Dissemination and international comparison of thermodynamic temperature in non-contact thermometry

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Outline

01 Dissemination of *T* above 960 ˚C at NMIJ

02 Radiation thermometry CMC review protocol

03 Plans to extend the dissemination of *T* down to the Indium point at NMIJ

04 Future key comparisons in non-contact thermometry

The *Mise en pratique* of the realization of the kelvin (*MeP*-K-19)

Absolute primary radiometric thermometry

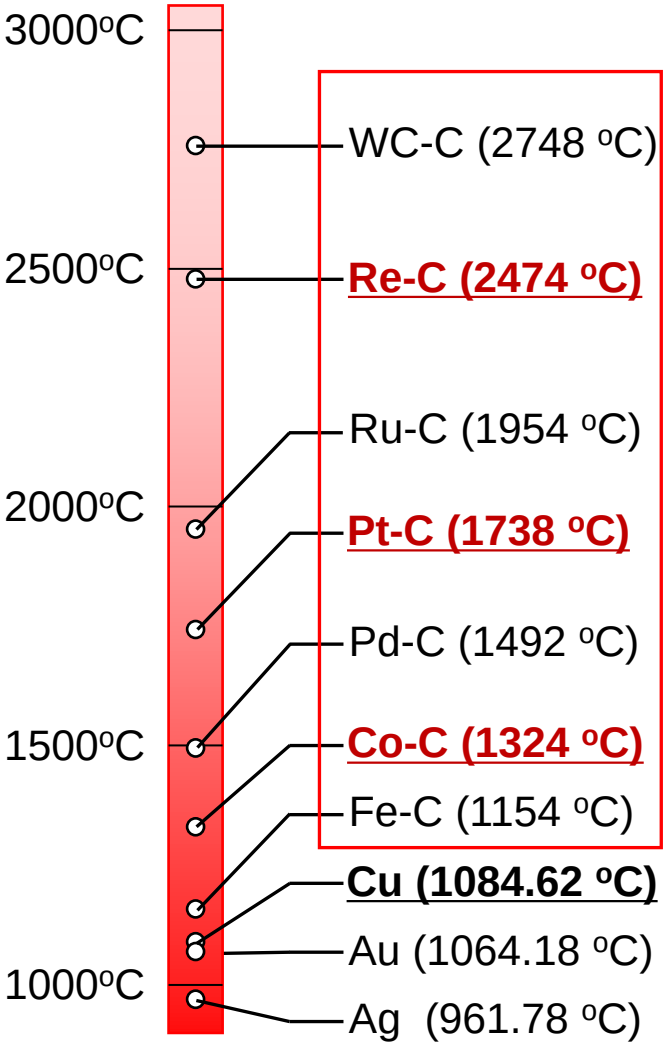
- Thermodynamic temperature (*T*) is determined without using a temperature fixed point.

Relative primary radiometric thermometry

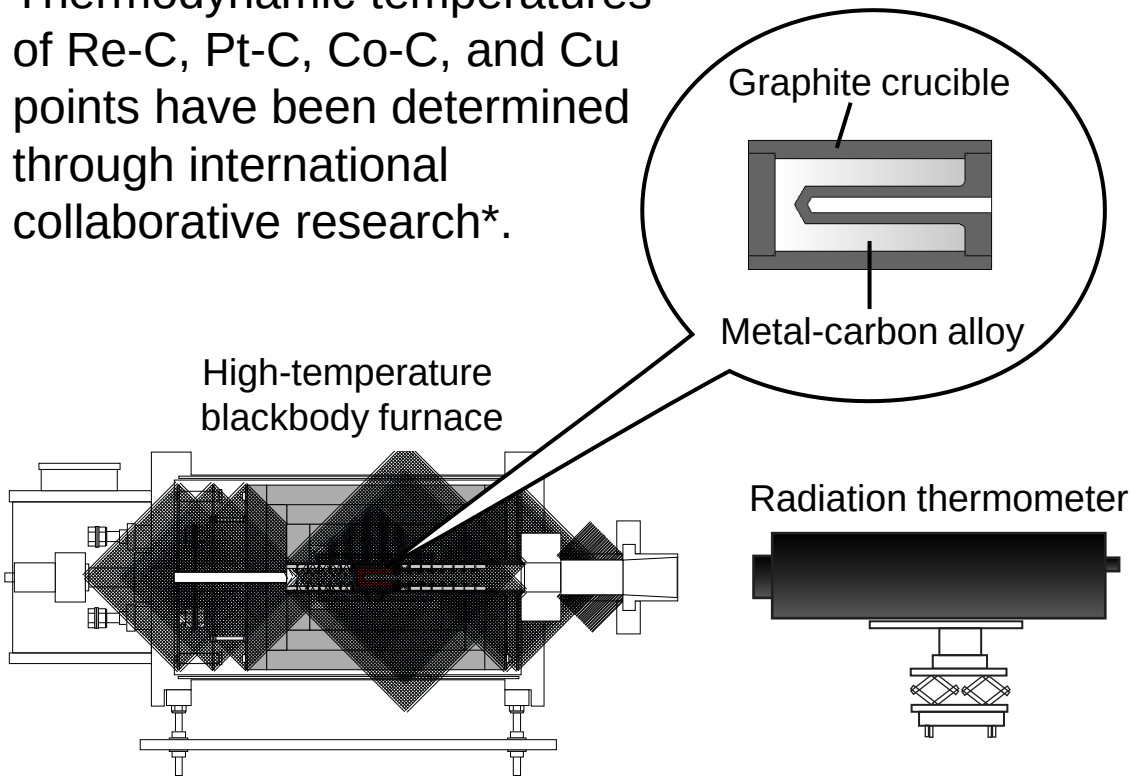
- *T* is determined using one or more temperature fixed-points.
- Each of the fixed points has a known thermodynamic temperature*.
- Interpolation or extrapolation from three or more fixed points does not require detailed measurements of responsivity.
- The relative method gives uncertainties that are only slightly higher than the absolute method.

*Tables for *T* of fixed points are given in the *MeP*-K annexes “Relative primary radiometric thermometry” and “Estimates of the differences T-T_{90}”.

High-temperature fixed points using metal-carbon system



Thermodynamic temperatures of Re-C, Pt-C, Co-C, and Cu points have been determined through international collaborative research*.



Since 2019, NMIJ has been disseminating *T* by relative method in the temperature range of 960 °C to 2800 °C.

