Realising the redefined kelvin – a Euramet perspective

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Introduction

- Context

  CCT 2017 recommendation and CCT Strategy (2017-2027)
- Regulatory role of the *mise en pratique* for the definition of the kelvin
- Evolutionary approach of realising the redefined kelvin

  T>1300 K, T<25 K

  Life extension of ITS-90

  Preparing for growth in primary thermometry in "central belt"
- Some questions for CCT

Context

CCT 2017 Recommendation and strategy

RECOMMENDATION T 1 (2017)

For a new definition of the kelvin in 2018

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- ”that the CIPM finalizes 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 eight 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”

RECOMMENDATION T 1 (2017)

For a new definition of the kelvin in 2018

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DONE

- "that the CIPM finalizes 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 eight digits will be adopted for the redefinition of the kelvin"

JUST BEGUN

- "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"

CCT Strategy 2017-2027

Future scans 2023-2027

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Definition of the kelvin

- "ITS-90 is kept up-to-date by incremental improvements of its realization and dissemination"
- "Requirement for ITS-XX is to be reviewed in terms of stakeholder needs and cost of implementation" (*i.e. review completed by 2027* – emphasis added)
- "Ensuring world-wide equivalence of temperature in this increasingly mixed situation will be a key role of CCT"

CCT Strategy 2017-2027

Future scans 2023-2027

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MeP-K-19

- "A reasonable time interval (certainly beyond 2027) needs to be given for the *MeP*-K-19 (and potential first iteration *MeP*-K-2X) to be fully implemented and the <u>2017 CCT recommendation concerning primary thermometry to be explored</u> before substantive discussions concerning ITS-XX are undertaken"
- "Disruption to ITS-90 may occur if the use of Hg is banned by health authorities. Research should be stimulated into appropriate alternatives and CCT <u>develop outline plan</u> of how to keep ITS-90 functioning in the light of that eventuality"

Not put into practice but be ready "just in case"

Summary

- **In 2017 CCT:**

  Recommendation T1:

  1. **Stimulated primary thermometry activity to explore temperature traceability by that route – *early stages***

  Strategy:

  2. **Stimulated incremental developments to extend the life of ITS-90 to give time for T1 recommendation to be explored**
  3. **Prepared thermometry community for possible ban in use of mercury**
  4. **Stated that any requirement for ITS-XX is to be reviewed in terms of stakeholder needs and cost of implementation**
  5. **Did not anticipate any change to ITS-90 until after 2027 (note wording)**
  6. **Ensuring world-wide equivalence of temperature in this mixed situation will be a key role of CCT**

Regulatory role for The *mise en pratique* for the definition of the kelvin (*MeP*-K-19) and KCs

The *MeP*-K-19 contents

- The definition of the kelvin
- Definition of terms related to primary thermometry especially

  Absolute primary thermometry – no fixed points

  Relative primary thermometry – fixed points with explicit T

- Criteria for inclusion of a thermodynamic method
- Outline of primary thermometry methods for realizing the kelvin based on fundamental laws of physics [Acoustic Gas Thermometry, Radiometry, Dielectric Constant Gas Thermometry, Refractive Index Gas Thermometry, Johnson Noise Thermometry]
- Defined temperature scales, ITS-90, PLTS-2000
- Supplementary inf. eg. consensus values of T-T_{90} & T-T_{2000}

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Will there be anarchy….?

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- Will each NMI realise and disseminate its own “scale”?

