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LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

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# REPORT TO CCT-WG-NCTH ACTIVITIES ON HTFPS

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Anaheim, April 3rd 2023

# PLAN

- HTFP activities in the Euopean project REAL-K
- Planned activities in the new European project MultiFixRad
- Discussion

# CONTEXT

- New definition of the kelvin in force since 2019: direct link to thermodynamic temperature (T) and the Boltzmann constant
- 20 years of active research on high temperature fixed points (HTFPs): reliable, robust and diverse possibilities
- Mise-en-Pratique of the new definition allows three paths:
  - ➢ Direct thermodynamic temperature measurement
  - ➢ Thermodynamic temperature mediated by HTFPs of known T
  - ➢ ITS-90 - still valid and fit for purpose

# FORMER STUDIES

- *From 2012 to 2015, Euramet EMRP project InK (implementing the new kelvin): Co-C, Pt-C, Re-C eutectic points studied – T assigned*

PHILOSOPHICAL TRANSACTIONS A

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Research

**Cite this article:** Woolliams ER *et al.* 2016 Thermodynamic temperature assignment to the point of inflection of the melting curve of high-temperature fixed points. *Phil. Trans. R. Soc. A* **374**: 20150044.
http://dx.doi.org/10.1098/rsta.2015.0044

Accepted: 25 August 2015

One contribution of 16 to a Theo Murphy meeting issue 'Towards implementing the new kelvin'.

**Subject Areas:**
thermodynamics

**Keywords:**
high-temperature fixed points, thermodynamic temperature, thermometry, temperature scale, kelvin, eutectics

**Author for correspondence:**

## Thermodynamic temperature assignment to the point of inflection of the melting curve of high-temperature fixed points

E. R. Woolliams[1], K. Anhalt[2], M. Ballico[3], P. Bloembergen[4,5], F. Bourson[6], S. Briaudeau[6], J. Campos[7], M. G. Cox[1], D. del Campo[8], W. Dong[5], M. R. Dury[1], V. Gavrilov[9], I. Grigoryeva[9], M. L. Hernanz[7], F. Jahan[3], B. Khlevnoy[9], V. Khromchenko[10], D. H. Lowe[1], X. Lu[5], G. Machin[1], J. M. Mantilla[8], M. J. Martin[8], H. C. McEvoy[1], B. Rougié[6], M. Sadli[6], S. G. R. Salim[6,11], N. Sasajima[4], D. R. Taubert[2], A. D. W. Todd[12], R. Van den Bossche[1,13], E. van der Ham[3], T. Wang[5], A. Whittam[1], B. Wilthan[2,†], D. J. Woods[12], J. T. Woodward[10], Y. Yamada[4], Y. Yamaguchi[4], H. W. Yoon[10] and Z. Yuan[5]

[1]National Physical Laboratory (NPL), Hampton Road, Teddington TW11 0LW, UK
[2]Physikalisch-Technische Bundesanstalt (PTB), Abbestrasse 2-12,

## The equilibrium liquidus temperatures of rhenium-carbon, platinum-carbon and cobalt-carbon eutectic alloys.

D. H. Lowe[1], A. D. W. Todd[2], R. Van den Bossche[3], P. Bloembergen[4], K. Anhalt[5], M. Ballico[6], F. Bourson[7], S. Briaudeau[7], J. Campos[8], M.G. Cox[1], D. del Campo[9], M.R. Dury[1], V. Gavrilov[10], I. Grigoryeva[10], M.L. Hernanz[8], F. Jahan[6], B. Khlevnoy[10], V. Khromchenko[11], X. Lu[4], G. Machin[1], J.M. Mantilla[9], M.J. Martin[9], H.C. McEvoy[1], B. Rougié[7], M. Sadli[7], S.G.R. Salim[7], N. Sasajima[12], D.R. Taubert[4], E. van der Ham[6], T. Wang[4], D. Wei[4], A. Whittam[1], B. Wilthan[5], D.J. Woods[2], J.T. Woodward[11], E.R. Woolliams[1], Y. Yamada[12], Y. Yamaguchi[12], H.W. Yoon[11], Z. Yuan[5]

| | T | u(T)(*k*=1) |
|---|---|---|
| Cobalt | 1597.475 | 0.075 |
| [Cobalt] | 1597.430 | 0.074 |
| Platinum | 2011.502 | 0.110 |
| Rhenium | 2747.902 | 0.228 |