*Woolliams, E., et al., *Phil. Trans R. Soc. A*. **374**: 20150044 (2016)
Lowe, D.H., et al., *Metrologia*, **54**, 390–398 (2017)

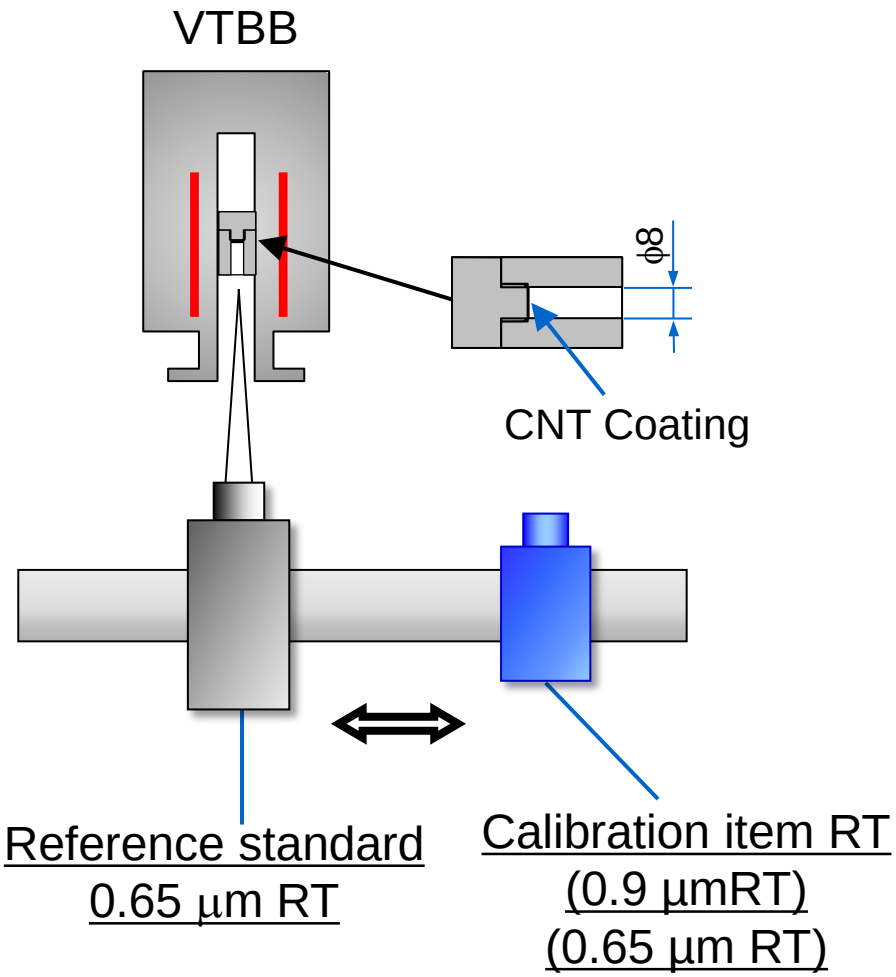
Calibration of radiation thermometer from 960 ºC to 2800 ºC

HTFPs with Thermodynamic temperatures

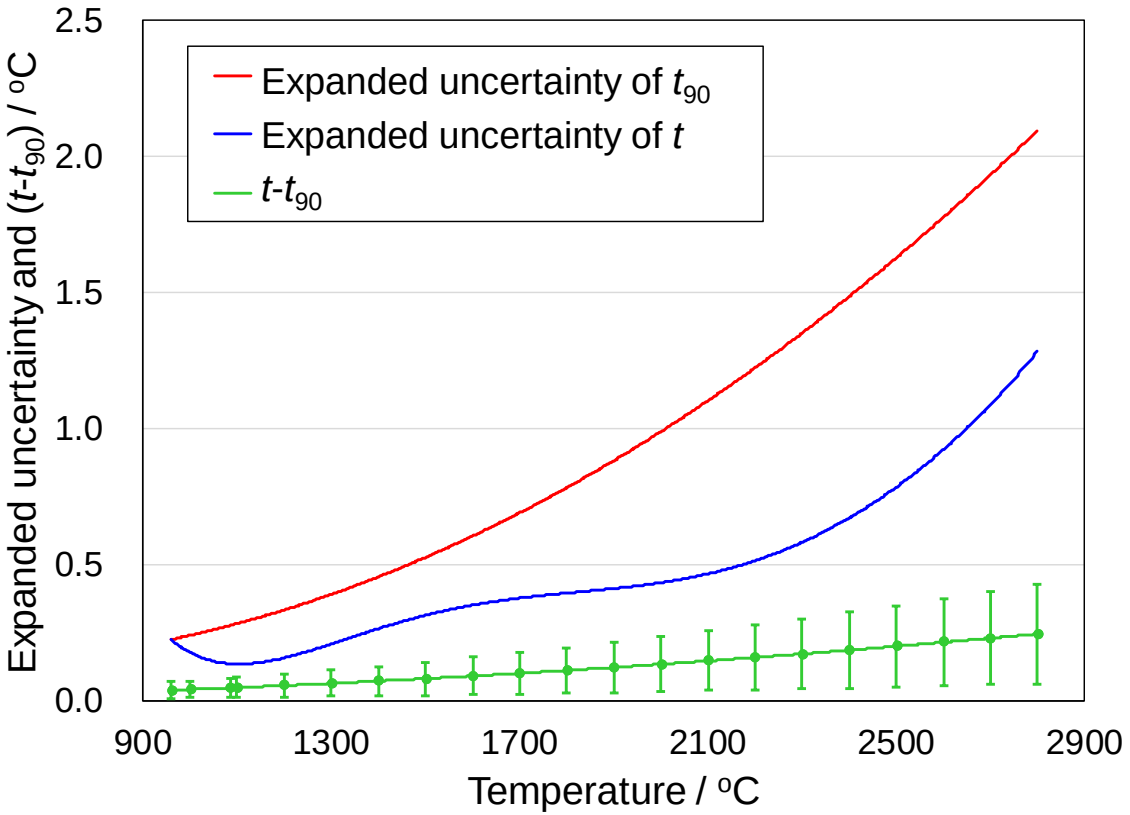
Cu | Co-C | Pt-C | Re-C

Reference standard RT

Calibration of a 0.65 μm RT by fixed-point interpolation method



Comparison of expanded uncertainty of t_{90} and t at NMIJ



NMIJ's CMC has improved significantly.

t - t_{90} and its uncertainty is extrapolated above Cu point using Planck's law.

