
CCT-K9.3

Realizations of the ITS-90 from 83.805 8 K to 692.677 K

KEY COMPARISON

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Final Report

CCT-K9.3

ITS-90 SPRT calibration from the Ar TP to the Zn FP

September 2026

(version 1)

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1. Acknowledgements

This comparison is based on EURAMET.T-K9 results [1] and closely follows that schema for presenting some of the results and a similar approach to the uncertainty evaluation. The authors therefore thank the pilot laboratories and the coordinator of that comparison for their enormous efforts, and especially Fernando Sparasci, whom we thank for allowing us to draw on his previous work in preparing this report.

2. Introduction

This is a report to the Consultative Committee for Thermometry (CCT) on the comparison CCT-K9.3 of SPRT calibration on the International Temperature Scale of 1990 (ITS- 90) from 83.805 8 K (the argon triple point) to 692.677 K (the zinc freezing point). The transfer standards used are long-stem SPRTs.

CCT-K9.3 is a comparison linked to the CIPM key comparison CCT-K9 via EURAMET.T-K9. The topology of the comparison is a star having a EURAMET.T-K9 participant (CEM) as pilot, which provides the link to the KCRV of the CCT-K9 (via EURAMET.T-K9. CEM is also the coordinator of the comparison, in charge of the collection of the measurement reports from all participants and the preparation of the final report.

This comparison has been organized with the aim to provide support to the Calibration Measurement Capabilities claimed by the participants INMs in this range.

The measurements of this comparison were performed from August 2023 to April 2025.

Participants

The list of participating laboratories is the following.

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It has to be noted that CESMEC was not available to finish the comparison because of the poor stability and behaviour of the travel standard elected, an Isotech 670SH with serial number 274. Among other things an instability higher than 15 mK at the triple point of water was observed. It was decided to withdrawn from the comparison by mutual agreement.

Although NMISA has participated in this comparison, they voluntarily decided to withdraw from it, so their results are not included in this report.

3. Protocol

3.1. Protocol

The protocol of this comparison was initially agreed between CEM, CESMEC, GEOSTM, LACOMET and NMISA. After receiving some comments from the CCT-WG-KC reviewers, a new version of the protocol (see annex 1), addressing all the reviewers' comments was sent, approved by the CCT-WG-KC and registered in the BIPM KCDB on December 2023.

Each participating NMI selected one SPRT of their own for being used in the comparison. NMIs calibrated their SPRTs at every available ITS-90 fixed point within the range of this comparison. The selected SPRTs were delivered to the pilot (CEM). The travelling thermometer and its initial calibration results were provided to the pilot laboratory, which assigned an identifier in the format L_j (with $j=1$, for GEOSTM and $j=2$ for LACOMET). Following the calibration realized by the pilot laboratory, the SPRTs were returned to their respective owners, and each NMI completed a final set of calibrations at their facility. All measurement results, corresponding uncertainties, and fixed-point cell uncertainty budgets were reported to the pilot laboratory in a format suggested by Appendices C and D in the CCT-K9.3 protocol (the protocol is included here as Annex I).

In order to provide a reliable linkage to the CCT-K9, via EURAMET.T-K9, the Pilot Laboratory (CEM) has used the same equipment as that used in EURAMET.T-K9.

3.2 Calculating temperature differences with CCT-K9 KCRV

We begin with an explicit derivation of the calculations used in this comparison. L_j identifies both the laboratory (with $j=1$, for GEOSTM and $j=2$ for LACOMET) and also the travelling thermometer of a given participating laboratory. It has to be noticed that in the case of L_2 , for LACOMET, the thermometer used for the FP of Hg and Ar is different from the one used in the FP of Zn, Sn, In and Ga (see table 4.1).

Resistance ratios, W (see W definition in ITS-90 [2]), were measured at each of the six fixed points included in this comparison. Each participating NMI L_j recorded initial values of $W_{L_j, \text{before}}$ for its travelling SPRT. The travelling SPRT was then transported to the pilot laboratory, CEM, where $W_{L_j, \text{CEM}}$ was measured. Finally, the SPRT returned to its NMI for a third and final measurement $W_{L_j, \text{after}}$. All W values may have included multiple realizations for each SPRT at each fixed point.

Average W values are calculated by:

$$\bar{W}_{L_j} = \frac{1}{2} (W_{L_j, \text{before}} + W_{L_j, \text{after}}) \quad (1)$$

The temperature difference $\Delta T_{(L_j - \text{CEM})}$ between the fixed-point realization performed at CEM, and each participating NMI L_j is calculated as:

$$\Delta T_{(L_j - \text{CEM})} = \frac{\bar{W}_{L_j} - W_{L_j, \text{CEM}}}{dW_r/dT} + C_j \quad (2)$$

where dW_r/dT represents the sensitivity of the reference function W_r defined in the ITS-90 and C_j is a term used to account for uncertainty associated with the travel, handling, or stability of the SPRT. Its expected value is assumed to be zero, with an associated uncertainty that will be discussed below.

The temperature difference $\Delta T_{(L_j - \text{KCRV})}$ between the fixed-point realized by the NMI L_j and the KCRV of CCT-K9 is calculated using the following equation:

$$\Delta T_{(L_j - \text{KCRV})} = \Delta T_{(L_j - \text{CEM})} + \Delta T_{(\text{CEM} - \text{KCRV})} \quad (3)$$

where $\Delta T_{(\text{CEM} - \text{KCRV})}$ is the difference between the fixed-point temperature realized by the pilot CEM and the KCRV of the CCT-K9 comparison. $\Delta T_{(\text{CEM} - \text{KCRV})}$ is retrieved from the EURAMET.T-K9 report [1], where it is named $\Delta T_{(L_{ij} - \text{KCRV})}$ (see equation 3 in [1]).

3.3 Calculating uncertainties

The standard uncertainties presented in this report are denoted by u . The corresponding expanded uncertainties, defining an interval estimated to have a level of confidence of 95.45 % are denoted by U .

Uncertainty budgets provided by each NMI are used to calculate the uncertainty of each laboratory's final value $\Delta T_{(Lj-KCRV)}$. The NMIs provided two uncertainty budgets, one associated to the 'before' measurement set and the other to the 'after' one. All the participating NMIs classified each uncertainty contribution in their budgets according to the evaluation method used, i.e. Type A, evaluated statistically, or Type B, evaluated in any other fashion. Conversely, at data analysis phase, and to follow the same approach to consider correlated and uncorrelated components as in the EURAMET.T-K9, the NMIs were asked to provide information on whether a contribution was strongly correlated between measurements (*systematic*) or fluctuated randomly (*random*). The uncertainty budgets reported in Annex III display the random/systematic breakdown for each laboratory.

The uncertainty in $\bar{W}_{Lj}$, arising from the combined 'before' and 'after' travelling measurement sets, is calculated combining the uncertainties provided by the NMI for these two sets. Random components were treated as completely uncorrelated and combined according to GUM [3] section 5.1.2. Systematic components were treated as correlated and combined according to GUM [3] section 5.2.2.

This leads to

$$u^2(\bar{W}_{Lj}) = \frac{1}{4} \left(\frac{u_R^2(W_{Lj,before})}{n_{before}} + \frac{u_R^2(W_{Lj,after})}{n_{after}} \right) + \left(\frac{u_S(W_{Lj,before})}{2} + \frac{u_S(W_{Lj,after})}{2} \right)^2 \quad (4)$$

where $u_R(W_{Lj,before})$ and $u_R(W_{Lj,after})$ are the random parts of the uncertainties respectively associated to the 'before' and 'after' measurements, n_{before} and n_{after} (see datasets in sections 4.4 to 4.6) are the number of realizations measured by that particular SPRT at the indicated fixed point respectively 'before' and 'after' travelling, and $u_S(W_{Lj,before})$ and $u_S(W_{Lj,after})$ are the systematic components of the 'before' and 'after' measurements.

Every SPRT used in the comparison is assigned a transfer uncertainty associated with its measurements at each fixed point. The transfer uncertainties $u(C_{Lj})$ are calculated from the shift in W measured at the NMI before and after transport to the pilot laboratory.

$$u(C_{Lj}) = \frac{1}{2\sqrt{3}} \frac{|W_{Lj,before} - W_{Lj,after}|}{dW_T/dT} \quad (5)$$

In other words, the transfer of the SPRT to and from the pilot laboratory introduces an uncertainty about the mean value $\bar{W}_{Lj}$, which is bounded by the minimum and maximum measured values, $W_{Lj,before}$ and $W_{Lj,after}$, and is assumed to have a rectangular distribution.

The total uncertainty in $\Delta T_{(Lj-CEM)}$ is then:

$$u_{(Lj-CEM)}^2 = \frac{1}{(dW_r/dT)^2} \left(u^2(\bar{W}_{Lj}) + u^2(W_{Lj,CEM}) \right) + u^2(C_{Lj}) \quad (6)$$

where is $u(W_{Lj,CEM})$ the uncertainty about the measurement of thermometer L_j carried out at the pilot laboratory, CEM.

The uncertainty associated to the temperature difference $\Delta T_{(Lj-KCRV)}$ is:

$$u_{(Lj-KCRV)}^2 = u_{(Lj-CEM)}^2 + u_{(CEM-KCRV)}^2 + 2u_{[(Lj-CEM),(CEM-KCRV)]} \quad (7)$$

where:

- $u_{(CEM-KCRV)}^2$ is the uncertainty associated to the deviation of the temperature of CEM from the CCT-K9 KCRV. $u_{(CEM-KCRV)}^2$ is retrieved from the EURAMET.T-K9 report [1], where it is named $u_{(Lij-KCRV)}^2$ (see equation (7) in [1]).
- $2u_{[(Lj-CEM),(CEM-KCRV)]}$ is the covariance associated to $\Delta T_{(Lj-CEM)}$ and $\Delta T_{(CEM-KCRV)}$, namely $2u_{[(Lj-CEM),(CEM-KCRV)]} = cov(\Delta T_{(Lj-CEM)}, \Delta T_{(CEM-KCRV)})$. This is a term accounting for the correlation of measurements carried out by the pilot laboratory CEM respectively in the EURAMET.T-K9 and CCT-K9.3. The evaluation of this correlation is detailed in the following section 3.4.

3.4 Estimating correlations between EURAMET.T-K9 and CCT-K9.3

The link between CCT-K9.3 and CCT-K9 KCRVs (via EURAMET.T-K9) is provided by the pilot laboratory CEM through equation (3), with the uncertainties expressed in equation (7). The uncertainties of CEM are counted in both the first two terms of equation (7) and are likely to be correlated. The third term of equation (7) accounts for this correlation and we explain here how we evaluated those correlations.

Here, to treat with this correlation term it was follow the same approach and assumptions described in 2.4. EURAMET.T-K9 report [1]. Thus the equation (7) can be written as:

$$u_{(Lj-KCRV)}^2 = u_{(Lj-CEM)}^2 + u_{(CEM-KCRV)}^2 - 2u_T(W_{Lj,CEM}, CCT-K9\Delta T_{CEM}) \quad (8)$$

where $CCT-K9\Delta T_{CEM}$ is the temperature realized in EURAMET.T-K9 by CEM.

The correlation term in equation (8) involves measurements performed at CEM, in the two comparisons, respectively CCT-K9.3 and EURAMET.T-K9. CEM refers, in section 4.2, the equipment used for measurements CCT-K9.3, which is substantially the same than the one used in EURAMET.T-K9.

Consequently, we considered that the systematic components of the CCT-K9.3 uncertainty budgets elaborated by CEM, $u_{S,T}(W_{Lj,CEM})$, are fully correlated with those provided by CEM in EURAMET.T-K9, $u_S(CCT-K9\Delta T_{CEM})$, leading to:

$$u_T(W_{Lj,CEM}, CCT-K9\Delta T_{CEM}) = u_{S,T}(W_{Lj,CEM}) \cdot u_S(CCT-K9\Delta T_{CEM}) \cong u_{S,T}^2(W_{Lj,CEM}) \quad (9)$$

The approximation in equation (9) is a consequence of the fact that the systematic uncertainties of CEM are nearly identical in CCT-K9.3 and EURAMET.T-K9, so

$$u_{S,T}(W_{Lj,CEM}) \cong u_S(CCT-K9\Delta T_{CEM}).$$

4. Devices used and measurement results

4.1. Devices used

The SPRTs used in the comparison are listed in Table 4.1.

Laboratory	SPRT ID	Fixed Points	Serial n.	Manufacturer	Model
GEOSTM	L ₁	Zn, Sn, Ga, Hg	339	ISOTECH	670SQ
LACOMET	L ₂₁	Zn, Sn, In, Ga	243	ISOTECH	670
	L ₂₂	Hg, Ar	541	ISOTECH	670SQ

Table 4.1. SPRTs used in this comparison.

4.2. Data collection at pilot laboratory

Comparison measurements at CEM were performed from February 2024 through July 2024. The fixed-point cells and the measurement systems were the same used in EURAMET.T-K9, in order to provide a link to the KCRV of the CCT-K9 through EURAMET.T-K9 results. CEM used the same control thermometers as those used in EURAMET.T-K9.

- The cells employed in CCT-K9.3 were:

Zinc FP: Zn 11

Tin FP: Sn 742876

In FP: In 97

Ga FP: Ga L8256

H₂O TP: H₂O 1136

Hg TP: Hg 62

Ar TP: Ar 29

The cells are the same as those used in EURAMET.T-K9.

- The measurement system used in CCT-K9.3 were:

Resistance bridge: ASL F900 (s/n 7432 001 001)

Standard resistors: Tinsley 5685-A 260083 (100 Ω)

The system is the same used in EURAMET.T-K9.

4.3. SPRT data collected from participating laboratories

NMIs reported their 'before' and 'after' W values according to the format established in the Appendix C of the CCT-K9.3 protocol. Each of the following tables includes values of W , and the associated expanded uncertainties U , as supplied by NMIs.

4.4. GEOSTM dataset

Fixed point		W	U (mK)	$n.$ <i>realizations</i>
Before Pilot	Zn	2.568 351 0	2.10	2
	Sn	1.892 486 7	1.60	2
	In			
	Ga	1.118 098 2	1.00	2
	Hg	0.844 191 9	1.10	2
	Ar			
At Pilot	Zn	2.568 355 1	1.24	2
	Sn	1.892 485 3	1.30	2
	In			
	Ga	1.118 097 1	0.31	2
	Hg	0.844 190 6	0.31	2
	Ar			
After Pilot	Zn	2.568 335 6	2.00	2
	Sn	1.892 473 3	1.60	2
	In			
	Ga	1.118 099 6	1.00	2
	Hg	0.844 187 3	1.00	2
	Ar			

Table 4.4. Data supplied by the participating laboratory GEOSTM ‘before’ and ‘after’, and data of measurements performed by pilot CEM. U is the expanded uncertainty at the $k = 2$ level.

4.5. LACOMET dataset

Fixed point		W	U (mK)	$n.$ <i>realizations</i>
Before Pilot	Zn	2.567 256 0	2.00	2
	Sn	1.891 861 8	1.42	2
	In	1.609 167 2	1.26	2
	Ga	1.118 019 4	0.50	2
	Hg	0.844 170 8	0.66	2
	Ar	0.215 995 9	0.86	2
At Pilot	Zn	2.567 258 9	1.09	2
	Sn	1.891 866 8	0.63	2
	In	1.609 169 5	0.69	2
	Ga	1.118 018 6	0.27	2
	Hg	0.844 170 5	0.56	2
	Ar	0.215 995 5	0.79	2
After Pilot	Zn	2.567 257 2	1.94	2
	Sn	1.891 862 3	1.14	2
	In	1.609 167 9	1.20	2
	Ga	1.118 019 0	0.54	2
	Hg	0.844 170 9	0.58	2
	Ar	0.216 000 0	1.00	2

Table 4.5. Data supplied by the participating laboratory LACOMET ‘before’ and ‘after’, and data of measurements performed by pilot CEM. U is the expanded uncertainty at the $k = 2$ level.

5. Results of the comparison

Tables and plots from section 5.1 through section 5.6 summarize the deviations ($\Delta T_{(Lj-KCRV)}$) of NMI results from the KCRV of CCT-K9 at each fixed point. Tables and plots from section 5.7 through section 5.9 provide the same results, organized by laboratory. Error bars in all of these plots show the uncertainty ($U_{(Lj-KCRV)}$) in the value $\Delta T_{(Lj-KCRV)}$ at the $k = 2$ level.

5.1 Zinc

The results of this comparison at the zinc point are summarized in Table 5.1 and Figure 5.1.

Laboratory	$\Delta T_{(Lj-KCRV)}$ mK	$U_{(Lj-KCRV)}$ mK
GEOSTM	-1.94	2.78
LACOMET	0.78	1.58

Table 5.1. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the zinc point. Uncertainties are displayed at the $k = 2$ level.