NO!..... though there will be independent NMI *T* realisations, to begin with covering part ranges

- The *MeP*-K-19 provides an important framework for guiding and regulating temperature realisation
- Reliable dissemination of SI unit the kelvin:
  - 2017 CCT strategy “Ensuring world-wide equivalence of temperature in this increasingly mixed situation will be a key role of CCT” – e.g. initiating appropriate KC/SC to ensure on-going comparability of measurements
  - Linked to KC there is a supervisory role for cmcs (e.g. CCT WG NCTherm: cmc review protocol for direct/indirect primary radiometry at high temperatures (Oct ‘19)

Evolutionary approach of realising the redefined kelvin

Realising the redefined kelvin

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- Given above considerations, both the CCT 2017 recommendation T1 and CCT Strategy 2017-2027, led to content of Euramet activity “Realising the redefined kelvin” (Real-K)
- Drew a range of European NMIs large and small to focus on common objective
- “begin to turn the kelvin redefinition into a reality”

- Real-K: September 2019 to April 2023

Aalto University

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

UNIVERSITY OF WARSAW

ECT* FBK FONDAZIONE BRUNO KESSLER
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

VTT

NPL
National Physical Laboratory

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

le cnam

LNE
Sharing a passion for progress

SMU
Slovak Institute of Metrology

CEM
CENTRO ESPAÑOL DE METROLOGÍA

INTiBS PAN
WROCŁAW

TÜBİTAK

IPQ

Univerza v Ljubljani

VSL

CZECH METROLOGY INSTITUTE

IPC
Technical Institute of Physics and Chemistry CAS

NIM

VNIIOFI

Four key activities of Real-K

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- **Realise & disseminate *T* >1300 K**

Assign definitive *T* to Fe-C (1426 K), Pd-C (1765 K), Ru-C (2226 K) and WC-C (3020 K); (U<0.02%) Establish *MeP*-K-19 by indirect primary radiometry (>1300 K) to be capable of superseding ITS-90 >Ag point by 2025

- **Realise and disseminate *T* (0.0009 K to 25 K)**

Through practical primary thermometry, Johnson Noise, Coulomb Blockade, gas based, Thermometry;

ITS-90 (<25 K) & PLTS-2000 superseded by ~2025

Four key activities of Real-K

- **Life extension activities of ITS-90**

  Preparing for possible mercury point replacement – investigating CO_2, SF_6 and also effect of not replacing mercury

  Non-uniqueness studies to reduce uncertainties

  Impact of removing Hg point

  To ensure ITS-90 is fit-for-purpose until at least 2030

- **Facilitation of full range primary thermometry**

  ab initio calculations and measurement of thermodynamic non-ideality of thermometric gases e.g. density and acoustic virial coefficients of Ar, Ne

  To increase the speed of primary gas based methods to same as using fixed-points for thermometer calibration (eliminate need for isotherms)