Uncertainties of selected set of HTFPs

HTFPs	Thermodynamic temperature (poi) /K	Uncertainty (poi) (k=2) /K
Fe-C	1426.92	0.15
Co-C	1597.39	0.13
Pd-C	1765.05	0.16
Pt-C	2011.43	0.18
Ru-C	2226.99	0.22
Re-C	2747.84	0.35
WC-C	3020.85	0.25

In the CCT-K10, the averaged laboratory uncertainty of the participants for RT (LP3) at 2500 ºC was about 1.3 ºC.

Relative primary radiometric thermometry using HTFPs is expected to have smaller uncertainty than the ITS-90 temperature scale.

Revised CMC Review Protocol for Radiation Thermometry

Is the CMC of *T* dissemination acceptable without international comparison of *T*?

➡ Yes.

Acceptance criteria for *T* dissemination have been added to the revised review protocol.

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Revised CMC Review Protocol for Radiation Thermometry

- *T* and ITS-90 dissemination using high-temperature fixed points (HTFPs) has been included.
- *T* realization and dissemination through three routes:
  1) absolute primary thermometry
  2) relative primary thermometry
  3) conversion from ITS-90 to *T* applying CCT authorized correction function
- *T* realization and dissemination is covering not only high temperature but all temperature ranges.

7. Items Used for Disseminating *T*

Service category		Examples of instrument or artifact	Condition	Criterion
7. Items Used for Disseminating T				
7.1.1	Fixed-point blackbody cells and apparatus	Hg/ Ga/ In/ Sn/ Zn/ Al/ Ag/ Au/ Cu point blackbody cell/furnace, High-temperature fixed point (HTFP) blackbody cells of Co-C/ Pt-C/ Re-C eutectic point, Fe-C/ Pd-C/ Ru-C eutectic point, WC-C peritectic point, Ni-C/ Rh-C/ Ir-C eutectic point, Cr_3C_2-C peritectic point	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of FP *T* [*2] available	"KC/SC result OK"
			KC/SC of RT *T* measurement[*2] only	"KC/SC(Scale) result OK"
				"KC/SC(Scale) result OK with $U_{\mathrm{NMI\ KC\ FP}}$"
			Not a primary realization / FP *T* assigned by ref. RT	"Ref. standard[*3] CMC OK"
7.1.2	Radiation thermometers (RT)	RT calibrated by *absolute primary* radiation thermometry, RT calibrated by *relative primary* radiation thermometry, RT calibrated by a VTBB against a reference thermometer	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of RT *T* measurement[*2] available	"KC/SC result OK"
			Relative primary RT	"Ref. standard[*4] CMC OK"
			Not a primary realization	"Ref. standard[*5] CMC OK"
7.1.3	Variable temperature blackbody radiation sources (VTBB)	VTBB calibrated by a standard radiation thermometer, VTBB calibrated by radiance comparison against a standard VTBB	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
				Ref standard[*6] thermometer CMC OK

Example 1

NMI's submitted Calibration Service and CMC

0.65 μm Radiation Thermometer, calibrated in *T*,
absolutely or by interpolation or extrapolation from HTFPs
(7.1.2 Radiation thermometers): $U_{\mathrm{NMI}\ T\ \mathrm{CMC}}$

Condition

NMI already has CMC entry for 0.65 μm Radiation Thermometer
in KCDB for 1.4.1 (Standard Radiation Thermometer): $U_{\mathrm{NMI\ ITS\ CMC}}$
and

$$U_{\mathrm{NMI}\ T\ \mathrm{CMC}} \geq \sqrt{U^2_{\mathrm{NMI\ ITS\ CMC}} + U^2_{T-\mathrm{ITS}}}$$

Review outcome

Automatic approval for the corresponding temperature range

Example 2

NMI's submitted Calibration Service and CMC

0.65 μm Radiation Thermometer, calibrated in *T*,
absolutely or by interpolation or extrapolation from HTFPs
(7.1.2 Radiation thermometers): $U_{\mathrm{NMI}\ T\ \mathrm{CMC}}$

Condition

NMI participated in CCT-K10, with "KC result OK": $U_{\mathrm{NMI\ KC/SC\ CMC}}$

and

$$U_{\mathrm{NMI}\ T\ \mathrm{CMC}} \geq \sqrt{U^2_{\mathrm{NMI\ KC/SC\ CMC}} + U^2_{T-\mathrm{ITS}}}$$

Review outcome

Automatic approval for the corresponding temperature range

1. Items Used for defining ITS-90

Service category		Examples of instrument or artifact	Condition	Criterion
1. Items Used for defining ITS-90				
1.1.2	Primary fixed-point cells for radiation thermometry	Ag/Au/Cu point blackbody cell	KC of FP available	"KC(FP)[*7] result OK"
			KC[*8] of ITS-90 scale only	"KC(Scale)[*9] result OK"
				"KC(Scale)[*9] result OK with $U_{\text{NMI KC FP}}$"
			Not a primary realization	"Ref. standard[*5] CMC OK"
1.2.2	Complete apparatus realizing fixed points for radiation thermometry	Ag/Au/Cu point blackbody furnace	KC of FP available	"KC(FP)[*7] result OK"
			KC[*8] of ITS-90 scale only	"KC(Scale)[*9] result OK"
				"KC(Scale)[*9] result OK with $U_{\text{NMI KC FP}}$"
			Not a primary realization	"Ref. standard[*5] CMC OK"
1.4.1	Standard Radiation Thermometers	0.65 μm / 0.9 μm standard RT with direct ITS-90 realization, 0.65 μm / 0.9 μm standard RT calibrated by comparison above 962 °C	Same wavelength[*10] as KC	"KC result OK"
			Not same wavelength as KC but same wavelength[*10] as SC	"KC result OK"& "SC result OK"
			Not same wavelength as KC and no SC with same wavelength[*10]	"KC result OK"
			Not a primary realization	"Ref. standard[*5] CMC OK"

