EURAMET TC Project
Final Report

Project Title

Hybrid comparison of SPRT calibration in the triple point of argon (83.8058 K) and the triple point of mercury (234.3156 K)

Coordinator, Institute, Country

Jovan Bojkovski (MIRS/UL-FE/LMK)

EURAMET Registration No.

1681

Subject Field

Thermometry

KCDB Identifier

--

Date

2024-11-13

EURAMET e.V., Bundesallee 100, 38116 Braunschweig, Germany
Phone: +49 531 592 1960   Fax: +49 531 592 1969   E-mail: secretariat@euramet.org
www.euramet.org

HYBRID COMPARISON BETWEEN MIRS/UL-FE/LMK AND FSB-LPM

SPRT calibration in the triple point of argon (83.8058 K) and the triple point of mercury (234.3156 K)

FINAL REPORT

Table of Contents

1. INTRODUCTION

This is a report to the Technical Committee for Thermometry of EURAMET (EURAMET TC-T) on the hybrid comparison of the ITS-90 realization in the triple point of argon (83.8058 K) and triple point of mercury (234.3156 K) through the calibration of SPRT between Laboratory of Metrology and Quality (MIRS/UL-FE/LMK), acting as Issuing NMI, and „Faculty of Mechanical Engineering and Naval Architecture, Laboratory for Process Measurement“ (FSB-LPM) as Applicant NMI.

1.1. Issuing NMI:

University of Ljubljana, Faculty of Electrical Engineering

Laboratory of Metrology and Quality (MIRS/UL-FE/LMK),

Address: Tržaška cesta 25, SI-1000 Ljubljana, Slovenia

Contact person:

Prof. dr. Jovan Bojkovski (Coordinator)

Tel.: +386 1 4768 798,

GSM: +386 51 388 659

e-mail: jovan.bojkovski@fe.uni-lj.si

1.2. Applicant NMI:

Faculty of Mechanical Engineering and Naval Architecture,

Laboratory for Process Measurement (FSB-LPM)

Address: Ivana Lučića 5, 10000 Zagreb, Croatia

Contact person:

Ivan Matas, mag. ing. mech.

GSM: +385 98 9709 836

e-mail: ivan.matas@fsb.unizg.hr

2. COMPARISON PROTOCOL

2.1. Protocol

Protocol of this hybrid comparison was prepared according to the relevant guidelines [1-3] and followed the outline from protocol of EURAMET.T-K9 comparison [4]. According to the protocol, Applicant NMI took care about the transport of the transfer standard between both laboratories. The Applicant NMI had hand-carried thermometer from the Issuing NMI and returned it to the Issuing NMI after completion of measurements. The transfer standard was handled with extreme care during transport and was inspected and cleaned after every travel. A stability check of the transfer standard, consisting of a triple point of water check, was carried out in both participating laboratories before starting any other measurements in the triple points and after all the measurements. The calibration procedure in each participating laboratory followed internal laboratory procedure for realisation of the fixed points. The calibration of the SPRT was conducted from higher to lower temperatures, first at mercury triple point (Hg TP, 234.3156 K) and then at the argon triple point (Ar TP, 83.8058 K). Before and after each calibration point, the *R*(TPW) value of the SPRT was measured. Minimum of 3 realizations of the triple point of argon and triple point of mercury plateau had to be achieved at each participating laboratory. The resistance of SPRT during the whole duration of the one plateau of the triple point of argon and mercury had to be recorded. Heat Flux (Immersion) profile for each fixed-point cell using the transfer standard (SPRT) for bottom 5 cm was determined. The reported values of $R(FP_i)$ and $R(TPW)$ were corrected for self-heating and for the hydrostatic head. The resistance ratio $W(FP_i)$ values determined at each participating laboratory were compared.

The complete agreed technical protocol is included in the Appendix I.

2.2. Calculation of the reference value and associated uncertainty

The reference value of the resistance ratio $W(FP_i)$ was calculated as average of the values obtained by Issuing NMI during first ($W(FP_i)_1$) and second set of measurements ($W(FP_i)_2$), according to the equation (1).

$$W(FP_i)_{ref} = \frac{W(FP_i)_1 + W(FP_i)_2}{2} \quad (1)$$

The temperature difference Δ*T* between the fixed-point realization performed at the Issuing NMI and Applicant NMI is calculated as:

$$\Delta T_{(ref-LPM)} = \frac{W(FP_i)_{ref} - W(FP_i)_{LPM}}{dW_r/dT} + drift \quad (2)$$

Where *drift* 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 associated uncertainty of the reference value included the uncertainty of the realisation and the drift of the transfer standard and was calculated according to the equation (3):

$$U[W(FP_i)_{ref}] = \sqrt{U[W(FP_i)_1]^2 + U[W(FP_i)_2]^2 + U(drift)^2} \quad (3)$$

The drift of the transfer standard was calculated from the shift of the resistance ratio $W(FP_i)$ obtained at each fixed point between first and second measurement at Issuing NMI:

$$U(drift) = \frac{1}{2\sqrt{3}} \frac{|W(FP_i)_2 - W(FP_i)_1|}{dW_r/dT} \quad (4)$$

Where dW_r/dT represents the sensitivity of the reference function *Wr* defined in the ITS-90.

