Bureau
International des
Poids et
Mesures

CCT

CCT Technical Workshop on “Traceability and Dissemination”

16th May, 2024

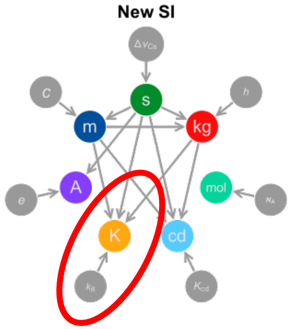
Perspectives for the dissemination of thermodynamic temperature in contact thermometry

Roberto Gavioso - INRiM

Outline Perspectives for the dissemination of thermodynamic temperature in contact thermometry

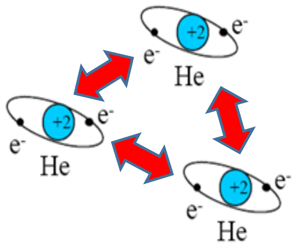
Definition of the kelvin

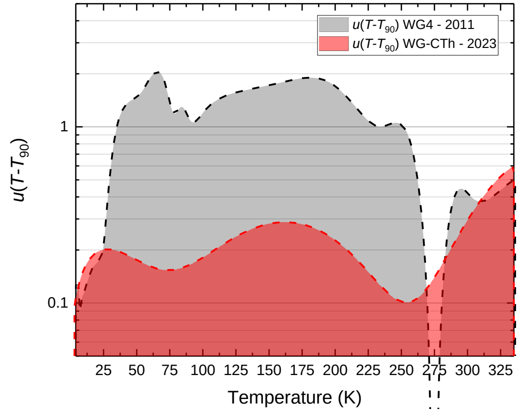
- motivations for the new definition
- consequences of the new definition



Primary Gas Thermometry

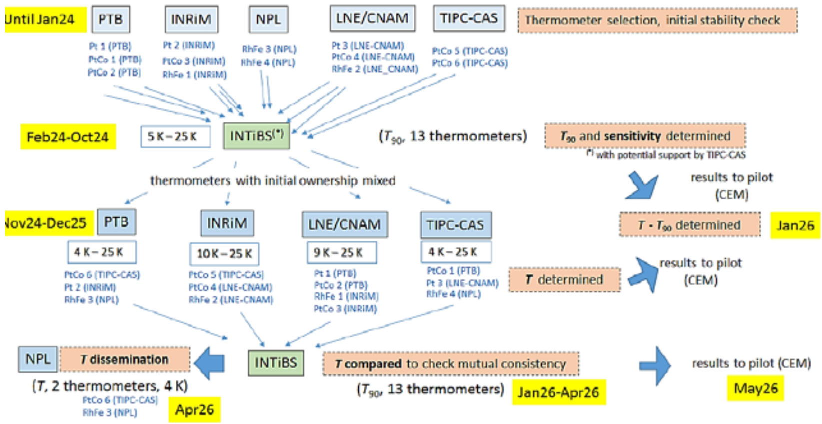
- recent progress of methods and related fields





Ready for dissemination?

- Dissemination in different ranges
- The DireK-T research project



Points for discussion

2019

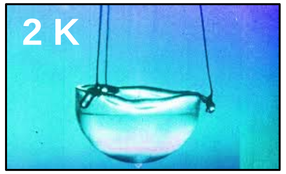
The new SI definition of the kelvin, based on an exact value of the Boltzmann constant, *k* comes into effect

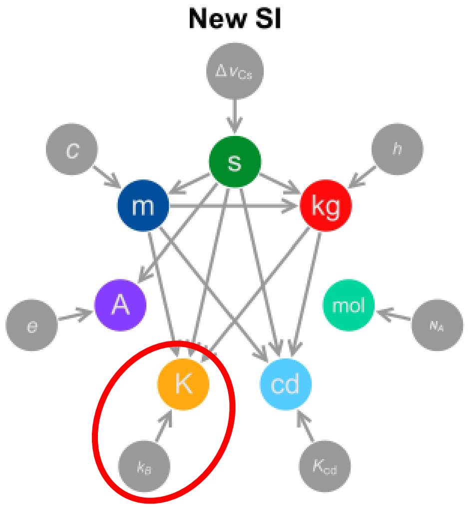
why change the old definition of the kelvin?

T_{TPW} = 273.16 K exactly

because it defines just one very special temperature

which obligates to compare any other temperature with T_{TPW} no matter how different (low or high) it is





also, because of the old definition of the kelvin, no temperature measurement can ever be made with lower uncertainty than the uncertainty with which T_{TPW} can be realised

also, because T_{TPW} = 273.16 K exactly was at the same time the definition of the unit and the recipe for the realization of the primary standard

a fixed exact value of the physical constant *k*

Uncertainty

Definition

a NEW

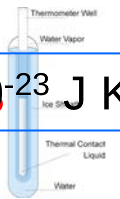
$k = 1.380649 \times 10^{-23}$ J K^{-1}

T_{TPW} = 273.16 K

everlasting?

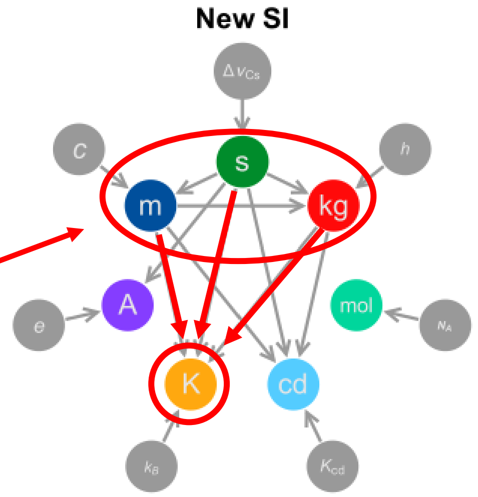
system

Realization



whatever we have (MeP)
whatever we may invent
in the future

consequences and implications of the new kelvin definition



primary thermometry - realization of standards

- T_{TPW} = 273.16 K loses its special status; to measure the temperature of an object, its thermal energy is no longer compared to the thermal energy of the TPW.
  Instead, the thermal energy of an object is now compared to the SI Joule, i.e. to the product $\Delta\nu_{Cs}\,h$
- If a primary thermometer will be significantly improved in the future, than both the value and the uncertainty of T_{TPW} (like that of any other T) may change. The new definition of the kelvin does not imply any intrinsic limitation on the minimum uncertainty which may futurely be achieved

practical thermometry - dissemination

- International Temperature Scales, will remain in use until primary methods will become just as accurate and practical. If and when this will happen, then ITS-90 will be abandoned and calibration may take place directly on the thermodynamic temperature scale
- particularly ITS-90 remains in use, nearly unvaried; it is still based on the same fixed points;
- calibration of thermometers, temperature traceability and dissemination remain practically unchanged

2019 – 2024
no change

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

Mise en pratique for the definition of the kelvin in the SI

Consultative Committee for Thermometry

Practical realization of the kelvin by primary thermometry

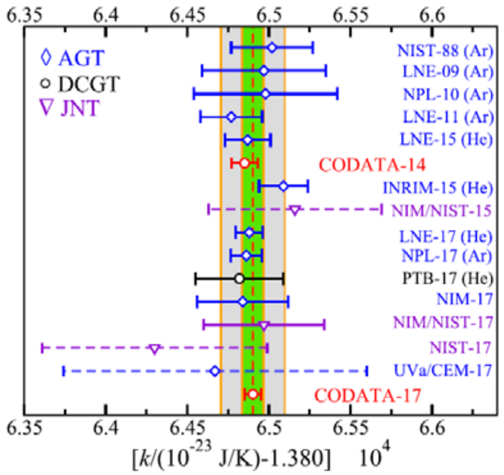
[..] In the future, as the primary methods evolve and are expected to achieve lower uncertainties, primary thermometers will become more widely used and gradually replace the ITS-90 and the PLTS-2000 as the basis of temperature measurement

progress?

