Temperature dissemination in a post-redefinition world

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Review

The revision of the SI—the result of three decades of progress in metrology

Michael Stock, Richard Davis, Estefanía de Mirandés and Martin J T Milton

Bureau International des Poids et Mesures, BIPM, Pavillon de Breteuil, 92310 Sèvres, France

THE KELVIN IS DEAD,
LONG LIVE THE KELVIN!

The redefinition of the kelvin – what's next?

The CCT Declaration of 2014 acknowledges the known short-comings of both defined temperature scales (CCT 2014)

- For the ITS-90: 'inherent weaknesses, including known discrepancies from T'.
- For the PLTS-2000: 'currently no resolution of its inherent discrepancy of ~6 % at the lowest temperatures'.

and concludes that new thermodynamic temperature determinations are required to support:

Living document

- 'In the short term: the introduction and implementation of the *mise en pratique* of the definition of the kelvin (*MeP*-K) through determining robust, reliable values of $T - T_{90}$ and $T - T_{2000}$'. Consensus
- 'In the medium term: facilitate direct dissemination of the redefined kelvin through developing robust and reliable methodologies to disseminate T, particularly at the extremes of temperature >1300 K and <1 K'.
- 'In the long term: generate the background data required for a new unified temperature scale of improved thermodynamic consistency compared to the currently defined scales'.

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Primary thermometers

- T: Thermodynamic temperature

Defined scales T_{scale} (approximations to T)

- T_{90}: International Temperature Scale of 1990 (ITS-90)
- T_{2000}: Provisional Low Temperature Scale of 2000 (PLTS-2000)
- T_{XX}: Future temperature scale (ITS-XX)

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SI Brochure – 9th edition (2019) – Appendix 2 — 20 May 2019

In the future, as the primary methods evolve and are expected to achieve lower uncertainties, primary thermometers will become more widely used and gradually replace the ITS-90 and the PLTS-2000 as the basis of temperature measurement.

- < 1K → middle ← > 1300 K
- Global transition likely messy and incomplete, smeared out in:
  - Time
  - Space
  - Temperature range
  - Position in calibration chain
- **Mixed dissemination environment**

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Standard platinum resistance thermometer interpolations in a revised temperature scale

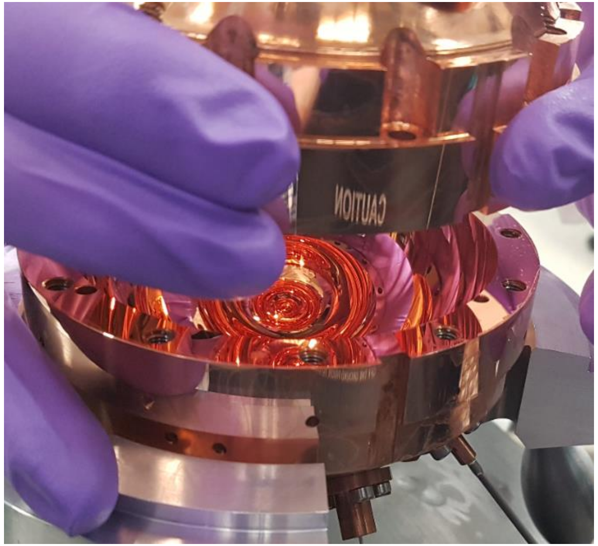
D R White[1] and P M C Rourke[2]

[1] Measurement Standards Laboratory, Lower Hutt PO Box 31310, New Zealand
[2] National Research Council, 1200 Montreal Rd., Ottawa, Ontario, Canada

Scale attributes (separable!):

- **Reproducibility**
- Thermodynamic **Accuracy**

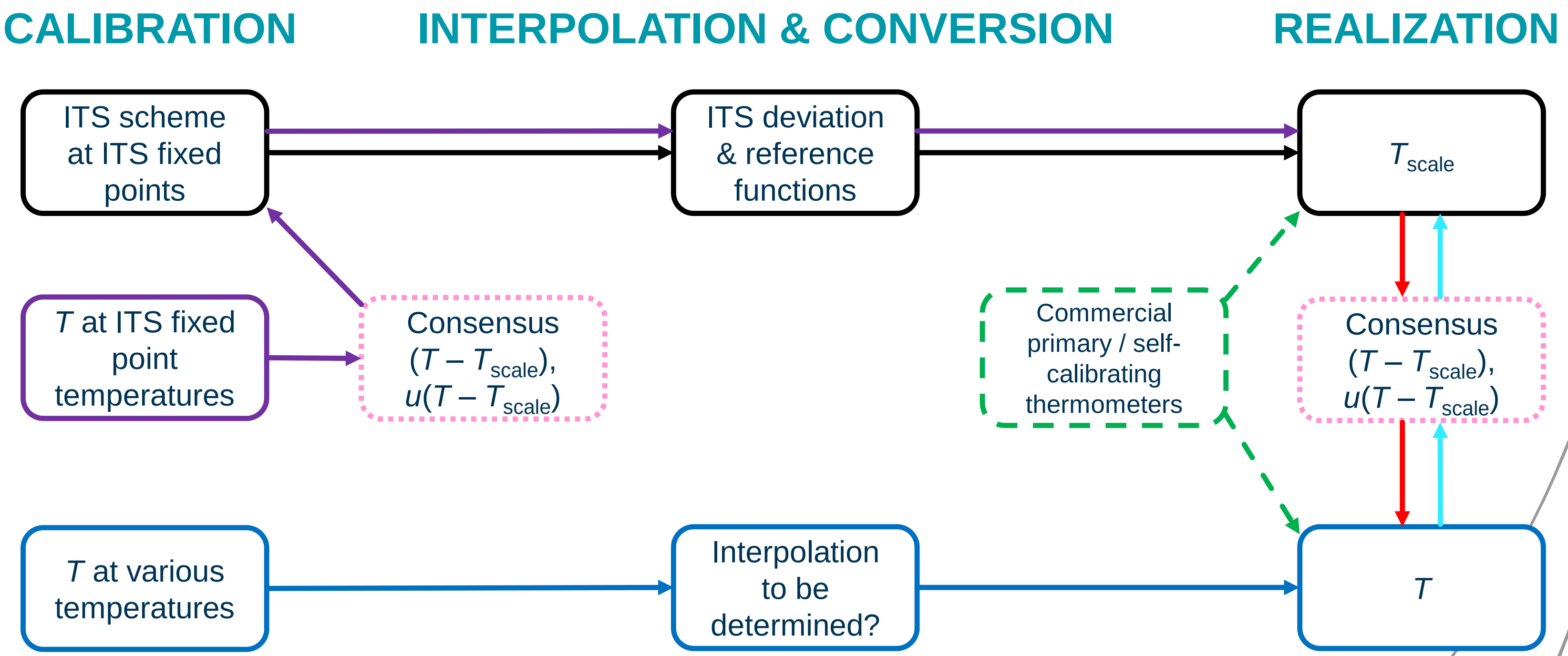
Temperature dissemination in a post-redefinition world