2. Items Used for Disseminating ITS-90

Service category		Examples of instrument or artifact	Condition	Criterion
2. Items Used for Disseminating ITS-90				
2.5.1	Secondary fixed-point blackbody cells and apparatus	Hg/ Ga/ In/ Sn/ Zn/ Al/ Ag/ Au/ Cu point blackbody cell/furnace, High-temperature fixed point (HTFP) blackbody cells of Co-C/ Pt-C/ Re-C eutectic point, Fe-C/ Pd-C/ Ru-C eutectic point, WC-C peritectic point, Ni-C/ Rh-C/ Ir-C eutectic point, Cr_3C_2-C peritectic point	Review based on protocol for corresponding service in Service Cat. 7.1.1	"*T* CMC OK"*1
			SC of FP available	"SC(FP)*7 result OK"
			SC*8 of ITS-90 scale only	"SC(Scale)*9 result OK"
				"SC(Scale)*9 result OK with $U_{NMI\ SC\ FP}$"
			Not a primary realization / FP T_{90} assigned by ref. RT	"Ref. standard*3 CMC OK"
2.5.2	Variable temperature blackbody radiation sources (VTBB)	VTBB calibrated by a standard radiation thermometer, VTBB calibrated by radiance comparison against a standard VTBB		"Ref. thermometer*6 CMC OK"
2.5.3	Strip lamps	Vacuum lamps, gas filled lamps		"KC result OK"
2.5.4	Radiation thermometers (RT)	3.9 μm / 8-14 μm RT including thermal imagers calibrated by VTBB against a reference thermometer, 0.9 μm / 1.6 μm RT calibrated by 3-fixed point / 4-fixed-point interpolation below Cu point, 0.65 μm / 0.9 μm RT calibrated by multiple high-temperature fixed point interpolation	*Same wavelength**10 as SC	"SC result OK"
			Not same wavelength*10 as SC	"SC result OK"
			No SC	"Ref. standard*11 CMC OK"
	Visual optical pyrometers	Disappearing filament pyrometer		"Ref. standard*12 CMC OK"

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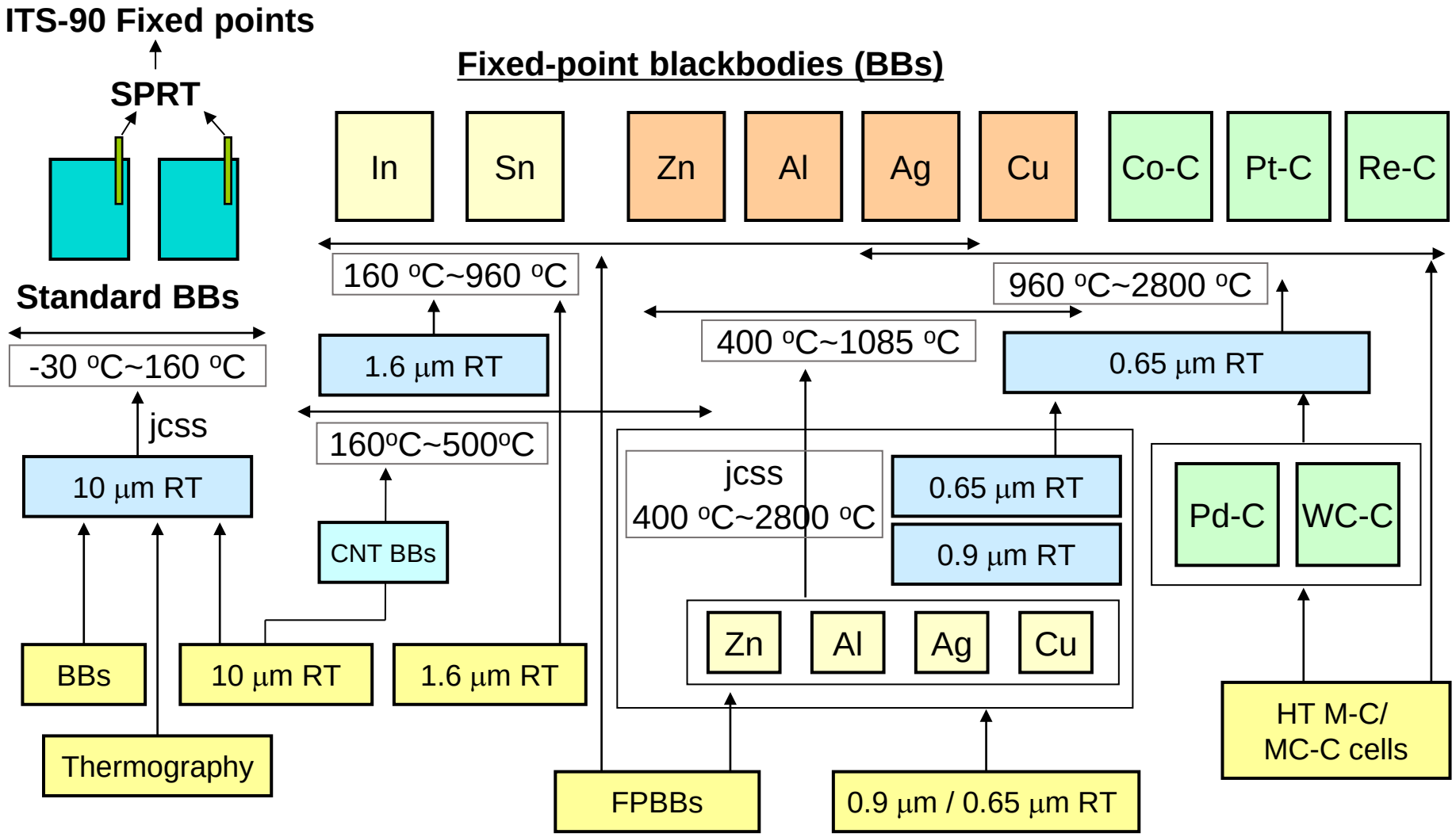
Radiation thermometry standards at NMIJ
(-30 °C to 2800 °C)