[] indicates non equilibrium values

# DISSEMINATION OF THERMODYNAMIC TEMPERATURE

PHILOSOPHICAL TRANSACTIONS A

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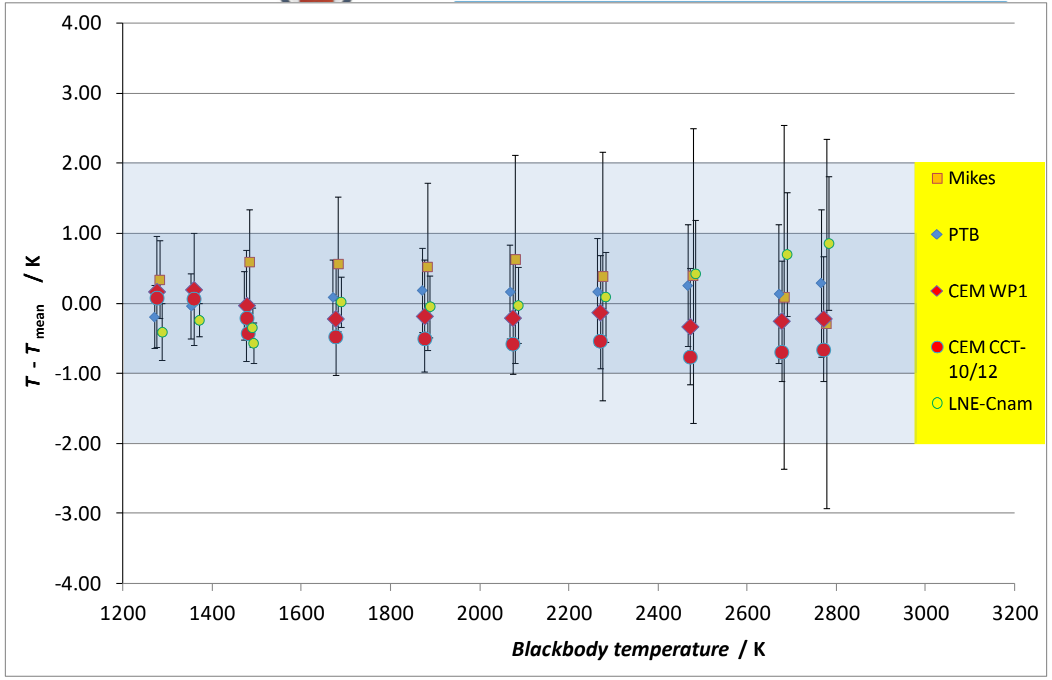
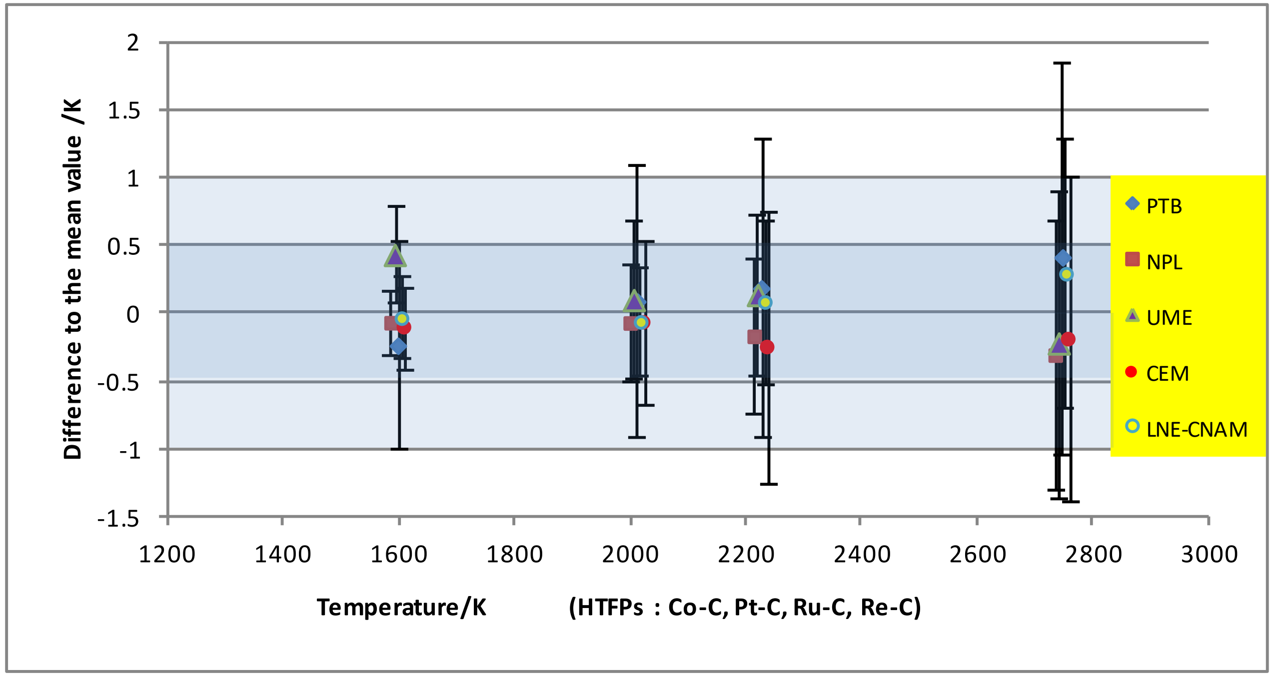
Dissemination of thermodynamic temperature above the freezing point of silver

