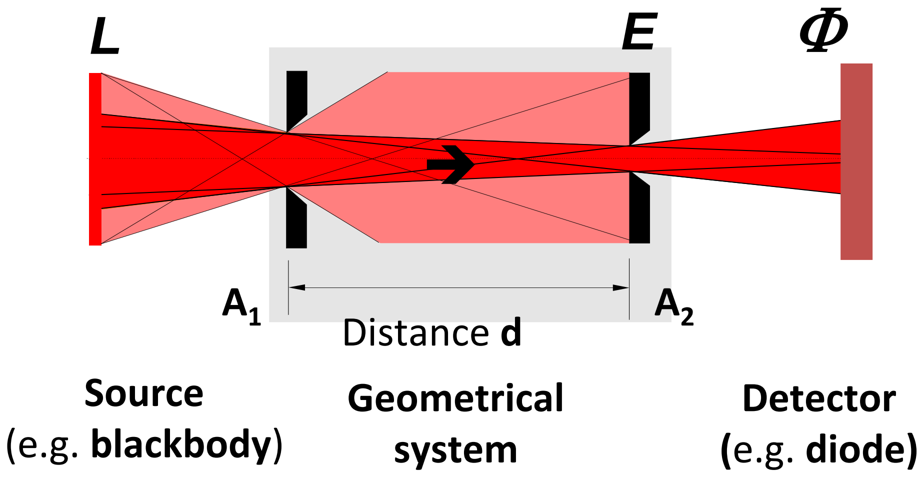
u	Speed of sound in the limit of zero ν
γ	Heat-capacity ratio (c_p / c_V)
k	Boltzmann constant
T	Temperature
m	mass of a gas particle
ν	Frequency

Quasi spheres and microwaves:

$$k = \frac{M}{\gamma_0 T_{\mathrm{TPW}} N_{\mathrm{A}}} c_0^2 \lim_{p \to 0} \left(\frac{\nu_{\mathrm{a}}(p)}{\langle \nu_{\mathrm{m}}(p) \rangle} \right)^2$$

Primary-thermometry methods: RT

Spectral-band Radiometric Thermometry



Planck law

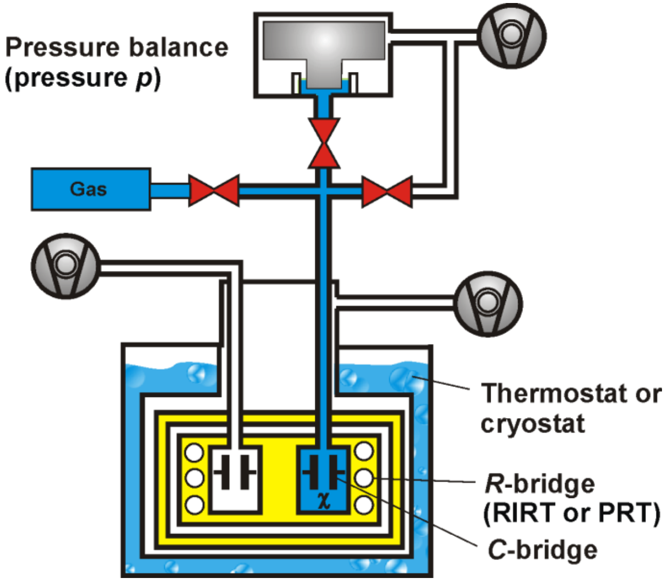
$$L_{b,\lambda}(\lambda,T)=\left(\frac{2hc^2}{\lambda^5}\right)\frac{1}{\exp(hc/\lambda kT)-1}$$

- L_λ Spectral radiance
- λ Wavelength in vacuo
- T Temperature
- h Planck constant
- k Boltzmann constant
- c Speed of light in vacuo
- E Irradiance ($E = \Phi / A_2 = A_1 L / d^2$)
- Φ Radiant power ($\Phi = A_1 A_2 L / d^2$)

- Absolute RT: absolute spectral responsivity, geometric factors defining the solid angle
- u(T) of order 0,1 K at 2800 K
- Appendices prepared

Primary-thermometry methods: PGT

Polarizing Gas Thermometry, e.g. Dielectric-Constant Gas Thermometry



Clausius-Mossotti equation combined with the ideal-gas law:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{p}{kT}\frac{\alpha_0}{3\varepsilon_0}$$

Measuring quantity :

$$\frac{C(p) - C(0)}{C(0)} = \underbrace{\varepsilon_r - 1}_{\chi} + \varepsilon_r \kappa_{eff}\, p$$

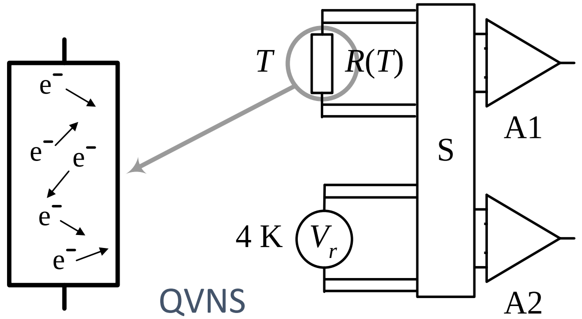
- ε_r dielectric constant
- ε_0 electric constant
- α_0 atomic polarizability
- κ_{eff} effective compressibility
- χ electric susceptibility
- p pressure
- T temperature