Calibration of radiation thermometers from 160 °C to 1085 °C

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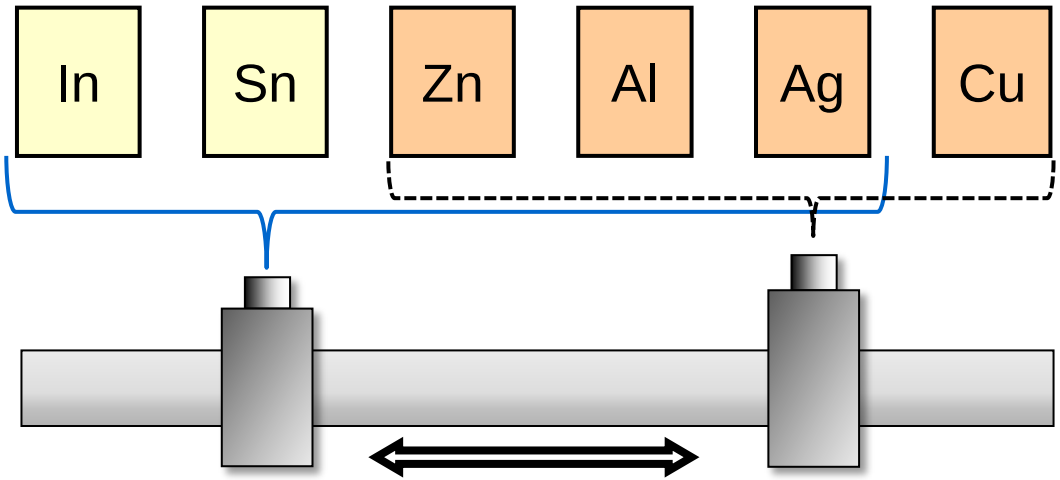
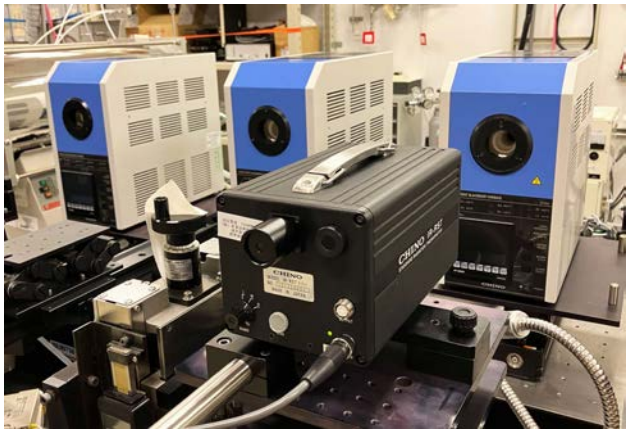
Fixed-point interpolation method





1.6 μm RT
(160 °C to 960 °C)

0.9 μm RT
(400 °C to 1085 °C)

Sakuma-Hattori equation

$$V(T) = \frac{C}{\exp\left(\frac{c_2}{A \cdot T + B}\right) - 1}$$

Calibration of 10 μm radiation thermometers from 160 °C to 500 °C

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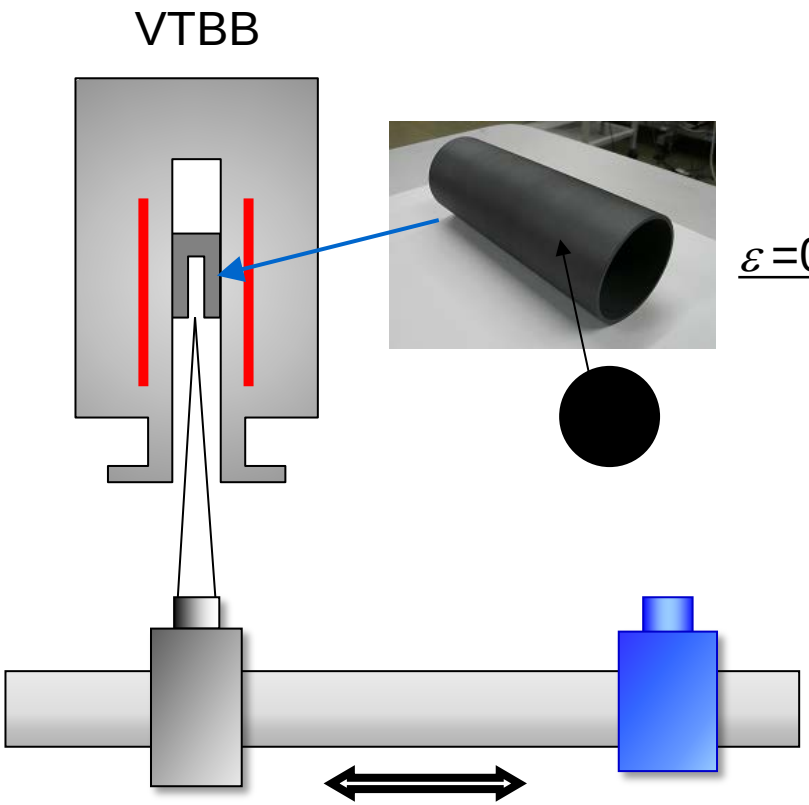
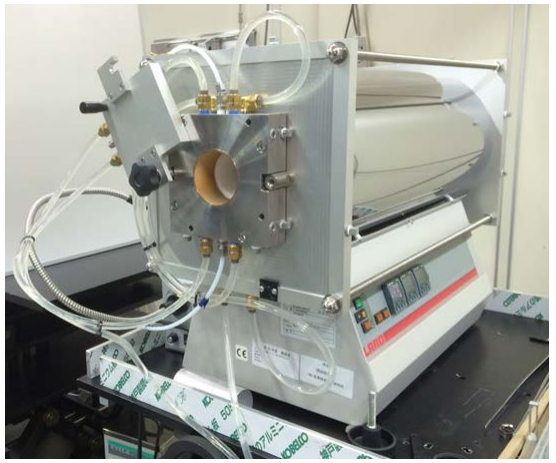
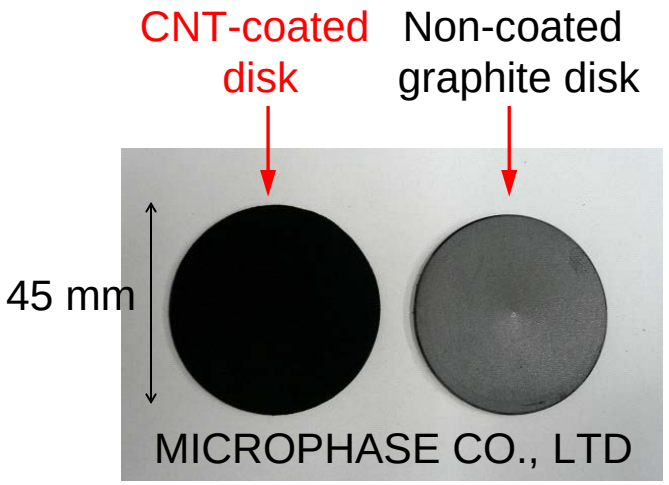
Create the Future, Collaborate Together

Comparison method





3-zone furnace



Dissemination of *T* down to the In point

Relative method in the temperature range below 1235 K

- The method used for relative primary radiometric thermometry has long been established as a secondary thermometry method[1)].
- The same technique, including uncertainty estimation[2)], is applicable to thermodynamic temperature measurements.
- *T* is determined using one or more temperature fixed points, each with a known thermodynamic temperature[3)].
- Acceptance criteria for *T* dissemination have been added to the revised review protocol.