Dissemination trials in the form of comparisons using Filter Radiometers or Pyrometers and HTFPs



# OBJECTIVES OF WORKPACKAGE1 (HIGH TEMPERATURE)

In the WP1 of this project, the general objective being demonstrate and establish traceability directly to the redefined kelvin from the silver freezing point to ~3000 K, the collaborative work was focused on:

- Characterising and selecting a set of cells at the points of Fe-C (1153 °C), Pd-C (1492 °C), Ru-C (1953 °C) and WC-C (2748 °C)
- Assigning collectively thermodynamic temperatures to the phase transitions either by absolute or relative methods : circulation of 2 sets of 4 cells in 8 labs.
- Testing thermodynamic temperature traceability schemes using HTFPs (towards NMIs and users)

Thus:

- extending the temperature range to 3020 K (WC-C)
- bridging the gap between Co-C / Pt-C (Pd-C) and Pt-C / Re-C (Ru-C)
- preparing thermodynamic references for thermocouples up to 1800 K (Fe-C and Pd-C)
- testing for the first time traceability routes in **thermodynamic temperature** towards industry and NMIs

# MAIN ACHIEVEMENTS OF THE PROJECT

☑ Construction of the cell completed

- About 30 cells constructed and tested in the producing labs for short-term stability and melting range

☑ Characterisation of the cells completed

- Effect of the temperature steps used to initiate melting
- Effect of the temperature gradient along the cell on the melting temperature
- Characterisation of Fe-C and Pd-C thermal effects in 3-zone furnaces (with optimum temperature profile tuning)

☑ Initial comparison of the cells completed

- Cells for T assignment identified (the best two cells)
- Cells for dissemination trials identified
- Spare cells in case of damage or loss during the circulation of the cells

☑ Assignment of thermodynamic temperatures

- Two batches of cells circulated in 6 NMIs (loop A: CEM, PTB , NPL, LNE-Cnam; loop B: NIM, Tubitak UME)
- Results reported

☑ Final comparison of the cells (ongoing)