- ❖ Main uncertainty components completely different from AGT
- ❖ $u(k)/k \approx 4$ ppm 2015
- ❖ Review paper: Metrologia 2015

Primary-thermometry methods: JNT

Johnson Noise Thermometry

Determination of k at the TPW



(Quantum-accurate pseudo-random Voltage-Noise Source traceable to voltage standard)

Nyquist law

$$\overline{U^2} = 4kTR\Delta f$$

U Voltage
k Boltzmann constant
T Temperature
R Resistance
Δf Bandwidth
Δt measurement time

- **U extremely small, typically < 2 µV rms → cross correlation of two channels**
- **Statistical uncertainty ~ 1 / √Δt**
- **ac-Josephson voltage synthesizers → QVNS → NT is operated as a comparator**
- **ADC + digital signal processing → Δf**
- **u(k)/k ≈ 4 ppm (Qu et al. 2015)**

Thermometry below 1 K

Basis: Superconducting QUantum Interferometer Devices (SQUIDs) with resolution near to the quantum limit

Voltage to frequency conversion
Current Sensing Noise Thermometry
Magnetic Field Fluctuation Thermometry

Relative uncertainty (0.1 – 1) %

Nomenclature: Defined temperature scales

Approximation to T, highly prescriptive, new quantities T_{XX}

Exact temperature values, based on primary thermometry, assigned to fixed points

Interpolating or extrapolating instruments

Interpolating or extrapolating equations

ITS-90: 17 fixed points (He-VP, H_2-VP, TP, MP, FP), CVGT, SPRT, RT

PLTS-2000: ^{3}He melting pressure, 4 intrinsic fixed points (T_{2000}, p_{2000})

Defined temperature scales

International Temperature Scale of 1990 (ITS-90)

- $T_{90} \geq 0.65$ K, lower limit caused by technical reasons (pressure measurement)
- $T - T_{90}$ larger than originally expected, see appendix of the *MeP*-K
- Prescription of the isotopic composition for H_2, Ne, and H_2O in Technical Annex
- $p_{vp}(T_{90})$ for He (0.65 K – 5.0 K) and H_2 (17.025 K – 17.045 K; 20.26 K – 20.28 K)
- Fixed points: 6 triple points, 1 melting point, 7 freezing points
- Uncertainty of fixed-point realisation from comparisons: 0.03 mK (H_2) – 4 mK (Ag)
- Interpolation / extrapolation: ICVGT (3 K – 25 K), SPRT (14 K – 1235 K), RT

Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000)

- $p_{mp}(T_{2000})$ for ^{3}He (3 MPa – 4 MPa)
- 4 intrinsic fixed points (p_{2000}, T_{2000})
- Relative thermodynamic uncertainty: 2% (0.9 mK) – 0.05% (1 K)
- $T_{2000} - T_{90}$ at 0.65 K: -1.6 mK
- PTB-2006 (Metrologia 2007) is compatible with PLTS-2000

Criteria for the inclusion of a method in the *MeP*-K

- Primary thermometry: Well derived equation of state
- Approximation to *T*: well derived formulas or empirical relations
- A complete uncertainty budget must be approved by CCT
- Uncertainty acceptable small
- At least two independent realisations
- Comparison with the results of already accepted methods
- Applicable over acceptable temperature ranges
- Detailed documentation in the open literature

SI brochure 2.2.1: definition of the kelvin

"The effect of this definition is that the kelvin is equal to the change of thermodynamic temperature that results in a change of **thermal energy** kT by $1.380\,649 \times 10^{-23}$ J."

Rationale for the term **thermal energy**:

On the implications of changing the definition of the base unit kelvin

Report to CIPM, prepared by CCT TG-SI in 2007, see section 4
www.bipm.org/en/committees/cc/cct/publications-cc.html

Only wording with term thermal energy endorsed by CCT !

Summary

1st Version of the *Mise en Pratique* of the definition of the kelvin (*MeP*-K)

- Technical Annex for the ITS-90.
- $T - T_{90}$ and $u(T - T_{90})$ → conversion of values .

Redefinition of the SI base unit kelvin

- Determination of k with $u(k)/k < 1$ ppm, at least two independent methods
- Explicit-constant definition: $k = 1.380\ 649 \times 10^{-23}$ J/K .

2nd Version of the *Mise en Pratique* of the definition of the kelvin (*MeP*-K)

- Nomenclature (taxonomy of methods)
- Criteria for the inclusion of a method
- Primary thermometry: Acoustic gas thermometry, radiometric thermometry, Johnson noise thermometry, polarizing gas thermometry (dielectric-constant gas thermometry, refractive-index gas thermometry)
- Defined ITSs: ITS-90 and PLTS-2000
- Technical Annex for the ITS-90 and T-T_{90} together with $u(T$-$T_{90})$

100-word statement for the users to the CCU

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.