3. DESCRIPTION OF THE EQUIPMENT AND RESULTS

3.1. Transfer standard

The transfer standard used for this hybrid comparison was quartz sheathed long-stem SPRT and was provided by „Issuing NMI". The technical data of the transfer standard are presented in Table 1.

Table 1. Technical data sheet of transfer standard

Manufacturer	Hart Scientific
Model	5681
Dimensions (diameter and length)	Φ = 7 mm, L = 520mm
Nominal resistance	25,5 Ω
Serial number:	1408
Measuring range:	-196 to 661 °C

3.2. Results

Results of both laboratories were reported in the measurement reporting worksheet according to the protocol. Measurement reporting worksheets of both laboratories can be seen in Appendix II. The summary of the measurement results obtained at fixed points is presented in Tables 3, 4 and 5. 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 of both participating laboratories are shown in Appendix III.

Table 2. Results of the measurements at TPW

No. and date of measurement	Participating laboratory	*R* (TPW), on receipt	*R* (TPW), final	*U* (TPW)
		Ω	Ω	mK
1st measurement, Jul 2 – Jul 4, 2024	MIRS/UL-FE/LMK	25.41284068	25.41314048	0.15
Aug 18 – Aug 23, 2024	FSB-LPM	25.4131567	25.4131527	0.46
2nd measurement, Sep 9 – Sep 12, 2024	MIRS/UL-FE/LMK	25.41315858	25.41315098	0.15

Table 3. Results of both participating laboratories at the TP Hg

No. and date of measurement	Participating laboratory	***R*** **(Hg)**	***W*** **(Hg)**	**No. of real.**	***U***
		Ω	**-**	**-**	**mK**
1st measurement, Jul 2 – Jul 4, 2024	MIRS/UL-FE/LMK	21.45262564	0.844156472	3	0.21
Aug 18 – Aug 23, 2024	FSB-LPM	21.45265393	0.844155444	3	1.54
2nd measurement, Sep 9 – Sep 12, 2024	MIRS/UL-FE/LMK	21.45267771	0.844157163	3	0.21

Table 4. Results of both participating laboratories at the TP Ar

No. and date of measurement	Participating laboratory	***R*** **(Ar)**	***W*****(Ar)**	**No. of real.**	***U***
		Ω	**-**	**-**	**mK**
1st measurement Jul 2 – Jul 4, 2024	MIRS/UL-FE/LMK	5.487474913	0.21593103	3	0.26
Aug 18 – Aug 23, 2024	FSB-LPM	5.487542739	0.215933113	3	1.85
2nd measurement, Sep 9 – Sep 12, 2024	MIRS/UL-FE/LMK	5.487524347	0.215932648	3	0.26

4. RESULTS OF THE COMPARISON

The results of the comparison are presented in Table 5 and graphically on Figure 1.

Table 5. Results of the comparison

	W **(Ar)**	***U*** **(Ar)**	***W*** **(Hg)**	***U*** **(Hg)**
	-	**mK**	**-**	**mK**
MIRS/UL-FE/LMK reference value	0.215932	0.276871	0.844157	0.215739783
FSB-LPM	0.215933	1.852	0.844155	1.536
deviation/mK	-0.29383	1.872582	0.340304	1.551076934

Figure 1 shows the difference between reference values determined by coordinating laboratory MIRS/UL-FE/LMK and values obtained at FSB-LPM. Determined deviations at both fixed points are well within the combined uncertainty limits that include the uncertainty of the realizations from both participating laboratories (presented in Table 5) and uncertainty due to the drift of the transfer standard. The combined uncertainty was calculated according to the equation (3).