2017

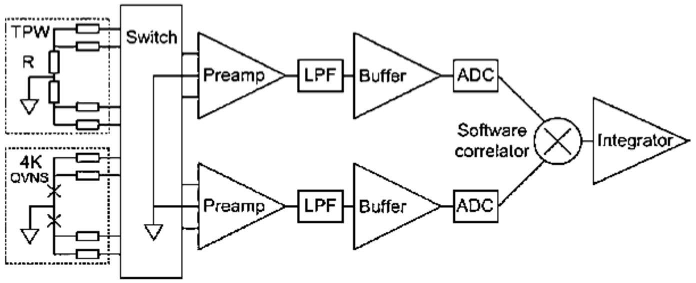
Primary thermometry methods basic relations to T

methods used for the determination of Boltzmann constant k



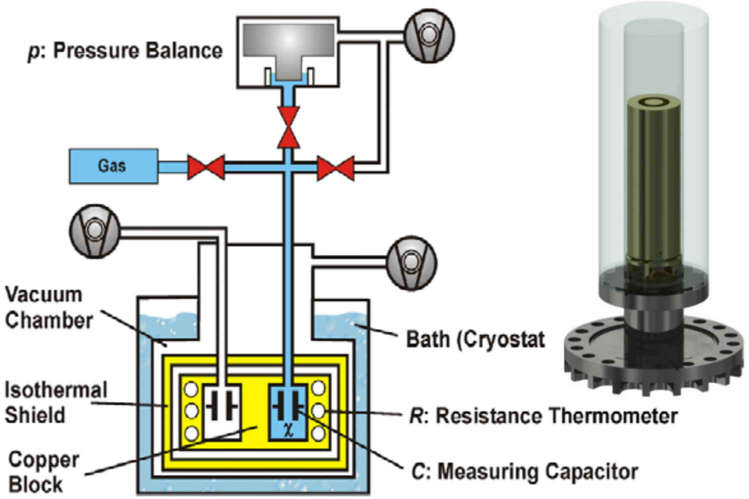
JNT

$$V_{\mathrm{rms}}^2 = 4kTR\Delta f$$



Johnson noise thermometry

Dielectric constant gas thermometry



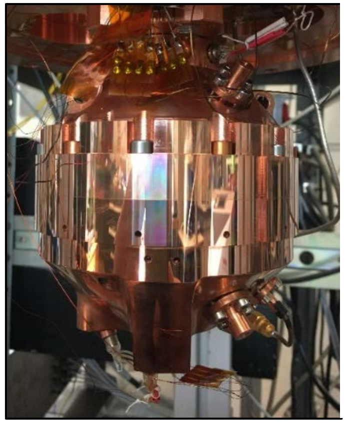
DCGT

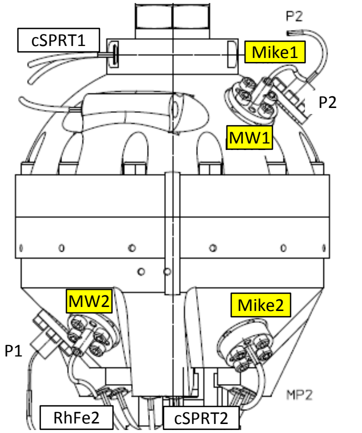
$$\frac{\varepsilon_{\mathrm{r}} - 1}{\varepsilon_{\mathrm{r}} + 2} = \frac{p}{RT} A_{\varepsilon}$$

$$\left[\frac{C(p) - C(0)}{C(0)}\right]_T = (\varepsilon_{\mathrm{r}} - 1) + \varepsilon_{\mathrm{r}} \kappa_{\mathrm{eff}}\, p$$

Acoustic gas thermometry

Refractive index gas thermometry





AGT ⟺ same apparatus ⟺ **RIGT**

$$u_0^{\,2} = \gamma_0 RT/M$$

$$\frac{n^2 - 1}{n^2 + 2} = \frac{p}{RT}\left(A_{\varepsilon} + A_{\mu}\right)$$

$$u_0 = c_0 \lim_{p \to 0}\left[\frac{f_{\mathrm{ac}}(p)}{\langle f_{\mathrm{mw}}(p)\rangle}\right]_T$$

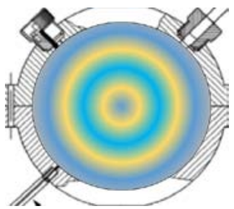
$$n = \left[\frac{\langle f_{\mathrm{mw}}(0)\rangle}{\langle f_{\mathrm{mw}}(p)\rangle (1 - \kappa_{\mathrm{eff}}\, p)}\right]_T$$

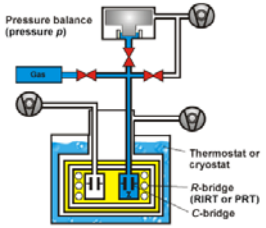
p pressure T temperature R gas constant M molar mass c_0 speed of light in vacuum
ε_{r} dielectric constant A_{ε}, A_{μ} molar electric, magnetic polarizabilities n refractive index
k_{eff} compressibility C capacitance f_{ac} $\langle f_{\mathrm{mw}}\rangle$ acoustic, microwave resonance frequencies

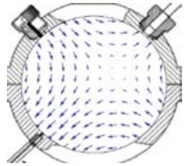
2017 - ongoing

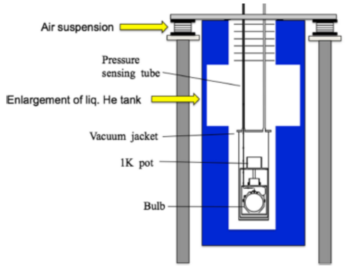
determination of $T - T_{90}$

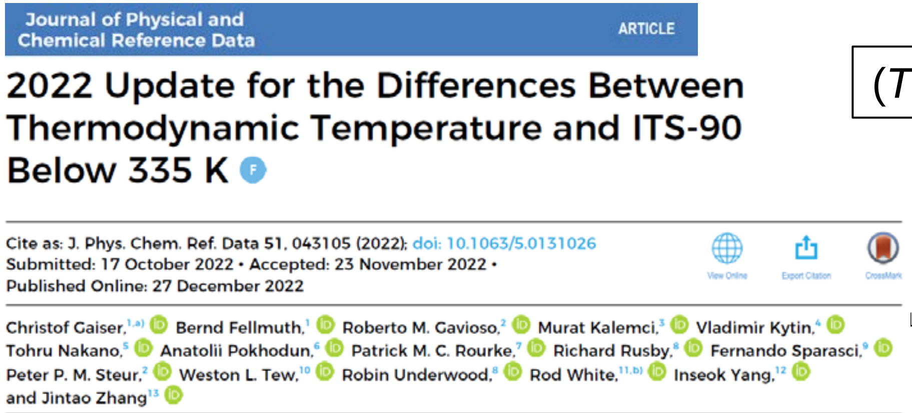
year	NMI	T range / K	$u(T-T_{90})$ / mK
AGT			
2017	NPL National Physical Laboratory	118 to 323	0.2 to 0.4
2019	INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA	236 to 430	0.25 to 0.9
2020	NIM	234 to 303	0.5 to 0.8
2020	VNIIFTRI	79 to 83	1.0
2020	NMIJ	283 to 303	0.7 to 0.8
2021	LNE IPC	**24.5**	0.25
DCGT			
2017	PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin	2.5 to 140	0.3 to 1.7
2020	PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin	50 to 200	0.3 to 1.6
2021	PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin	4 to 25	0.2 to 0.3
RIGT			
2020	NRC-CNRC Canada	25 to 161	0.5 to 1.7
2021	INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA	14 to 161	1.7 to 2.9
2021	IPC LNE	5 to 25	0.1 to 0.25
CVGT			
2017	NMIJ	3 to 25	0.6 to 1









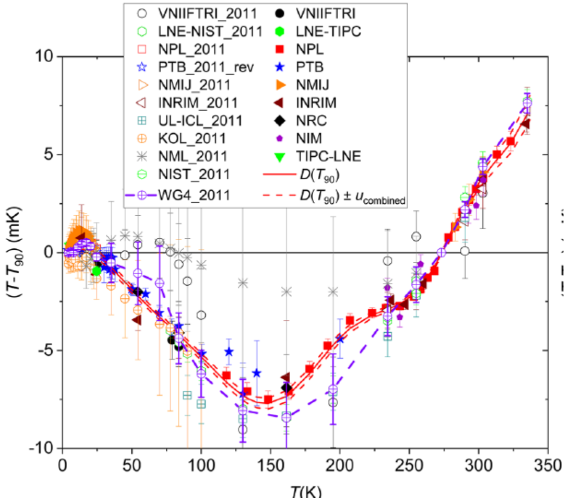


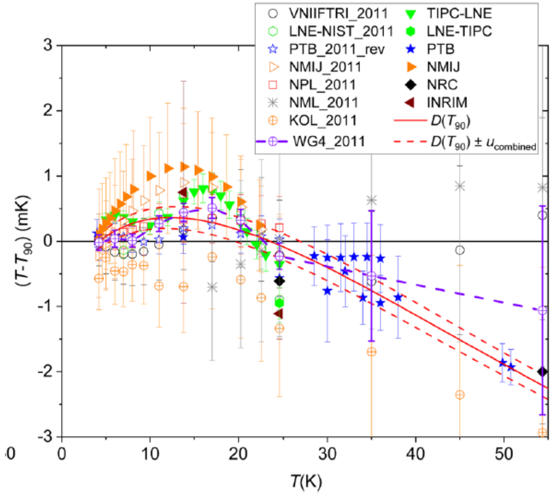
Journal of Physical and Chemical Reference Data ARTICLE