- Determination of the drift of the circulating cells

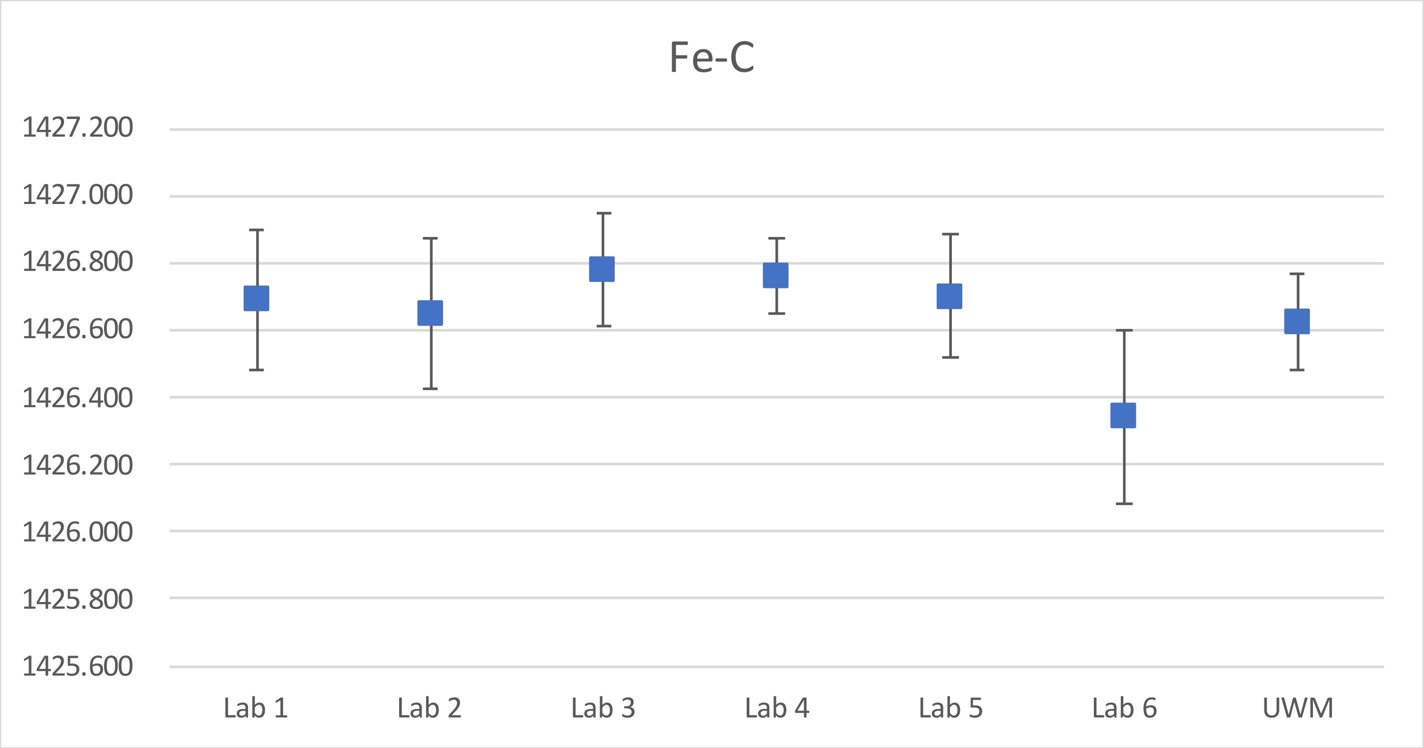
# T ASSIGNMENT TO THE PHASE TRANSITIONS (FE-C, PD-C, RU-C, WC-C)

- Circulation of the cells in two loops:
  - Loop A: PTB, CEM, LNE-Cnam, NPL
  - Loop B: (VNIIOFI), TUBITAK-UME, NIM, (INRIM)
    - Timetable: early fall 2021 – late winter 2022

- Measurement of the thermodynamic temperature of the circulating cells
  - Direct method (a radiation thermometer calibrated in thermodynamic temperature values) at PTB, NIM, CEM, Tubitak UME and LNE-Cnam
  - Indirect method (using high-temperature fixed points with –previously – assigned T) at NPL, CEM, LNE-Cnam and Tubitak UME