Realise & disseminate *T* >1300 K

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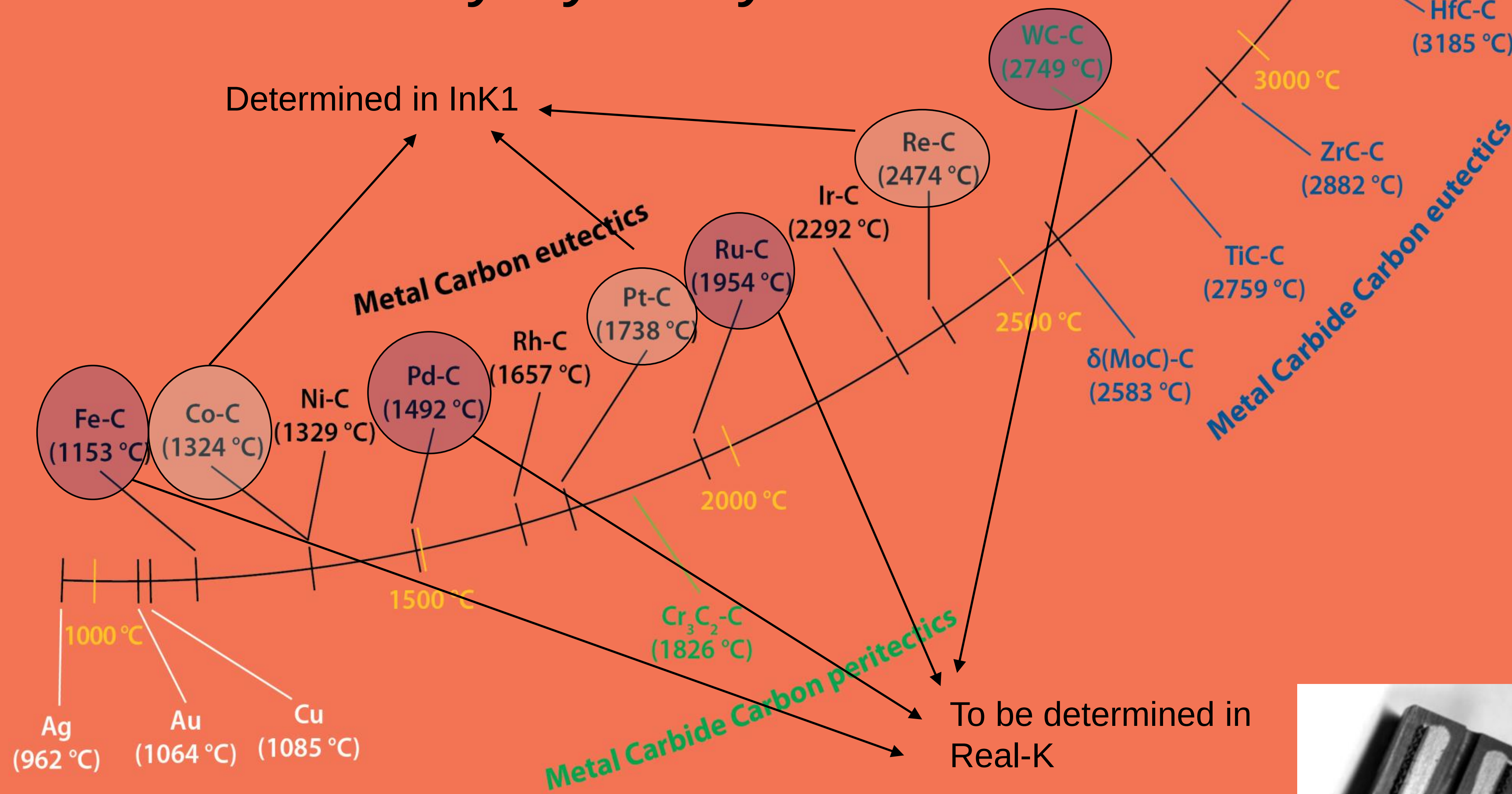
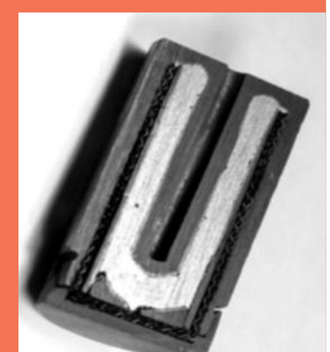
- Develop practical procedures for realising and disseminating thermodynamic temperature >Ag point mediated by HTFPs
- Undertake full scale *dissemination* trial of thermodynamic temperature using HTFPs with the *MeP*-K-19 approved approach
- Recommendation to CCT in 2023 for realising and *disseminating* thermodynamic temperature >Ag point by indirect primary radiometry

HTFPs whose *T* is known with low uncertainty by early-2022





Machin, G., “Twelve years of high temperature fixed point research: a review”, *AIP Conf. Proc*. **1552**, 305 (2013); doi: 10.1063/1.4821383

Current situation: ITS-90

ITS-90 above the silver freezing point: extrapolation using Planck's law in ratio form

Ag (1235 K)
Au (1337 K)
Cu (1358 K)