OUTLINE

- Routes to dissemination
- Reproducibility: T_{90} *vs.* T_{XX} *vs.* T
- Dissemination path examples
- Thermodynamic inaccuracy of the ITS-90
- KCs and CMCs for primary thermometers
- Further T dissemination issues
- Summary and discussion

Routes to dissemination



Reproducibility: T_{90} vs. T_{XX} vs. T

ILLUSTRATIVE EXAMPLE

- Capsule standard platinum resistance thermometer (CSPRT) calibration: T_{90}, T_{XX}, T
- Triple point of equilibrium hydrogen at 13.8033 K to triple point of water at 273.16 K
- NRC CSPRT comparison block data set, direct calculations from experimental measurements:
    - Type 1 non-uniqueness (subrange inconsistency “SRI”)
    - Type 3 non-uniqueness (artifact dependence “NU3”)
    - Propagation of uncertainties from fixed points (“PoU”)

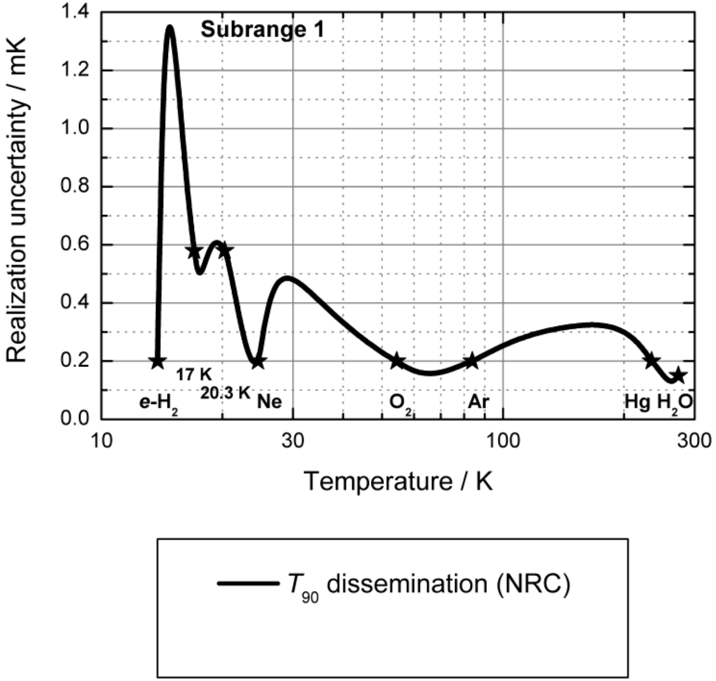
ITS-90 reproducibility, xenon fixed point substitution and new interpolating equations between 13.8033 K and 273.16 K

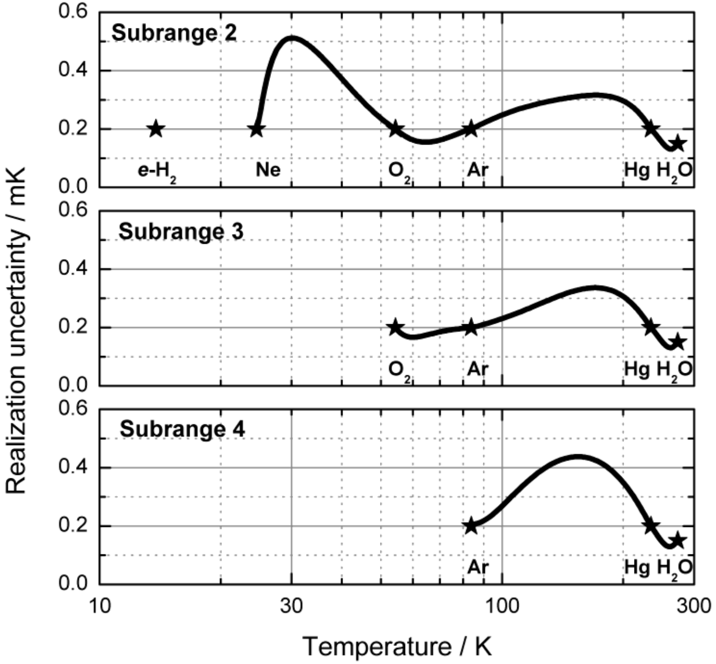
(To be submitted)