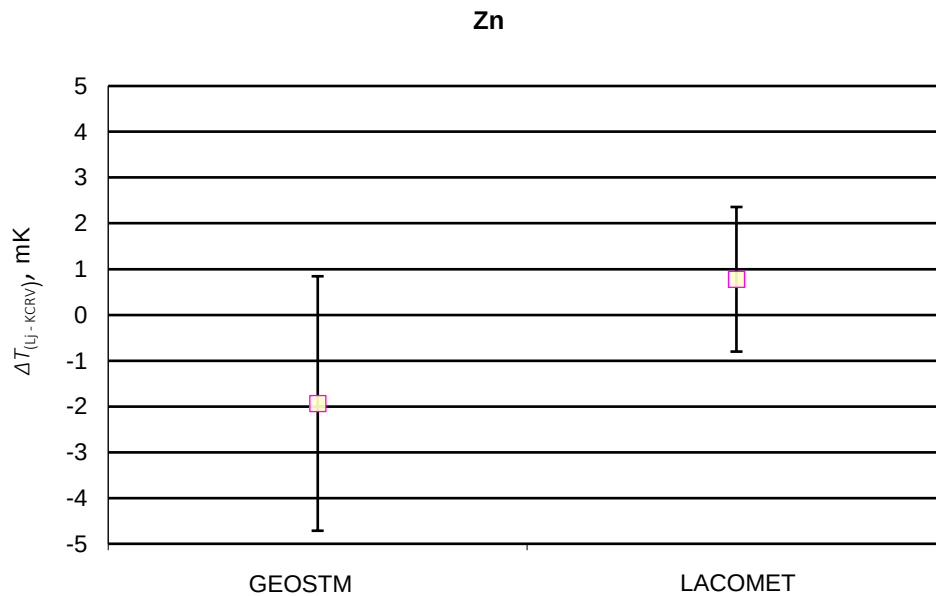


Figure 5.1. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the zinc point. Error bars represent uncertainty $U_{(Lj-KCRV)}$

5.2 Tin

The results of this comparison at the tin point are summarized in Table 5.2 and Figure 5.2.

Laboratory	$\Delta T_{(Lj - KCRV)}$ mK	$U_{(Lj - KCRV)}$ mK
GEOSTM	-1.28	2.28
LACOMET	-0.17	1.13

Table 5.2. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the tin point. Uncertainties are displayed at the $k = 2$ level

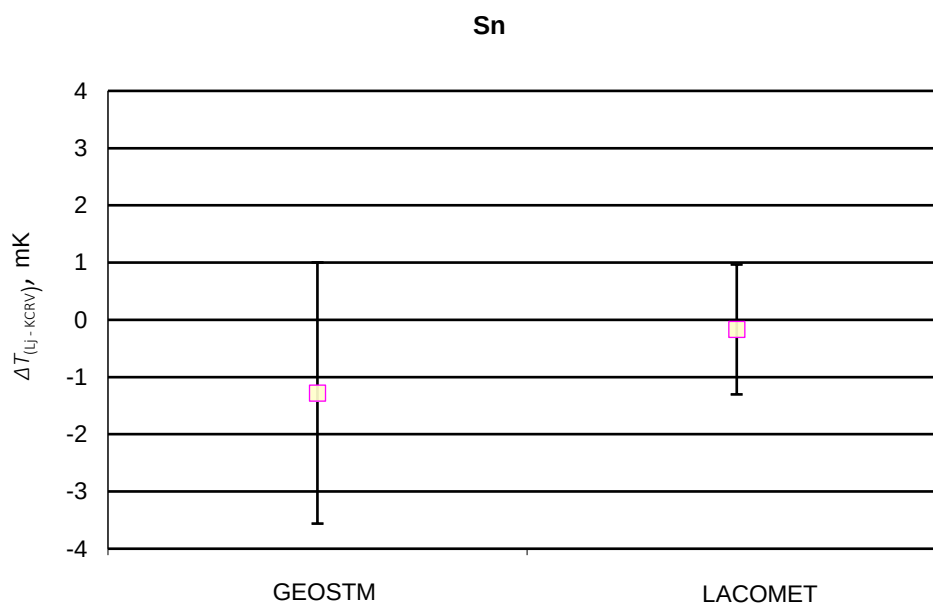


Figure 5.2. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the tin point. Error bars represent uncertainty $U_{(Lj - KCRV)}$

5.3 Indium

The results of this comparison at the indium point are summarized in Table 5.3 and Figure 5.3.

Laboratory	$\Delta T_{(Lj - KCRV)}$ mK	$U_{(Lj - KCRV)}$ mK
GEOSTM		
LACOMET	-0.05	0.89

Table 5.3. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the indium point. Uncertainties are displayed at the $k = 2$ level

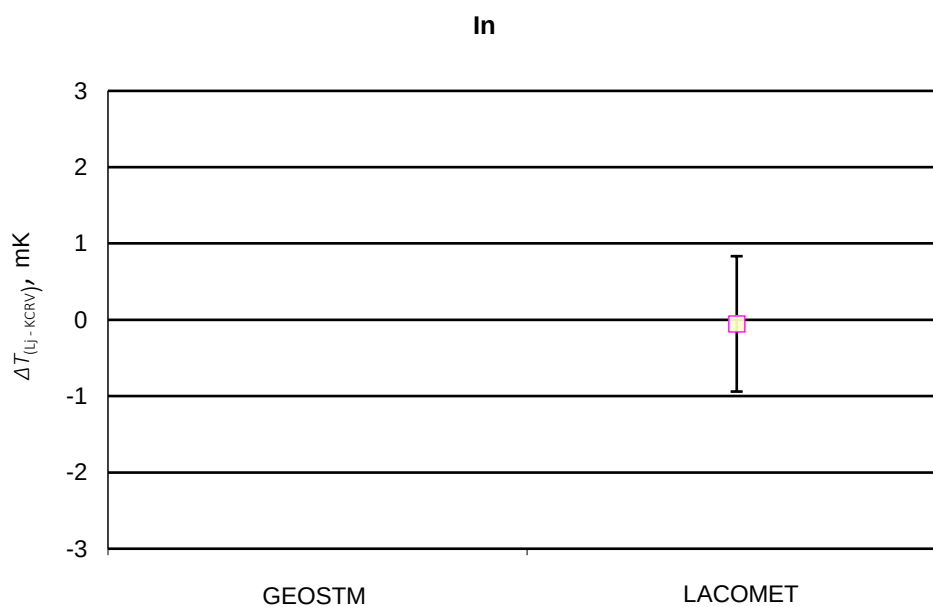


Figure 5.3. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the indium point. Error bars represent uncertainty $U_{(Lj-KCRV)}$

5.4 Gallium

The results of this comparison at the gallium point are summarized in Table 5.4 and Figure 5.4.

Laboratory	$\Delta T_{(Lj - KCRV)}$ mK	$U_{(Lj - KCRV)}$ mK
GEOSTM	0.53	1.23
LACOMET	0.21	0.63

Table 5.4. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the gallium point. Uncertainties are displayed at the $k = 2$ level

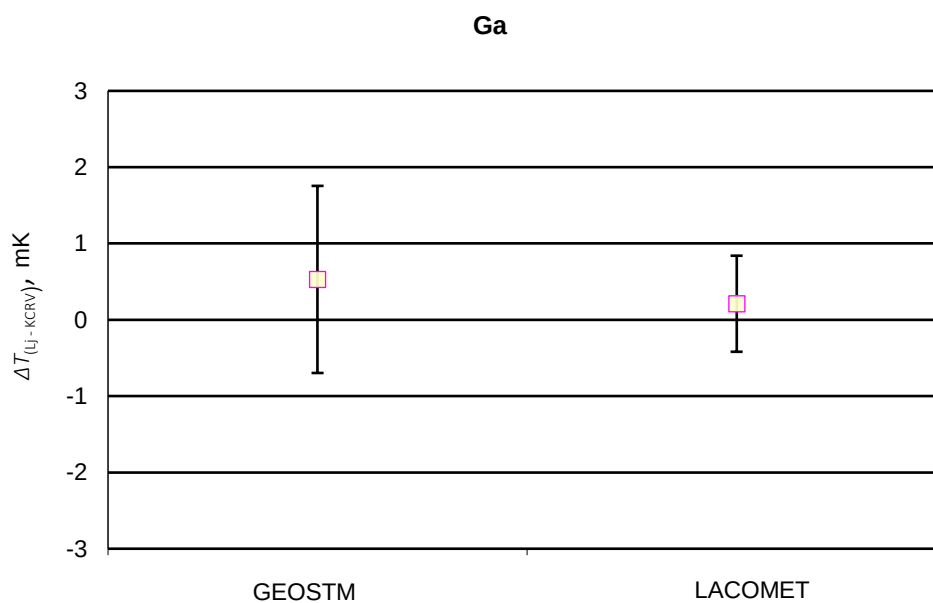


Figure 5.4. Deviations $\Delta T_{(Lj-KCRV)}$ measured at the gallium point. Error bars represent uncertainty $U_{(Lj-KCRV)}$

5.5 Mercury

The results of this comparison at the mercury point are summarized in Table 5.5 and Figure 5.5.

Laboratory	$\Delta T_{(Lj - KCRV)}$ mK	$U_{(Lj - KCRV)}$ mK
GEOSTM	0.41	1.62
LACOMET	0.74	0.93

Table 5.5. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the mercury point. Uncertainties are displayed at the $k = 2$ level

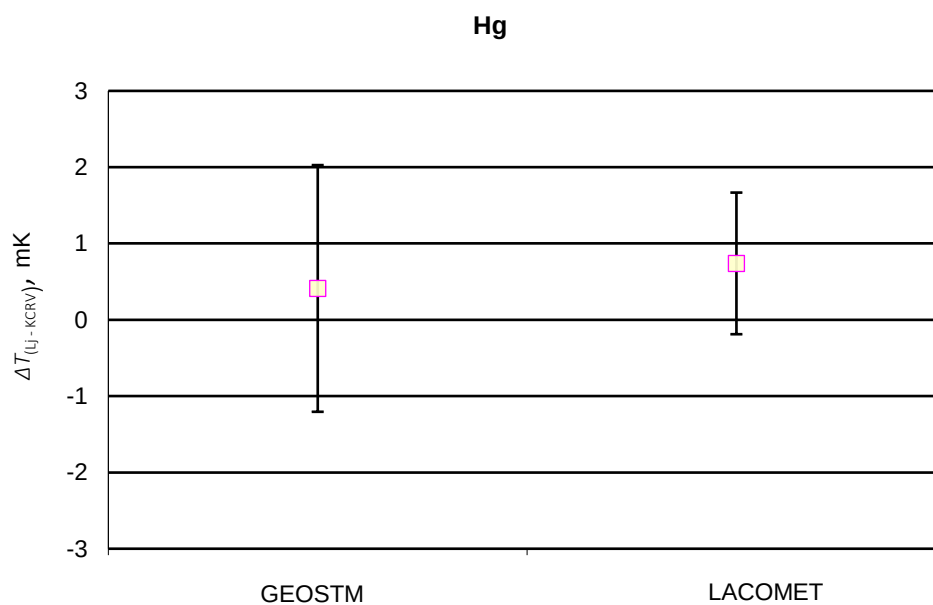


Figure 5.5. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the mercury point. Error bars represent uncertainty $U_{(Lj - KCRV)}$

5.6 Argon

The results of this comparison at the argon point are summarized in Table 5.6 and Figure 5.6.

Laboratory	$\Delta T_{(Lj - KCRV)}$ mK	$U_{(Lj - KCRV)}$ mK
GEOSTM		
LACOMET	-0.04	1.49

Table 5.6. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the argon point. Uncertainties are displayed at the $k = 2$ level

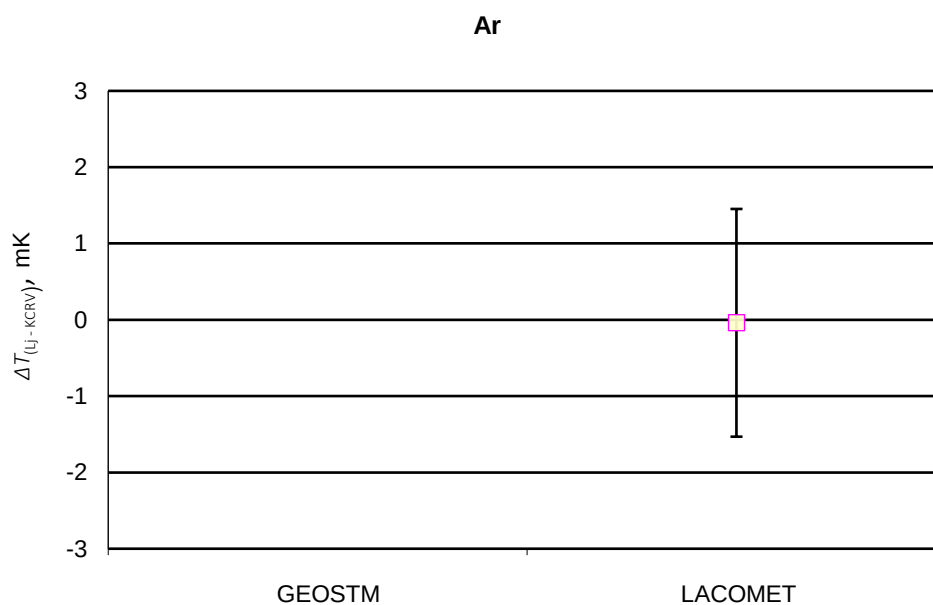


Figure 5.6. Deviations $\Delta T_{(Lj - KCRV)}$ measured at the argon point. Error bars represent uncertainty $U_{(Lj - KCRV)}$

5.7 GEOSTM - results

	$\Delta T_{(Lj - KCRV)}$	$U_{(Lj - KCRV)}$
	mK	mK
Zn	-1.94	2.78
Sn	-1.28	2.28
In		
Ga	0.53	1.23
Hg	0.41	1.62
Ar		

Table 5.7. . Deviations $\Delta T_{(Lj-KCRV)}$ at each fixed-point measured at GEOSTM. Uncertainties are displayed at the $k = 2$ level

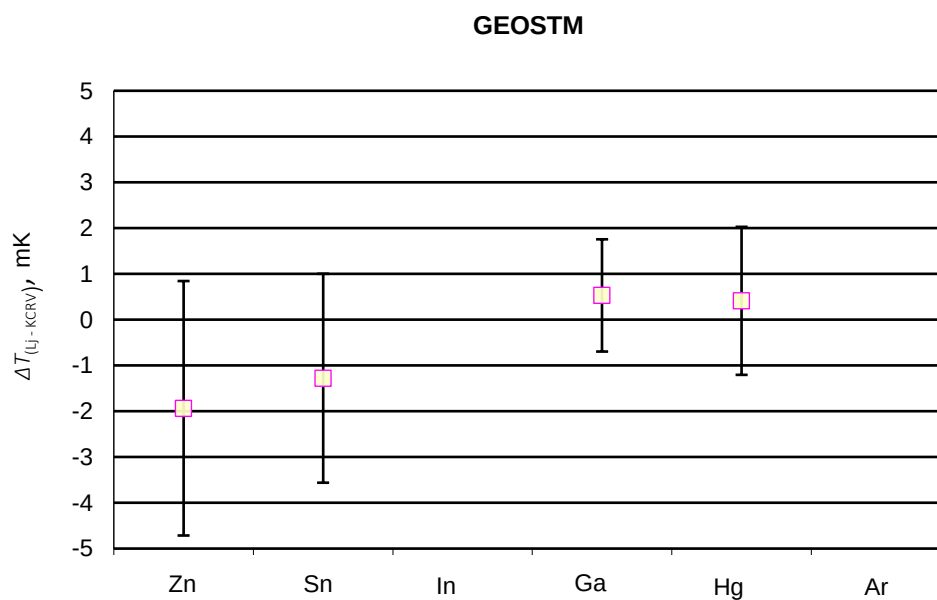


Figure 5.7. Deviations $\Delta T_{(Lj-KCRV)}$ at each fixed-point measured at GEOSTM. Error bars represent uncertainty $U_{(Lj-KCRV)}$

5.8 LACOMET - results

	$\Delta T_{(Lj - KCRV)}$	$U_{(Lj - KCRV)}$
	mK	mK
Zn	0.78	1.58
Sn	-0.17	1.13
In	-0.05	0.89
Ga	0.21	0.63
Hg	0.74	0.93
Ar	-0.04	1.49

Table 5.8. . Deviations $\Delta T_{(Lj-KCRV)}$ at each fixed-point measured at LACOMET. Uncertainties are displayed at the $k = 2$ level