2022 Update for the Differences Between Thermodynamic Temperature and ITS-90 Below 335 K

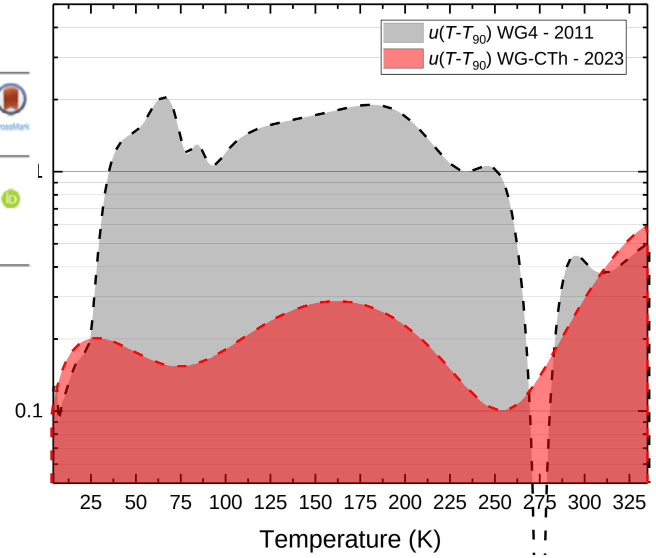
Cite as: J. Phys. Chem. Ref. Data 51, 043105 (2022); doi: 10.1063/5.0131026
Submitted: 17 October 2022 • Accepted: 23 November 2022 •
Published Online: 27 December 2022

Christof Gaiser,[1,a)] Bernd Fellmuth,[1] Roberto M. Gavioso,[2] Murat Kalemci,[3] Vladimir Kytin,[4] Tohru Nakano,[5] Anatolii Pokhodun,[6] Patrick M. C. Rourke,[7] Richard Rusby,[8] Fernando Sparasci,[9] Peter P. M. Steur,[2] Weston L. Tew,[10] Robin Underwood,[8] Rod White,[11,b)] Inseok Yang,[12] and Jintao Zhang[13]





$(T - T_{90})$ new consensus estimate



our current estimate of $(T-T_{90})$ is nearly one order more accurate than it used to be in 2011

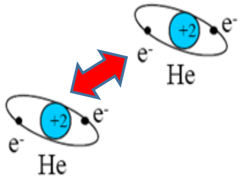
T ↔ T_{90}

results of calibration of thermometers by realizing T or ITS-90 are now intercheangable with low additional uncertainty

2019 - ongoing

remarkable progress of *ab initio* calculations of gas thermophysical and electromagnetic properties

UNIVERSITY OF WARSAW

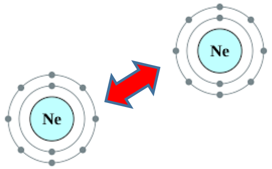


2 He Helium 4.003

improved **pair potential**

$B_\rho(T)$, $\beta_a(T)$
7.5x more accurate

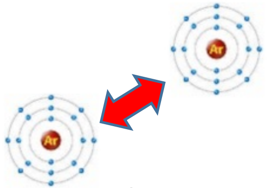
10 Ne Neon 20.180



HELMUT SCHMIDT UNIVERSITÄT

improved **pair potential**

$B_\rho(T)$, $b_\varepsilon(T)$, $\beta_a(T)$, $\lambda_0(T)$, $\eta_0(T)$
(5 to10)x more accurate



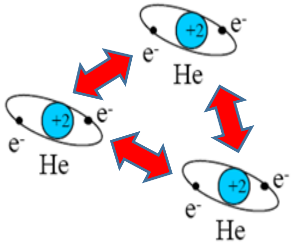
18 Ar Argon 39.948

UNIVERSITY OF WARSAW

improved **pair potential**

$B_\rho(T)$, $\beta_a(T)$, $\lambda_0(T)$, $\eta_0(T)$
expected 3x more accurate

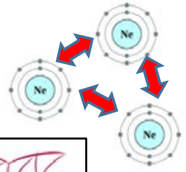
improved **3-body potential** $\phi\,(r,\theta)$



$C_\rho(T)$, $\gamma_a(T)$
(3 to5)x more accurate

UNIVERSITY OF WARSAW

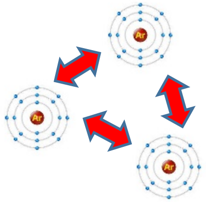
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS



HELMUT SCHMIDT UNIVERSITÄT

improved **3-body potential** $\phi\,(r,\theta)$

expected soon



UNIVERSITY OF WARSAW

important for all gas primary methods AGT, DCGT, RIGT, CVGT

also significantly improved **2nd and 3rd dielectric virials**

particularly important for DCGT, RIGT

2 He Helium 4.003 | 10 Ne Neon 20.180 | 18 Ar Argon 39.948

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

NIST

UNIVERSITY OF WARSAW

also significantly improved **electric polarizability & magnetic susceptibility**

2 He Helium 4.003 | 10 Ne Neon 20.180

HELMUT SCHMIDT UNIVERSITÄT

UNIVERSITY OF WARSAW

Real-K – Realising the redefined kelvin
Euramet project 2019 - 2023
coordinated by G. Machin NPL

methods of primary thermometry: **isotherm** vs **single state** measurements

example: acoustic gas thermometry (AGT)

$$u_0^2(T) = \gamma_0 kT/m$$

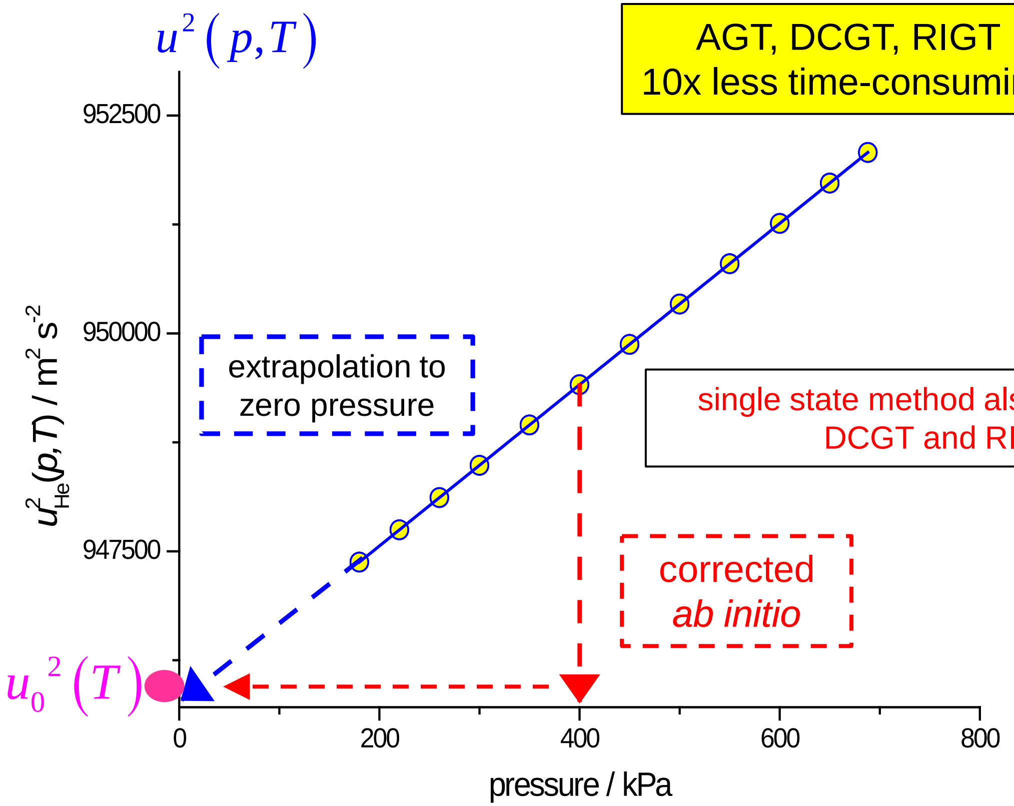
acoustic virial coeffs. $\beta_a(T)$, $\gamma_a(T)$, ..

$$u^2(p,T) = u_0^2(T)\left(1+\beta_a(T)\rho(p,T)+\gamma_a(T)\rho(p,T)^2+\dots\right)$$

$$p = \rho RT\left(1+B_\rho(T)\rho(p,T)+C_\rho(T)\rho(p,T)^2+D_\rho(T)\rho(p,T)^3+\dots\right)$$

R molar gas constant

density virial coeffs. $B_\rho(T)$, $C_\rho(T)$, ..



AGT, DCGT, RIGT
10x less time-consuming

single state method also applies to DCGT and RIGT

Facilitations from improved ab initio calculation

measuring with gases other than He

AGT, DCGT, RIGT
(10 to100) x less sensitive to contamination

particularly important for AGT at high *T*

Table 2. Sensitivity of u^2 to impurities (Moldover *et al* 1988).