P M C Rourke

National Research Council, 1200 Montreal Road, Ottawa, ON, K1A 0R6 Canada

Reproducibility: T_{90}

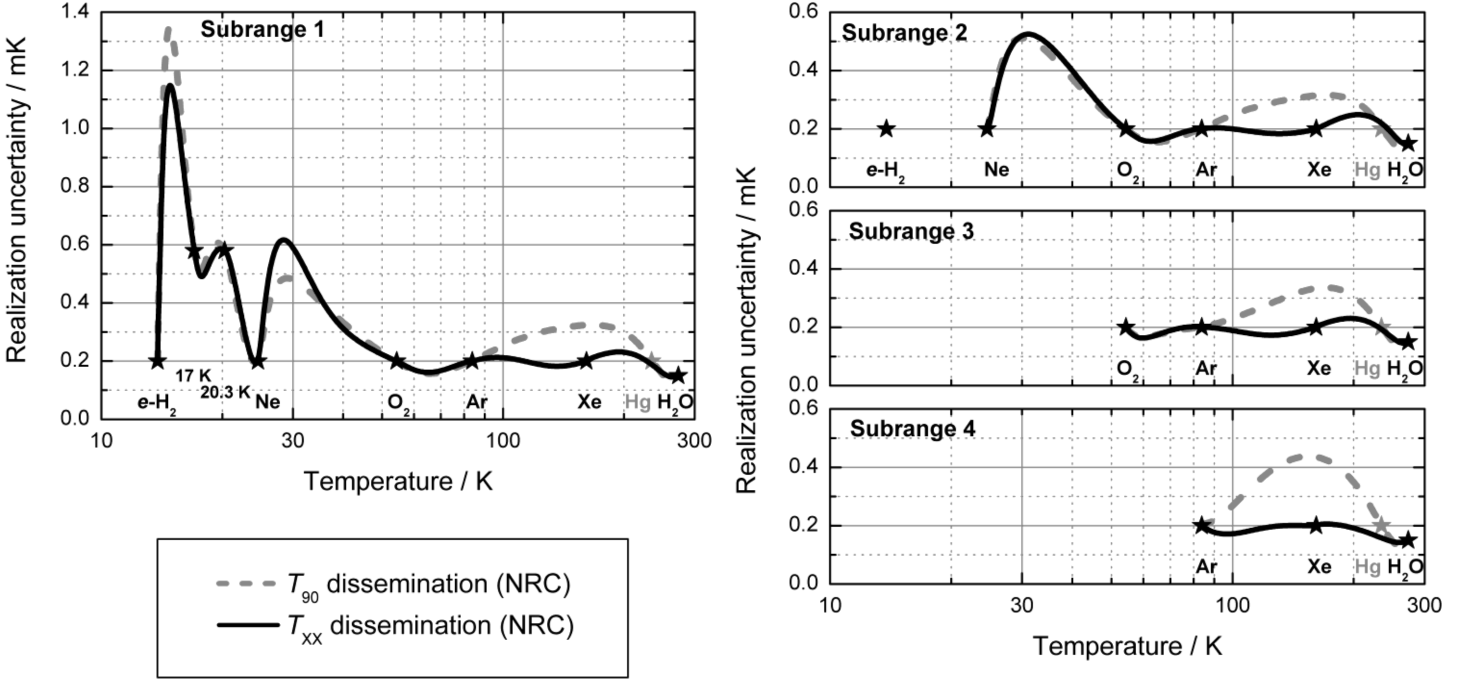




NRC k = 1 CSPRT calibration uncertainties

- 0.15 mK @ TPW
- 0.20 mK @ Hg, Ar, O_2, Ne & e-H_2
- 0.58 mK @ 20.3 K & 17 K
- Hill *et al.* "CCT-K2.5 Final Report" 2015

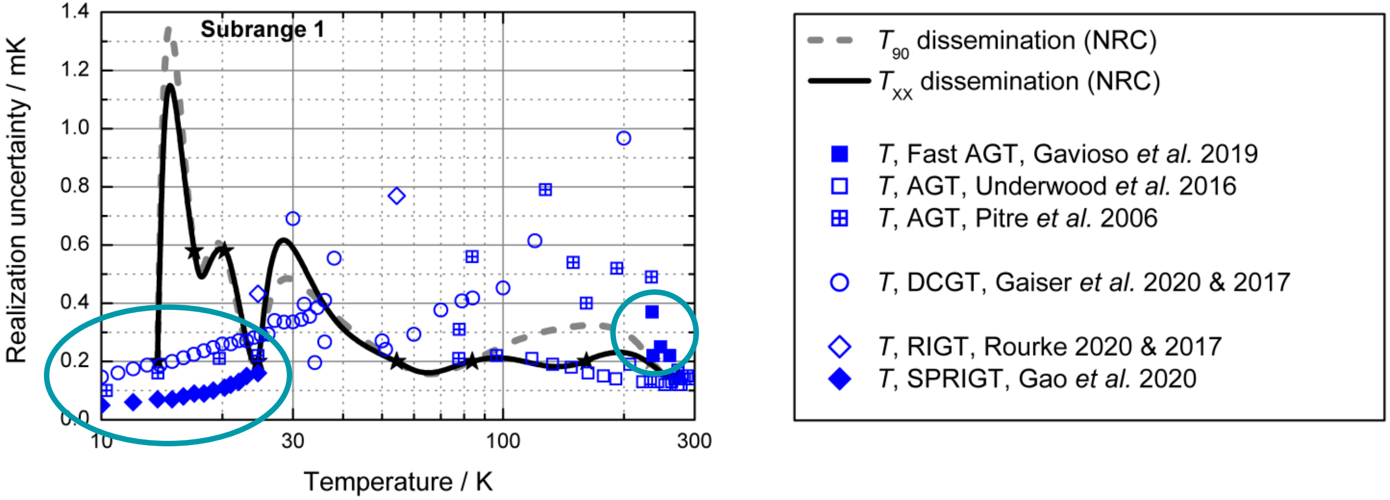
Reproducibility: T_{90} vs. T_{XX}



ITS-XX "Lite"

- Xenon replaces mercury
- New deviation functions for subranges 1, 2 & 3
- Same reference function as ITS-90
- More reproducible scale, same thermodynamic inaccuracy
- Minimally disruptive?

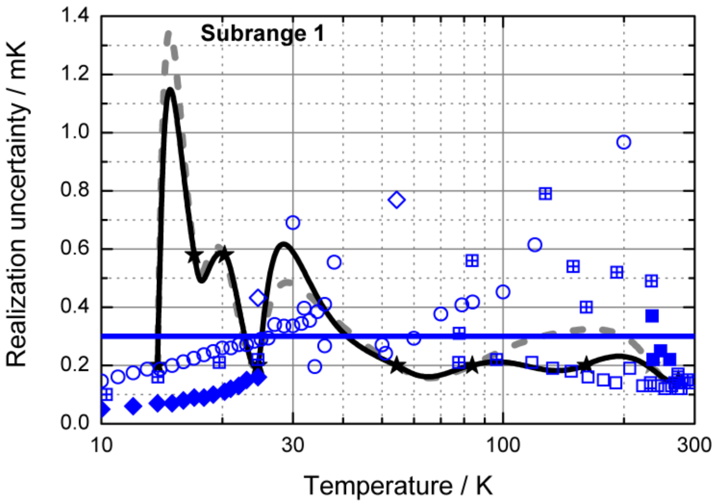
Reproducibility: T_{90} vs. T_{XX} vs. T

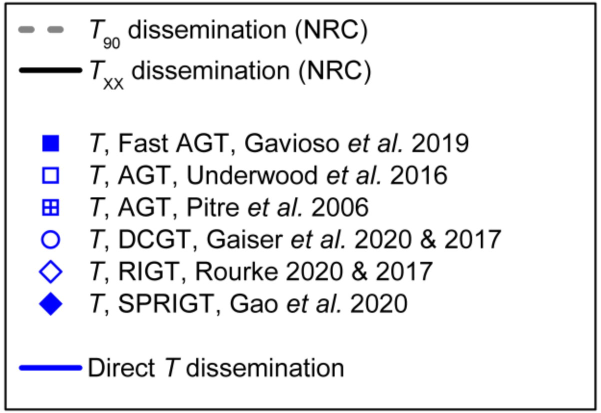


u(*T*)