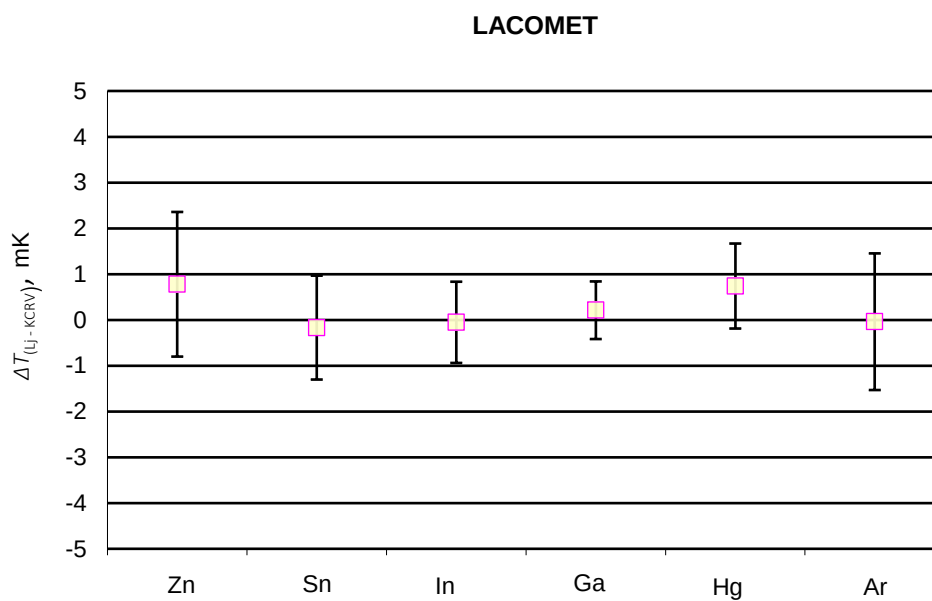


Figure 5.8. Deviations $\Delta T_{(Lj-KCRV)}$ at each fixed-point measured at LACOMET. Error bars represent uncertainty $U_{(Lj-KCRV)}$

6. References

[1] “*EURAMET.T-K9 regional key comparison ITS-90 SPRT calibration from the Ar TP to the Zn FP*” Fernando Sparasci et al 2024 *Metrologia* 61 03005, DOI 10.1088/0026-1394/61/1A/03005

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ANNEX I. PROTOCOL

Key comparison CCT-K9.3 ITS-90 SPRT Calibration from the Ar TP (83.805 8 K) to the Zn FP (692.677 K)

Technical Protocol

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Draft 03

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1. INTRODUCTION

The instructions and procedures given here shall be followed by the participants in this comparison. By accepting this technical protocol, the participant laboratories agree to follow the general and technical instructions written in this document and the content in the MRA document *Measurement comparisons in the CIPM MRA* [1].

This comparison is designed as a “collapsed star”. CEM, that has previously participated in the EURAMET.T-K9 (linked to the CCT-K9), will be the pilot participant to link the others participants to the CCT-K9.

The resulting calibration results will be calculated by NMIs personnel and submitted to the pilot laboratory (see section 8).

The final results of the comparison will be determined by the pilot laboratory and presented as degrees of equivalence between the participants. A link to the parent CCT-K9 comparison will be also provided for the fixed points of Ar, Hg, Ga, In, Sn and Zn.

This protocol matches closely the corresponding EURAMET.T-K9.

2. PARTICIPANTS

The pilot laboratory and coordinator is CEM (Spain).

The other participants are:

- CESMEC (Chile)
- GEOSTM (Georgia)
- LCM (Costa Rica)
- NMISA (South Africa)

Contact persons with their addresses are given in Table 1.

Table 1. Participating NMIs

Country	NMI	Acronym	Shipping Address	Contact Person
Spain	Centro Español de Metrología	CEM	C/Alfar, 2. 28760 Tres Cantos, Madrid. España.	Raúl Caballero e-mail: rcaballero@cem.es Phone: +34 918 074 822 M ^a José Martín e-mail: mjmartinh@cem.es Phone: +34 918 074 714
Chile	Centro de Estudios, Medición y Certificación de Calidad	CESMEC S.A.	Av. Marathon 2595, Macul, Santiago. Chile	Marinka Quezada marinka.quezada@bureauveritas.com Phone: +569 64220872 Jimmy Angla jimmyv.angla@bureauveritas.com Phone: +569 6445 9384
Georgia	Georgian National Agency for Standards and Metrology	GEOSTM	Chargali street 67, Tbilisi 0178, Georgia	Nino Mikanadze e-mail: nino_mikanadze@yahoo.com Yuri Chelidze temperature.geostm@gmail.com
Costa Rica	Laboratorio Costaricense de Metrología	LCM	LCM, Ciudad de la Investigación, Universidad de Costa Rica, San Pedro, Montes de Oca, San José, Costa Rica.	Luis Fernando Chaves Santacruz e-mail: lchaves@lcm.go.cr
South Africa	National Metrology Institute of South Africa	NMISA	Building 5 – CSIR Campus Meiring Naude Road Brummeria Pretoria 0001	Efrem Ejigu e-mail: EEjigu@nmisa.org Phone: +27 12 947 2748 Matome Maloba Email: MMaloba@nmisa.org Phone: +27 12 947 2806 Yanga Ntlosi Email: YNtlosi@nmisa.org Phone: +27 12 947 2896

3. COMPARISON METHODOLOGY

3.1. Comparison topology:

A star comparison with CEM, an EURAMET.T-K9 participant, as pilot linking the measurements of the other participants to the CCT-K9 KCRV. The SPRTs will be calibrated by the fixed points method.

The measurement sequence is as follows:

- 1) Each participant will select his own SPRTs based on his own criteria for suitability and will convey the selection criteria to the Pilot Laboratory.
- 2) Each participant will calibrate the selected SPRTs. After calibrating the selected SPRTs, the participant will deliver the SPRTs to the pilot (CEM).
- 3) The pilot (CEM) will calibrate all participants' SPRTs. After calibrating them, the pilot (CEM) will deliver each SPRTs to its participant.
- 4) Each participant will repossess their thermometer and will make a recalibration.

- 5) SPRTs are to be measured at every available fixed-point over the range of the comparison.

3.2. Timetable of comparison

An schema of the project timeline is as follow:

Protocol Agreement	September, 2023
Transfer Standards Sent to pilot	December, 2023/February, 2024
Transfer Standards Returned to NMIs	June/July, 2024
Transfer Standards Re-Measured by NMIs	September, 2024
Draft A Report Completed	November, 2024

A more detailed timetable is on appendix E.

4. TRAVELLING STANDARDS

Each participant will select his own ITS-90 SPRTs to participate as travelling standards in this comparison. More details on every SPRT selected is on appendix F.

4.1. Transportation of travelling standards

Option Carry in hand (preferred):

The SPRTs must be handled with care and only by qualified metrology personnel. Hand-carriage of the SPRTs from the participant lab to the pilot and vice versa is recommended and under the responsibility (and costs) of the participant.

Option Currier:

The travelling standards, when sending by currier, will be packed in a suitable transport box. The transport box can be easily opened for customs inspection.

4.2. Test upon receipt and final test at the participant laboratories

The SPRTs will be calibrated by participants and CEM by the fixed point method. This includes an initial and a final stability tests of the resistances of the SPRTs at the triple point of water before the transportation to CEM from participant laboratories and after arrival at the participant laboratories.

4.3. Failure of travelling standard

In case of loss or damage to any of the SPRTs, due to transport, the laboratory will inform to the other one of the same bilateral comparison: if they are all of the SPRTs,

that part of the comparison will end; if there are still any SPRT useable, the comparison will continue with those SPRTs in the associated fixed points.

4.4. Organizational aspects

Each participant institute (not CEM) will cover the costs of sending his thermometers between the participant institute and CEM by using a courier, including associated taxes. SPRTs will be covered by an insurance policy, paid by the participant institute (each for their own SPRTs, CEM not included), in case of loss or damage due to transportation.

4.5. Communication flows

The participant institutes (not CEM) will inform to the pilot (CEM) of the arrival of the travelling standards.

The participant institutes will inform to the pilot (CEM) the initial and final stability tests of the resistances of the SPRTs at the triple point of water before the transportation to CEM and after arrival at the participant institute.

The participant institutes will inform to CEM if there are any measurement delays.

After the participant institute (not CEM) has completed the measurements, this institute will send a measurement report to the pilot laboratory (CEM).

CEM will ask to the participant institute (not CEM) to check their data values in case their shows an apparently anomalous result before issuing the draft A.

CEM will write the Draft A of the final report. This Draft will be sent to every participant institute. The participant institutes will have two weeks to send their feedback. No reply will be interpreted as a tacit approval.

Draft A will be corrected accordingly up to consensus is reached and afterwards submitted to CCT-WG-KC for review.

CEM will prepare Draft B and it will be submitted to the CCT-WG-KC.

5. MEASUREMENT INSTRUCTIONS AND PROCEDURES

5.1. Measurand

The measurand for this comparison will be defined through $W(t_{90})$ values, being

$$W(t_{90}) = \frac{R(t_{90})}{R_{TPW}} \quad (1)$$

where $R(t_{90})$ is the value of the SPRT resistance at temperature t_{90} and R_{TPW} is the resistance value of the SPRT at the triple point of water measured after the measurement at the fixed point.

5.2. Preliminary check

After the CEM measurements, when travelling standards are received back at the participant laboratory, they will be inspected to check if they seem to have external and visible damage due to transportation. In case they seem to be with no damage, the participant laboratory will proceed to measure their R_{TPW} values. The participant laboratory will send the corresponding report to the pilot (Appendix A).

5.3. Measurements

Every participant will inform about their standards and equipment used (Appendix B).

The electrical resistance measurement will be carried out with two currents: I_1 and I_2 by using four wires for electrical connections, and extrapolated to 0 mA. The current values used should be notified to the pilot laboratory.

The corrections due to self-heating effect should be evaluated and reported. All the measurements should also be corrected for the hydrostatic head and residual gas effect to obtain the corrected resistance values (appendix C).

5.4. SPRTs

5.4.1. SPRTs cleaning

To avoid devitrification, (detailed by the CCT document “Guide to the Realization of the ITS-90. Platinum Resistance Thermometry. 4.3 Devitrification”). “using silica-sheathed platinum resistance thermometers above 100 °C, they should be carefully cleaned with pure ethanol and dried with clean paper or cloth. The cleaning with diluted nitric acid followed by washing with clear water is also suitable.” [2]

5.4.2. Stabilization procedure for SPRTs calibrated till **Zn**

Before starting measurements at the fixed points, the SPRTs should follow a stabilization procedure passing through the following sequence:

1. Measurement at the triple point of water (TPW)
2. Carefully insert the SPRT into a furnace at 480 °C.
3. Anneal the SPRT for two hours at 480 °C
4. Carefully remove the SPRT from the furnace directly to the room environment.
5. Re-determine the value of resistance at the TPW.

If the change of the resistance value at TPW is equivalent to 0.3 mK or greater, the participant should consider whether to repeat steps 2 to 5 in order to try to reduce the resistance value at TPW or increase the corresponding uncertainty.

If the change of the resistance value at TPW is less than 0.3 mK the calibration can be performed.

5.4.3. Stabilization procedure for SPRTs calibrated below **Ga**

For those SPRTs whose upper fixed-point is **Galium** no stabilization/anncaling is needed.

5.4.4. Measurement procedure

Measurements at the fixed points should be performed in order of decreasing temperatures alternating with a measurement at the triple point of water.

The laboratories have to follow their normal practice when realizing the ITS-90. For each fixed point the measurand for this comparison will be defined through $W(t_{90})$ values:

$$W(t_{90}) = \frac{R(t_{90})}{R_{TPW}} \quad (2)$$

where

$R(t_{90})$: is the value of the SPRT resistance at temperature t_{90}

R_{TPW} : is the resistance value of the SPRT at the triple point of water, measured after the measurement at the fixed point.

$R(t_{90})$ and R_{TPW} should have been corrected for self-heating, hydrostatic head and if any the pressure effect. At least 2 different phase transitions will be performed. The different values will be delivered together with the calculated mean.

For each fixed point cell used in the comparison, it has to be determined (using the circulating SPRT) the change of phase transition temperature, dT , versus immersion depth, dh . These measurements will be reported in a graph where the theoretical dT/dh curve, using the hydrostatic pressure coefficients (mK/m of liquid) given in the ITS-90 text, and the measured dT/dh curve will be plotted.

5.5. Measurements at the pilot lab

The pilot (CEM) should carry out the calibration of the SPRTs using the same equipment as was used in the EURAMET.T-K9, or equipment which is known to be compatible with that equipment. It is recommended that one of the SPRTs used by the Pilot in the EURAMET.T-K9 is also included in the calibration experiments. The cells used by the pilot in this comparison should be, if possible, those used in the EURAMET.T-K9, to provide a proper link with the CCT-K9 (via EURAMET.T-K9).

6. EVALUATION OF THE RESULTS OF THE THERMOMETERS

Once the SPRTs are back to the participant laboratory from CEM it is necessary to check their stability. To do so, the participant laboratory will carry out the ensuing actions:

- Stabilization of the SPRT as detailed in 5.4.
- Measurement W at the freezing points and/or triple points (depending on which SPRT) 5.4.

The result of these measurements, with their associated uncertainties, will be reported to CEM to be included in the final report.

7. UNCERTAINTIES

Uncertainty analysis according to the "Guide to the Expression of Uncertainty in Measurement", JCGM 100:2008, GUM 1995 with minor corrections, First edition September 2008 must be performed for both laboratories. The uncertainty analysis must include the following terms and other items that the participating laboratory wants to include:

- Phase transition repeatability
- Chemical impurities and isotopic composition for the TPW
- Hydrostatic-head errors
- Bridge measurement errors:
 - effects of changes in reference resistors
 - non-linearity of bridge
 - quadrature effects in ac measurements

- resolution
- repeatability of the measurements at each fixed point
- Uncertainty propagated from the TPW
- Heat flux-immersion errors
- Errors in gas pressure
- Errors in the choice of freezing point value from plateau of the freezing curve
- SPRT internal Insulation leakage (if any)

8. REPORT OF RESULTS AND LINKAGE MECHANISM

The reports with the results provided by the participants will include the information requested in Appendix C and Appendix D.

For each fixed point cell used in the comparison, a graph where is plotted the measured and theoretical dT/dh curve using the hydrostatic pressure coefficients (mK/m of liquid) given in the ITS-90 text will be also provided, together with examples of their phase transition curves.

Every participant laboratory shall fill out the Appendix C and Appendix D spreadsheet and send it to CEM.

8.1. Method of analysis of the results and link to the CCT-K9 KCRV

CEM will collect the results of the participants. That means the data values and the uncertainties. The results to be reported are temperature differences and measurement uncertainty.

For each fixed point the fixed-point realization temperature differences between CEM and the participant laboratory (before and after CEM measurements) will be calculated according to:

$$\Delta T_{XX, LAB-CEM} = (W_{XX, LAB} - W_{XX, CEM}) \cdot s \quad (4)$$

Where XX represents the different fixed points and s is the first derivative of the inverse reference function. LAB represents the participant laboratory.

The uncertainty of this difference will be calculated based on the uncertainties reported by CEM and the participant laboratory and the drift of the travelling standards, calculated based on the measurements performed by the participant laboratory at the beginning and end of the comparison:

$$u^2(\Delta T_{XX, LAB-CEM}) = u^2(T_{XX, LAB}) + u^2(T_{XX, CEM}) + u^2(T_{XX, drift}) \quad (5)$$

The ΔT_{XX} values will be used to link the results of this comparison to the CCT-K9 through the CEM differences with respect the CCT-K9 KCRV obtained in the EURAMET.T-K9 according to the following equation

$$\Delta T_{XX, LAB-CCT-K9} = \Delta T_{XX, LAB-CEM} - \Delta T_{XX, CCT-K9-CEM} \quad (6)$$

With the corresponding uncertainty:

$$u^2(\Delta T_{XX, LAB-CCT-K9}) = u^2(\Delta T_{XX, LAB-CEM}) + u^2(\Delta T_{XX, CCT-K9-CEM}) \quad (7)$$

Where:

$$\Delta T_{XX, \text{CCT-K9-CEM}} = T_{XX, \text{CCT-K9}} - T_{XX, \text{CEM}} \quad (8)$$

Being $T_{XX, \text{CCT-K9}}$ the CCT-K9 reference value for the XX fixed point.

8.2. Comparison report

CEM will ask to participant laboratories to check their data values in case their show an apparently anomalous result before issuing the draft A.