Impurity	M/ (g mol^{-1})	γ_0	D^a in He	D^a in Ar
H_2	2	1.4^a	0.23	0.68
He	4	5/3		0.9
H_2O	18	1.32^a	−3.93	0.12
Ne	20	5/3	−4.0	0.5
N_2	28	1.4^a	−6.27	0.03
O_2	32	1.4^a	−7.3	−0.07
Ar	40	5/3	−9.0	
CO_2	44	1.4^a	−10.3	−0.37
Kr	84	5/3	−20.0	−1.1
Xe	131	5/3	−31.8	−2.3

[a] Values at 273 K. For polyatomic gases, D and γ_0 are temperature-dependent. $D \equiv (1/u^2)(\mathrm{d}u^2/\mathrm{d}x)$

DCGT, RIGT
Ne 2x more polarizable than He
Ar 4x more polarizable than Ne
DCGT and RIGT become more sensitive at lower pressures

methods of primary thermometry:
absolute vs **relative**

example: acoustic gas thermometry (AGT)

absolute AGT

used for determination of k

$$T = \frac{m}{\gamma_0 k} u_0^2$$

T thermodynamic temperature
k Boltzmann constant
u_0^2 speed of sound at zero pressure
m atomic mass
γ_0 ideal gas heat capacity ratio

relative AGT

used for determination of $T - T_{90}$

$$T = T_{\mathrm{ref}} \frac{u_0^2(T)}{u_0^2(T_{\mathrm{ref}})}$$

T_{ref} reference thermodynamic temperature

various *flavours* of **relative** measurements

example: refractive index gas thermometry (RIGT)

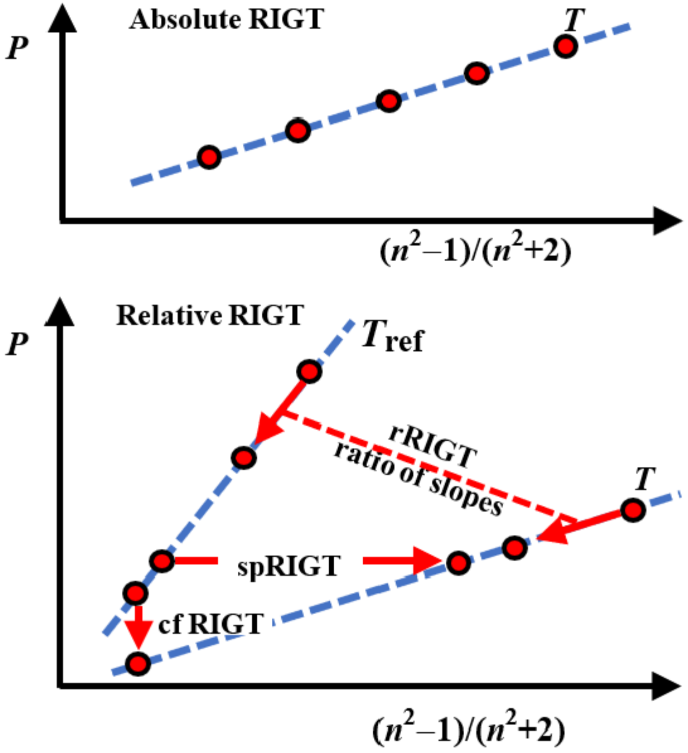


FIG. 4. Measurement trajectories for RIGT in the variables pressure (p) and refractive index (n). Blue dashed lines represent isotherms. Top: Absolute RIGT takes many data points on an isotherm at the unknown temperature T. Bottom: Relative rRIGT takes several measurements on a reference isotherm T_{ref} and on an unknown isotherm T. Single pressure (spRIGT) uses data at one pressure. Constant frequency (cfRIGT) uses data at one value of the refractive index n.

relative RIGT by isotherm ratio

$$\frac{T}{T_{\mathrm{ref}}} = \lim_{p\to 0}\left(\frac{n^2(p,T)-1}{n^2(p,T_{\mathrm{ref}})-1}\right)$$

drastically reduces accuracy requirement on compressibility determination

single pressure p_x **sp**RIGT

$$\frac{T}{T_{\mathrm{ref}}} \approx \left(\frac{n^2(p_x,T)-1}{n^2(p_x,T_{\mathrm{ref}})-1}\right)$$

drastically reduces accuracy requirement on pressure measurement

single refractive index-frequency f_x **cf**RIGT

$$\frac{T}{T_{\mathrm{ref}}} \approx \left(\frac{p(T,n_x)-1}{p(T_{\mathrm{ref}},n_x)-1}\right)$$

eliminates frequency dependent errors

all these methods also apply to DCGT

Are we ready for dissemination of *T* as an alternative to ITS-90?

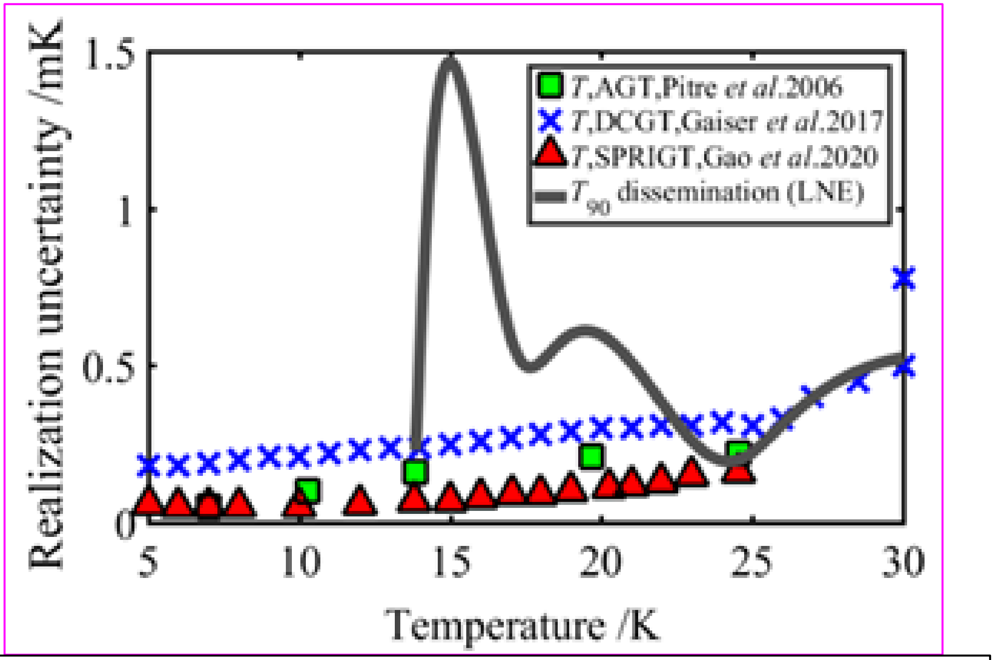
Below 25 K

difficulties in the realization of T_{90}

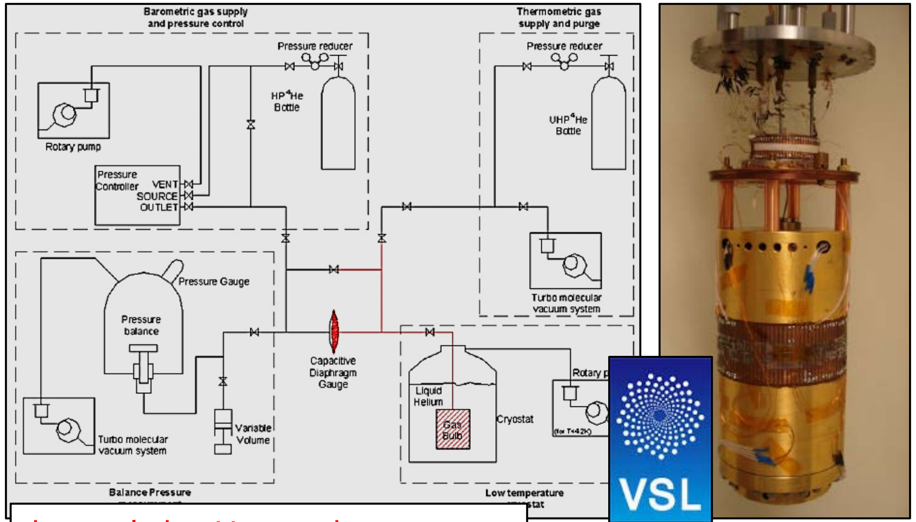
Complex situation with different technical approaches overlapping in ranges

- 0.65 K to 5 K ^{3}He, ^{4}He vapour pressure thermometry;
- 3 K to ~24.6 K interpolating He gas thermometer;
- above ~13.8 K fixed-points and capsule SPRTs.