- Multiple techniques
- "Fast" methods
- Consistent low-temperature performance

Dissemination path examples: direct *T* dissemination

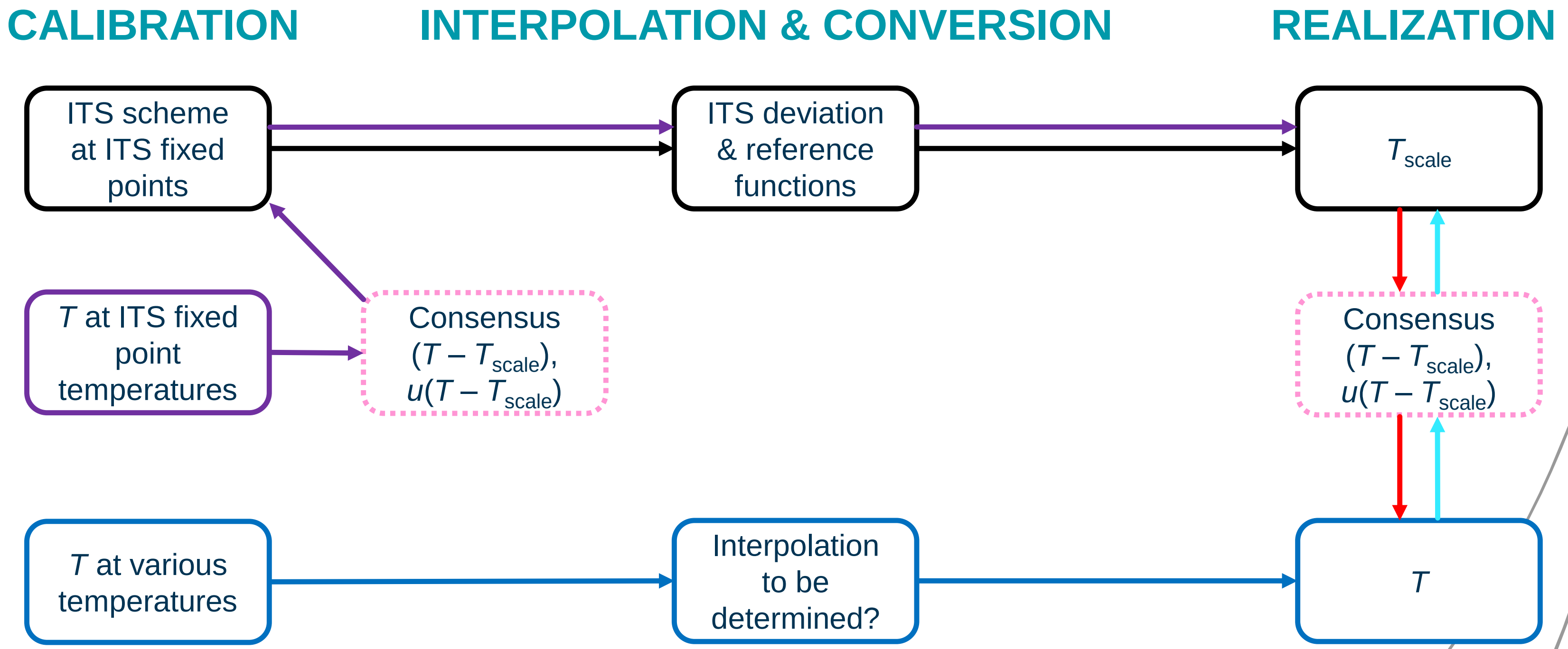




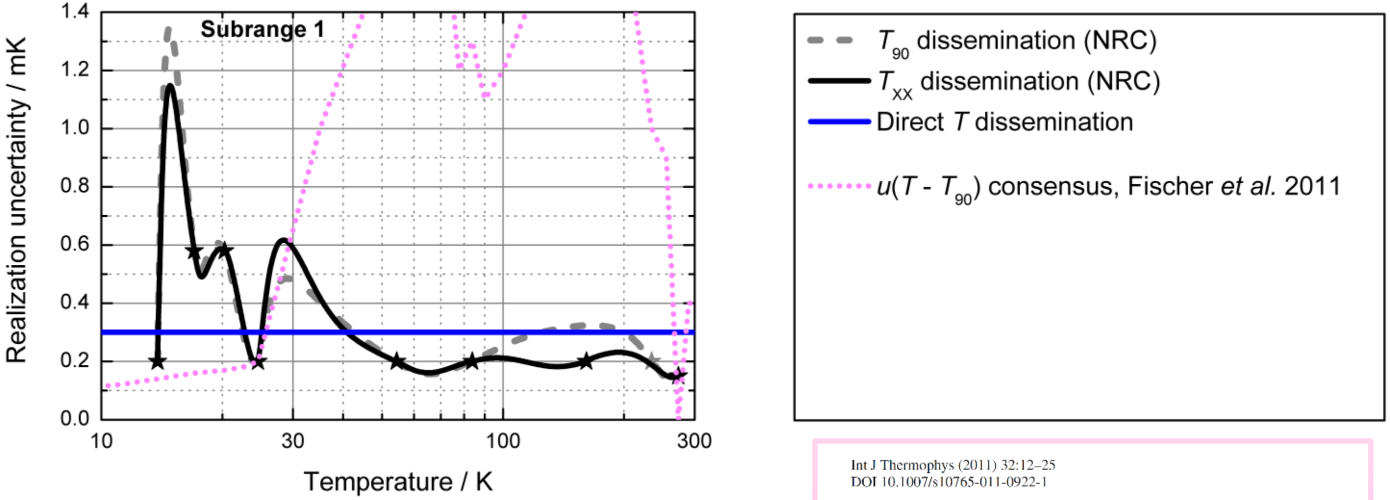
Direct *T* dissemination

- Research *vs.* calibration
- *u*(*T*) ~ 0.3 mK likely attainable for dissemination with near-future technology

Dissemination path examples

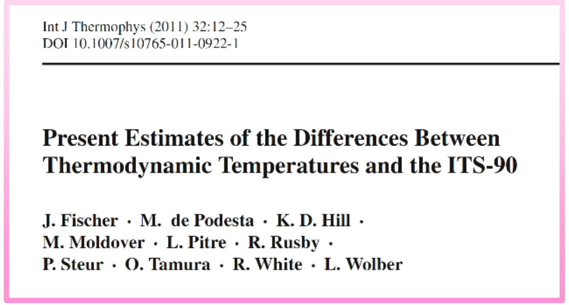


Dissemination path examples: conversion using $(T - T_{scale})$ & $u(T - T_{scale})$



Community consensus 2011

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



Int J Thermophys (2011) 32:12–25
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Present Estimates of the Differences Between Thermodynamic Temperatures and the ITS-90

J. Fischer · M. de Podesta · K. D. Hill · M. Moldover · L. Pitre · R. Rusby · P. Steur · O. Tamura · R. White · L. Wolber