3300 K+

Very large temperature difference between reference and high temperatures,
potential for large extrapolation uncertainties in ITS-90

$$\frac{L_\lambda(T_{90})}{L_\lambda[T_{90}(X)]} = \frac{\{\exp(c_2[\lambda T_{90}(X)]^{-1}) - 1\}}{\{\exp(c_2[\lambda T_{90}]^{-1}) - 1\}}$$

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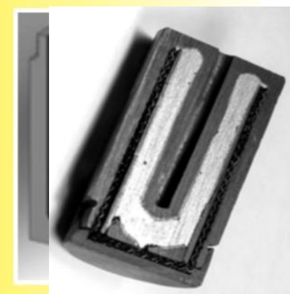
Real-K:

Early-mid 2020s: Primary thermometry (*MeP*-K-19)

Thermodynamic temperature realised and disseminated by indirect primary radiometry,
robust reliable low uncertainty interpolation through parameterised Planck law

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{AT + B}\right) - 1}$$



Reliable temperatures to be determined in Real-K project

Fe-C (1426 K) **Pd-C (1765 K)** **Ru-C (2226 K)** **WC-C (3020 K)**

Co-C (1597 K) **Pt-C (2011 K)** **Re (2748 K)**

Ag (1235 K)
Au (1337 K)
Cu (1358 K)

Reliable temperatures determined in InK project

Realise and disseminate *T* (0.0009 K to 25 K)

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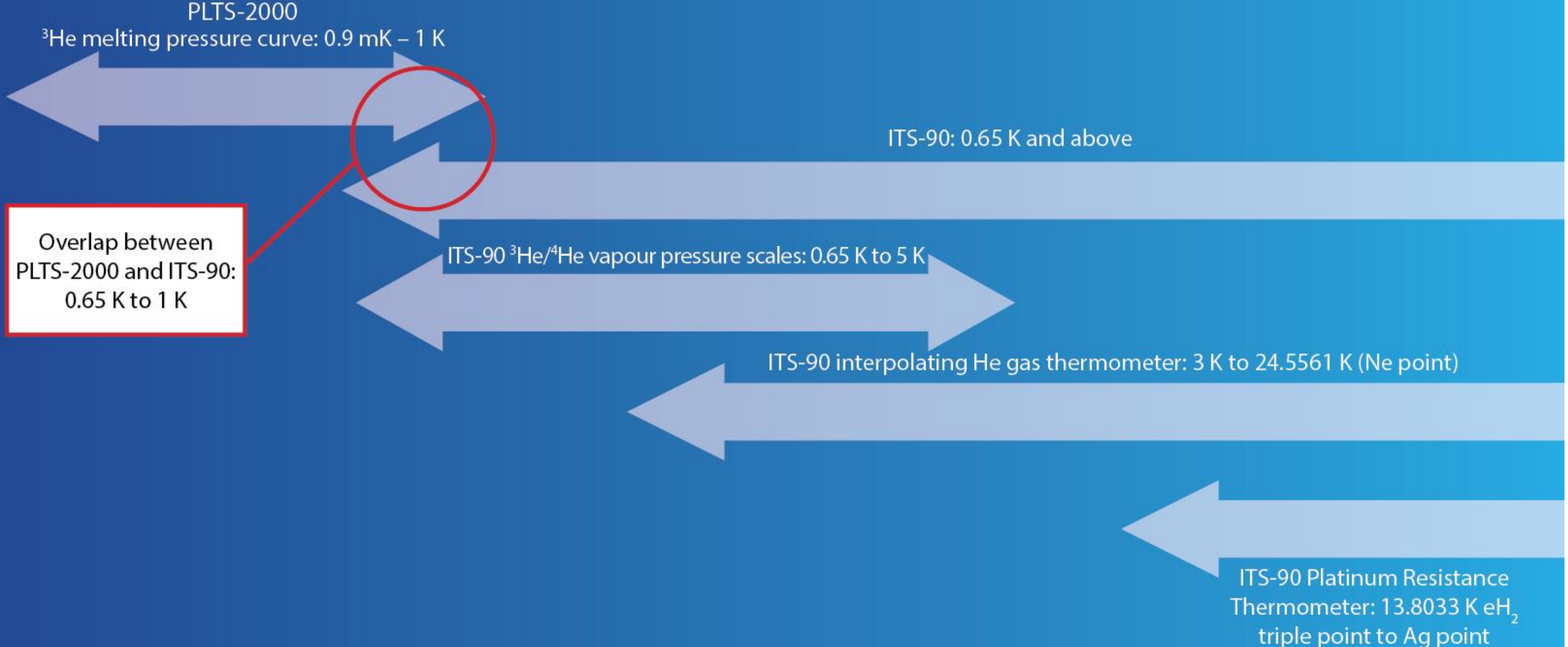
- **Realise and disseminate *T* (0.0009 K to 25 K)**