There is no obstacle to the dissemination of thermodynamic temperatures down to the Indium point.

1. "TECHNIQUES FOR APPROXIMATING THE INTERNATIONAL TEMPERATURE SCALE OF 1990", Chap. 10.
2. P. Saunders et al. "Uncertainty Budgets for Calibration of Radiation Thermometers below the Silver Point", (2008) *Int. J. Thermophys.* 29:1066-1083
3. Estimates of the Differences $T - T_{90}$.

7. Items Used for Disseminating *T*

Service category		Examples of instrument or artifact	Condition	Criterion
7. Items Used for Disseminating T				
7.1.1	Fixed-point blackbody cells and apparatus	Hg/ Ga/ In/ Sn/ Zn/ Al/ Ag/ Au/ Cu point blackbody cell/furnace, High-temperature fixed point (HTFP) blackbody cells of Co-C/ Pt-C/ Re-C eutectic point, Fe-C/ Pd-C/ Ru-C eutectic point, WC-C peritectic point, Ni-C/ Rh-C/ Ir-C eutectic point, Cr_3C_2-C peritectic point	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of FP *T* [*2] available	"KC/SC result OK"
			KC/SC of RT *T* measurement[*2] only	"KC/SC(Scale) result OK"
				"KC/SC(Scale) result OK with $U_{\text{NMI KC FP}}$"
			Not a primary realization / FP *T* assigned by ref. RT	"Ref. standard[*3] CMC OK"
7.1.2	Radiation thermometers (RT)	RT calibrated by *absolute primary* radiation thermometry, RT calibrated by *relative primary* radiation thermometry, RT calibrated by a VTBB against a reference thermometer	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of RT *T* measurement[*2] available	"KC/SC result OK"
			Relative primary RT	"Ref. standard[*4] CMC OK"
			Not a primary realization	"Ref. standard[*5] CMC OK"

2. Items Used for Disseminating ITS-90

Service category		Examples of instrument or artifact	Condition	Criterion
2. Items Used for Disseminating ITS-90				
2.5.1	Secondary fixed-point blackbody cells and apparatus	Hg/ Ga/ In/ Sn/ Zn/ Al/ Ag/ Au/ Cu point blackbody cell/furnace, High-temperature fixed point (HTFP) blackbody cells of Co-C/ Pt-C/ Re-C eutectic point, Fe-C/ Pd-C/ Ru-C eutectic point, WC-C peritectic point, Ni-C/ Rh-C/ Ir-C eutectic point, Cr_3C_2-C peritectic point	Review based on protocol for corresponding service in Service Cat. 7.1.1	"*T* CMC OK"*1
			SC of FP available	"SC(FP)*7 result OK"
			SC*8 of ITS-90 scale only	"SC(Scale)*9 result OK"
				"SC(Scale)*9 result OK with $U_{\mathrm{NMI\ SC\ FP}}$"
			Not a primary realization / FP T_{90} assigned by ref. RT	"Ref. standard*3 CMC OK"
2.5.4	Radiation thermometers (RT)	3.9 μm / 8-14 μm RT including thermal imagers calibrated by VTBB against a reference thermometer, 0.9 μm / 1.6 μm RT calibrated by 3-fixed point / 4-fixed-point interpolation below Cu point, 0.65 μm / 0.9 μm RT calibrated by multiple high-temperature fixed point interpolation	*Same wavelength*10 as SC	"SC result OK"
			Not same wavelength*10 as SC	"SC result OK"
			No SC	"Ref. standard*11 CMC OK"
	Visual optical pyrometers	Disappearing filament pyrometer		"Ref. standard*12 CMC OK"

Uncertainty of the dissemination of *T*

Comparison of NMIJ's ITS CMC and uncertainty of T-T_{90}

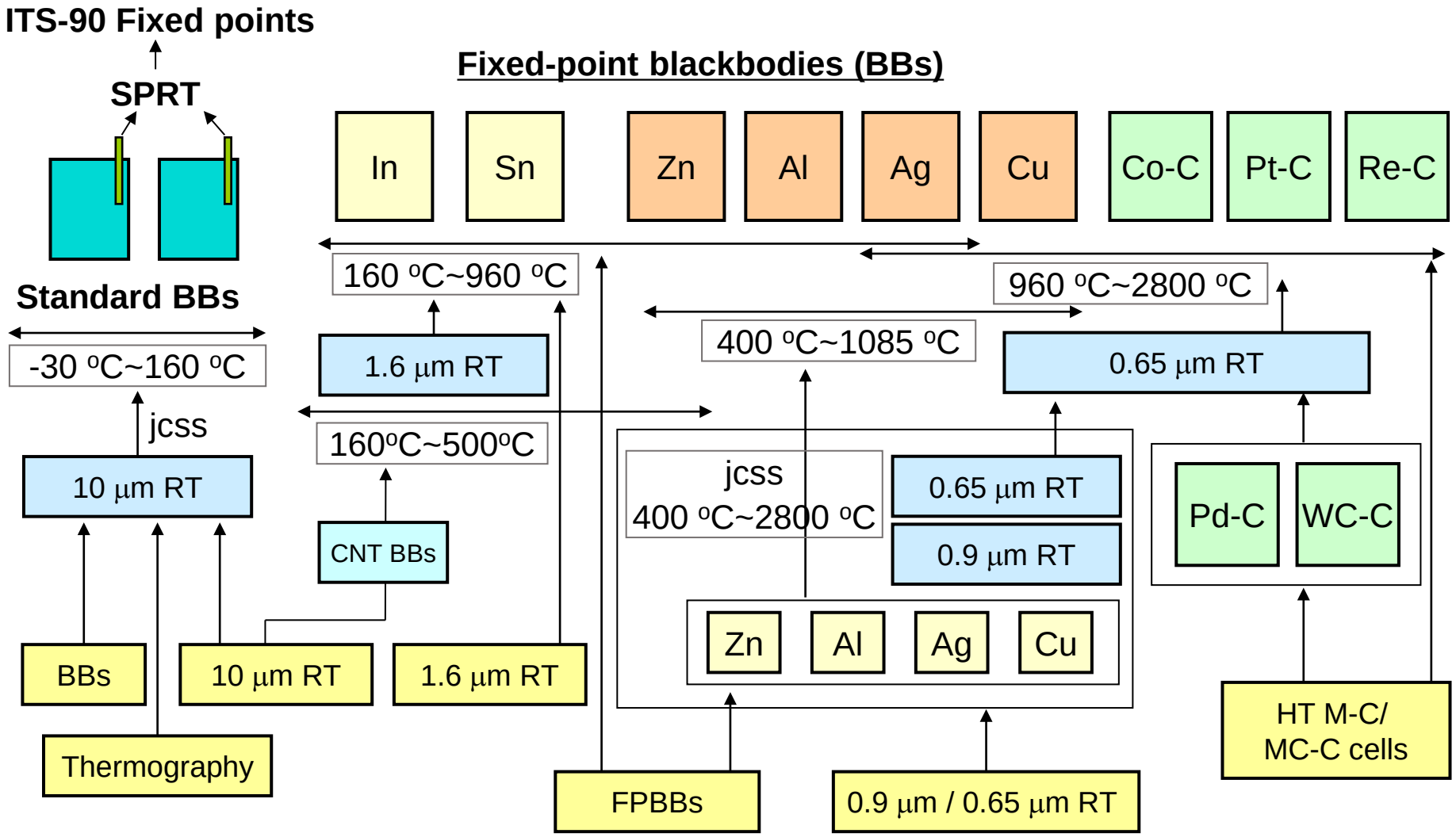
Fixed points	NMIJ's ITS CMC (mK)	T-T_{90}* (mK)	Uncertainty T-T_{90}* (mK)
Cu	100	52.1	40
Ag	100	46.2	28
Al	100	28.7	14
Zn	100	13.8	14
Sn	100	11.5	2.6
In	110	10.1	1.6