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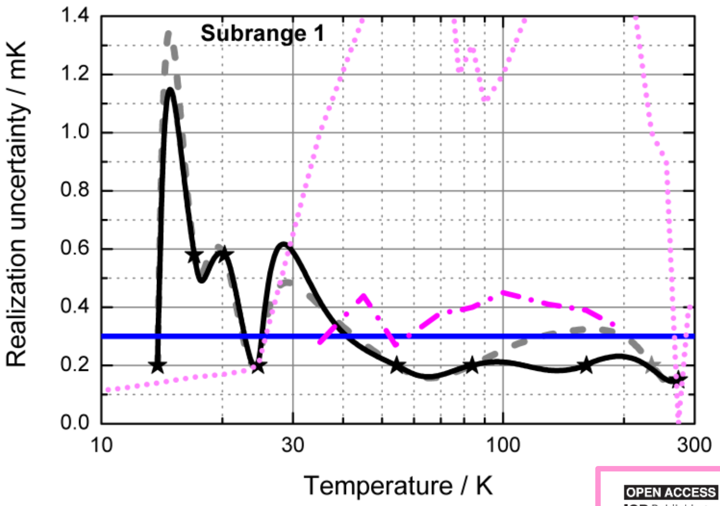

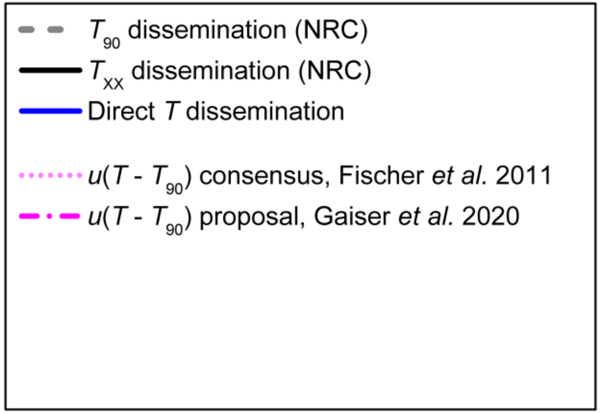

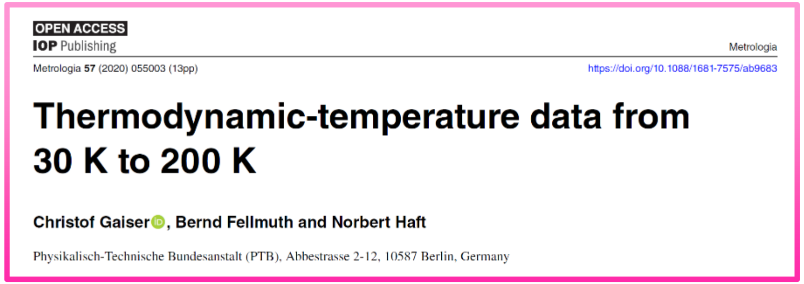

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Thermodynamic-temperature data from 30 K to 200 K

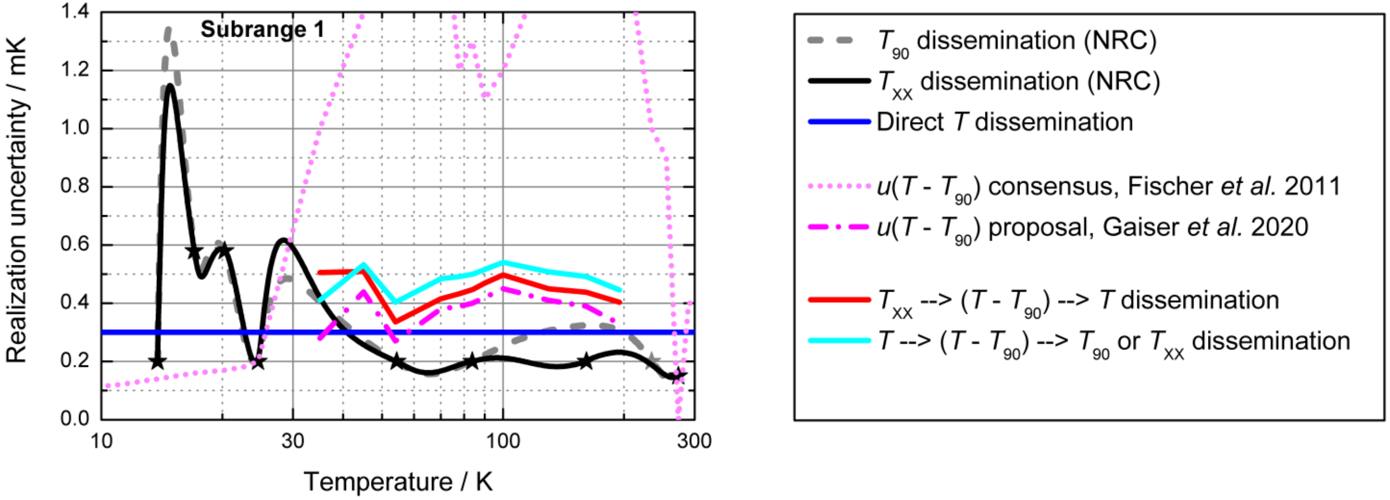
Christof Gaiser, Bernd Fellmuth and Norbert Haft

Physikalisch-Technische Bundesanstalt (PTB), Abbestrasse 2-12, 10587 Berlin, Germany

Community consensus

- Experimental work on-going worldwide, over entire temperature range of defined scales
- More reliable consensus $(T - T_{90})$ imminent?
  - Gaiser *et al.* 2020
  - CCT-WG-CTh
  - 4 K to 303 K or 430 K?

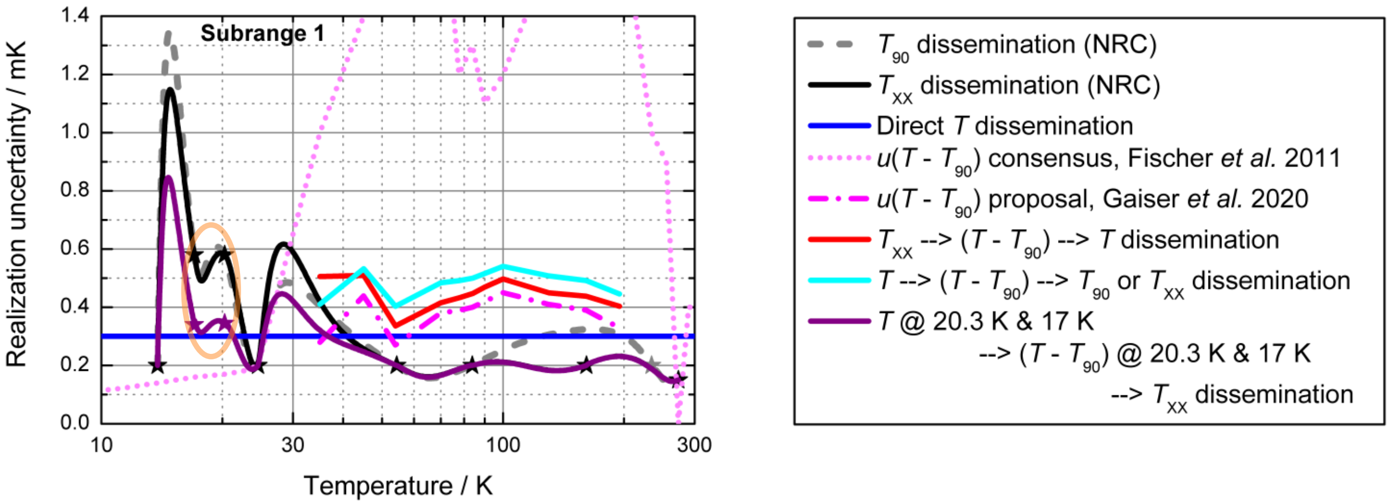
Dissemination path examples: conversion using ($T - T_{scale}$) & $u(T - T_{scale})$