  Through practical primary thermometry, Johnson Noise, Coulomb Blockade, gas based, Thermometry;

  ITS-90 (<25 K) & PLTS-2000 superseded by ~2025

Current situation: PLTS-2000/ITS-90



Current situation: PLTS-2000/ITS-90

PLTS-2000
^{3}He melting pressure curve: 0.9 mK – 1 K

ITS-90: 0.65 K and above

Overlap between PLTS-2000 and ITS-90: 0.65 K to 1 K

ITS-90 ^{3}He/^{4}He vapour pressure scales: 0.65 K to 5 K

ITS-90 interpolating He gas thermometer: 3 K to 24.5561 K (Ne point)

ITS-90 Platinum Resistance Thermometer: 13.8033 K eH_2 triple point to Ag point

Real-K:

Early-mid 2020s: Primary thermometry (*MeP*-K-19)

pMFFT 0.9 mK to 5 K

CBT ~10 mK to ~30 K

(SP)RIGT, Fast AGT ~5 K and above

Summary of Real-K and short term forward look (to ~2027)

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- By end of Real-K (Spring 2023)
  - High temperature (>1300 K) dissemination trialled and recommendation to CCT for parallel ITS-90/*T*
  - Low temperature dissemination *T* <25K processes and facilities in place, recommendations concerning ITS-90, PLTS-2000 and *T*
  - ITS-90 life extension activity undertaken
  - Essential gas based thermophysical properties with required uncertainties to facilitate rapid primary thermometry in place
- Post Real-K foresee temperature range expansion of gas based primary thermometry techniques for *T* realisation and dissemination

Longer term (2025+) Towards practical primary thermometry

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- Why anchor temperature traceability in the NMI?

- Growth in practical primary thermometry providing real time *in-situ* linkage to the kelvin
- Sensor self-validation as an intermediate step
- Photonic thermometry ….
- Practical primary thermometers – e.g. JNT over wide range of temperatures? acoustic thermometers? Doppler Broadening Thermometers?

Questions for the CCT to consider in 2020s

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- Questions for CCT to consider as situation evolves:

  Are there any newly identified significant user needs driving a need for a new temperature scale (*i.e.* is ITS-90 seriously deficient from a user point of view)?

  Will ITS-20XX ever be needed?

  Is the community ready if Hg was banned? ITS-90?

  Will defined temperature scales ever be fully supplanted by thermodynamic methods?

  How is the SI unit for temperature dissemination to be regulated in mixed *T*, ITS-90, PLTS-2000 situation?

  How are *in-situ* practical primary thermometers to be viewed re providing traceability? Does this need validating? How?

Summary

National Physical Laboratory

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  CCT 2017 recommendation and Strategy (2017-2027)
- Regulatory role of the *mise en pratique* for the definition of the kelvin and KCs
- These deliberations led to Evolutionary approach embodied in the Euramet realising the redefined kelvin activity

  T>1300 K, T<25 K

  Life extension of ITS-90

  Preparing for growth in primary thermometry in "central belt"
- Rise in practical primary thermometry
- Some questions for CCT