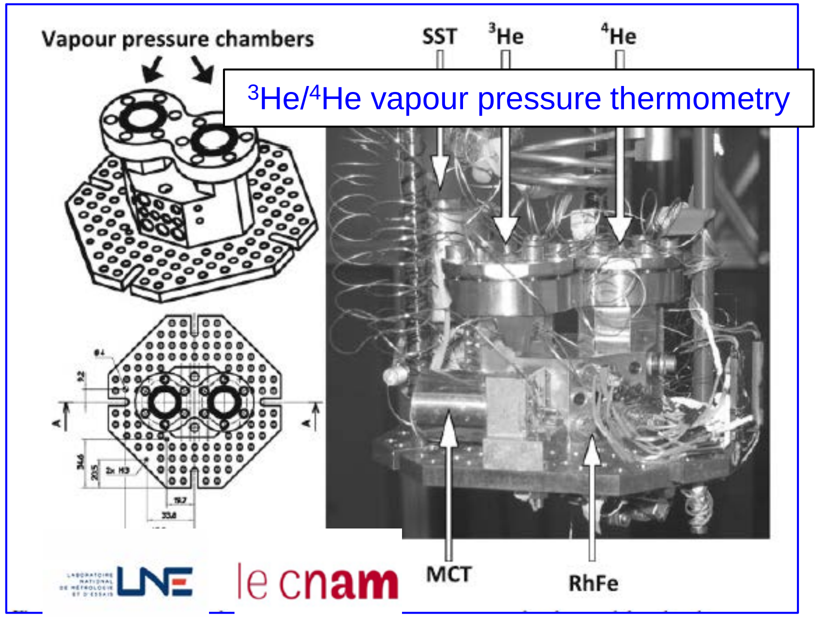
Because of the complexity there are very few full ITS-90 realisations globally in this temperature range. Also, temperature sensors used in this range, for instance to disseminate a wire-scale are increasingly more difficult to retrieve



2022 uncertainties of realizations of *T* (AGT, DCGT, RIGT) and T_{90} between 13.8 K and 25 K



interpolating He gas thermometer

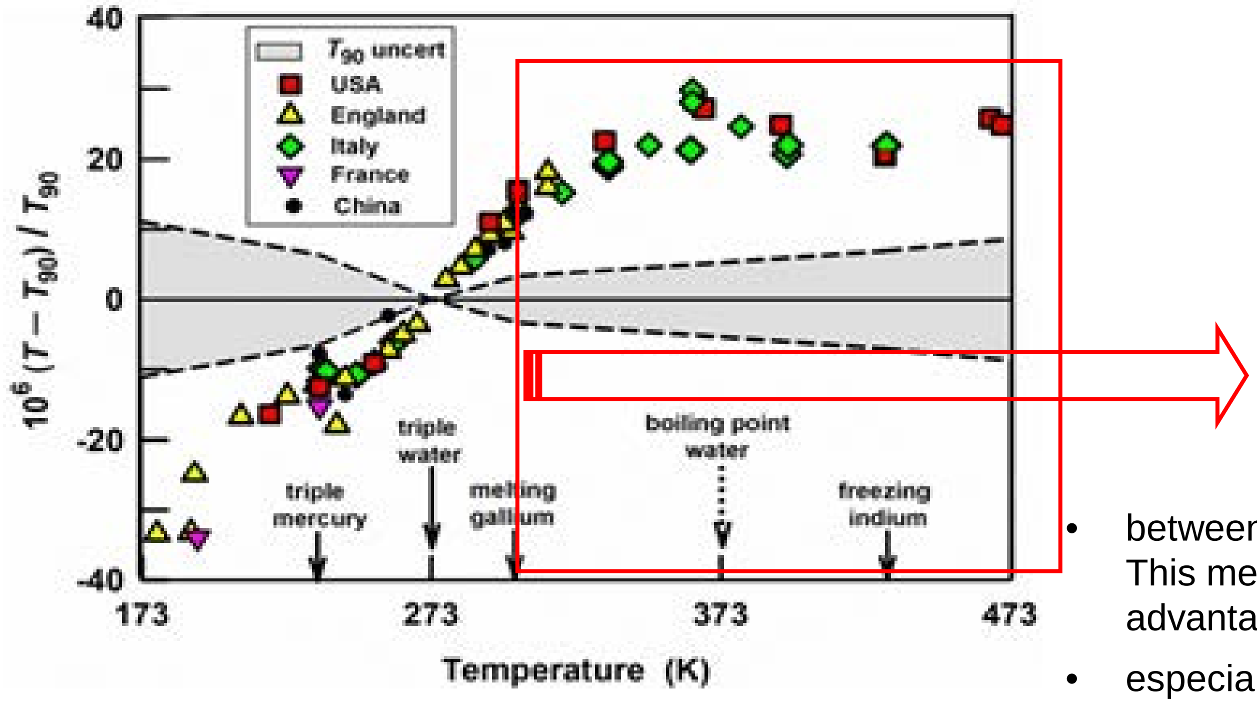


^{3}He/^{4}He vapour pressure thermometry

Are we ready for dissemination of *T* as an alternative to ITS-90?

relative primary thermometry

between 25 K and 303 K



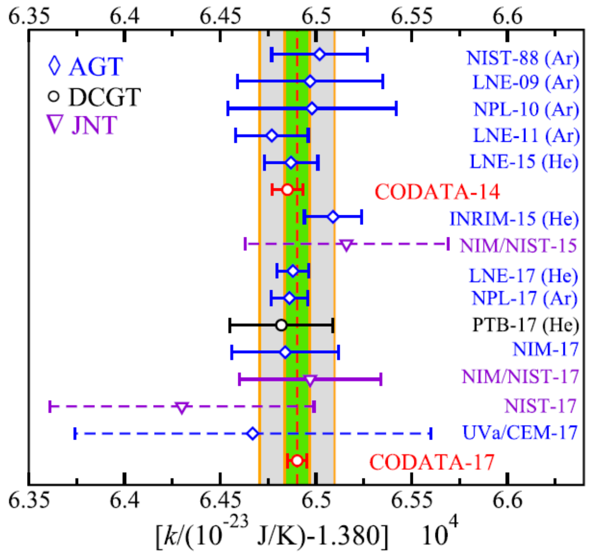
above 303 K up to?

determination of T-T_{90} differences

at 273.16 K

absolute
primary thermometry

$$\text{best } u(T) = 0.6 \text{ ppm}$$



Boltzmann constant k

- between 25 K and 303 K, relative primary thermometry still usually refers to T_{TPW}. This method leads to more accurate determinations but it does not fully exploit the advantages inherent in the new definition;
- especially below 120 K, most determinations of *T* were taken at fixed points, while it is in the intervals where non-uniqueness uncertainty contributions prevail that measuring *T* instead of T_{90} may represent a significant advantage
- successive determinations of *k* and $T - T_{90}$ were both inevitably biased by previous results. These comparisons were not as meaningful and challenging as a blind comparison
- above the Ga point and only up to 500 K, very few determinations of $T - T_{90}$ were obtained over the last 25 years; it would be interesting to develop thermodynamic standards up to at least the Zn or Al point to overlap to the range where radiometric primary thermometers come into play

European Partnership on Metrology
Call 2022 – Digital Transformation, Health, Integrated European Metrology, Normative and Research Potential

Dissemination of the redefined kelvin (DireK-T) research project

project proposal & successful presentation to review conference: **G. Machin**

coordination **R. Gavioso**

approved for funding in December 2022
started in September 2023
duration 3 years

Main Technical objectives

- **WP1** - **Thermodynamic temperature realisation** and **dissemination** in the range **4 K** to **25 K** using thermodynamic methods (AGT, DCGT, RIGT) to NMIs without primary thermometry capabilities **using temperature sensors as transfer standards** with a **target uncertainty in the dissemination of 0.3 mK** ($k = 1$).
- **WP2 - Thermodynamic temperature realisation** and **dissemination** in the range **25 K** to **300 K** using thermodynamic methods (AGT, DCGT) to NMIs without primary thermometry capabilities **using temperature sensors** as **transfer standards** with a **target uncertainty in the temperature dissemination of 0.25 mK at 25 K and 0.6 mK at 300 K** ($k = 1$).
- **WP3 -** To develop a coherent framework for **thermodynamic temperature dissemination (**i.e. a **protocol)** to **ensure consistency of the dissemination of temperature** from NMIs to users over the temperature range **4 K to 300 K whether it is by thermodynamic temperature *T* or the defined scale (ITS-90)** and **to develop a recommendation to CCT about the measurement uncertainties and the level of equivalence between these approaches**.
- **WP4 -** To **establish** an **initial capability** for the **realisation** and dissemination **of thermodynamic temperature between 300 K** and at least **700 K** with T-T_{90} **target uncertainty of 0.6 mK at 300 K and 7 mK at 700 K** ($k = 1$).