$T_{scale} \rightarrow T$

$T \rightarrow T_{scale}$

Dissemination path examples:
T punch in at defined scale fixed point(s)

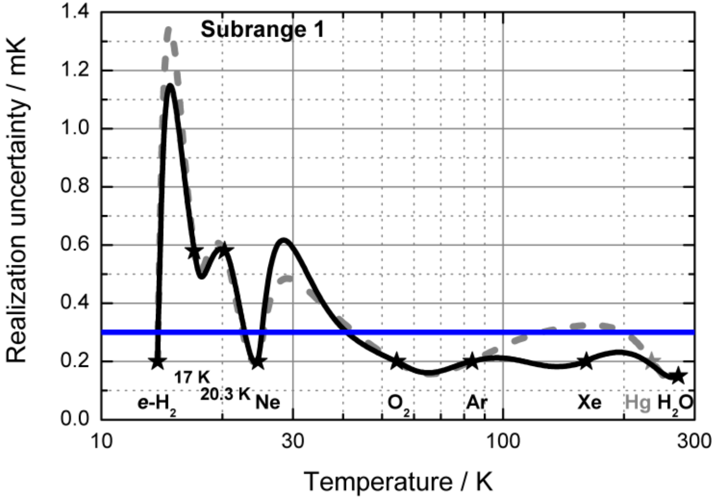


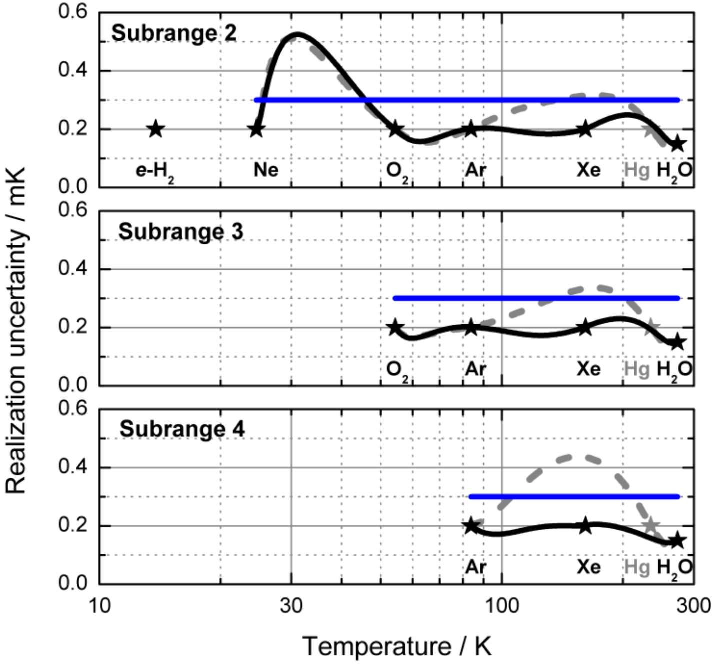
$T_{scale} \rightarrow T$

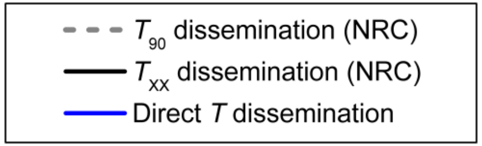
$T \rightarrow T_{scale}$

- Primary thermometers may replace:
  - Interpolating gas thermometers (IGTs)
  - Hydrogen vapour pressure (e-H_2 VP) systems
  - Other fixed points?