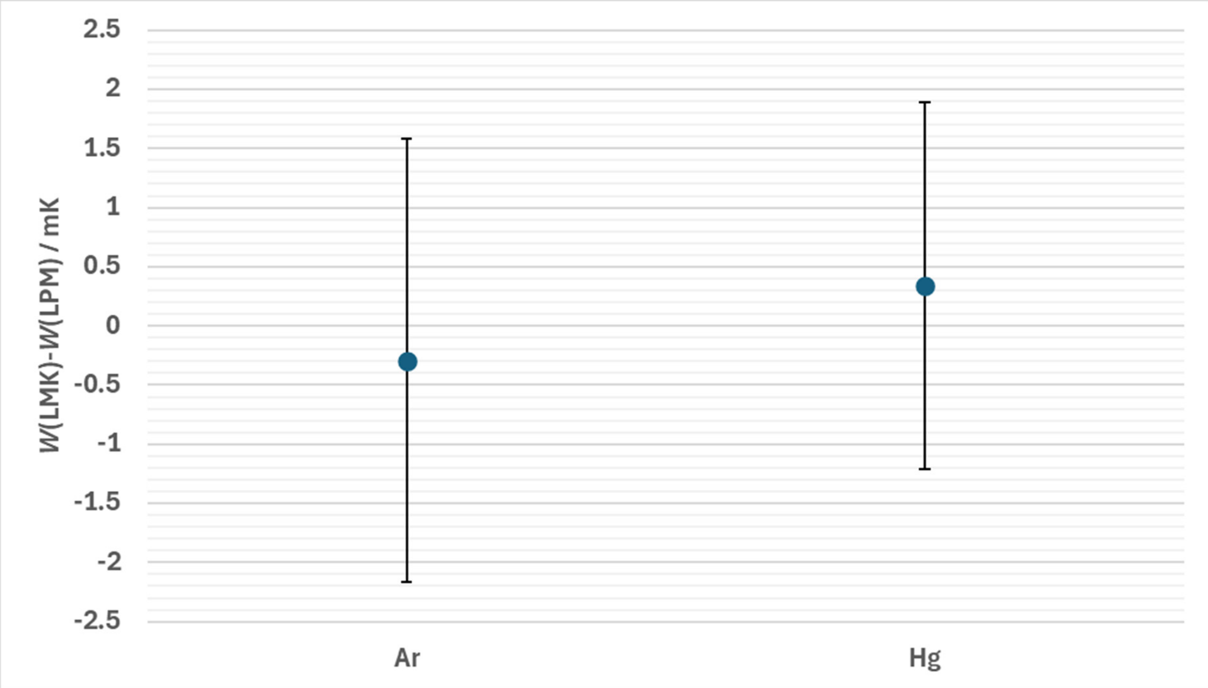


Figure 1. Deviation of FSB-LPM results from the reference value (LMK)

5. REFERENCES

1. **EURAMET, Guide on Comparisons**, EURAMET Guide No. 4 Version 2.0, April 2021.
2. **Measurement comparisons in the CIPM MRA, Guidelines for organizing, participating and reporting**, CIPM MRA-G-11, v1.1, January 2021
3. APMP, **APMP guideline for using Hybrid Comparisons as CMC evidences**, November 2020
4. **EURAMET.T-K9 final protocol; Regional key comparison; ITS-90 SPRT Calibration from the Ar TP to the Zn FP**
5. **EA, Expression of the Uncertainty of Measurement in Calibration, EA-4/02 rev.03,** 2022.
6. **ISO "Evaluation of measurement data - Guide to the expression of uncertainty in measurement"**, JCGM 100:2008, GUM 1995 with minor corrections

APPENDIX I – Technical protocol

HYBRID COMPARISON BETWEEN MIRS/UL-FE/LMK AND FSB-LPM

SPRT calibration in the triple point of argon (83.8058 K) and the triple point of mercury (234.3156 K)

TECHNICAL PROTOCOL

Hybrid comparison between MIRS/UL-FE/LMK and FSB-LPM October 2024
Technical protocol Stranica 1 od 10

Table of Contents

1. INTRODUCTION

The purpose of the this hybrid comparison is to compare realization of the ITS-90 in the triple point of argon (83.8058 K) and triple point of mercury (234.3156 K) through the calibration of SPRT between Laboratory of Metrology and Quality (MIRS/UL-FE/LMK), acting as Issuing NMI, and „Faculty of Mechanical Engineering and Naval Architecture, Laboratory for Process Measurement“ (FSB-LPM) as Applicant NMI.

The transfer standard used will be quartz sheathed long-stem standard platinum resistance thermometer (SPRT) and will be provided by „Issuing NMI“. The resistance ratio $W(FP_i)$ values determined at each participating laboratory will be compared.

This protocol has been drawn up in accordance with relevant guidelines for conduction of interlaboratory comparisons [1-3]. It describes the objectives of the comparison, the organization and the procedures that the participants must follow during the implementation of the measurements, the analysis and the reporting of the results.

1.1. Issuing NMI:

University of Ljubljana, Faculty of Electrical Engineering

Laboratory of Metrology and Quality (MIRS/UL-FE/LMK),

Address: Tržaška cesta 25, SI-1000 Ljubljana, Slovenia

Contact person:

Prof. dr. Jovan Bojkovski (Coordinator)

Tel.: +386 1 4768 798,

GSM: +386 51 388 659

e-mail: jovan.bojkovski@fe.uni-lj.si

1.2. Applicant NMI:

Faculty of Mechanical Engineering and Naval Architecture,

Laboratory for Process Measurement (FSB-LPM)

Address: Ivana Lučića 5, 10000 Zagreb, Croatia

Contact person:

Ivan Matas, mag. ing. mech.