Project consortium

no.	Participant Type	Short Name	Organisation legal full name	Country
1	Internal Beneficiary	INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
2	Internal Beneficiary	CEM	Centro Español de Metrología	Spain
3	Internal Beneficiary	CMI	Cesky Metrologicky Institut	Czechia
4	Internal Beneficiary	CNAM	Conservatoire national des arts et métiers	France
5	Internal Beneficiary	INTiBS	Instytut Niskich Temperatur i Badan Strukturalnych im. Wlodzimierza Trzebiatowskiego Polskiej Akademii Nauk	Poland
6	Internal Beneficiary	LNE	Laboratoire national de métrologie et d'essais	France
7	Internal Beneficiary	PTB	Physikalisch-Technische Bundesanstalt	Germany
8	Internal Beneficiary	SMD	Federale Overheidsdienst Economie, KMO, Middenstand en Energie	Belgium
9	Internal Beneficiary	TUBITAK	Turkiye Bilimsel ve Teknolojik Arastirma Kurumu	Turkey
10	Internal Beneficiary	UL	Univerza v Ljubljani	Slovenia
11	External Beneficiary	NPL	NPL Management Limited	United Kingdom
12	Unfunded Beneficiary	ITRI	Industrial Technology Research Institute Incorporated	Taiwan, Province of China
13	Unfunded Beneficiary	NIM	National Institute of Metrology - NIM	China
14	Unfunded Beneficiary	TIPC-CAS	Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences	China

Financial budget

	Total
Labour (€)	1 681 765.48
Subcontracts (€)	
T&S (€)	155 795.00
Equipment (€)	18 616.00
Other Goods, Works and Services (€)	433 916.00
Internally Invoiced Goods and Services (€)	
Indirect (€)	572 523.12
Total costs (€)	2 862 615.60
Costs as % of Total costs	
Total Eligible Costs (€)	2 862 615.60
EU contribution (€)	2 065 740.60
EU contribution as % of total EU contribution	
Months	358.8

coordination

WP leaders

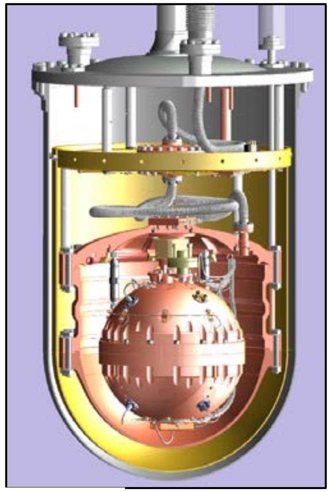
partners

collaborating partners

WP1: Practical thermodynamic temperature dissemination between 4 K and 25 K

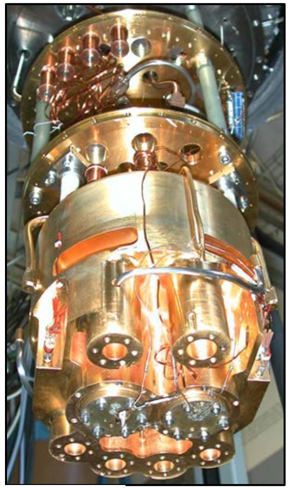
- Dissemination of thermodynamic temperature T in range 4 - 25 K; target $u(k=1)$ 0.3 mK
- Three mise en pratique for the definition of the kelvin (*MeP*-K-19) approaches (AGT, DCGT and RIGT) used to minimise systematic uncertainty
- New values of T-T_{90} in range
- Assessment of stability and sensitivity of different kinds of temperature sensors