Dissemination path examples



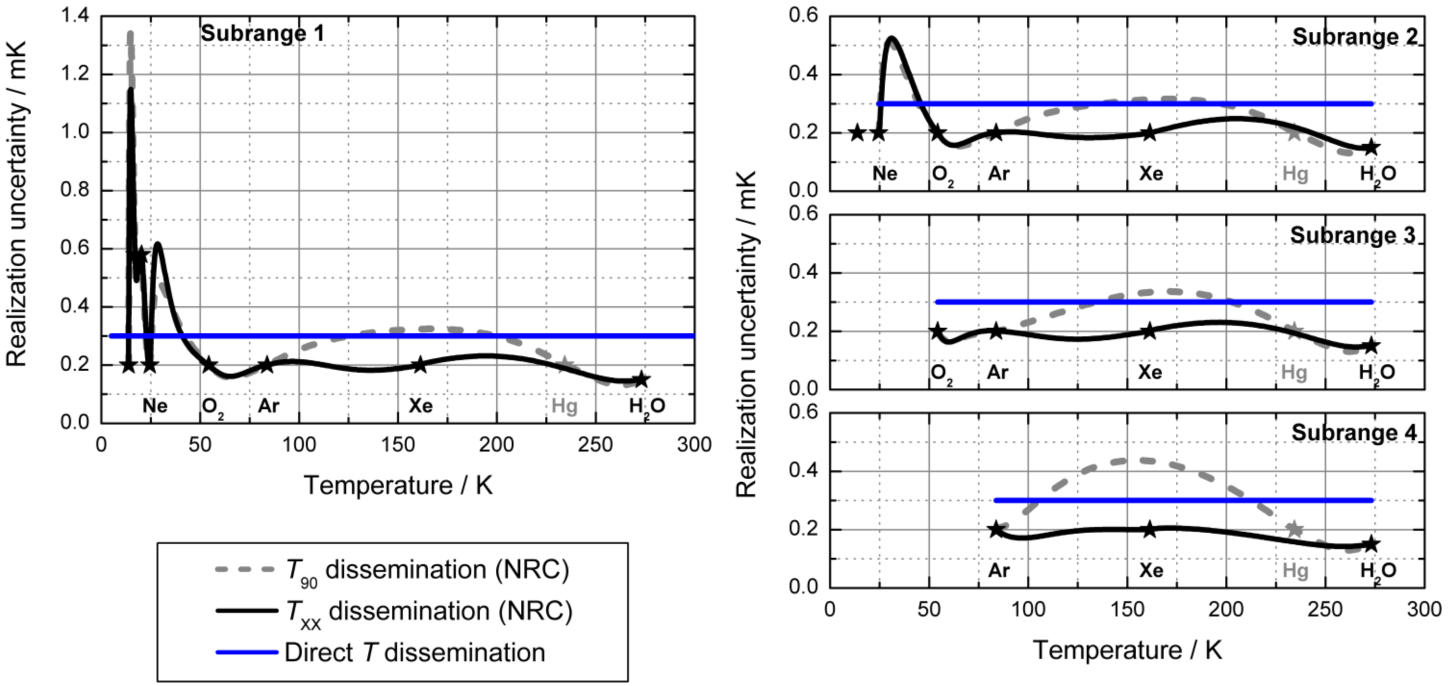




Reproducibility of direct *T* competitive with defined scale

- Up to 24.5 K
- IGTs / *e*-H_2 VP systems already cumbersome
- Looks good in 24.5 K to 54 K range too

Dissemination path examples



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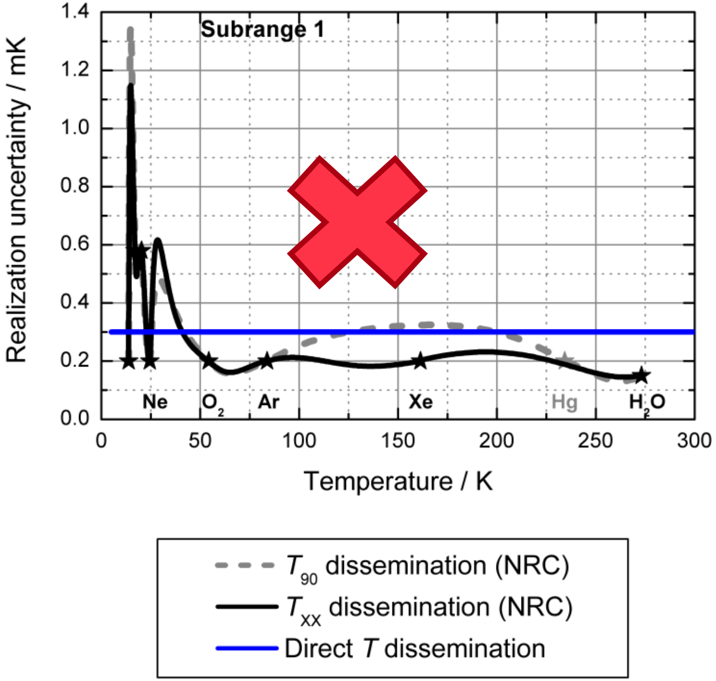
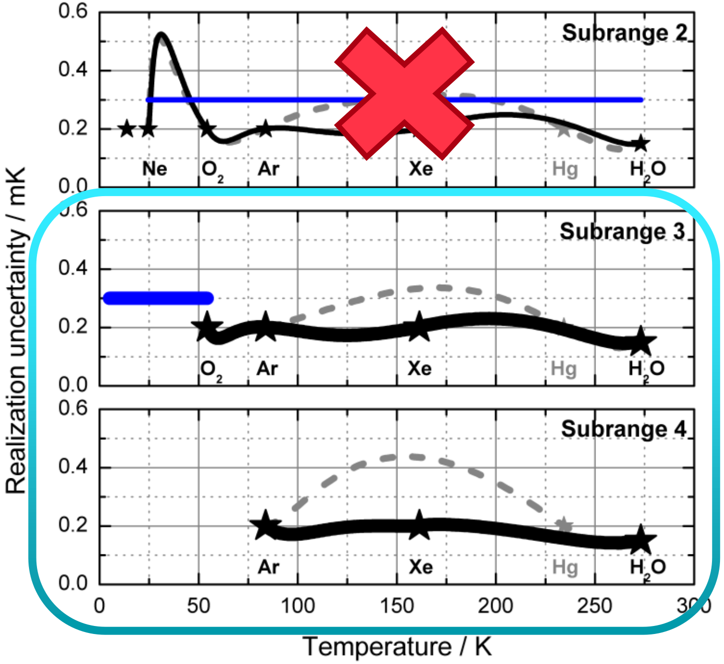
Optimum reproducibility approach

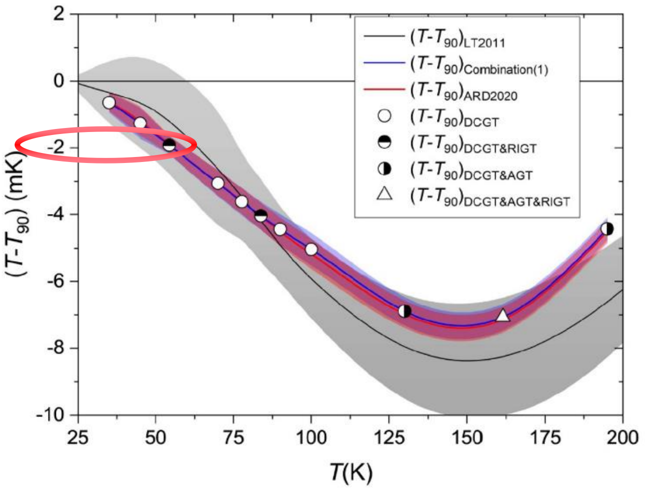




Dissemination:
T < 54 K, T_{XX} > 54 K

- Primary thermometry displaces ITS subranges 1 & 2
- ITS-XX "Lite" subranges 3 & 4 have excellent reproducibility, need few calibration points
- Changeover at the triple point of oxygen
- But...