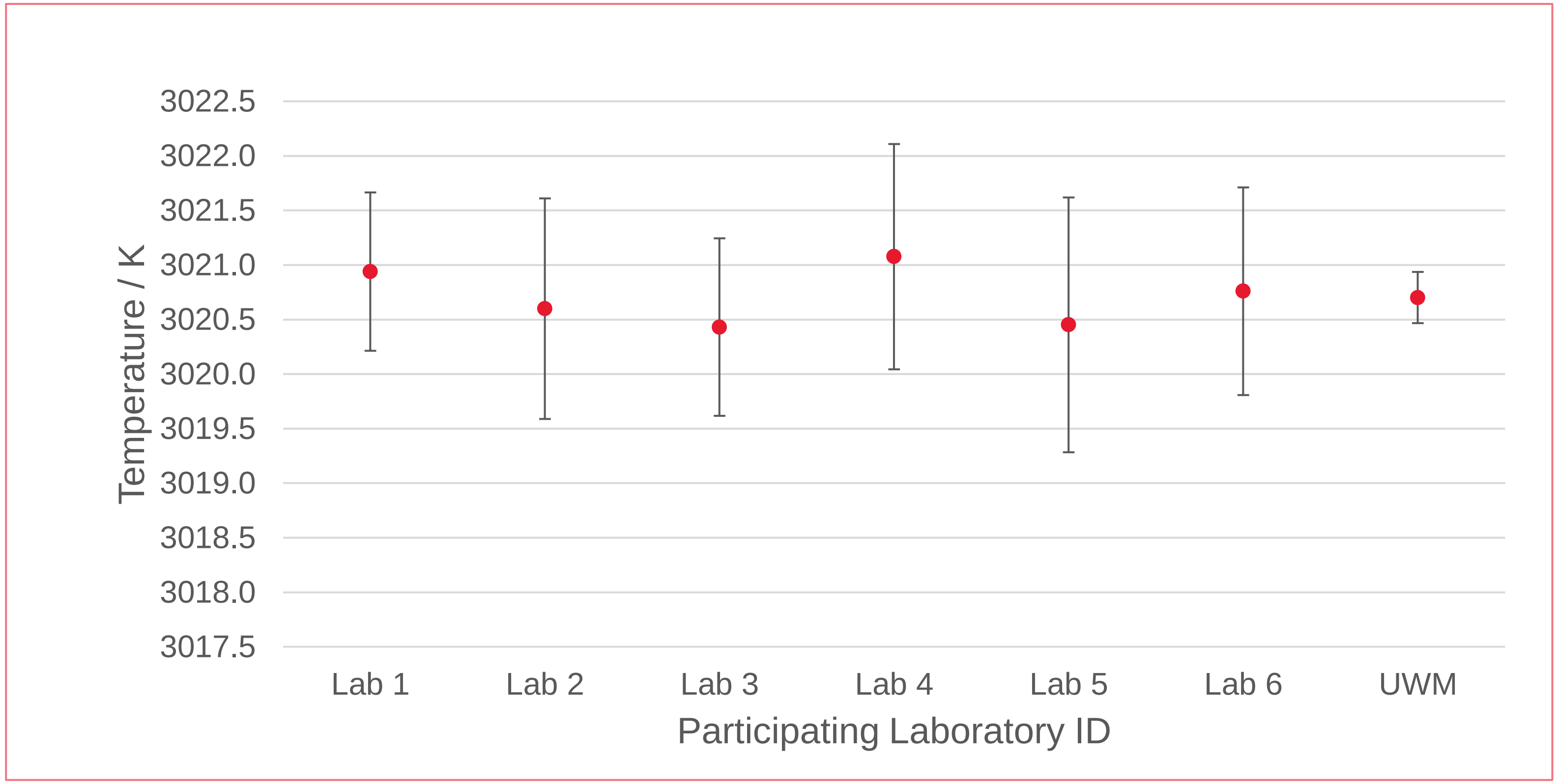
- Determination of the (weighted) mean temperature for each phase transition