GSM: +385 98 9709 836

e-mail: ivan.matas@fsb.unizg.hr

1.3. Projected timeline

Protocol Agreement:	August-October 2024
Transfer Standard calibration at Issuing NMI:	first half of August 2024
Transfer Standard calibration at Applicant NMI:	second half of August 2024
Transfer Standard recalibration at Issuing NMI:	September 2024
Draft of comparison report:	October 2024

All the deadlines will be determined on a basis of email agreement between the Issuing NMI and the Applicant NMI.

1.4. Transportation of the equipment

The Applicant NMI takes care about the transport between both laboratories. The Applicant NMI will hand-carry the thermometer from the Issuing NMI and return it to the Issuing NMI after **completion of** measurements. After the transport and unpacking, the equipment shall be inspected. If the equipment has any visible damage due to transportation, this must be reported to the Issuing NMI before the calibration begins.

2. DESCRIPTION OF THE EQUIPMENT

2.1. Transfer standard

The transfer standard used will be long-stem SPRT and will be provided by „Issuing NMI".

Manufacturer: Hart Scientific

Model: 5681

Dimensions (diameter and length): Φ = 7 mm, L = 520mm

Nominal resistance: 25,5 Ω

Serial number: 1408

Measuring range: -196 to 661 °C

2.2. Handling

2.2.1. Packing and unpacking

Procedure for unpacking is following:

1. Inspect the transportation box for damage. If the box is damaged, the Issuing NMI shall be contacted before continuing.
2. Unpack the equipment and check that all equipment mentioned in the section "Description of equipment" is present.
3. If any equipment is missing, the Issuing NMI shall be contacted.
4. Inspect the equipment. If any of the equipment shows visible signs of damage, the Issuing NMI shall be contacted.

The packing procedure is as follows:

1. Before packing, slowly heat up thermometer to room temperature and clean it using alcohol.
2. Place the thermometer in the transportation box.
3. Check that all the equipment mentioned in the section "Description of equipment" is packed before the equipment is transported.

2.2.2. Precautions

- As SPRT is a very sensitive to vibration and mechanical shock, it must be handled with care and only by qualified metrology personnel.
- When not in use, SPRT has to be securely stored.
- Check that the SPRT is completely clean and dry before placing it in the fixed points.
- Ensure that SPRT is at room temperature and clean before placing it in the transportation box.
- The transfer standard used in this comparison must not be modified, adjusted or used for any purpose other than described in this document.

Refer to the manual or contact the Issuing NMI in a case of doubt about any of the above-mentioned precautions.

3. HYBRID COMPARISON/CALIBRATION PROCEDURE

3.1. Hybrid comparison procedure

According to [3], hybrid comparison, when the transfer standard is provided by the Issuing NMI, should follow the flowchart presented at Figure 1, with the minor change in step 16 considering that both Issuing and Applicant NMI belong to different RMO (EURAMET).

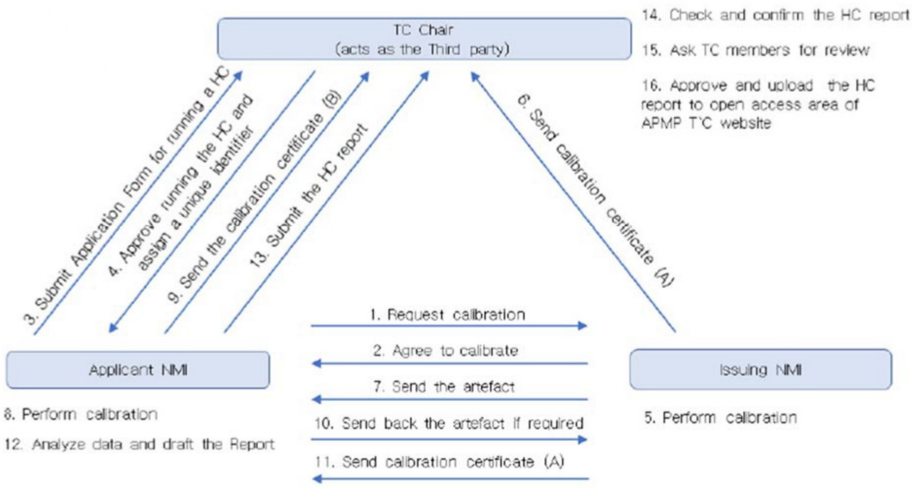


Figure 1. Basic flowchart of the hybrid comparison [3]

3.2. Calibration procedure

The calibration procedure in each participating laboratory should follow internal laboratory procedure for realisation of the fixed points and include following:

- The calibration shall proceed from higher to lower temperatures. The SPRTs shall be calibrated at mercury triple point (Hg TP, 234.3156 K) and argon triple point (Ar TP, 83.8058 K).
- Before and after each calibration point, the *R*(TPW) value of the SPRT must be measured.
- Minimum of 3 realizations of the triple point of argon and triple point of mercury plateau.
- Recording of the resistance of SPRT during the whole duration of the one plateau of the triple point of argon and mercury
- Determination of Heat Flux (Immersion) profile for each fixed-point cell using the transfer standard (SPRT) for bottom 5 cm
- The values of $R(FP_i)$ and $R(TPW)$ must be corrected for self heating, the hydrostatic head and if applicable, the pressure effect. In order not to increase the uncertainty on the comparison of the results the $R(FP_i)$ values given by the different participating NMI must approximately correspond to the same percentage of metal in liquid phase. This percentage is not easy to determine. So, it is better to use the concept of percentage of time of the total duration of the plateau. It is asked that the $R(FP_i)$ values correspond to the percentage of time given in the table below [4]

Fixed point	Type	% of time passed since starting of plateau
Ar	Triple	20 to 40 %
Hg	Triple	60 to 80 %

A stability check on the transfer standard will be carried out both at the beginning and upon return of the transfer standard to the Issuing NMI. The stability check consists of a triple point of water check of the transfer standard before starting any other measurements in the triple points.

4. REPORTING OF THE RESULTS

The measurement results should be reported on the report given in Appendix A adopted from [5].

The results shall be sent to the Issuing NMI no later than 3 weeks after having finalized the calibration. Electronic reporting by e-mail is preferred.

In the report form, the participants should fill in details about the applied method, equipment used (fixed-point cell, resistance bridge, standard resistor) and traceability.

Calibration results should be supplied in the form of:

$$W(FP_i) = \frac{R(FP_i)}{R(TPW)}$$

where $R(FP_i)$ is the resistance of the SPRT in the fixed points of argon and mercury and $R(TPW)$ is the resistance in the TPW cell obtained after the measurement of $R(FP_i)$.

The values of $R(FP_i)$ and $R(TPW)$ should also be reported and must be corrected for self-heating and the hydrostatic pressure, so that *W*(FP) value is equivalent to the ITS-90 assigned temperature value for 0 mA according to:

$$R(FP_i) = R_{meas}(FP_i) + \Delta R_{sh} + \Delta R_{hydr}$$

Where:

$R_{meas}(FP_i)$ - the resistance measured at fixed point FP_i

ΔR_{sh} - the self-heating correction to the resistance

ΔR_{hydr} - the hydrostatic head correction to the resistance

The applied corrections can be expressed in terms of temperature by simply dividing each one of them by the SPRT sensitivity coefficient $(dR/dT)_{FP_i}$ at the temperature of the fixed point FP_i:

$$\Delta T_{sh} = \frac{\Delta R_{sh}}{(dR/dT)_{FP_i}}$$

$$\Delta T_{hydr} = \frac{\Delta R_{hydr}}{(dR/dT)_{FP_i}}$$

The uncertainties *u*[*W*(FP)] and *u*[*R*(TPW)] should also be reported. The recorded resistance during the whole duration of the one plateau of each fixed point should be reported in the form of the graph. The results of the Heat Flux (Immersion) test for the bottom 5 cm of each fixed point should be graphically reported and compared to the ideal hydrostatic head correction.

5. MEASUREMENT UNCERTAINTY

The measurement uncertainty should be evaluated in accordance with internal laboratory procedures and relevant international guidelines [6,7] for every fixed point in the comparison. The measurement uncertainty analysis should include following components if applicable:

- Repeatability of readings
- Uncertainty linked with purity
- Uncertainty linked with hydrostatic pressure correction
- Uncertainty linked with perturbing heat exchanges in
- Uncertainty linked with self-heating correction
- Uncertainty linked with bridge and standard resistor
- Uncertainty linked with AC/DC current

- Uncertainty linked with gas pressure
- Repeatability of readings in the triple point of water (TPW)
- Repeatability of temperature of TPW realized by cell
- Short repeatability of calibrated SPRT
- Uncertainty linked with purity and isotopic composition of TPW
- Uncertainty linked with hydrostatic pressure correction in TPW
- Uncertainty linked with perturbing heat exchanges in TPW
- Uncertainty linked with self-heating correction in TPW
- Uncertainty linked with bridge linearity
- Uncertainty linked with AC/DC current
- Uncertainty linked with internal insulation leakage
- Uncertainty linked with stability of reference resistor
- Uncertainty linked with temperature of reference resistor
- Wt scatter

Explanation and proposal for evaluation above mentioned uncertainty budget components are given in [4].

The suggested uncertainty budget is given in Appendix B.