5. Latest news from CCT

A new TG on emerging technologies under CCT WG-CTh is formed.

C C

Collaboration between CCT WG-ENV and WMO

T

3 new CC objectives decided by CIPM and CCT strategy

New TG on Emerging Technologies under the WG-CTh

Chaired by Dr Zeeshan Ahmed (NIST)

6 focus areas :

- ***Primary Thermometers***
  - Optomechanical Thermometry
  - Optical Thermometry
    (refractive index based e.g. Fabry-Perot Cavity Spectroscopy)
  - Nanoelectronics based thermometry
    (e.g. Coulomb Blockade thermometry)
  - Quantum Conductance

- ***ITS-90 Traceable Thermometry***
  - Optical thermometry Resonators (microwave to UV, free space optics)
  - Photonic Thermometry
    (Fiber based thermometry; Mesoscopic Whispering gallery mode resonators; Nano-photonics; silicon/diamond/SiN/III-V materials)

New TG on Emerging Technologies under the WG-CTh

- The task group agreed on a schedule of topics to cover in ***photonic thermometry***.
  - Basics of photonics including fiber optics and on-chip technology (brief discussion included theoretical background on EM radiation, common devices used in measurement schemes and some practical challenges in interrogation of on-chip devices)
  - A discussion of photonic thermometry is currently underway. So for we have covered:
    - Materials properties
    - Theory of Ring Resonator devices
    - Next up: *Theory of Photonic Crystal Cavity devices*, *Theoretical Thermal Limit, Theoretical concerns in device operation, Practical device fabrication related concerns, Practical measurement science concerns,* and *Common noises sources in whispering gallery mode resonators* including opto-mechanical devices (primary thermometer*)*

- Photonic chips have been made available to VTT and CEM by NIST to help setup their respective photonic thermometry programs

Collaboration between CCT WG-ENV and WMO

CCT WG Environment has been in close collaboration with the **World Meteorological Organization**

- **WMO CIMO. interlaboratory comparison** for temperature pressure and humidity within the MeteoMet project (coordinator A. Merlone): pilot: UL LMK Ljubliana and ARSO (WMO RIC center RA VI). Two loops with 17 calibration laboratories participating of respective European (WMO Region VI) hydro meteorological agencies concluded in 2017 and report delivered in 2018 and successfully published as IOM Report No. 128.

- **WMO CIMO. Expert team on instrument intercomparisons.**
  Dr C. Garcia Izquierdo elaborated a feasibility study about a future intercomparison of air thermometers and radiations shields. This proposal was submitted to CIMO management group for its consideration as future activity

Collaboration between CCT WG-ENV and WMO

☐ WMO Commission of Climatology

Participation at the WMO CCl 17th session. A. Merlone as delegate. 10-13 April 2013 Geneve

Participation in the expert team for the evaluation of two temperature extremes (Kuwait - Mitrabah 2016 54℃, Pakistan Turbat 2017 54 ℃). Special comparison of thermometers having recorded the values. Work concluded, paper being prepared.

☐ WMO Task Team on Radiation References

The WMO A5 task team on Radiation met in November 2017 at NPL and identified several open points regarding the improvement of traceability of the WISG operated at PMOD Davos. It was agreed on that the transfer instruments in use to provide the traceability of the WISG to currently one blackbody will be better characterized and the traceability to more blackbodies will be established. This work will be performed over the next 3 years in the MetEOC3 project with the aim to reduce the uncertainty from currently 5 Wm^{-2} to 2 Wm^{-2}.

Three new CC objectives decided by CIPM

- to progress the state-of-the art by providing a global forum for NMIs to exchange information about the state of the art and best practices

- to define new possibilities for metrology to have impact on global measurement challenges by facilitating dialogue between the NMIs and new and established stakeholders

- to demonstrate and improve the global comparability of measurements. Particularly by working with the RMOs in the context of the CIPM MRA to:
  - plan, execute and monitor KCs, and to
  - support the process of CMC review.

CCT strategy in line with CC objectives

- Fulfilling the terms of reference relevant to thermal metrology as defined by the CIPM as stated in the “Responsibilities of Consultative Committees”;
- Providing recommendations to the CIPM for the definition and realization of the SI unit of temperature - the kelvin - and of temperature scales and derived quantities;
- Recommending research in thermal metrology in specific domains to maintain the SI in relation to the kelvin, including the definition of the kelvin and its realization, and that of the units of derived quantities;
- Supporting NMIs provision of traceability to thermal metrology quantities;
- Encouraging NMIs to address emerging thermal metrology needs;
- Providing guidance on thermal metrology to users;
- Maintaining an exchange with stakeholders and awareness of the stakeholder needs.

Acknowledgements

My deepest gratitude goes to

Dr. Susanne Picard, CCT Secretary

Dr. Joachim Fischer, TG-SI President

Dr. Bernd Fullmuth, TG-K President

and all the other CCT members

Bureau International des Poids et Mesures

for their great contributions to the Kelvin redefinition

中国计量科学研究院
National Institute of Metrology,China

Thank you

Bureau International des Poids et Mesures

中国计量科学研究院
National Institute of Metrology,China