measurement of T



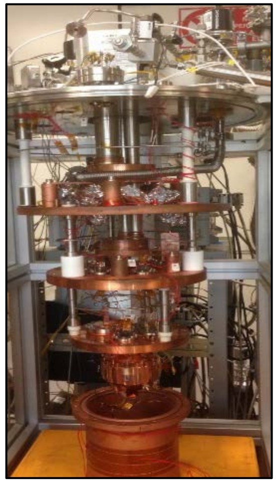
AGT

LNE
Le progrès, une passion à partager

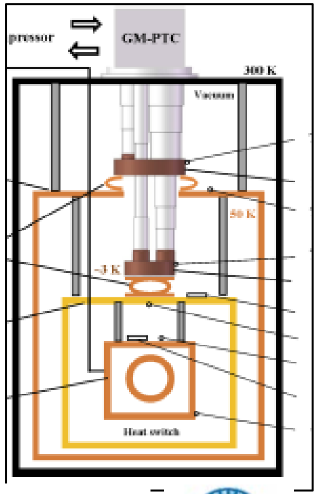


DCGT

PTB

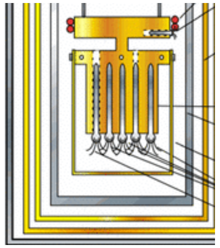


INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA



RIGT + AGT

IPC



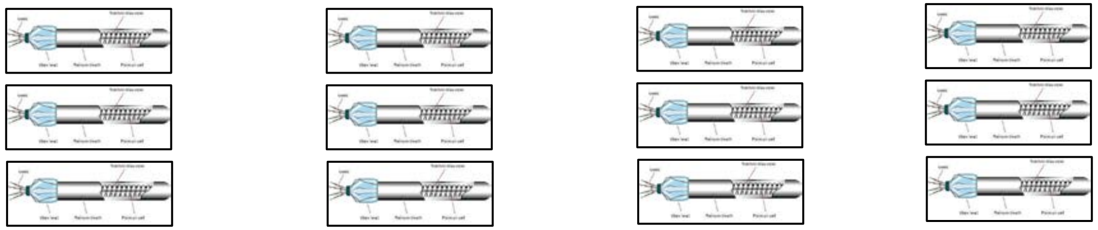
measurement of T_{90}

INTiBS PAN
WROCŁAW

comparison of T

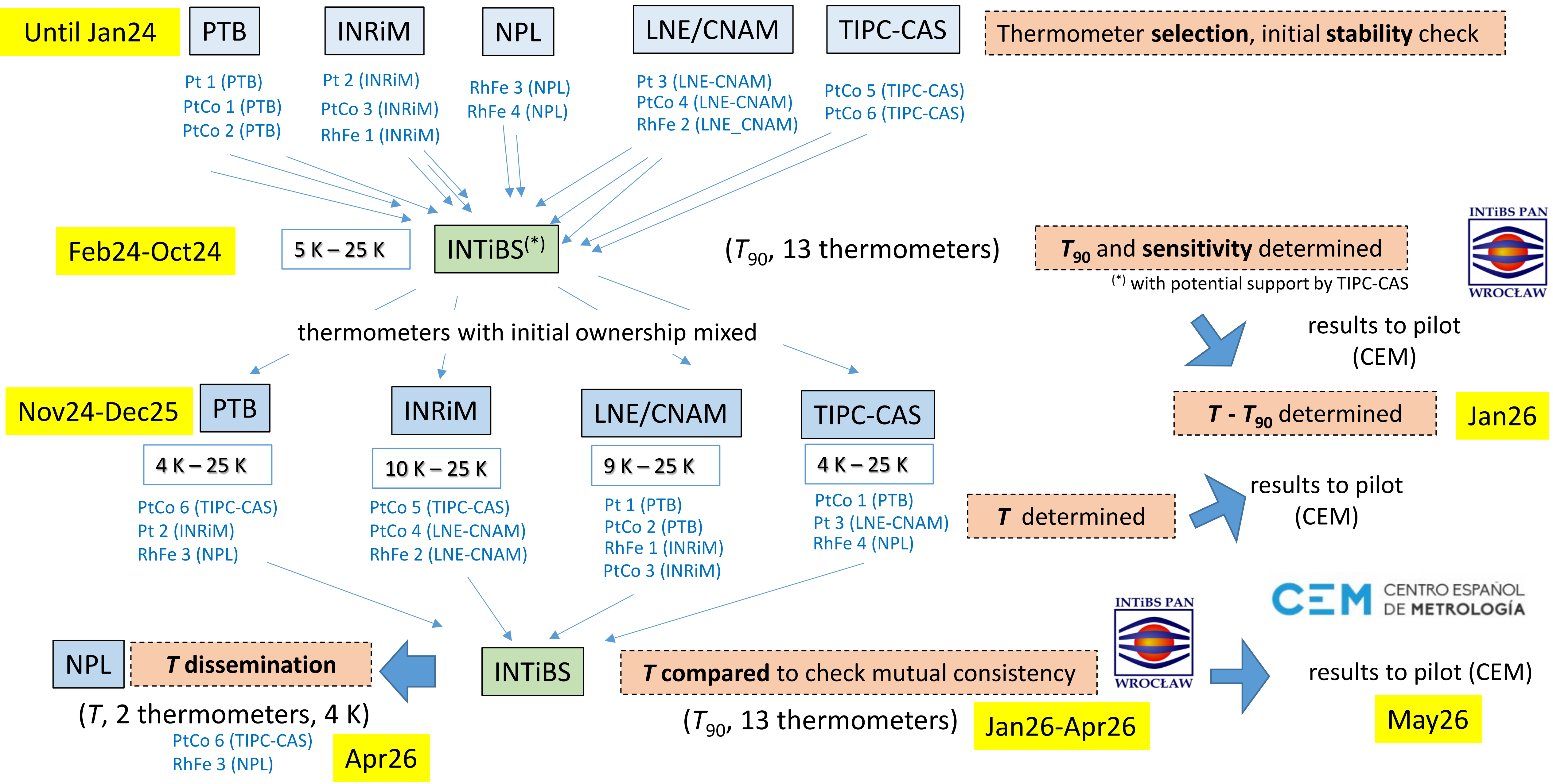
to **pilot**

CEM
CENTRO ESPAÑOL DE METROLOGÍA



13 transfer standards **RhFe**, **Pt-Co** and **Pt** capsule thermometers

WP1 workflow 4 K to 25 K Rh-Fe, Pt-Co, Pt sensors



Until Jan24

PTB

INRiM

NPL

LNE/CNAM

TIPC-CAS

Thermometer **selection**, initial **stability** check

Pt 1 (PTB)
PtCo 1 (PTB)
PtCo 2 (PTB)

Pt 2 (INRiM)
PtCo 3 (INRiM)
RhFe 1 (INRiM)

RhFe 3 (NPL)
RhFe 4 (NPL)

Pt 3 (LNE-CNAM)
PtCo 4 (LNE-CNAM)
RhFe 2 (LNE_CNAM)

PtCo 5 (TIPC-CAS)
PtCo 6 (TIPC-CAS)

Feb24-Oct24

5 K – 25 K

INTiBS(*)

(T_{90}, 13 thermometers)

***T_{90}* and sensitivity determined**

(*) with potential support by TIPC-CAS

thermometers with initial ownership mixed

results to pilot
(CEM)

Nov24-Dec25

PTB

4 K – 25 K

PtCo 6 (TIPC-CAS)
Pt 2 (INRiM)
RhFe 3 (NPL)

INRiM

10 K – 25 K

PtCo 5 (TIPC-CAS)
PtCo 4 (LNE-CNAM)
RhFe 2 (LNE-CNAM)

LNE/CNAM

9 K – 25 K

Pt 1 (PTB)
PtCo 2 (PTB)
RhFe 1 (INRiM)
PtCo 3 (INRiM)

TIPC-CAS

4 K – 25 K

PtCo 1 (PTB)
Pt 3 (LNE-CNAM)
RhFe 4 (NPL)

***$T - T_{90}$* determined**

Jan26

***T* determined**

results to pilot
(CEM)

NPL

***T* dissemination**

(T, 2 thermometers, 4 K)

PtCo 6 (TIPC-CAS)
RhFe 3 (NPL)

Apr26

INTiBS

***T* compared** to check mutual consistency

(T_{90}, 13 thermometers)

Jan26-Apr26

results to pilot (CEM)

May26

WP2 workflow 25 K to 303 K

all thermometers are cSPRTs (Pt)

INTiBS
25 K – TPW
Pt 1 (PTB)
Pt 2 (INRiM)

same used in WP1 from PTB and INRiM

CEM
83 K – 303 K
Pt 4 (CEM)
Pt 5 (CEM)

INRiM
83 K – 303 K
Pt 6 (INRiM)
Pt 7 (INRiM)

UL
83 K – 303 K
Pt 8 (UL)
Pt 9 (UL)

CMI
83 K – 303 K
Pt 10 (CMI)
Pt 11 (CMI)

SMD
83 K – 303 K
Pt 12 (SMD)
Pt 13 (SMD)

Until Aug24

Thermometer selection and T_{90} **determined**

(T_{90}, 12 thermometers)

results to pilot (CEM)

$T - T_{90}$ **determined**

Jan26

results to pilot (CEM)

Nov24-Dec25

INRiM
25 K – 161 K
Pt 1 (PTB)
Pt 4 (CEM)

PTB
25 K; 70 K – 100 K
Pt 2 (INRiM)
Pt 7 (INRiM)

LNE/CNAM
83 K – 303 K
Pt 5 (CEM)
Pt 8 (UL)
Pt 10 (CMI)
Pt 12 (SMD)

NPL
83 K – 303 K
Pt 6 (INRiM)
Pt 9 (UL)
Pt 11 (CMI)
Pt 13 (SMD)

KRISS
173 K – 303 K
Pt 14 (KRISS)

NRC
25 K – TPW
Pt 15 (NRC)
Pt 16 (NRC)

TIPC-CAS
25 K – 83 K
Pt 17 (TIPC-CAS)

T determined

INTiBS range 25 K – 83 K

(4 thermometers)
Pt 1 (PTB)
Pt 2 (INRiM)
Pt 17 (TIPC-CAS)
Pt 15 (NRC)

Jan26-Apr26

UL Range 83 K – 303 K

(12 thermometers)
CEM, INRiM, UL, CMI, SMD, KRISS, 1 NRC

***T* compared** to check m

ay26

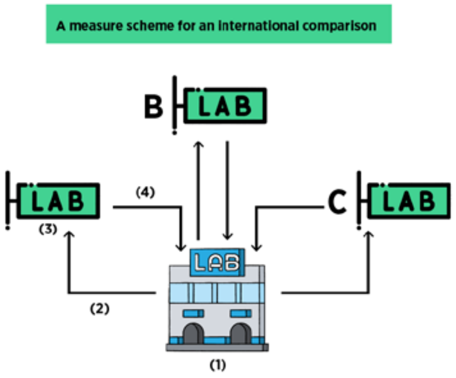
results to

developing AGT capabilities ($T - T_{90}$) Hg to Ga

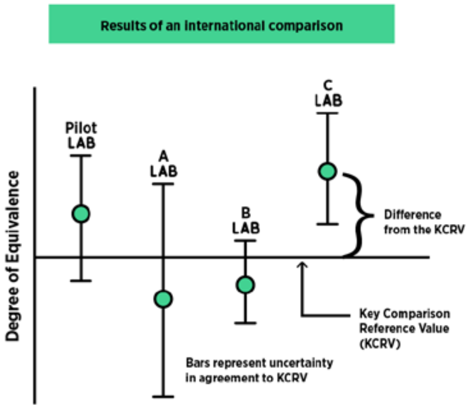
WP3 – piloting the comparison

CEM CENTRO ESPAÑOL DE METROLOGÍA

CEM has a well demonstrated previous experience in participating and/or piloting key comparisons in thermometry: e.g. EURAMET.T-K9, CCT-K10, CCT-K7.2021, SIM.T-K9.1 (pilot) and EURAMET.T-S3 (pilot).



(1) Pilot of lead laboratory measures multiple sets of comparison standards.
(2) Pilot lab sends a test of standards to each participating lab.
(3) Each lab measures their set and returns it to the pilot.
(4) Pilot lab remeasures all sets



- First ever framework to ensure consistent dissemination of temperature (whether by thermodynamic temperature T or defined scale (ITS-90)
- First ever documented level of equivalence for dissemination and traceability between T and T_{90}
- Recommendation report to CCT on how to realise and disseminate T in range, and proposals for future revision of the MeP-K-19

1) The first main expected outcome of the comparison is the determination of the differences $T-T_{90}$.

$$(T_{90,\mathrm{i,INTiBS}},\ R(T_{90,\mathrm{i,INTiBS}}))$$

$$(T_{\mathrm{i,NMI}},\ R(T_{\mathrm{i,NMI}}))$$

1A) Based on the calibration equation

$$T_{\mathrm{i,NMI}} - T_{90}(R(T_{\mathrm{i,NMI}}))$$

1B) Based on the sensitivity coefficient

$$s_i = \mathrm{d}R(T_{90})/\mathrm{d}T_{90} \sim \mathrm{d}R(T)/\mathrm{d}T$$

$$T - T_{90} = T_{\mathrm{i,NMI}} - [T_{90,\mathrm{i,INTiBS}} + (R_{i,\mathrm{NMI}} - R_{i,\mathrm{INTiBS}}) / s_i]$$

2) The second expected outcome of the comparison is the determination of the differences ($T_{NMI1} - T_{NMI2}$) between the thermodynamic calibrations from different primary experiments.