All uncertainties are expanded uncertainties (k = 2).
*Estimates of the differences T-T_{90}

Radiation Thermometry CMC Review Protocol

$$U_{\mathrm{NMI}\ T\ \mathrm{CMC}} \geq \sqrt{U^2_{\mathrm{NMI\ ITS\ CMC}} + U^2_{T-\mathrm{ITS}}}$$

Radiation thermometry standards at NMIJ
(-30 °C to 2800 °C)



7. Items Used for Disseminating *T*

Service category		Examples of instrument or artifact	Condition	Criterion
7. Items Used for Disseminating T				
7.1.1	Fixed-point blackbody cells and apparatus	Hg/ Ga/ In/ Sn/ Zn/ Al/ Ag/ Au/ Cu point blackbody cell/furnace, High-temperature fixed point (HTFP) blackbody cells of Co-C/ Pt-C/ Re-C eutectic point, Fe-C/ Pd-C/ Ru-C eutectic point, WC-C peritectic point, Ni-C/ Rh-C/ Ir-C eutectic point, Cr_3C_2-C peritectic point	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of FP *T* [*2] available	"KC/SC result OK"
			KC/SC of RT *T* measurement[*2] only	"KC/SC(Scale) result OK"
				"KC/SC(Scale) result OK with $U_{\text{NMI KC FP}}$"
			Not a primary realization / FP *T* assigned by ref. RT	"Ref. standard[*3] CMC OK"
7.1.2	Radiation thermometers (RT)	RT calibrated by *absolute primary* radiation thermometry, RT calibrated by *relative primary* radiation thermometry, RT calibrated by a VTBB against a reference thermometer	Review based on protocol for corresponding service in Service Cat. 1 & 2	"ITS CMC OK"[*1]
			KC/SC of RT *T* measurement[*2] available	"KC/SC result OK"
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Key comparisons of *T* above the silver point

The CCT K10 radiation thermometry comparison

- ITS-90 realizations above the silver point

Comparison artifacts

- Two transfer radiation thermometers
- HTFP blackbody cells
- Transfer Cu fixed point (for drift checks)

A similar method can be used to make key comparisons of thermodynamic temperatures.

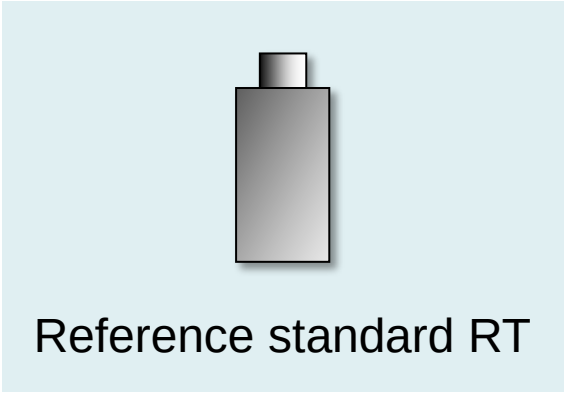
Key comparison of *T* above silver point