CEM will write the Draft A of the final report. This Draft will be sent to participant laboratories. The participant laboratories will have two weeks to send their feedback. No reply will be interpreted as a tacit approval.

Draft A will be corrected accordingly and afterwards submitted to CCT-WG-KC for review, becoming Draft B.

If the CCT-WG-KC has any observation on this Draft B, CEM will prepare a new Draft B attending this observations and will it send it to the participant laboratories for consensus. The participant laboratories will have two weeks to send their feedback. No reply will be interpreted as a tacit approval.

Once this Draft B is corrected accordingly up to consensus is reached and the observations of the CCT-WG-KC attended, this Draft will be submitted to the CCT-WG-KC for its approval as a final report.

8.3. Reference

1. MRA Document (January 2021): [*Measurement comparisons in the CIPM MRA, CIPM MRA-G-11*](#), Version 1.1
2. CCT Guidebooks: Guides to Thermometry. Guide to the realization of the ITS-90. Part 5- Platinum resistance thermometry (2021)

Appendix A

Format of Reception

In order to have information about the comparison development and, if it is necessary to take adequate corrective actions, the participant laboratory must send by e-mail to the pilot laboratory this format after the first measurement at 0.01 °C.

Laboratory and contact person: _____

Travelers standards arrived on the day: _____

Are there some damage signals due to transport? Yes/Not _____

Description, in case of damage: _____

Measurement at 0.01 °C:

- Resistance (with I_1): _____ Ω
- Resistance (with I_2): _____ Ω
- Resistance (0 mA): _____ Ω
- Immersion correction: _____ Ω
- Expanded Uncertainty: _____ °C

The participant laboratories could also declare the first (upon receipt) and last resistance values at the TPW. This might be helpful for keeping track of the SPRTs in the case there are drifts.

Comments:

Appendix B Instrumentation Details

Key comparison CCT-K9.3

Laboratory name	
Bridge	
Manufactured	
Type	
AC or DC	
If AC, give Frequency	
If DC, give Period of reversal	
Normal measurement current	
Self-heating current	
Evaluation of linearity of resistance	
Bridge (yes or not)	
If yes, How?	
Reference resistor	
Manufactured / type	
Reference resistor temperature control (yes or not)	
If yes, How?	
TPW Cell	
Manufactured / model	
Serial number	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
How are mantles maintained (ice, bath, ...)	
Zn Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
Zn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	
Typical duration of the melting / freezing plateaux	
Sn Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
Sn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	
Typical duration of the melting / freezing plateaux	
In Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
In Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	

Typical duration of the melting / freezing plateaux	
Ga Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
Ga Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	
Typical duration of the melting / freezing plateaux	
Hg Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
Hg cryostat	
Type (cryocooler, bath,...)	
Typical duration of the melting plateaux	
Ar Cell	
Manufactured / model	
Is it a primary reference? (if not explain its traceability)	
Immersion depth of middle of the SPRT sensitive element/cm	
Closed cell or open	
Nominal purity	
Immersion depth of middle of the SPRT sensitive element/cm	
Ar cryostat	
Type (cryocooler, bath,...)	
Typical duration of the melting plateaux	

Appendix C

RESULTS

Key comparison CCT-K9.X

Laboratory name:

SPRT Manufacturer:

Model:

serial/number:

Date	Point	R measured Ω	Self heating Ω	Hydrostatic Ω	Pressure Ω	R corrected Ω	W
	Zn						
	TPW						
	Zn						
	TPW						
Average of <i>W</i> for Zn							
	Sn						
	TPW						
	Sn						
	TPW						
Average of <i>W</i> for Sn							
	In						
	TPW						
	In						
	TPW						
Average of <i>W</i> for In							
	Ga						
	TPW						
	Ga						
	TPW						
Average of <i>W</i> for Ga							
	Hg						
	TPW						
	Hg						
	TPW						
Average of <i>W</i> for Hg							
	Ar						
	TPW						
	Ar						
	TPW						
Average of <i>W</i> for Ar							

Appendix D

Uncertainty analysis

Key comparison CCT-K9.3

Laboratory name:

Fixed point:

Ser.-No. of SPRT:

Quantity Q_i	Components	Standard uncertainty $u_{(Q_i)}$	Degrees of freedom components evaluated by a type A method * V_1	Sensitivity coefficient	Uncertainty contribution u_i in mK
Combined uncertainty					
Effective degrees of freedom					
Expanded uncertainty					

Appendix E
TIMETABLE OF COMPARISON

Measurement sequence	Description	Time Period
1	Each Participant calibrates his SPRTs.	Planned September 1 st , 2023 to December 31 st , 2023
2	Each participant brings (in hand) his SPRTs to CEM (or courier picks up SPRTs from participant and delivers his SPRTs to CEM)	Planned January 1 st to February 28 th , 2024
3	CEM calibrates every SPRTs.	Planned March 1 st to May 31 th , 2024
4	Courier picks up SPRTs from CEM and delivers to each participant his SPRTs.	Planned June 1 st to June 15 th , 2024
5	Each participant recalibrated his SPRTs.	Planned June 16 th to September 15 th , 2024
6	Draft A Report CEM submitted to participants	Planned by November 1 st , 2024
7	Draft A observations submitted to CEM	Planned by November 15 th , 2024
8	Draft B submitted to CCT WG KC	Planned by November 30 th , 2024
9	Draft B CCT WG KC observations submitted to CEM	Planned by December 15 th , 2024
10	Draft B Report submitted by CEM to participants	Planned by January 10 th , 2025
11	Draft B observations submitted to CEM	Planned by January 30 th , 2025
12	Draft B submitted to CCT WG KC	Planned by February 15 th , 2025
13	Report approved by CCT WG KC. Report publication	Planned by March 1 st , 2025

Appendix F

TRAVELLING STANDARDS

CESMEC Travelling standards

Category	SPRT-A.1
Manufacturer	<i>To full fill by CESMEC</i>
Model	<i>To full fill by CESMEC</i>
Serial number:	<i>To full fill by CESMEC</i>
Length / mm	<i>To full fill by CESMEC</i>
Diameter / mm	<i>To full fill by CESMEC</i>
Nominal resistance at TPW	
Fixed points	Hg, Ga, In., Sn, Zn

GEOSTM Travelling standards

Category	SPRT-B.1
Manufacturer	Fluke
Model	5683
Serial number:	
Length / mm	520 mm
Diameter / mm	7 mm
Nominal resistance at TPW	
Fixed points	Hg, Ga, In., Sn, Zn

LCM Travelling standards

Category	SPRT-C.1	SPRT-C.2	SPRT-C.3
Manufacturer	ISOTECH	ISOTECH	ISOTECH
Model	670SQ	670SQ	670
Serial number:	541	543	243
Length / mm	480	480	650
Diameter / mm	7,5	7,5	7,5
Nominal resistance at TPW			
Fixed points	Ar, Hg, Ga	Hg, Ga, In, Sn, Zn	Hg, Ga, In, Sn, Zn

NMISA Travelling standards

Category	SPRT-D.1
Manufacturer	CHINO
Model	R800-2
Serial number:	RS183-03
Length / mm	600 mm
Diameter / mm	7±0.5 mm
Nominal resistance at TPW	
Fixed points	Ar - Zn

Appendix G
DOCUMENT REVISION HISTORY

Version	Date	Description	Change
01	February 17 th , 2023	First Draft	No apply
02	July 12 th , 2023		Some data from the participants were included
03	October 31 st , 2023		

ANNEX II. Detailed Instrumentation Used By Participants

II.1. GEOSTM – Instrumentation Used

Laboratory name	Temperature and humidity reference unit
Bridge	Resistance measuring bridge with scanner (Super thermometer)
Manufactured	Fluke. USA
Type	1595A
AC or DC	
If AC, give Frequency	
If DC, give Period of reversal	
Normal measurement current	1 mA
Self-heating current	1.42 mA
Evaluation of linearity of resistance	
Bridge (yes or not)	
If yes, How?	
Reference resistor	
Manufactured / type	"England, ASL"
Reference resistor temperature control (yes or not)	Yes
If yes, How?	Oil Thermostat
TPW Cell	
Manufactured / model	USA, Fluke. model 5901D-G
Serial number	1369
Is it a primary reference? (if not explain its traceability)	key comparison #593/RU/13
Immersion depth of middle of the SPRT sensitive element/cm	24 cm
How are mantles maintained (ice, bath, ...)	Triple point water thermostat
Zn Cell	
Manufactured / model	USA Fluke 5906
Is it a primary reference? (if not explain its traceability)	key comparison #593/RU/13
Immersion depth of middle of the SPRT sensitive element/cm	17 cm
Closed cell or open	closed
Nominal purity	99.9999
Immersion depth of middle of the SPRT sensitive element/cm	17 cm
Zn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	3 zones
Typical duration of the melting / freezing plateaux	freezing plateaux

Sn Cell	
Manufactured / model	Russia VNIIM, T30 #189
Is it a primary reference? (if not explain its traceability)	key comparison #593/RU/13
Immersion depth of middle of the SPRT sensitive element/cm	17 cm
Closed cell or open	Closed
Nominal purity	99.9999
Immersion depth of middle of the SPRT sensitive element/cm	17 cm
Sn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	3 zones
Typical duration of the melting / freezing plateaux	freezing plateaux
Ga Cell	
Manufactured / model	USA, Fluke. model 5943
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	152 mm
Closed cell or open	Closed
Nominal purity	99.99999
Immersion depth of middle of the SPRT sensitive element/cm	152 mm
Ga Furnace	Ga Furnance Thermostat
Type (1 zone, 3 zones, heat pipe, ...)	Programmable 9230
Typical duration of the melting / freezing plateaux	Melting plateau

Hg Cell	Ampule of mercury
Manufactured / model	USA, Fluke; 5900E
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	210 mm
Closed cell or open	closed
Nominal purity	99.99999
Immersion depth of middle of the SPRT sensitive element/cm	210 mm
Hg cryostat	
Type (cryocooler, bath,...)	7037 cryocooler
Typical duration of the melting plateaux	Melting plateau

II.2. LACOMET – Instrumentation Used

Laboratory name	LACOMET
Bridge	
Manufactured	ISOTECH
Type	TTI-3
AC or DC	DC
If AC, give Frequency	---
If DC, give Period of reversal	8 s
Normal measurement current	1 mA
Self-heating current	$\sqrt{2}$ mA
Evaluation of linearity of resistance	Yes
Bridge (yes or not)	Yes
If yes, How?	Using an RBC
Reference resistor	
Manufactured / type	TINSLEY / model 5685A Nominal value 25 Ω
Reference resistor temperature control (yes or not)	Yes
If yes, How?	Oil bath
TPW Cell	
Manufactured / model	ISOTECH / A11-50-270
Serial number	1203
Is it a primary reference? (if not explain its traceability)	Primary reference
Immersion depth of middle of the SPRT sensitive element/cm	25,3 cm
How are mantles maintained (ice, bath, ...)	Bath
Zn Cell	
Manufactured / model	ISOTECH / 17672QCO
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
Closed cell or open	Open
Nominal purity	6N
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
Zn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	Heat pipe
Typical duration of the melting / freezing plateaux	8 h

Sn Cell	
Manufactured / model	ISOTECH / 17669QCO
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
Closed cell or open	Open
Nominal purity	6 N
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
Sn Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	3 zones
Typical duration of the melting / freezing plateaux	9 h
In Cell	
Manufactured / model	ISOTECH / 17668QCO
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
Closed cell or open	Open
Nominal purity	6N
Immersion depth of middle of the SPRT sensitive element/cm	17,3 cm
In Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	1 zone
Typical duration of the melting / freezing plateaux	11 h
Ga Cell	
Manufactured / model	ISOTECH / ITL-M-17401
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	20,3 cm
Closed cell or open	Closed
Nominal purity	7N
Immersion depth of middle of the SPRT sensitive element/cm	20,3 cm
Ga Furnace	
Type (1 zone, 3 zones, heat pipe, ...)	1 zone
Typical duration of the melting / freezing plateaux	16 h

Hg Cell	
Manufactured / model	ISOTECH / ITL-M-17724
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	14,3
Closed cell or open	Closed
Nominal purity	7 N
Immersion depth of middle of the SPRT sensitive element/cm	14,3
Hg cryostat	
Type (cryocooler, bath,...)	Cryostat
Typical duration of the melting plateaux	12 h
Ar Cell	
Manufactured / model	ISOTECH / 471
Is it a primary reference? (if not explain its traceability)	Yes
Immersion depth of middle of the SPRT sensitive element/cm	12,1 cm
Closed cell or open	
Nominal purity	6 N
Immersion depth of middle of the SPRT sensitive element/cm	12,1 cm
Ar cryostat	
Type (cryocooler, bath,...)	Pressure controlled dewar
Typical duration of the melting plateaux	3,5 h

ANNEX III. Detailed uncertainty tables

The following tables contain detailed uncertainties supplied by each NMI, along with the uncertainties determined at the pilot laboratory (CEM).

The columns named “Type” provide information to indicate whether an uncertainty component is related to either a random (R) or a systematic effect (S).

III.1. GEOSTM - uncertainty

	Zn mK	Sn mK	Ga mK	Hg mK	Type
W't values reproduction	0.76	0.558	0.278	0.383	A (R)
Chemical impurities and isotopic composition	0.300	0.25	0.29	0.23	B (S)
Hydrostatic Head errors	0.170	0.14	0.12	0.11	B (S)
Component of uncertainty correction relating to self-heating	0.07	0.06	0.04	0.06	B (S)
non-linearity of bridge	0.07	0.07	0.07	0.07	B (S)
Effect related with a standard coil	0.045	0.045	0.045	0.045	B (S)
Component of uncertainty of thermal equilibrium	0.09	0.08	0.08	0.08	B (S)
component relating to water triple point uncertainty	0.64	0.49	0.3	0.277	B (S)
Combined uncertainty	1.06	0.80	0.52	0.55	
Expanded uncertainty ($k = 2$) (coverage probability ~95 %)	2.1	1.6	1.0	1.1	

Table III.1.a Uncertainty budget supplied by GEOSTM, valid for measurements performed before SPRT travelling.

	Zn mK	Sn mK	Ga mK	Hg mK	Type
Phase Transition Realization Repeatability	0.233	0.135	0.082	0.028	A (R)
Bridge (repeatability, non-linearity, AC quadrature)	0.186	0.135	0.100	0.096	A (S)
Reference resistor stability	0.002	0.002	0.002	0.002	B (S)
Chemical impurities	0.326	0.171	0.039	0.057	B (S)
Hydrostatic-head	0.031	0.025	0.014	0.082	B (S)
Propagated TPW	0.141	0.109	0.058	0.043	B (S)
SPRT self-heating	0.038	0.040	0.031	0.031	B (R)
Heat Flux	0.129	0.058	0.012	0.014	B (S)
Insulation leakage	0.000	0.000	0.002	0.002	B (S)
SPRT Pt Oxidation	0.385	0.585	0.024	0.025	B (S)
Gas pressure	0.025	0.019	0.001	0.003	B (S)
Combined uncertainty	0.62	0.65	0.15	0.15	
Expanded uncertainty ($k = 2$) (coverage probability ~95 %)	1.24	1.30	0.31	0.31	

Table III.1.b Uncertainty budget determined at CEM on GEOSTM SPRT.

	Zn mK	Sn mK	Ga mK	Hg mK	Type
Wt values reproduction	0.67	0.597	0.273	0.395	A (R)
Chemical impurities and isotopic composition	0.30	0.25	0.29	0.23	B (S)
Hydrostatic Head errors	0.05	0.05	0.05	0.05	B (S)
Component of uncertainty correction relating to self-heating	0.085	0.05	0.04	0.06	B (S)
non-linearity of bridge	0.07	0.07	0.07	0.07	B (S)
Effect related with a standard coil	0.045	0.045	0.045	0.045	B (S)
Component of uncertainty of thermal equilibrium	0.12	0.11	0.11	0.12	B (S)
component relating to water triple point uncertainty	0.62	0.456	0.269	0.203	B (S)
Combined uncertainty	0.97	0.80	0.49	0.51	
Expanded uncertainty (k =2) (coverage probability ~95 %)	2.0	1.6	1.0	1.0	

Table III.1.c Uncertainty budget supplied by GEOSTM, valid for measurements performed after SPRT travelling.