2A) Based on the calibration equation

$$\begin{aligned} T_{1,\mathrm{PTB}} - T_{2,\mathrm{LNE}} = {} & [(T_{1,\mathrm{PTB}} - T_{90,1,\mathrm{INTIBS}})_{T_{\mathrm{PTB}}} - (T_{2,\mathrm{LNE}} - T_{90,2,\mathrm{INTIBS}})_{T_{\mathrm{LNE}}}] \\ & + [(T - T_{90})_{T_{\mathrm{PTB}}} - (T - T_{90})_{T_{\mathrm{LNE}}}] \end{aligned}$$

2B) Based on the sensitivity

$$T_{\mathrm{PTB}}\ ,\ R_{1,\mathrm{PTB}}(T_{\mathrm{PTB}}) = R_{1,\mathrm{PTB}} \qquad R_{1,\mathrm{INTIBS}}(T_{\mathrm{INTIBS}}) = R_{1,\mathrm{INTIBS}}$$

$$T_{\mathrm{LNE}}\ ,\ R_{2,\mathrm{LNE}}(T_{\mathrm{LNE}}) = R_{2,\mathrm{LNE}} \qquad R_{2,\mathrm{INTIBS}}(T_{\mathrm{INTIBS}}) = R_{2,\mathrm{INTIBS}}$$

$$T_{\mathrm{INTIBS\_PTB}} = T_{\mathrm{PTB}} + (R_{1,\mathrm{INTIBS}} - R_{1,\mathrm{PTB}})/s_1$$

$$T_{\mathrm{INTIBS\_LNE}} = T_{\mathrm{LNE}} + (R_{2,\mathrm{INTIBS}} - R_{2,\mathrm{LNE}})/s_2$$

The weighted average $< T_{\mathrm{INTIBS\_PTB}}, T_{\mathrm{INTIBS\_LNE}}, \ldots >$ will be calculated and named $<T_{\mathrm{INTIBS}}>$ and the differences $T_{\mathrm{INTIBS\_NMI}} - <T_{\mathrm{INTIBS}}>$ evaluated for each NMI.

WP4 – Establishing primary thermometry capability from 300 K to 700 K

- New primary thermometry capability (AGT) for the realisation and dissemination of thermodynamic temperature T in range 300 - 700 K with target uncertainties $u(k=1)$ 0.6 mK at 300 K; 7 mK at 700 K
- New values of $T - T_{90}$ in range as required by CCT recommendation T1 2021

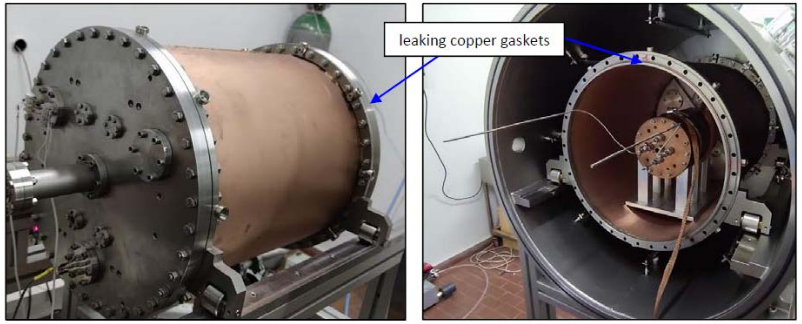
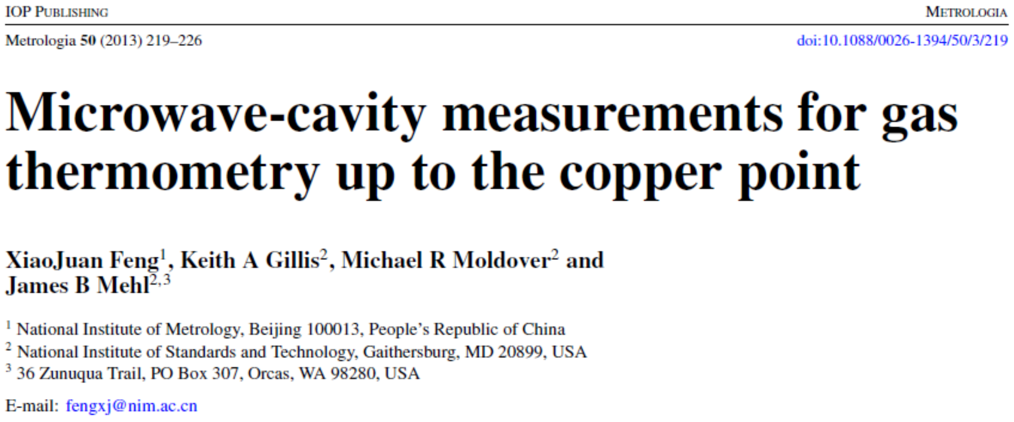


Figure 8 – Experimental gas-tight vessel comprised by a cylindrical copper body (400 mm diameter, 450 mm length) welded to stainless steel head flanges. The vessel is rated for operation up to 1 MPa at 900 K.

300 K to 700 K

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA



IOP Publishing | Metrologia

Metrologia **50** (2013) 219–226 | doi:10.1088/0026-1394/50/3/219

Microwave-cavity measurements for gas thermometry up to the copper point

XiaoJuan Feng[1], Keith A Gillis[2], Michael R Moldover[2] and James B Mehl[2,3]

[1] National Institute of Metrology, Beijing 100013, People's Republic of China
[2] National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
[3] 36 Zunuqua Trail, PO Box 307, Orcas, WA 98280, USA

E-mail: fengxj@nim.ac.cn

350 K to 700 K

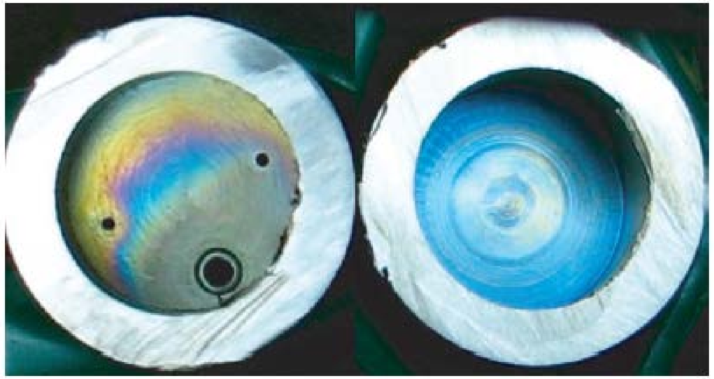


Figure 3. Small test cavity after exposure to 45 mol of argon for 15 h at temperatures ranging from 870 K to 1270 K. The argon entered through the 2.2 mm ID tube at the left and exited through the two 1.0 mm diameter ports that led to the coaxial cables.

NPL
National Physical Laboratory

323 K to 505 K

ITRI
Industrial Technology
Research Institute

300 K to 573 K

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

WP5 – Dissemination and impact (communication)

economie

SPF Economie, P.M.E., Classes moyennes et Energie

FPS Economy, DG Quality and Safety, *Metrology* Division (SMD)

Dissemination

- Reports and Recommendation submitted to CCT (particularly about equivalence of T and T_{90} and respective uncertainties)
- Scientific papers (at least 15) all Open Access
- Complete scientific Data in Open Repositories
- Presentation at International Conferences (at least 20); dedicated session at Tempmeko 2025
- Article in Trade Journals
- Training Activities including secondment and staff exchanges open to partners from outside the project

Communication

- Maintenance of project website and curation of newsletter to stakeholders (currently 45, more welcome)
- Organization of Royal Society Theo Murphy meeting: "The redefined kelvin – progress and prospects" (February 2025)
- Summer School "Contemporary issues in primary thermometry" under the auspices of the Spanish Academy of Science in Summer 2026

Exploitation

- Input to future revision of the MeP-K mise en pratique for the definition of the kelvin
- Dissemination of thermodynamic wire scales
- Extension of Certified Measurement Capabilities (CMCs) across a network of NMIs

Concluding Remarks and Points for Discussion

We expect that **the scientific activities in this project will**

- make **thermodynamic** temperature **standards more widely diffuse**:
  - realized and available at an increasing number of NMIs;
  - used for wire-scale dissemination of T to NMIs without primary thermometry capabilities (or in the course of developing them);
  - become more practical (more robust, simple, easy to operate, designed for long stem SPRTs at least above the Ar point
- **favour a mixed framework for the dissemination of the kelvin** where:
  - both T & T_{90} dissemination would be accepted, interchangebale, and their degree of equivalence and respective uncertainty is firmly assessed
- **lead to new CMCs** with calibration capabilities which can be tailored to customers' requirements

Critical points

- the project is very ambitious with a tight schedule to deliver all the targeted objectives;
- a blind comparison of thermodynamic temperatures has never been attempted; reported results will most certainly show some inconsistencies, like it previously happened for some reported determinations of *k.* These issues, when correctly identified, will still be welcome as they may speed up improvements and simplifications of the methods
- most activities rely on the performance of the sensors used as transfer standards, which suffer their intrinsic limitations, e.g. in terms of fragility, poor availability and, for specific models in specific ranges, complicated sensitivity functions.