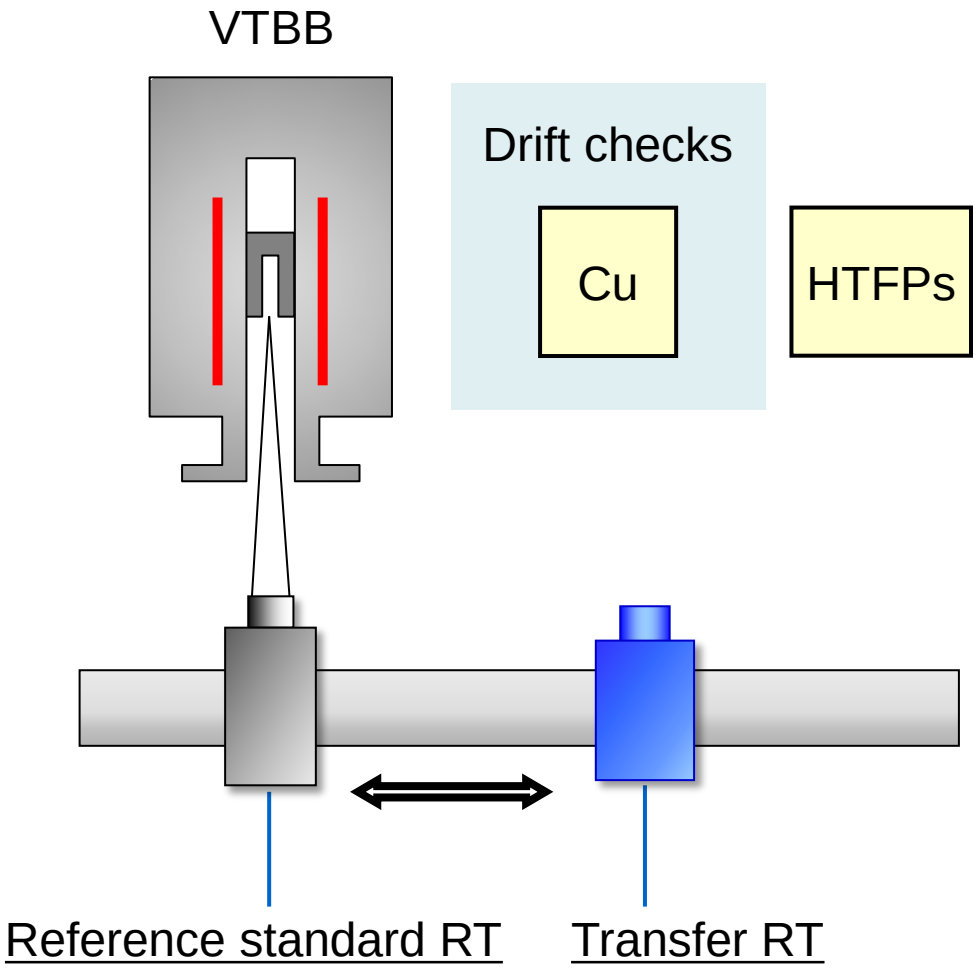
Comparison artifacts

- One or two transfer radiation thermometers
- HTFP blackbody cells and transfer Cu fixed point (for drift checks)

Key comparisons of *T* above the silver point

RT is calibrated in terms of thermodynamic temperature using the absolute or relative method.





Key comparisons of *T* below the silver point

Temperature range below 1235 K

- Comparison of *T* by relative primary radiometric thermometry is possible.
- Comparisons of fixed-point blackbodies are possible.

⇩

Same as comparisons of ITS-90 below silver point.

However,

- *T* measurements in non-contact thermometry by the absolute method below the silver point require further research.
- All NMIs are still disseminating T_{90}.
- A more meaningful comparison can be made after the new determination of T-T_{90} above 400 K.

⇩

We need further discussion in the WG-NCTh.

Summary

- *T* realization and dissemination is possible in all temperature ranges.
- Acceptance criteria for *T* dissemination have been added to the revised review protocol.
- Key comparisons of *T* above the silver point are possible.
- Key comparisons of *T* below the silver point need further discussion in the WG-NCTh.

Is the temperature range limited?

***MeP*-K-19**

4.2 Spectral-band radiometric thermometry (1235 K and above)

1. Introduction

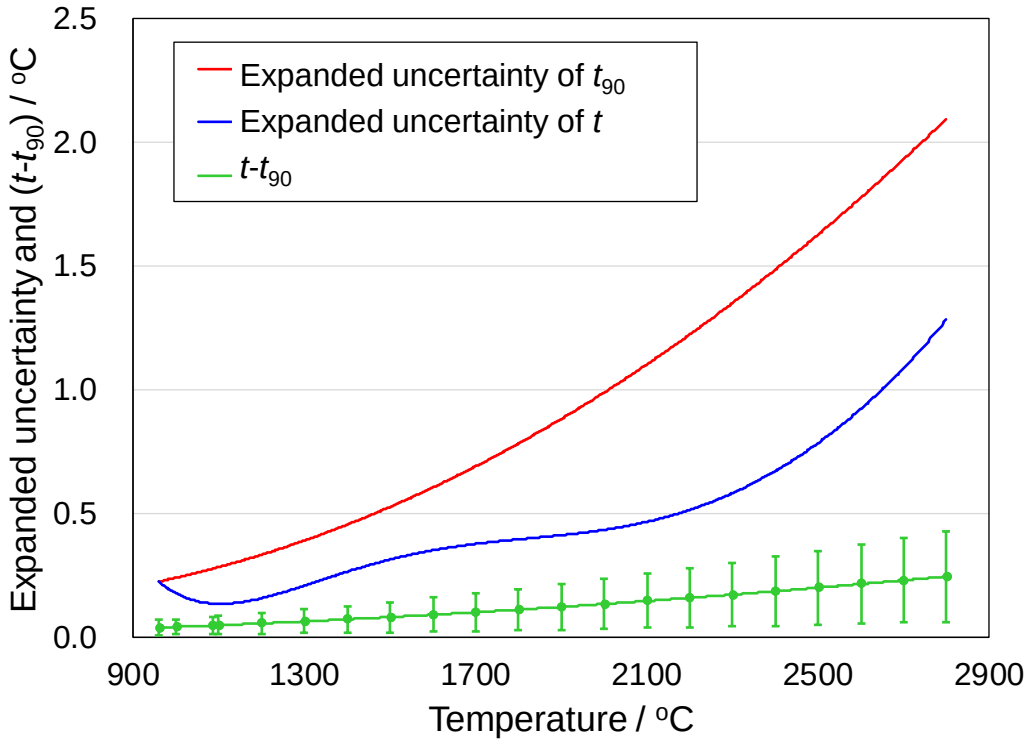
The definition of the kelvin of 2018 does not imply any particular experiment for its practical realization.
Any method capable of deriving a temperature value traceable to the set of seven reference constants can, in principle, be used.
Thus, the list of methods given is not meant to be an exhaustive list of all possibilities, but rather a list of those methods that are easiest to implement and/or that provide the smallest uncertainties and which are officially recognized as primary methods by the relevant Consultative Committee.

It would be preferable to

- Remove "1235 K and above" from section 4.2.
- Add the reference to “Estimates of the Differences T-T_{90}” and “Uncertainty budgets for calibration of radiation thermometers below the silver point” in Section 4.2.3.

New determinations of T-T_{90} above 400 K are important

	CCT-K10 t_{90} (°C)	*MeP*-K t (°C)	Δt (°C)
Ru-C	1952.99	1953.84	0.85
WC-C	2747.25	2747.70	0.45



Uncertainty of the dissemination of *T*

Comparison of NMIJ's ITS CMC and uncertainty of T-T_{90}

Fixed points	NMIJ's ITS CMC (mK)	T-T_{90}* (mK)	Uncertainty T-T_{90}* (mK)
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All uncertainties are expanded uncertainties (k = 2).
*Estimates of the differences T-T_{90}

Radiation Thermometry CMC Review Protocol

$$U_{\mathrm{NMI}\ T\ \mathrm{CMC}} \geq \sqrt{U^2_{\mathrm{NMI\ ITS\ CMC}} + U^2_{T-\mathrm{ITS}}}$$