III.2. LACOMET uncertainty

	Zn	Sn	In	Ga	Hg	Ar	Type
	mK	mK	mK	mK	mK	mK	
Bridge repeatability	0.072	0.051	0.070	0.040	0.058	0.060	A (R)
SPRT self-heating	0.148	0.112	0.144	0.083	0.120	0.126	B (R)
SPRT stability	0.005	0.025	0.006	0.005	0.002	0.031	B (R)
SPRT oxidation	0.036	0.031	0.055	0.011	0.192	0.146	B (R)
Bridge non linearity	0.037	0.035	0.034	0.029	0.030	0.028	B (S)
Bridge resolution	0.008	0.008	0.008	0.007	0.007	0.006	B (S)
Reference resistor short term stability	0.085	0.080	0.078	0.067	0.070	0.065	B (S)
Phase transition realization repeatability	0.257	0.498	0.218	0.085	0.016	0.041	B (R)
Hydrostatic-Head	0.100	0.060	0.077	0.004	0.017	0.002	B (S)
Gas pressure	0.005	0.003	0.004	0.001	-	-	B (S)
Chemical impurities	0.388	0.073	0.159	0.004	0.095	0.053	B (S)
Heat flux / Conduction	0.502	0.321	0.432	0.099	0.123	0.335	B (R)
Slope of Plateau	0.475	0.171	0.113	0.063	0.093	0.128	B (R)
TPW propagation	0.514	0.303	0.297	0.160	0.130	0.034	B (R)
Combined uncertainty	1.00	0.71	0.63	0.25	0.33	0.43	
Expanded uncertainty ($k=2$) (coverage probability ~95 %)	2.00	1.42	1.26	0.50	0.66	0.86	

Table III.2.a. Uncertainty budget supplied by LACOMET, valid for measurements performed before SPRTs travelling.

	Zn mK	Sn mK	In mK	Ga mK	Hg mK	Ar mK	Type
Phase Transition Realization Repeatability	0.323	0.169	0.034	0.010	0.221	0.061	A (R)
Bridge (repeatability, non-linearity, AC quadrature)	0.143	0.131	0.115	0.102	0.096	0.233	A (S)
Reference resistor stability	0.002	0.002	0.002	0.002	0.002	0.002	B (S)
Chemical impurities	0.326	0.171	0.270	0.039	0.057	0.028	B (S)
Hydrostatic-head	0.031	0.025	0.038	0.014	0.082	0.048	B (S)
Propagated TPW	0.151	0.108	0.090	0.062	0.045	0.011	B (S)
SPRT self-heating	0.050	0.052	0.050	0.038	0.030	0.022	B (R)
Heat Flux	0.129	0.058	0.100	0.012	0.014	0.304	B (S)
Insulation leakage	0.000	0.000	0.000	0.002	0.002	0.000	B (S)
SPRT Pt Oxydation	0.121	0.076	0.095	0.013	0.091	0.003	B (S)
Gas pressure	0.025	0.019	0.028	0.001	0.003	0.014	B (S)
Combined uncertainty	0.54	0.32	0.35	0.13	0.28	0.39	
Expanded uncertainty ($k=2$) (coverage probability ~95 %)	1.08	0.63	0.69	0.27	0.56	0.79	

Table III.2.b Uncertainty budget determined at CEM on LACOMET SPRTs.

	Zn	Sn	In	Ga	Hg	Ar	Type
	mK	mK	mK	mK	mK	mK	
Bridge repeatability	0.065	0.065	0.052	0.041	0.061	0.070	A (R)
SPRT self-heating	0.138	0.140	0.116	0.088	0.129	0.149	B (R)
SPRT stability	0.002	0.000	0.024	0.010	0.003	0.015	B (R)
SPRT oxidation	0.148	0.048	0.170	0.038	0.046	0.294	B (R)
Bridge non linearity	0.037	0.035	0.034	0.029	0.030	0.028	B (S)
Bridge resolution	0.008	0.008	0.008	0.007	0.007	0.006	B (S)
Reference resistor short term stability	0.085	0.080	0.078	0.067	0.070	0.065	B (S)
Phase transition realization repeatability	0.131	0.148	0.036	0.080	0.052	0.018	B (R)
Hydrostatic-Head	0.100	0.060	0.077	0.004	0.017	0.002	B (S)
Gas pressure	0.005	0.003	0.004	0.001	-	-	B (S)
Chemical impurities	0.388	0.073	0.159	0.004	0.095	0.053	B (S)
Heat flux / Conduction	0.502	0.321	0.432	0.099	0.123	0.335	B (R)
Slope of Plateau	0.475	0.171	0.113	0.063	0.093	0.128	B (R)
TPW propagation	0.474	0.356	0.266	0.195	0.145	0.039	B (R)
Combined uncertainty	0.97	0.57	0.60	0.27	0.29	0.50	
Expanded uncertainty ($k=2$) (coverage probability ~95 %)	1.94	1.14	1.20	0.54	0.58	1.00	

Table III.2.c Uncertainty budget supplied by LACOMET, valid for measurements performed after SPRTs travelling.

ANNEX IV. Immersion profiles

IV.1. GEOSTM immersion profiles

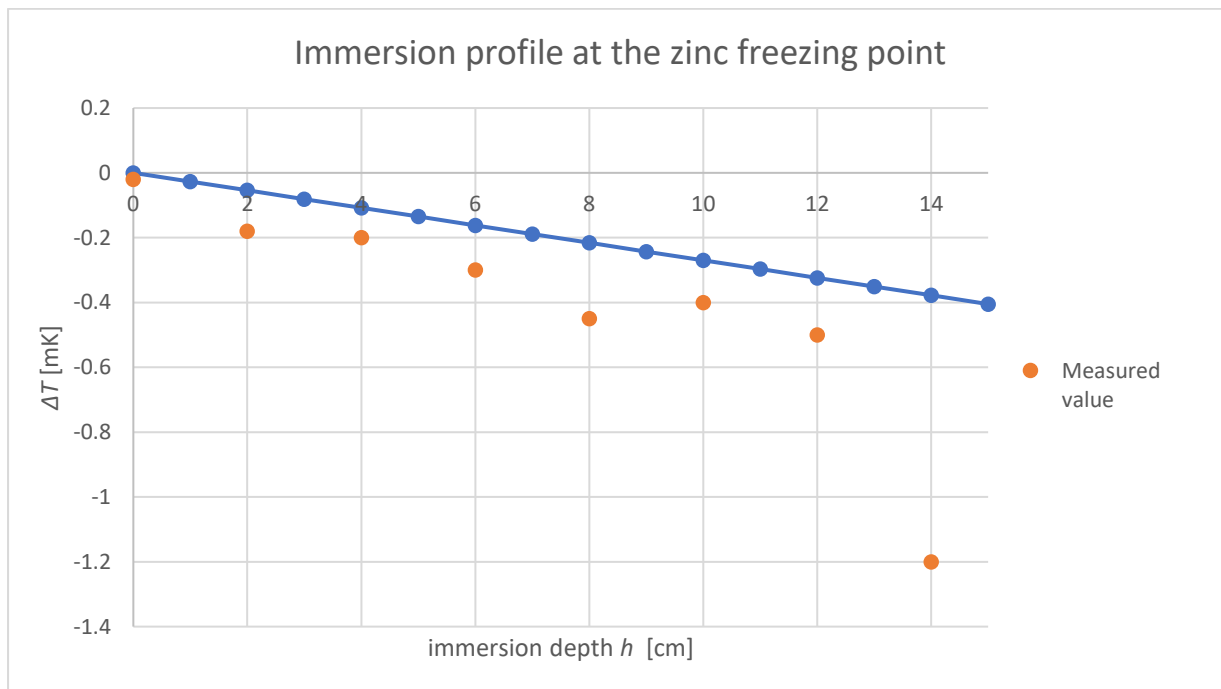


Figure IV.1.1. GEOSTM immersion profile of SPRT 339 at the Zn freezing point.

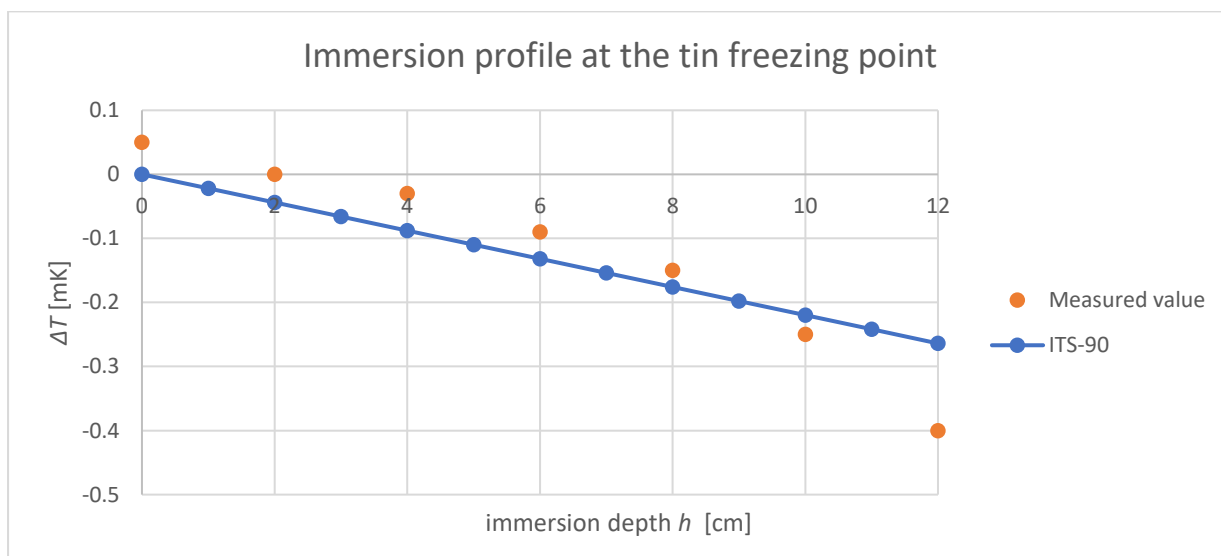


Figure IV.1.2. GEOSTM immersion profile of SPRT 339 at the Sn freezing point.

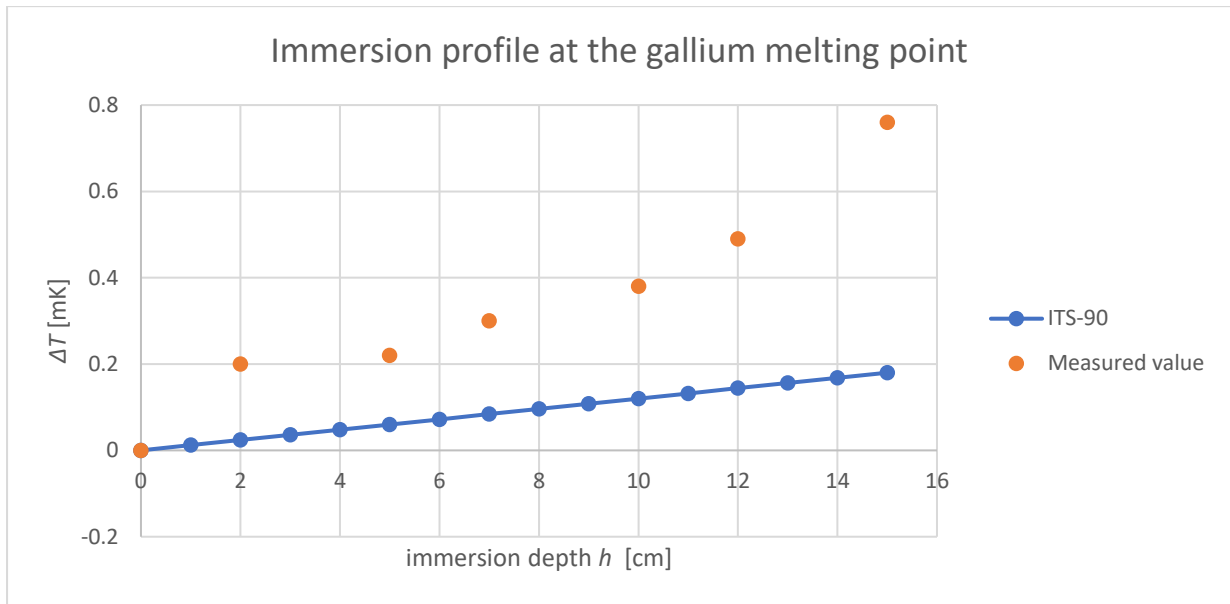


Figure IV.1.3. GEOSTM immersion profile of SPRT 339 at the Ga melting point.

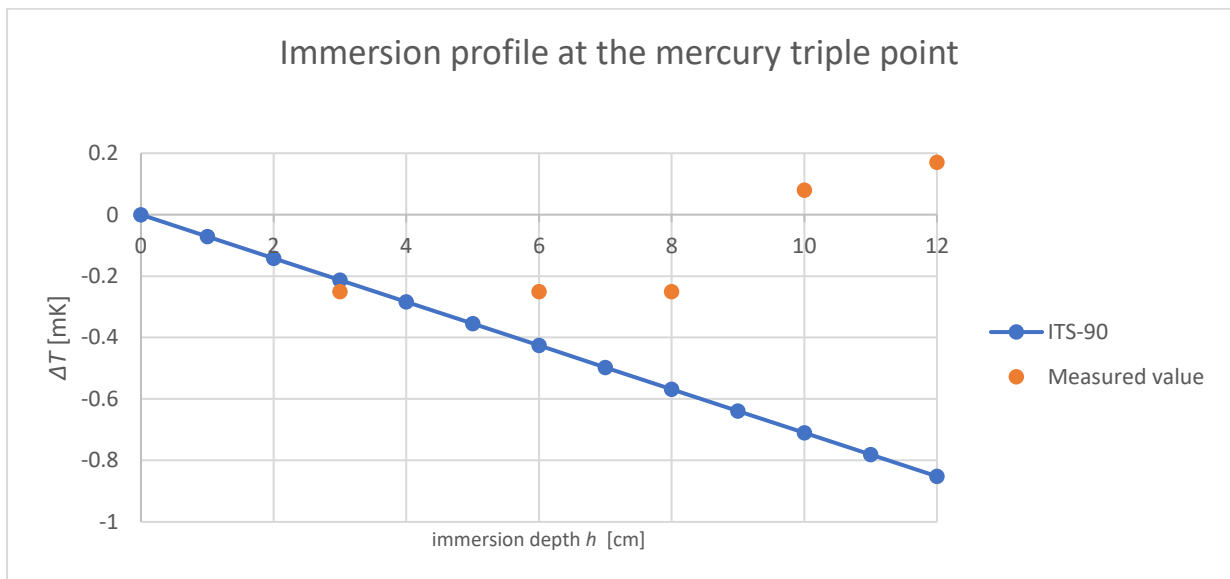


Figure IV.1.4. GEOSTM immersion profile of SPRT 339 at the Hg triple point.

IV.2 LACOMET immersion profiles

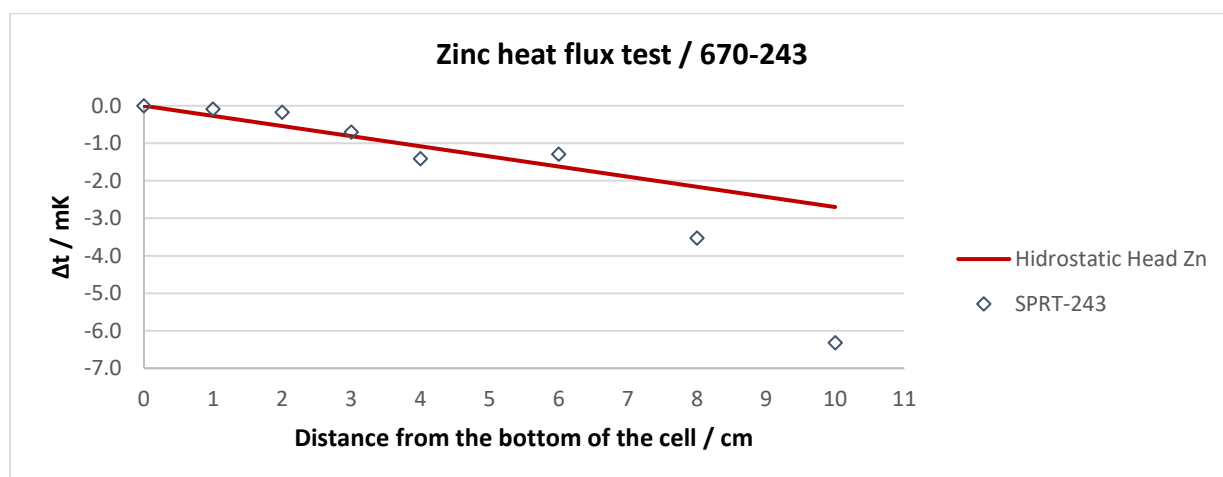


Figure IV.2.1. LACOMET immersion profile of SPRT 243 at the Zn freezing point.