6. REFERENCES

1. **EURAMET, Guide on Comparisons**, EURAMET Guide No. 4 Version 2.0, April 2021.
2. **Measurement comparisons in the CIPM MRA, Guidelines for organizing, participating and reporting**, CIPM MRA-G-11, v1.1, January 2021
3. APMP, **APMP guideline for using Hybrid Comparisons as CMC evidences**, November 2020
4. E Renaot et al, **Final Report on EUROMET.T-K3: Regional key comparison of the realisations of the ITS-90 from 83.8058 K to 692.677 K**, 2007, Metrologia 44 03001
5. **EURAMET.T-K9 final protocol; Regional key comparison; ITS-90 SPRT Calibration from the Ar TP to the Zn FP**
6. **EA, Expression of the Uncertainty of Measurement in Calibration, EA-4/02 rev.03,** 2022.
7. **ISO "Evaluation of measurement data - Guide to the expression of uncertainty in measurement"**, JCGM 100:2008, GUM 1995 with minor corrections

Appendix A: Measurement Reporting Worksheet

Participating NMI

On receipt R (TPW)

	$\bar{R}$(FP)	$\bar{W}$(FP)	$u[\bar{W}(\text{FP})]$, mK	n(*)	Comments (if any)
Mercury					
Argon					

(*)number of realizations

Final R (TPW) | TPW Uncertainty

Fixed-Point Cell Information

	Type/manufacturer/serial nr.	Open or sealed	L (cm)(*)	Traceability
Mercury				
Argon				

(*)maximum thermometer Immersion depth into the substance measured to the thermal centre of the SPRT sensing element, cm

Measurement System

Resistance Ratio Bridge Model	
Reference Resistor Model	
Resistor Enclosure Stability, mK	

Corrections

	self-heating		**hydrostatic**	
	correction, mK	$u_{correction}$, mK	correction, mK	$u_{correction}$, mK
$\bar{R}$(Hg)				
$\bar{R}$(Ar)				

Plateau of FP(Hg):

Page 1

Hybrid comparison between MIRS/UL-FE/LMK and FSB-LPM October 2024

Technical protocol Stranica 8 od 10

Plateau of FP(Ar):

Heat-flux (immersion) test results during realization of the FP(Hg):

Heat-flux (immersion) test results during realization of the FP(Ar):

Appendix B: Suggested Uncertainty Budget for the Determination of the *W*-Value of an SPRT

Participating NMI

	Ar		Hg		
	mK	df	mK	df	Type A or B(*)
Phase Transition Realization Repeatability					
Bridge (repeat., non-linearity, AC quadrature)					
Reference resistor stability					
Chemical Impurities					
Hydrostatic-head					
Propagated TPW					
SPRT self-heating					
Heat Flux					
Insulation leakage					
SPRT Pt Oxydation					
Gas pressure					

Combined Standard Uncertainty				

Expanded Uncertainty (k=2, using effective df)				

(*) write A or B depending on the method used

df: degree of freedom

APPENDIX II – Measurement reporting worksheets

1st measurement at MIRS/UL-FE/LMK, Jul 2 – Jul 4, 2024

Participating NMI	MIRS/UL-FE/LMK

On receipt R(TPW) 25.4128407

	$\bar{R}$(FP)	$\bar{W}$(FP)	$u[\bar{W}(\mathrm{FP})]$, mK	n(*)	Comments (if any)
Mercury	21.4526256	0.84415647	0.11	3	
Argon	5.4874749	0.21593109	0.13	3	

(*)number of realizations

Final R(TPW) 25.4131405 TPW Uncertainty 0,15 mK (k =2)

Fixed-Point Cell Information

	Type/manufacturer/serial nr.	Open or sealed	L (cm)(*)	Traceability
Mercury	Isotech Hg 125	sealed	17.5	
Argon	Pond K52, 13234	sealed	15.5	

(*)maximum thermometer Immersion depth into the substance measured to the thermal centre of the SPRT sensing element, cm

Measurement System

Resistance Ratio Bridge Model	ASL F900
Reference Resistor Model	Tinsley 5685A
Resistor Enclosure Stability, mK	±2 mK

Corrections

	self-heating		**hydrostatic**	
	correction, mK	$u_{correction}$, mK	correction, mK	$u_{correction}$, mK
$\bar{R}$(Hg)	-1.13	0.02	-1.243	0.035
$\bar{R}$(Ar)	-0.998	0.02	-0.512	0.016

2nd measurement at MIRS/UL-FE/LMK, Sep 9 – Sep 12, 2024

Participating NMI	MIRS/UL-FE/LMK

On receipt R(TPW) 25.4131586

	$\bar{R}$(FP)	$\bar{W}$(FP)	$u[\bar{W}(\mathrm{FP})]$, mK	n(*)	Comments (if any)
Mercury	21.4526777	0.84415716	0.11	3	
Argon	5.48752435	0.21593265	0.13	3	

(*)number of realizations

Final R(TPW) 25.413151 TPW Uncertainty 0,15 mK (k=2)

Fixed-Point Cell Information

	Type/manufacturer/serial nr.	Open or sealed	L (cm)(*)	Traceability
Mercury	Isotech Hg 125	sealed	17.5	
Argon	Pond K52, 13234	sealed	15.5	