# ASSIGNING THERMODYNAMIC TEMPERATURES TO THE PHASE TRANSITION OF FE-C




| T(Fe-C), K | U(k=2), K |
|---|---|
| **1426.626** | **0.15** |

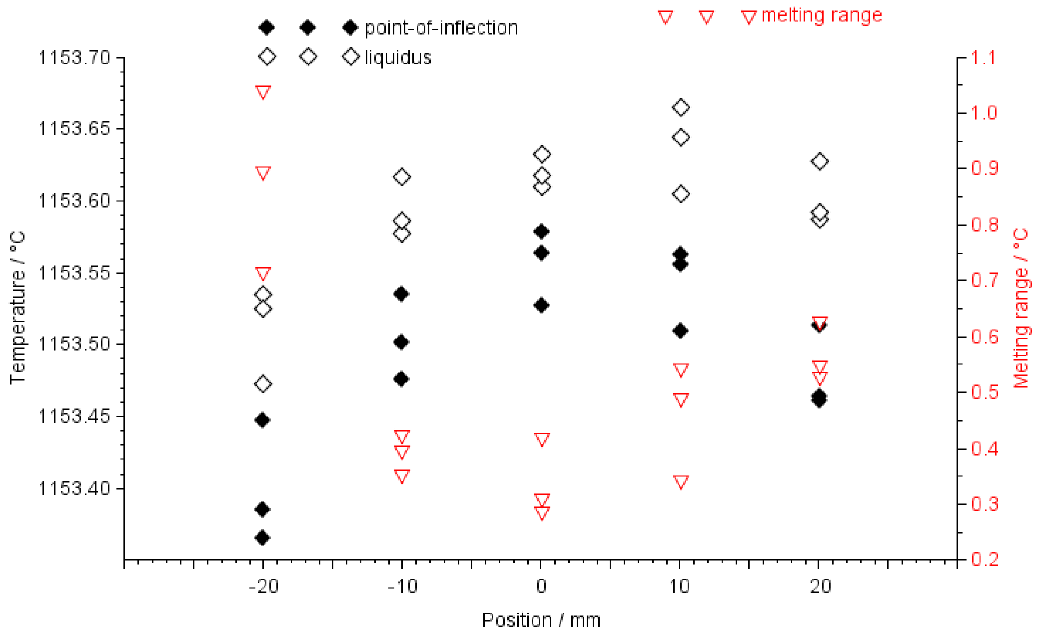
# ASSIGNING THERMODYNAMIC TEMPERATURES TO THE PHASE TRANSITION OF WC-C



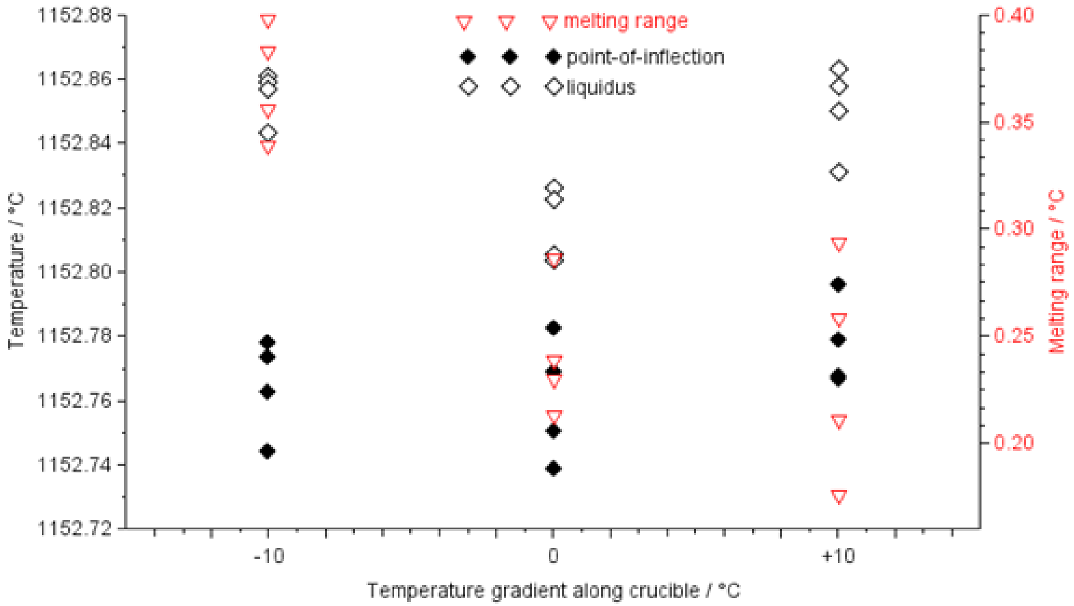

| T(WC-C), K | U(k=2), K |
|---|---|
| 3020.702 | 0.24 |

# THERMAL EFFECTS

- Study the influence of changing furnace temperature profiles and melt-initiation temperature steps on the measured phase transition temperatures.
- Estimate the thermal effect uncertainties to be accounted for.