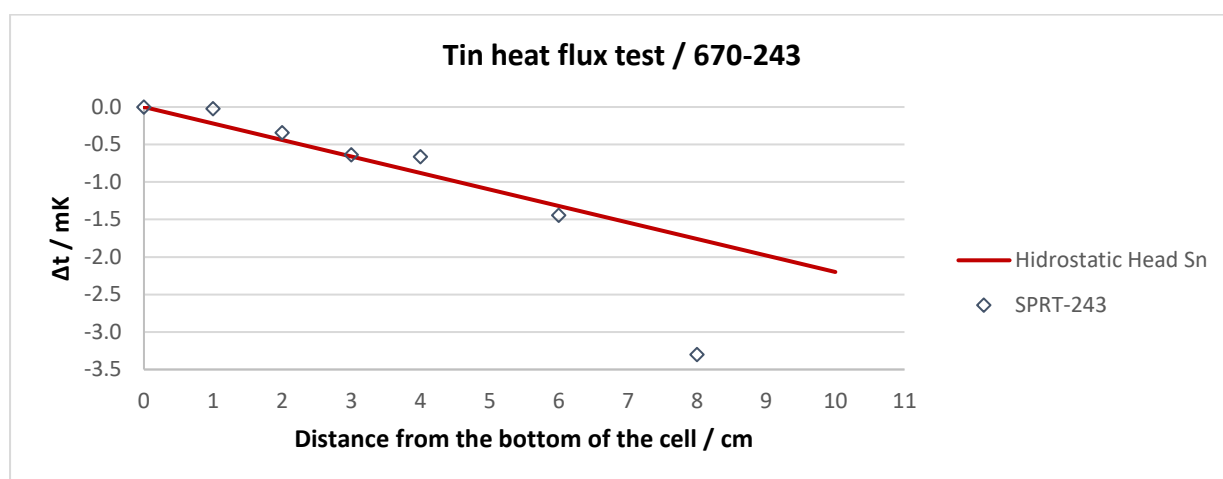


Figure IV.2.2. LACOMET immersion profile of SPRT 243 at the Sn freezing point.

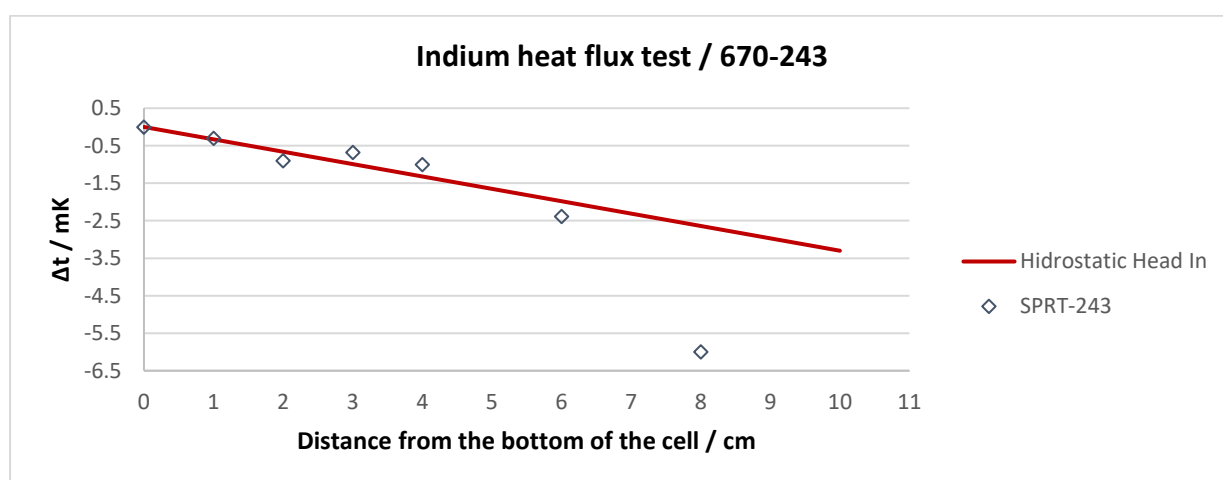


Figure IV.2.3. LACOMET immersion profile of SPRT 243 at the In freezing point.

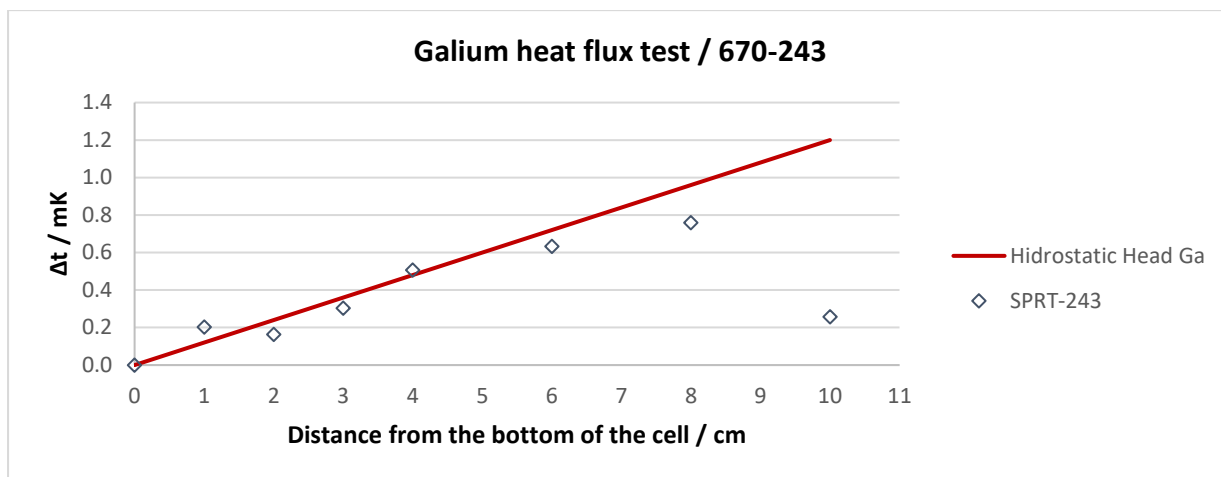


Figure IV.2.4. LACOMET immersion profile of SPRT 243 at the Ga melting point.

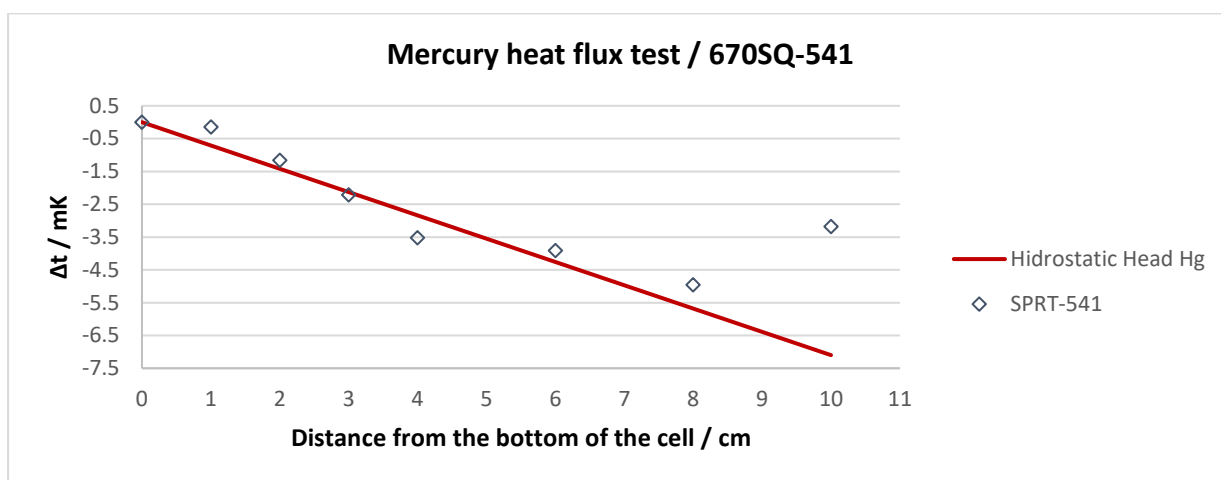


Figure IV.2.5. LACOMET immersion profile of SPRT 541 at the Hg triple point.

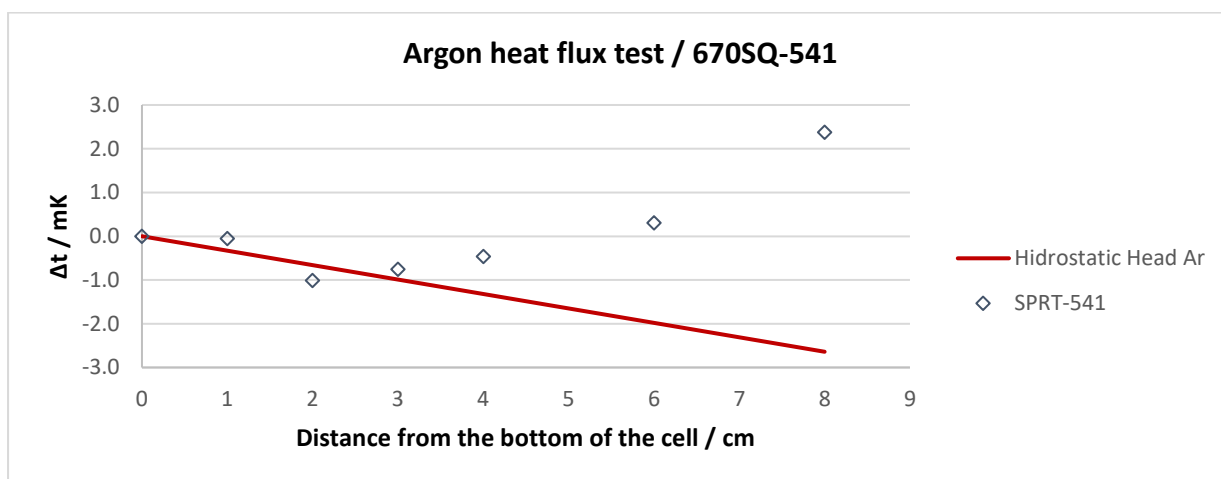


Figure IV.2.6. LACOMET immersion profile of SPRT 541 at the Ar triple point.

ANNEX V. Phase transition curves

The graphs included below correspond to example of the phase transition curves of the fixed point cells used by the participants during the comparison.

V.1. GEOSTM phase transition curves

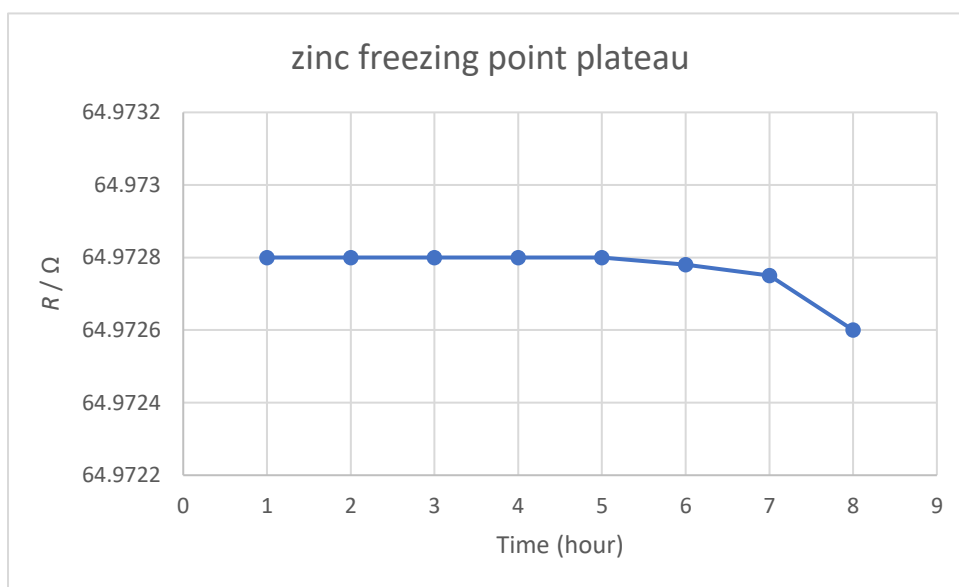


Figure V.1.1. GEOSTM Zn phase transition curve.

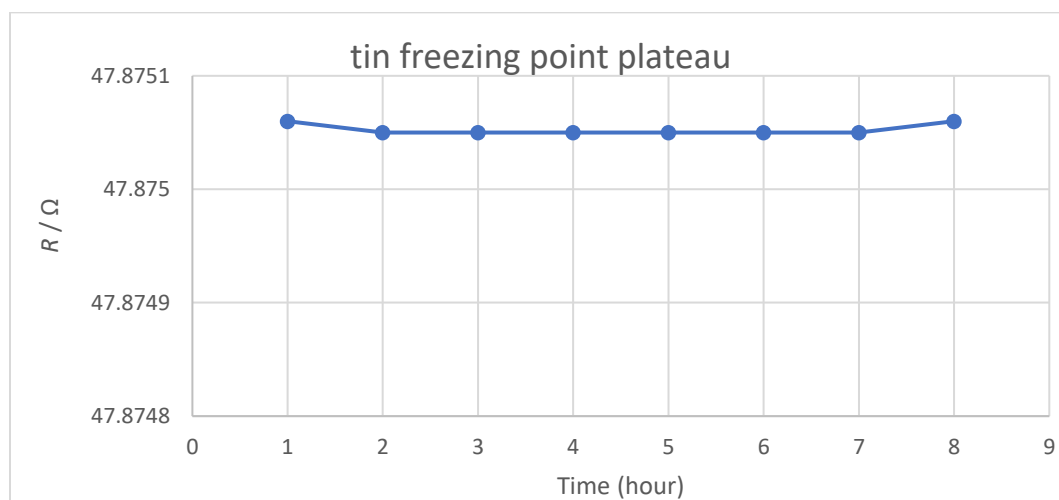


Figure V.1.2. GEOSTM Sn phase transition curve.

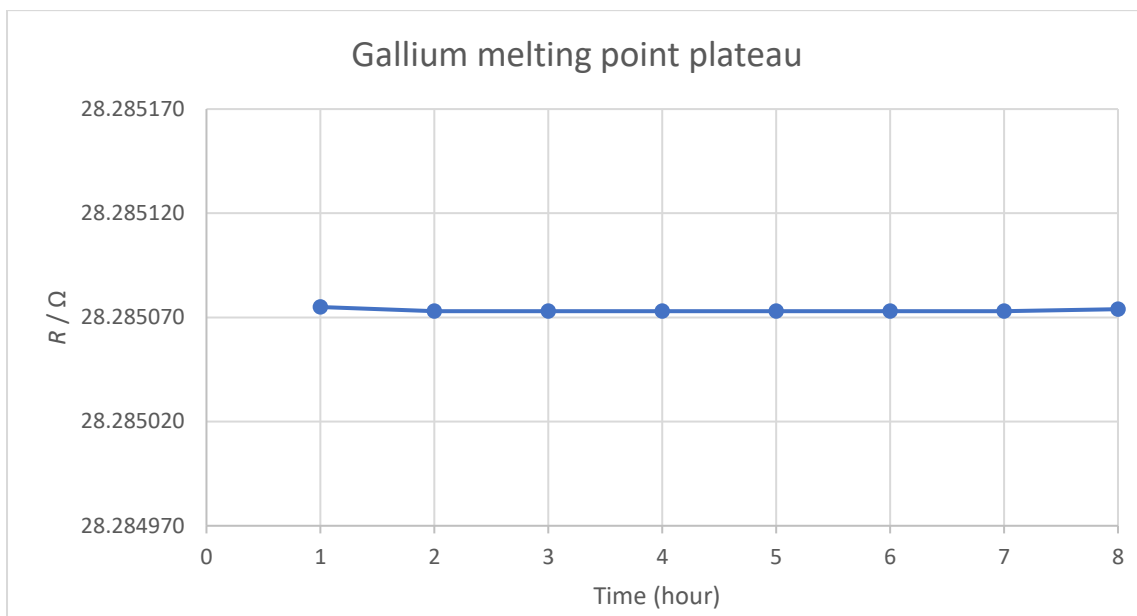


Figure V.1.3. GEOSTM Ga phase transition curve.