(*)maximum thermometer Immersion depth into the substance measured to the thermal centre of the SPRT sensing element, cm

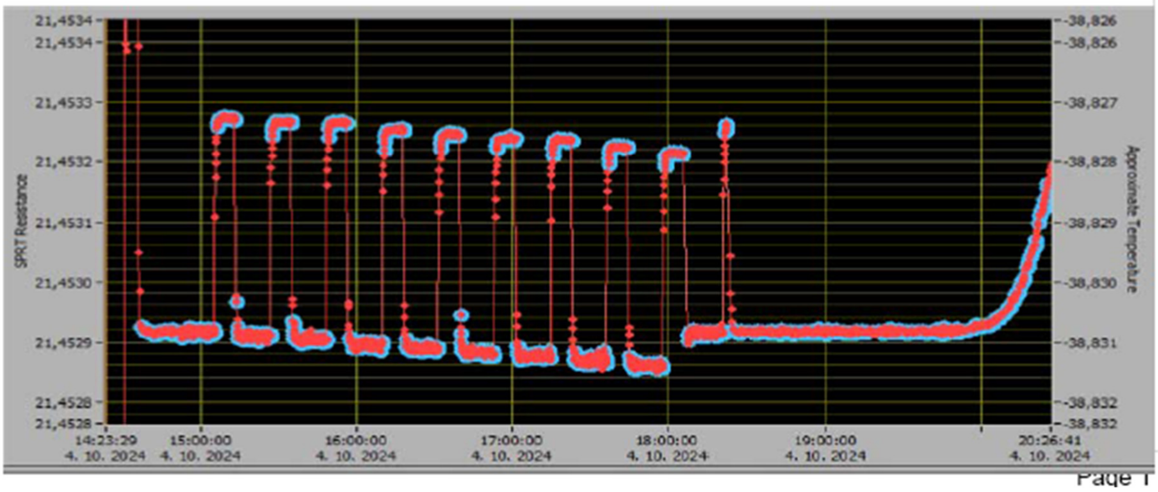
Measurement System

Resistance Ratio Bridge Model	ASL F900
Reference Resistor Model	Tinsley 5685A
Resistor Enclosure Stability, mK	±2 mK

Corrections

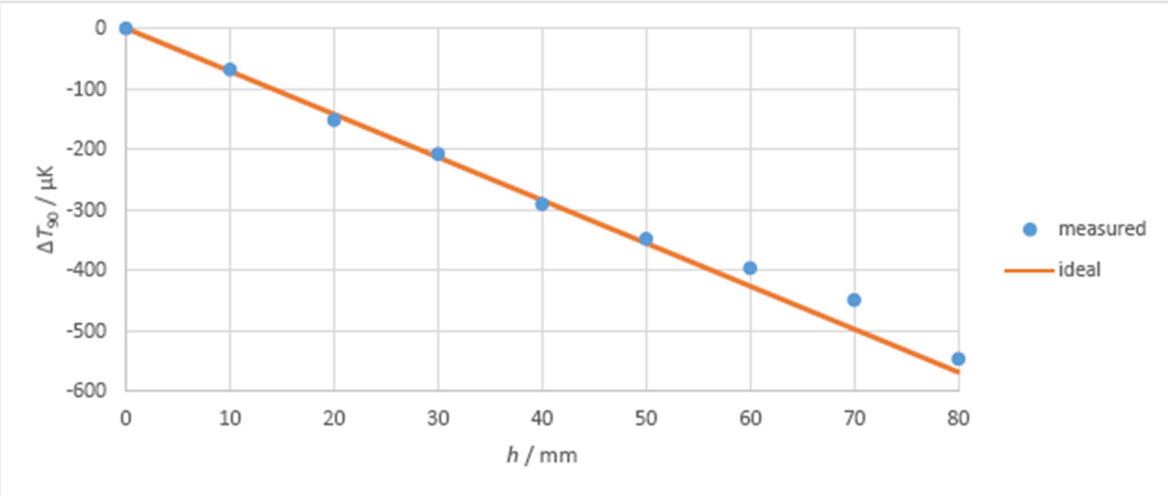
	self-heating		hydrostatic	
	correction, mK	$u_{correction}$, mK	correction, mK	$u_{correction}$, mK
$\bar{R}$(Hg)	-1.08	0.02	-1.243	0.035
$\bar{R}$(Ar)	-1.06	0.02	-0.512	0.016

Plateau of FP(Hg):