**1Z furnace**




**3Z furnace**

F-2: High Temperature Fixed Points Weds 5th Apr Magic Kingdom 2 10:45 – 12:15 (D. Lowe)

# SUMMARY

This work has allowed the **collective and independent** determination of the thermodynamic temperature of the phase transition of four high temperature fixed points. We know now that:

- ✓ The **relative primary thermometry measurement** method is efficient and easier than the absolute primary method
- ✓ The **two methods agree** perfectly (within the uncertainties)
- ✓ The set of 7 HTFPs with assigned thermodynamic temperatures will allow the **realisation and the dissemination of thermodynamic temperature** in the future with unprecedented uncertainty levels
- ✓ The ITS-90 scheme above the silver point (>1000 °C) can still be applied for thermodynamic temperature (reative method with one fixed point)
  - ➢ High-temperature fixed points with assigned thermodynamic temperature represent a **validated thermodynamic temperature scale!**

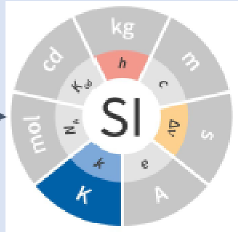
# MULTIFIXRAD/ A NEW RESEARCH POTENTIAL JRP

## Background

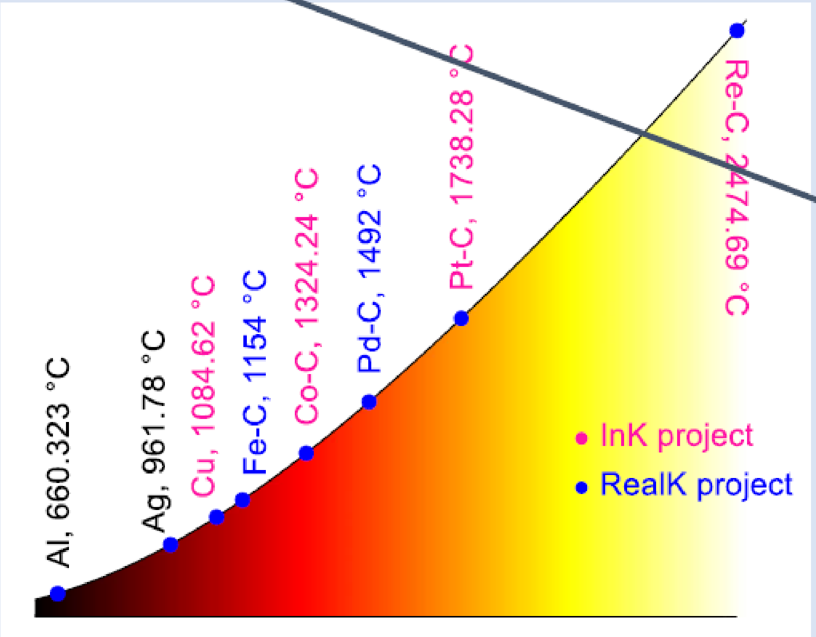
Main objective:
to aid 6 NMIs in establishing a primary temperature scale at the highest level.

Revised *MeP*-K: Relative primary pyrometry
Fixed points + Planck law

First principles








Assigned thermodynamic temperatures

Three strategies:

- 1 fixed point (linearity, band)
- 2 fixed points (band)
- 3 fixed points (none)

# MULTIFIXRAD/ A NEW RESEARCH POTENTIAL JRP

EURAMET

## WP 1

*Knowledge transfer, ITS-90 realisation by extrapolation*

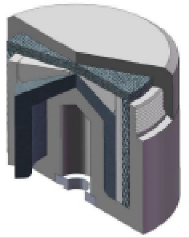
Workshops, training

Strategy plans for emerging institutes

Images: Freepik.com

## WP 2

*High temperature fixed points*



- Construction
- Characterisation
- Maintenance

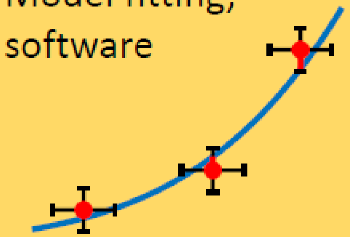
Emerging institutes select a subset

## WP 3

*Interpolation instrument and realisation of the scale*

- Construction, SSE, linearity, spectral response

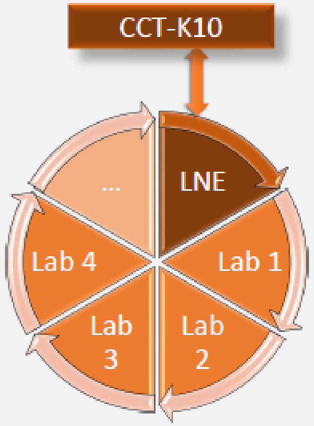
- Model fitting, software



## WP 4

*Interlaboratory comparison (ILC)*

- Verify performance!