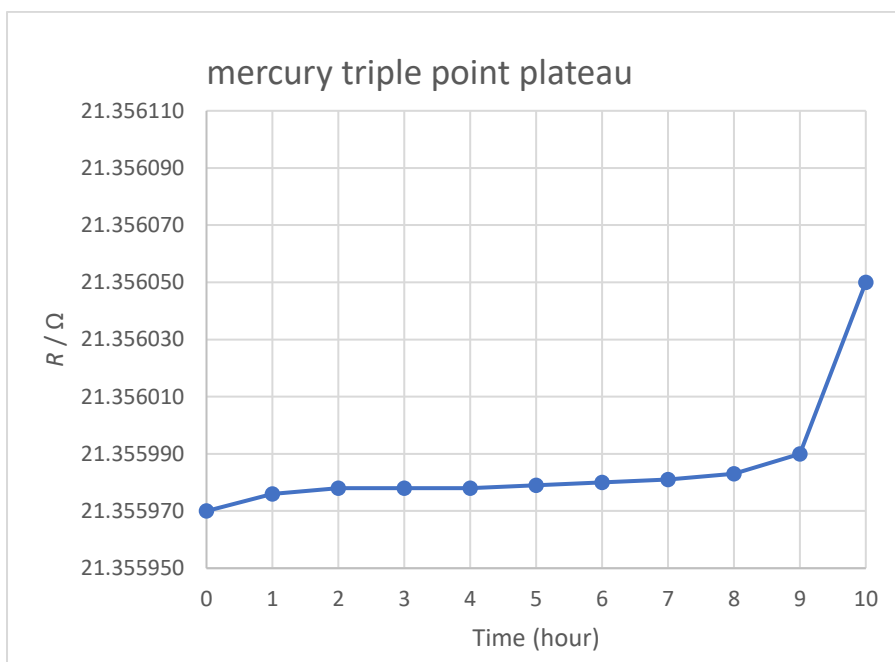


Figure V.1.4. GEOSTM Hg phase transition curve.

V.2 LACOMET phase transition curves

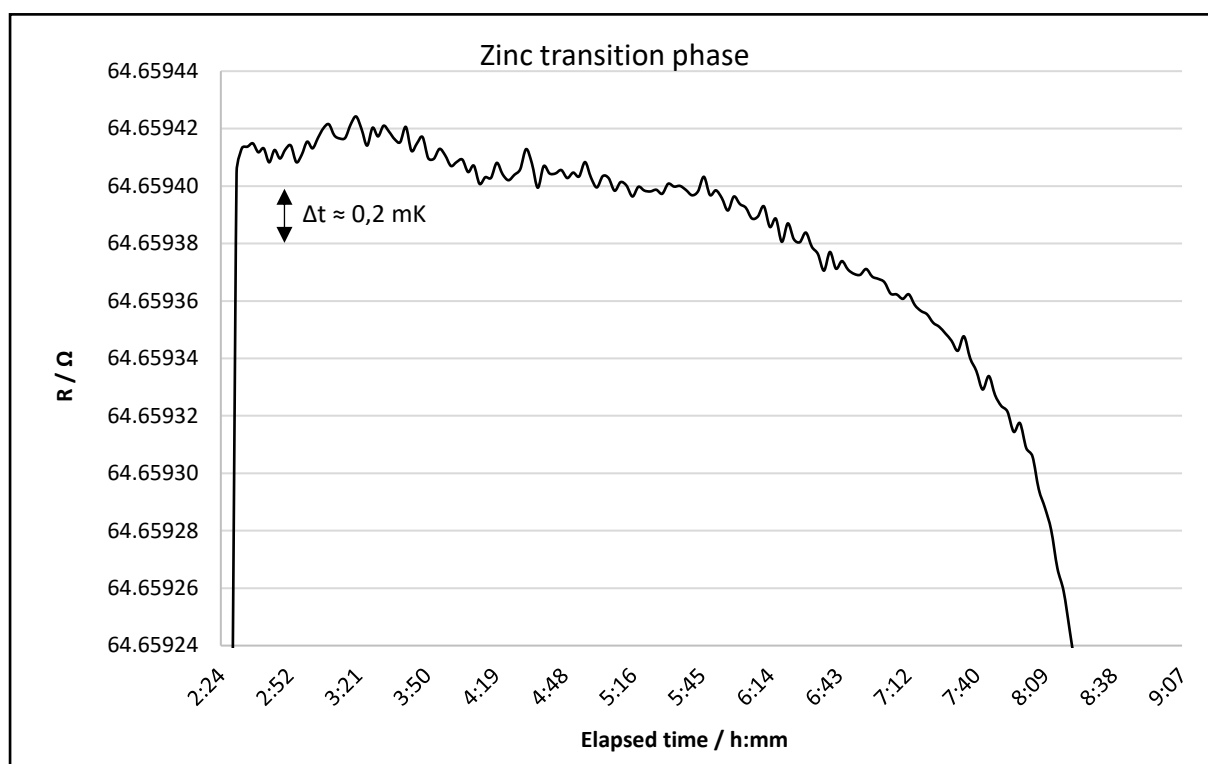


Figure V.2.1. LACOMET Zn phase transition curve.



Figure V.2.2. LACOMET Sn phase transition curve.

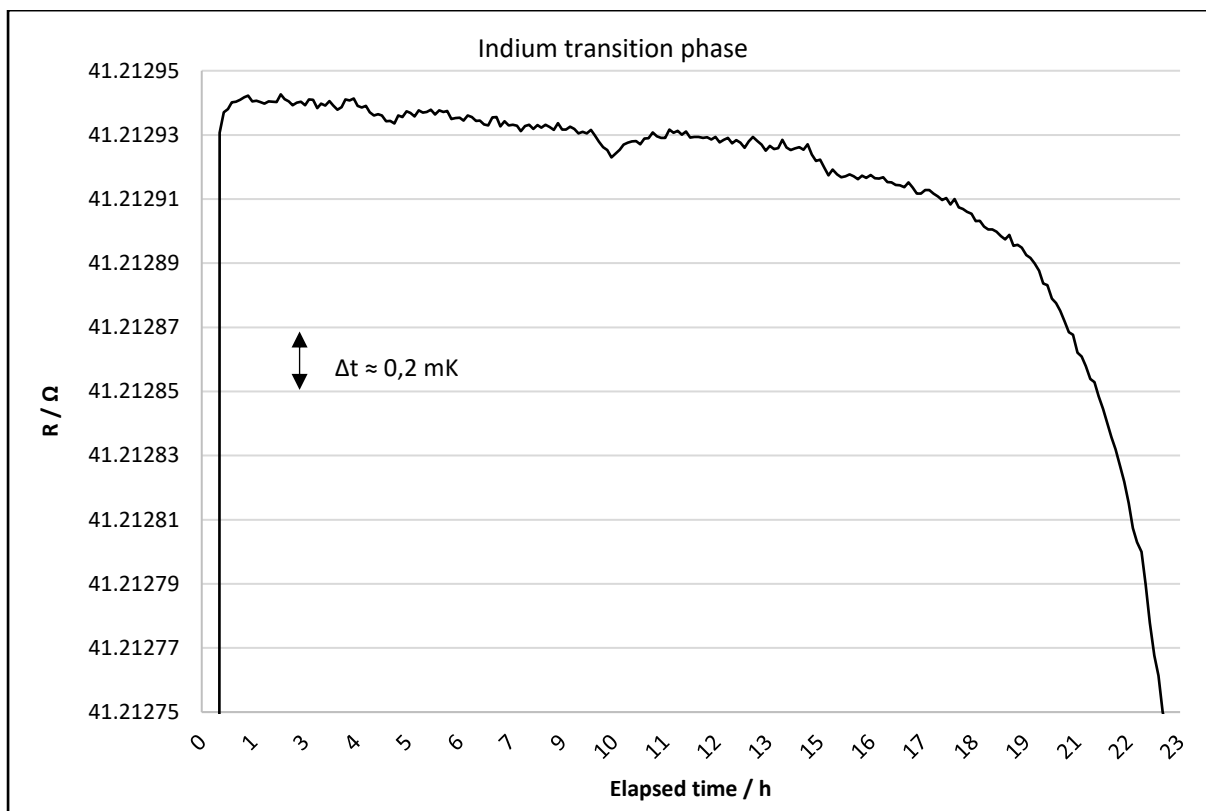


Figure V.2.3. LACOMET In phase transition curve.

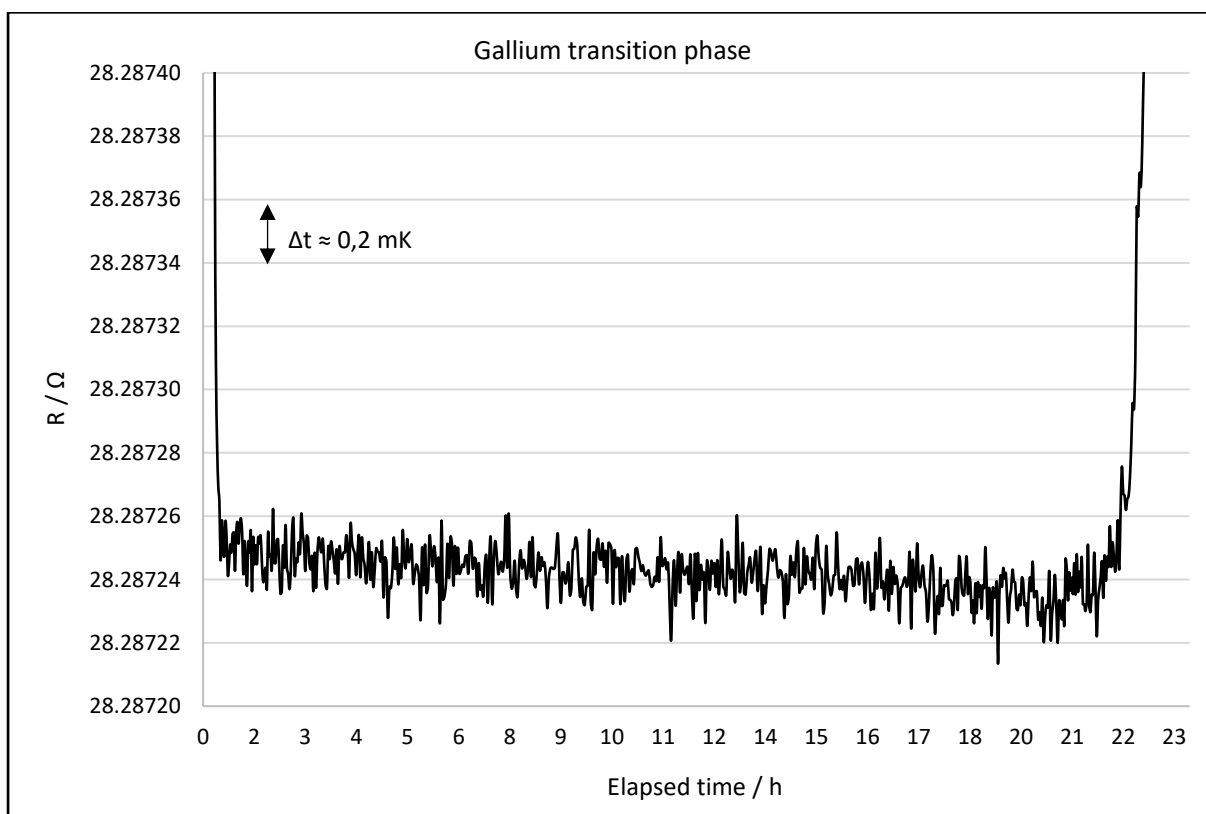


Figure V.2.4. LACOMET Ga phase transition curve.

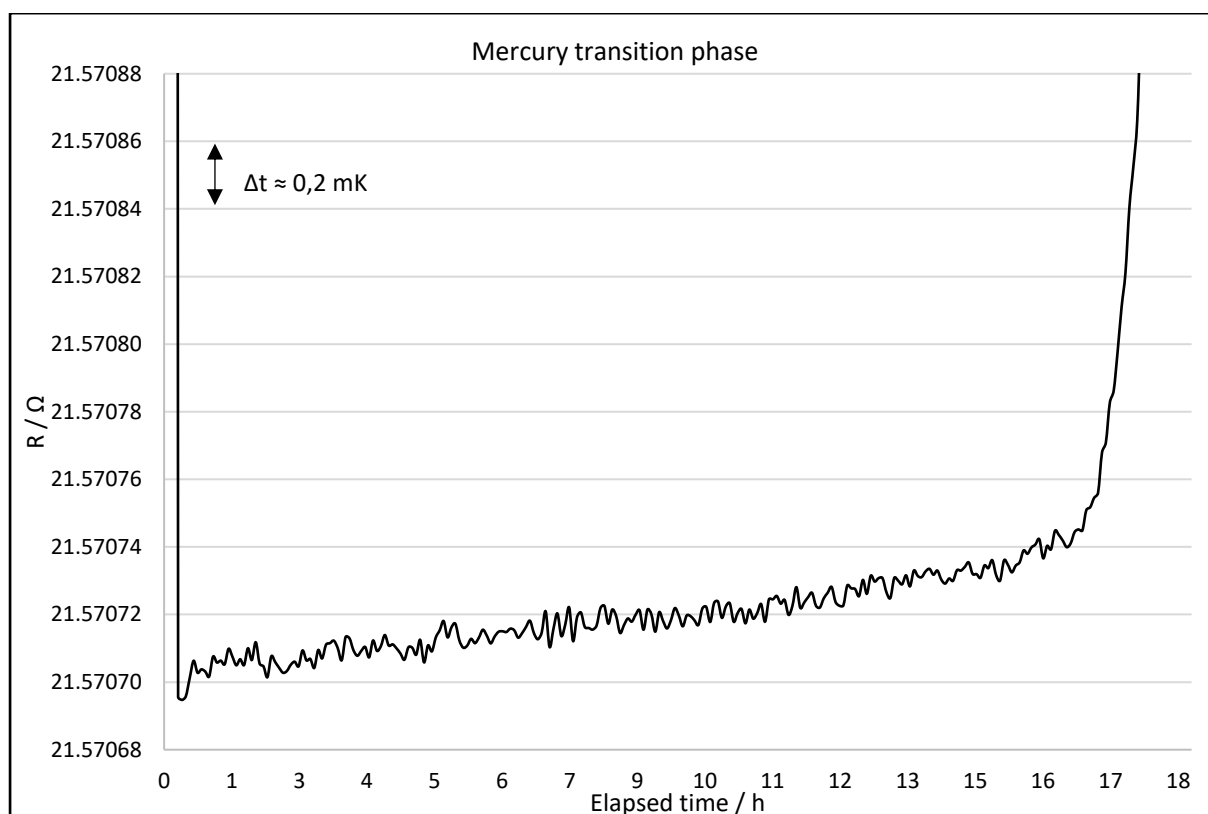


Figure V.2.5. LACOMET Hg phase transition curve.

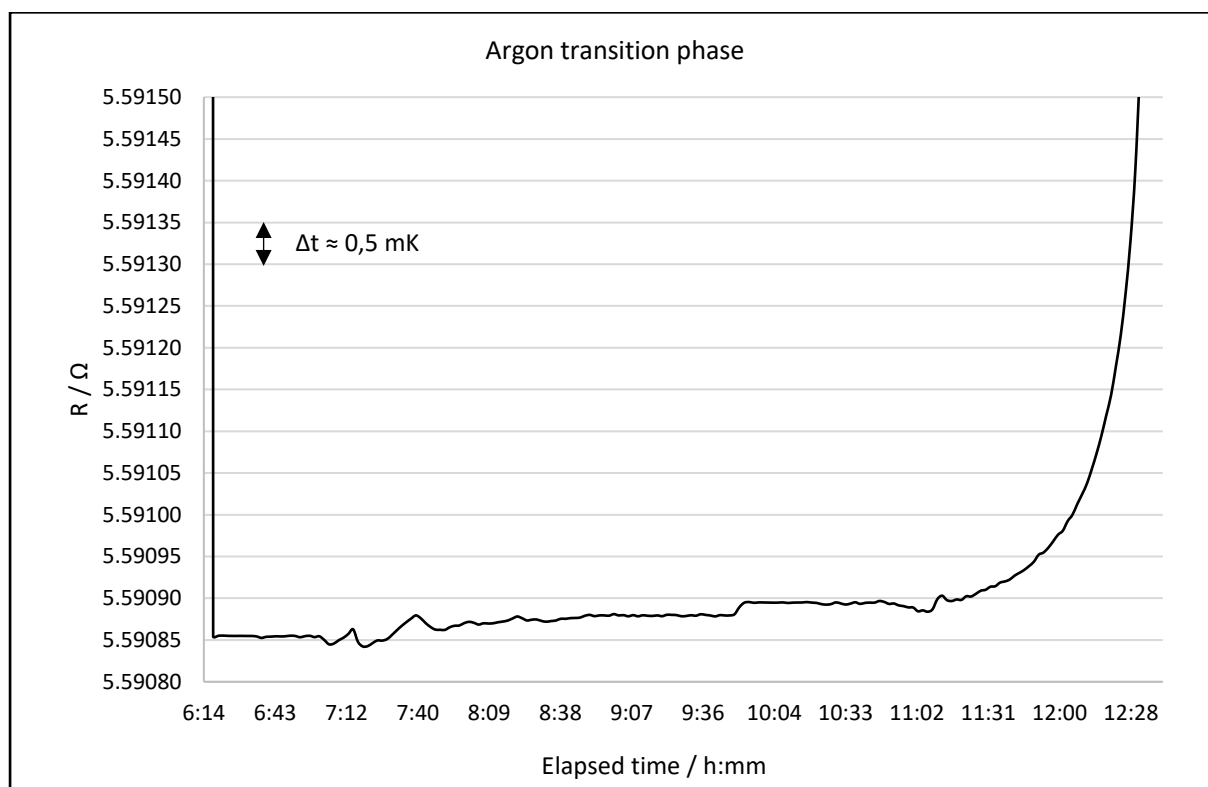


Figure V.2.6. LACOMET Ar phase transition curve.