Thermodynamic inaccuracy of the ITS-90



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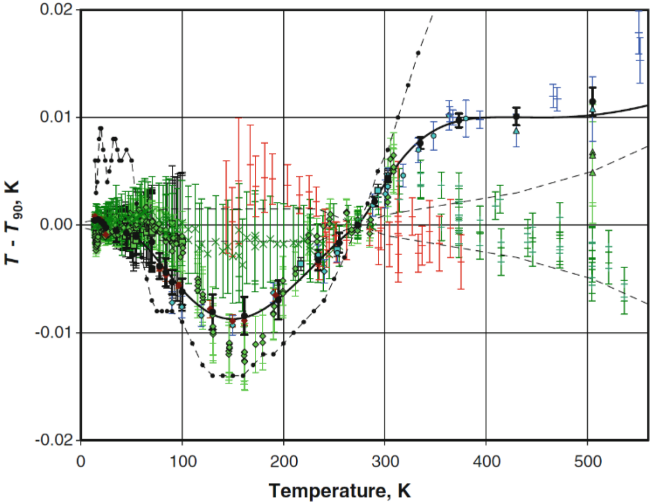
ITS-90 is a poor approximation to thermodynamic temperature

- 2 mK discrepancy at 54 K = 10× $u_{\mathrm{NRC}}(T_{90})$
- Big step change if dissemination switches from T to approximation-to-T (defined scale) here
- Cross-converting incurs additional uncertainty
- Even worse at 84 K and beyond
- Problem may become pervasive, unless:
  - Direct dissemination of the kelvin according to its new definition is confined to temperature regions where $T_{\mathrm{scale}} \approx T$; or
  - Thermodynamic accuracy of defined scales are improved

Thermodynamic inaccuracy of the ITS-90



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At higher temperatures too

- $(T - T_{90}) \approx 400$ mK = 0.4 K at 3000 °C
- Second radiation constant $c_{2,90} \neq c_2 \equiv h\ c\ /\ k$
- Non-uniqueness of the ITS-90 ≈ 100 mK = 0.1 K at 3000 °C

All are now defined constants of the SI

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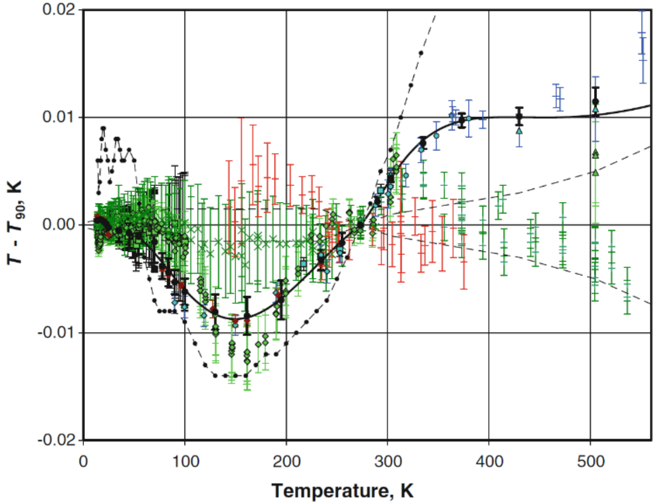
Metrologia 57 (2020) 045007 (7pp) https://doi.org/10.1088/1681-7575/ab8d7c

The non-uniqueness of ITS-90 above the silver point and its impact on values of $T - T_{90}$

Peter Saunders
Measurement Standards Laboratory of New Zealand, PO Box 31-310, Lower Hutt, New Zealand

Thermodynamic inaccuracy of the ITS-90



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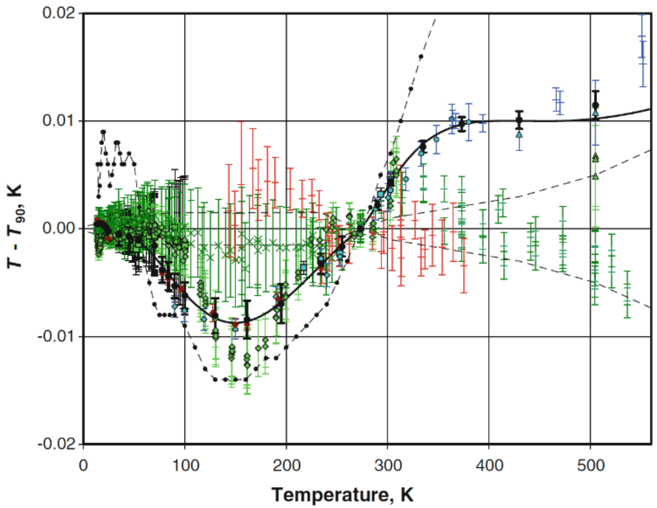
- Dissemination patchwork:
  - Time
  - Space
  - Temperature range
  - Position in calibration chain
- Mixed dissemination environment
- **Danger of confusion between T and T_{90} in broader downstream community**

Thermodynamic inaccuracy of the ITS-90



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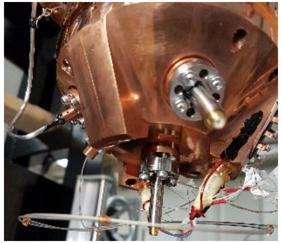
ITS-XX "Deluxe"

- Dissemination patchwork:
  - Time
  - Space
  - Temperature range
  - Position in calibration chain
- Mixed dissemination environment
- **Danger of confusion between T and T_{90} in broader downstream community**
- Cost of confusion *vs.* cost of new scale?
- Metrology ⇒ applications

KCs and CMCs for primary thermometers: beware pre-ITS-style laboratory scales!



Key Comparisons

- Exchanging primary thermometers unfeasible
- SPRTs as transfer standards?
  - What if reproducibility / stability of primary thermometers eclipses SPRTs?
  - *E.g.* improvement: lamps → radiation thermometers
- Additional uncertainty: $T \leftrightarrow T_{\mathrm{scale}}$

Calibration and Measurement Capabilities

- Non-contact thermometry leading the way
  - Simultaneously handle CMC review process for T_{scale} & T
  - Higher uncertainties
  - Manageable NMI workload
- Commercial primary / “self-calibrating” thermometers?

Further *T* dissemination issues

To think about...

- Implications for core industrially-relevant long-stem SPRT range: triple point of argon (84 K) to freezing point of aluminum (660 °C)
- Calibration points, interpolation, non-uniqueness, propagation of uncertainty
  - Prescribed for defined scales; limited number of cal. points / subranges
  - Direct *T* dissemination cal. points & interpolation could be anything
  - More complicated if new interpolating instruments begin to be used at the highest levels (Task Group on Emerging Technologies!)
- What if primary thermometers not meeting criteria for inclusion in the *MeP*-K begin to used “in the wild”?

LSPRTs on the way to NIST for CCT-K9

Summary and discussion

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Mixed T_{scale} and T dissemination world

- ITS-XX “Lite” more reproducible than ITS-90, same thermodynamic inaccuracy, low disruption
- Near future T dissemination: reproducibility likely competitive with defined scales up to 54 K
- Costs of downstream T & T_{scale} confusion *vs.* disruption of introducing thermodynamically-accurate ITS-XX “Deluxe”
- Better metrology enables new applications & technologies
- Primary thermometers:
  - Key Comparisons & Calibration and Measurement Capabilities
  - Implications for industrially-relevant 84 K to 660 °C LSPRT range
  - Calibration points, interpolation, non-uniqueness, propagation of uncertainty

THANK YOU

Patrick Rourke • patrick.rourke@nrc-cnrc.gc.ca