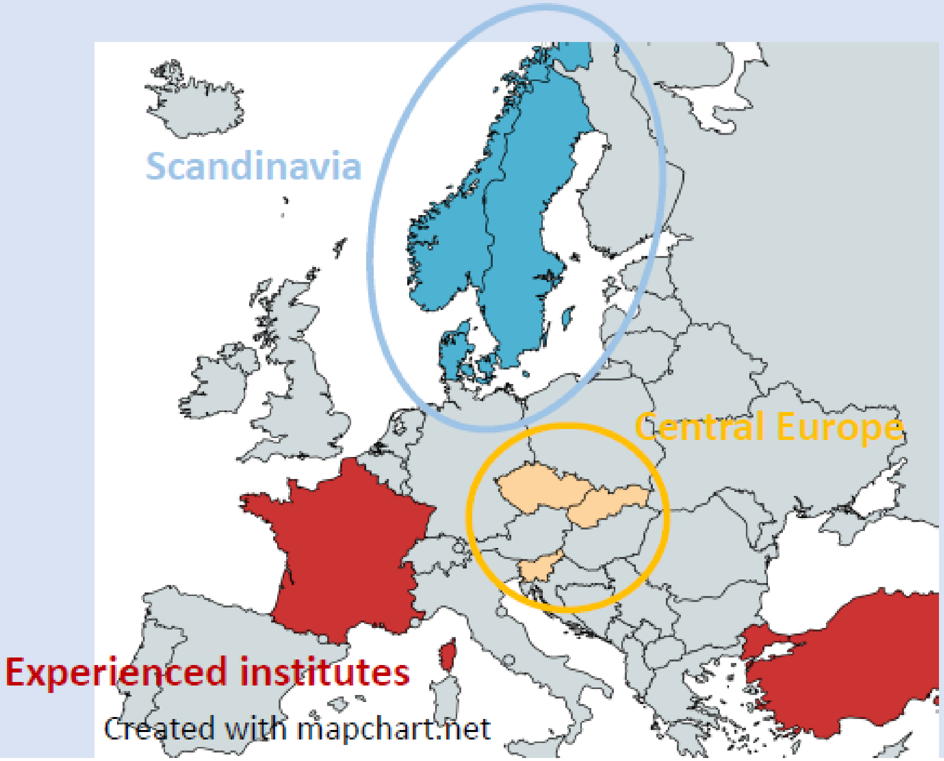

Link to CCT-K10
Basis for new CMCs for emerging institutes

# MULTIFIXRAD/ A NEW RESEARCH POTENTIAL JRP

## Impact

Metrology: improved regional

- Collaboration
- Specialisation
- Services
- Research capacity




## Outputs

- Practical implementation of new possibilities in *MeP*-K@HT
- Improved precision at NMIs
- 5+ peer reviewed papers
- 20+ presentations at conferences
- Training materials for the e-learning platform of EURAMET
- Best practice guide
- ILC report
- Stakeholder workshop

Start date: 1st June 2023

# GUIDE « INDUSTRIAL RADIATION THERMOMETRY »

Members: Lenka Knazovicka (CMI), Helen McEvoy (NPL), Maria-Jose Martin (CEM), Ferruccio Girard (INRIM), Howard Yoon (NIST), Peter Saunders (MSL), Ricardo Sohn Moretz (INMETRO), Daniel Cardenas Garcia (CENAM), Mohamed Sadli (LNE-Cnam)

- ✓ Mainly two parts: solid-state detectors (high temperatures), thermal detectors (low temperatures)
- ✓ Oriented for users – examples relating to différents types of measurements
- ✓ Collaborative work on a single shared document (online) in a first step
- ✓ Iterative approach : contributions, consolidation (PS/MS), exchanges, changes…

➢ Draft still under construction. Initial objective was Mid 2023, will probably shift ~6 months.