V.3 CEM phase transition curves

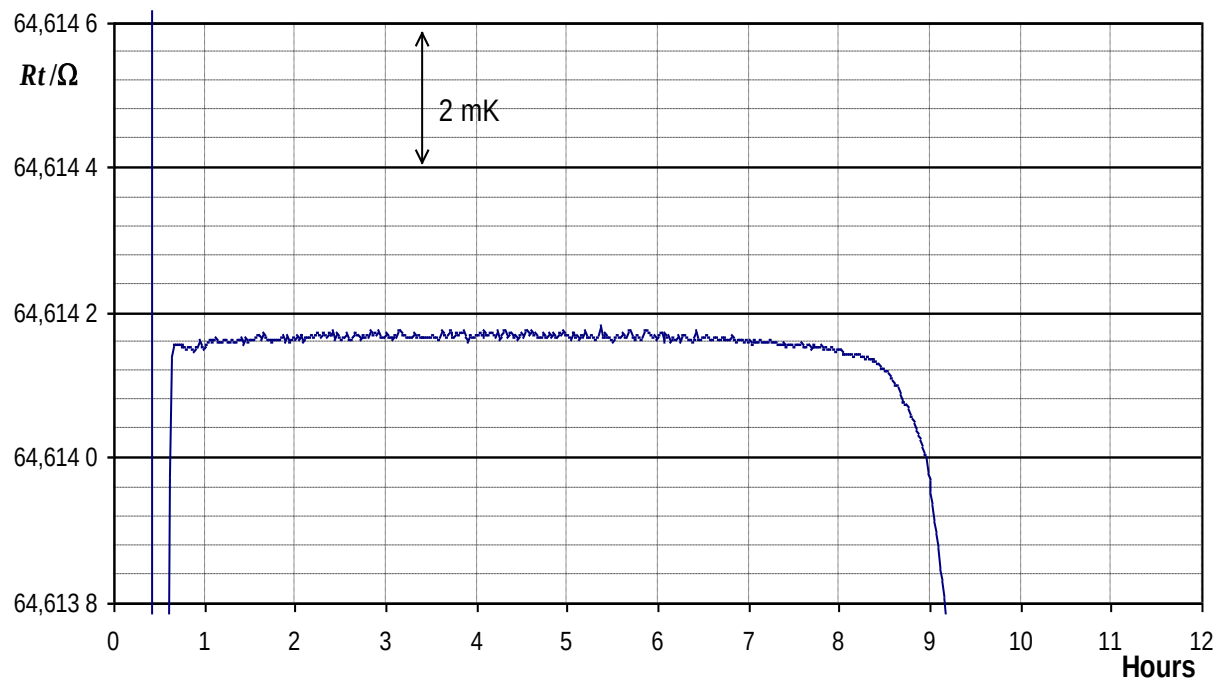


Figure V.3.1. CEM Zn phase transition curve.

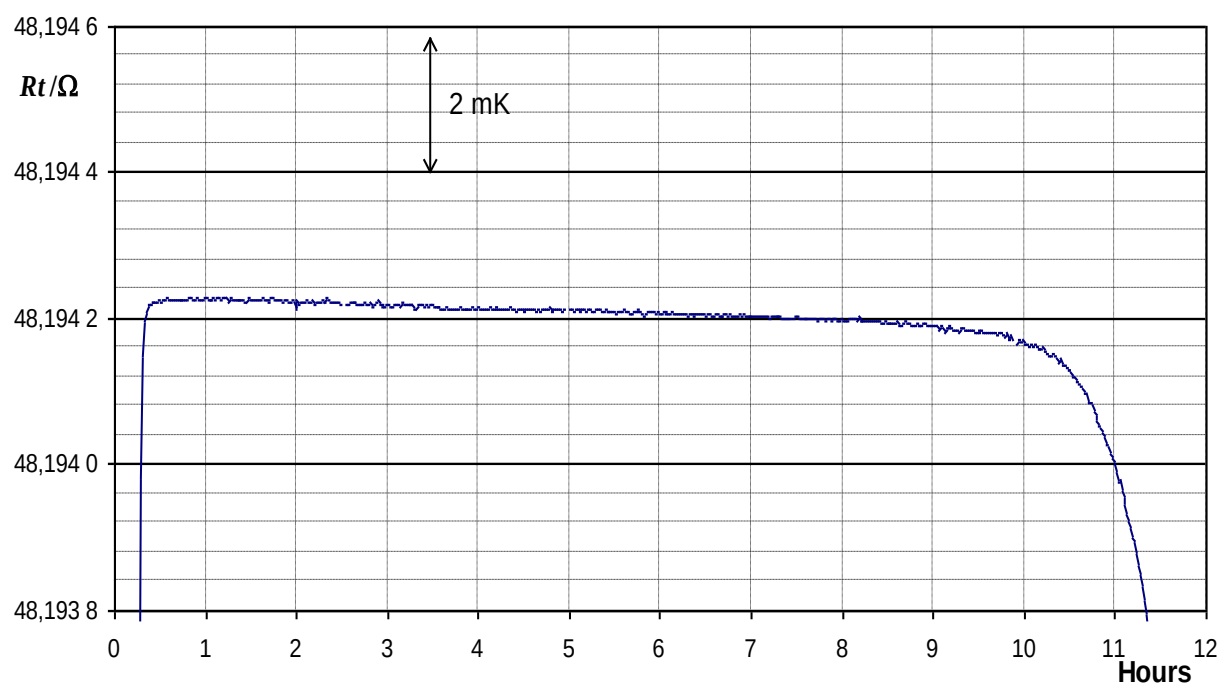


Figure V.3.2. CEM Sn phase transition curve.

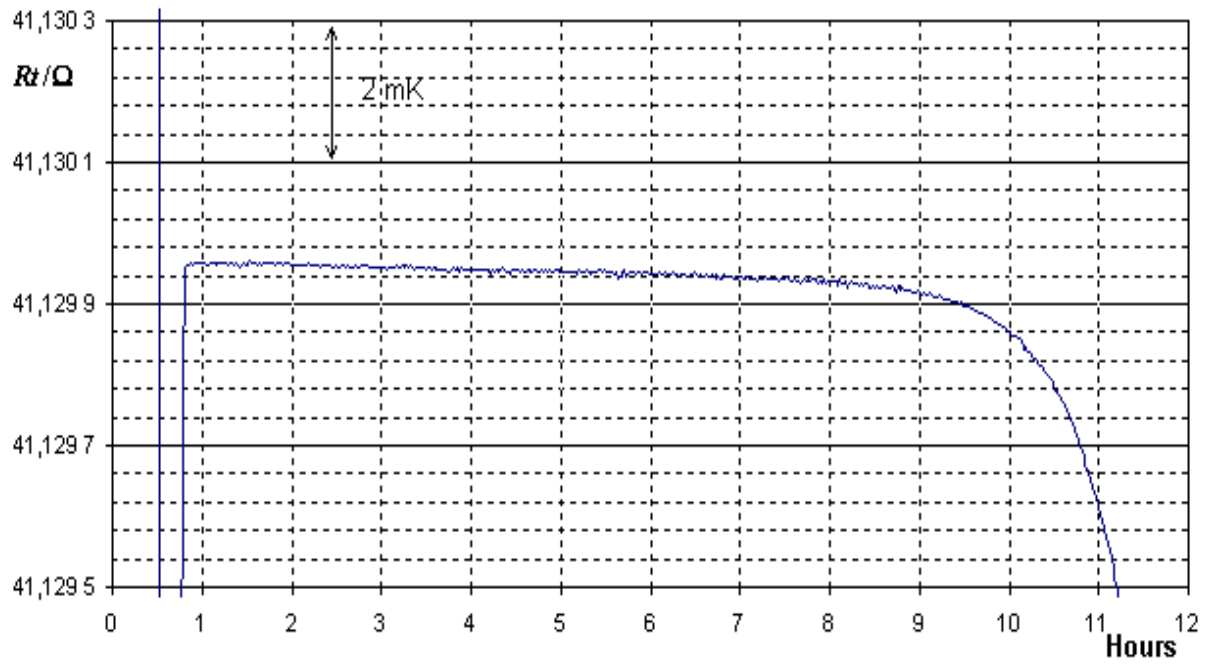


Figure V.3.3. CEM In phase transition curve.

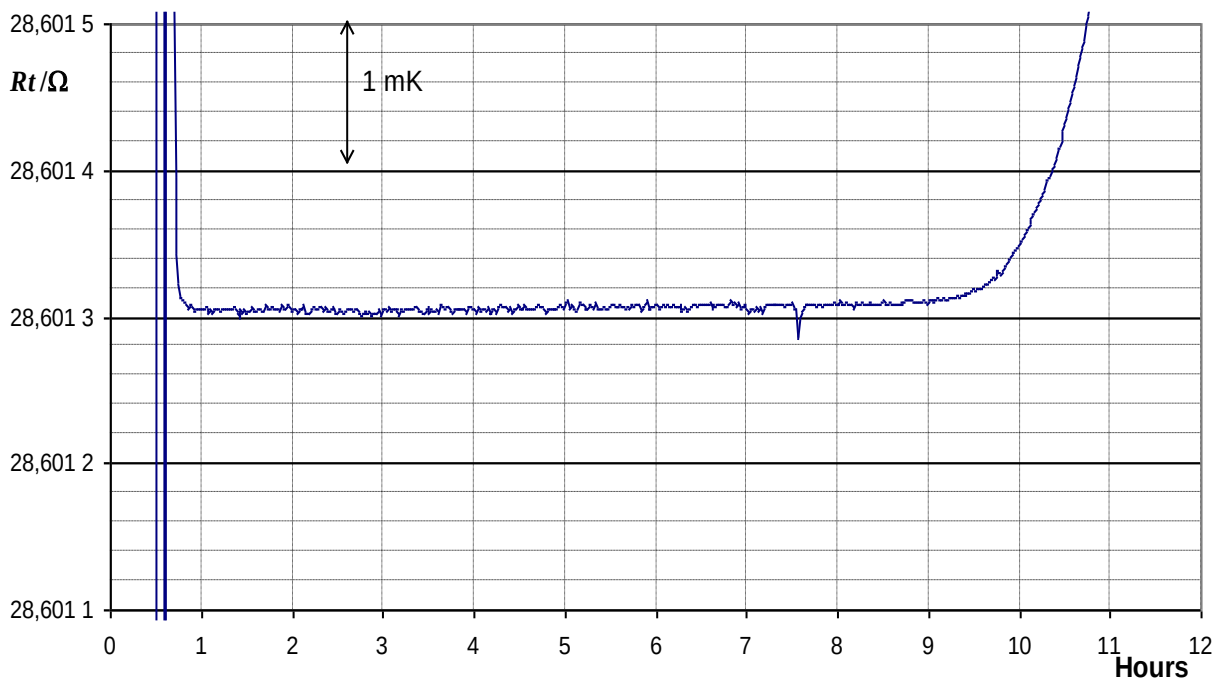


Figure V.3.4. CEM Ga phase transition curve.

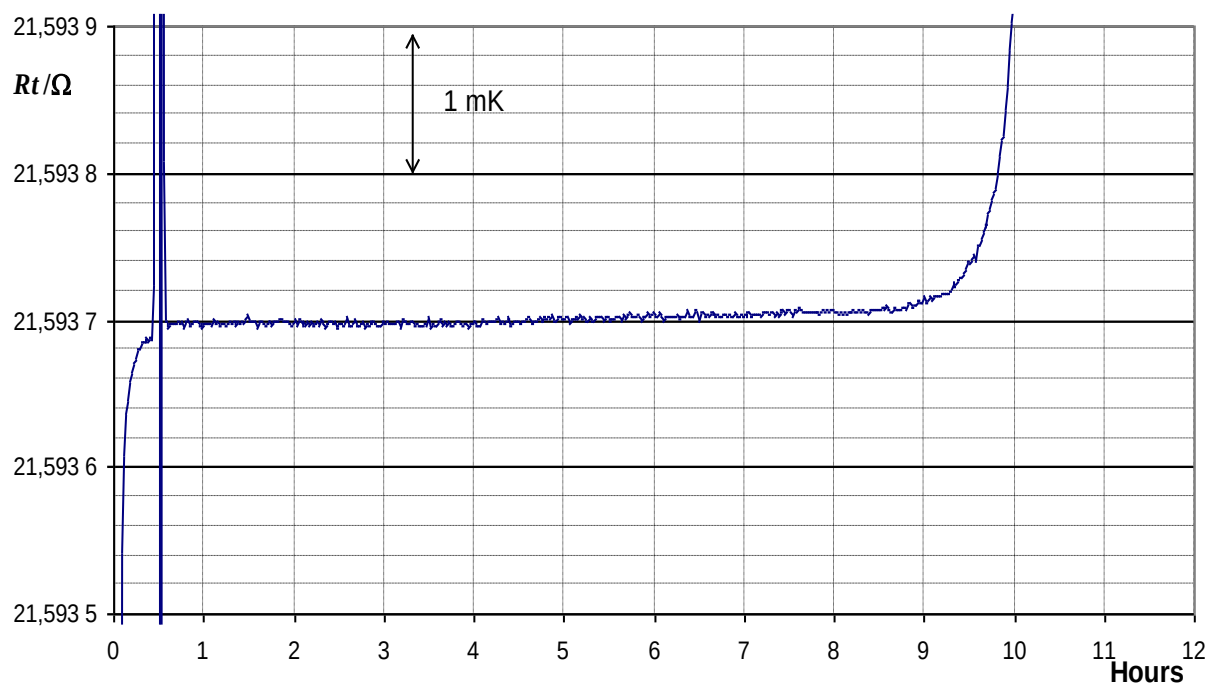


Figure V.3.5. CEM Hg phase transition curve.

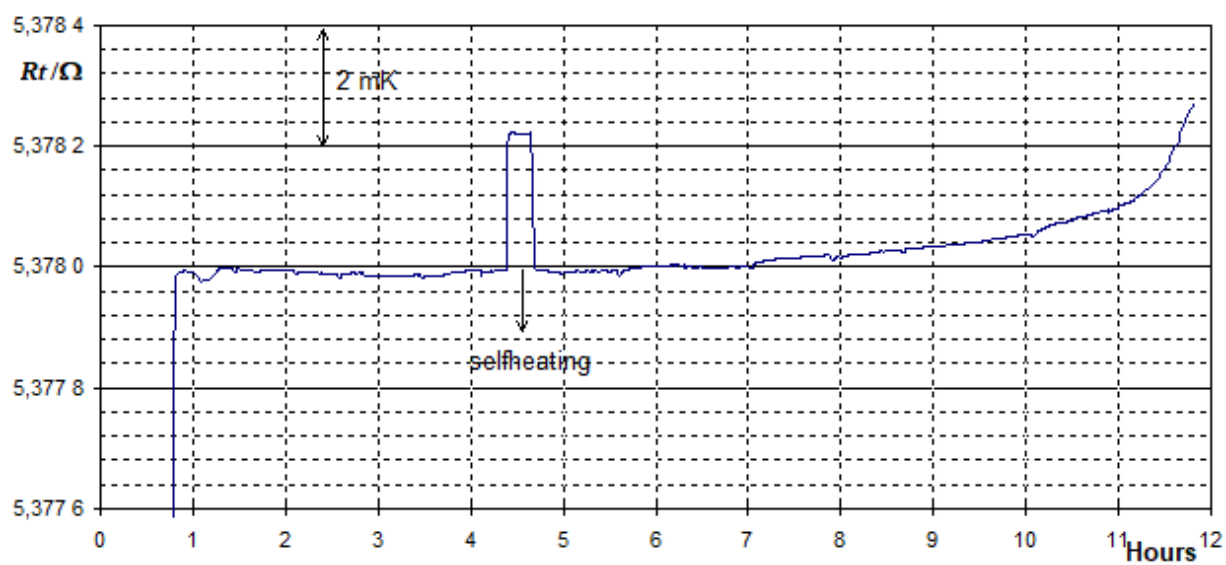


Figure V.3.6. CEM Ar phase transition curve.