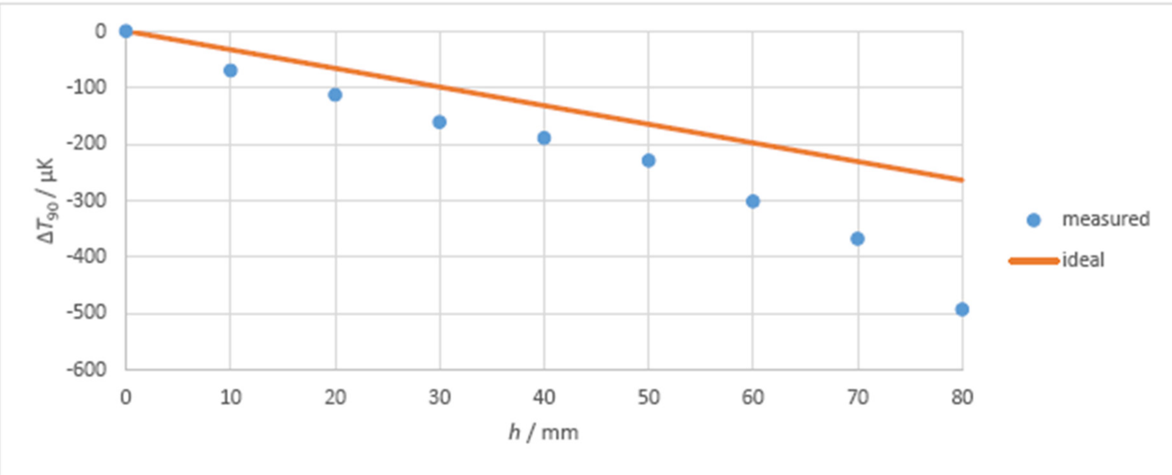


Plateau of FP(Ar):

Heat-flux (immersion) test results during realization of the FP(Hg):



Heat-flux (immersion) test results during realization of the FP(Ar):



Page 2

Measurement at FSB-LPM, Aug 18 – Aug23, 2024

Participating NMI	Faculty of Mechanical Engineering and Naval Architecture - Laboratory for Process Measurements (FSB-LPM), Croatia

On receipt R(TPW) 25.4131567 Ω

	$\bar{R}(\mathrm{FP}), 0\ \mathrm{mA}$	$\bar{W}(\mathrm{FP}), 0\ \mathrm{mA}$	$u[\bar{W}(\mathrm{FP})]$ $(k=1)$, mK	n(*)	Comments (if any)
Mercury	21.45265393	0.844155444	0.757	3	corr. to EURAMET.T-K9 T_{KCRV}
Argon	5.487542739	0.215933113	0.735	3	corr. to value from cal. Certificate N°1260-Th-09 from LNE Cnam

(*)number of realizations

Final R(TPW)	TPW Uncertainty
25.4131527 Ω	0.456 mK (k=2)

Fixed-Point Cell Information

	Type/manufacturer/serial nr.	Open or sealed	L (cm)(*)	Traceability
Mercury	ITL-M-17724 / Isotech / Hg248	sealed	17.5	EURAMET.T-K9
Argon	INM/Sorime/Ar-INM-36-FSB-LPM	sealed	9.5	LNE-Cnam

(*)maximum thermometer Immersion depth into the substance measured to the thermal centre of the SPRT sensing element, cm

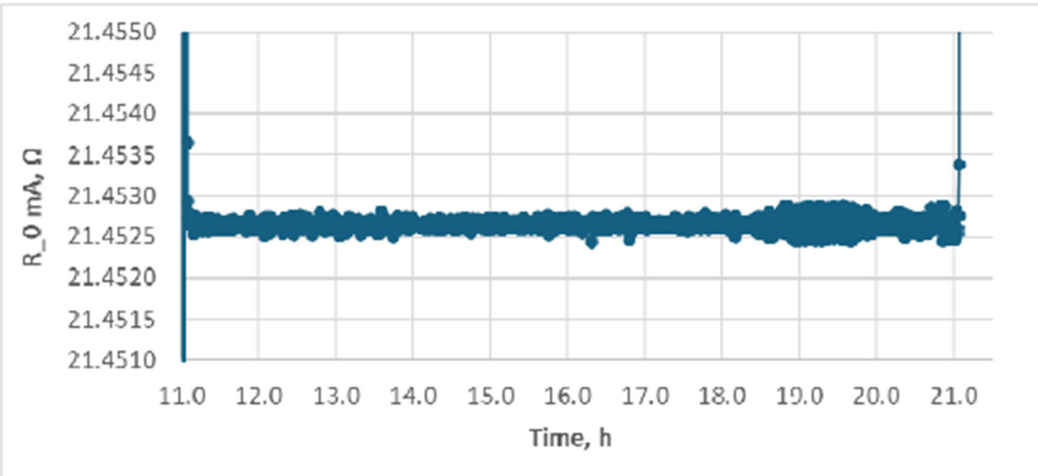
Measurement System

Resistance Ratio Bridge Model	Automatic Systems Laboratories LTD, (ASL) F18, SN:009137/03
Reference Resistor Model	Tinsley 5685A, 100 Ω, SN: 6419/15
Resistor Enclosure Stability, mK	±50 mK, Oil bath

Corrections

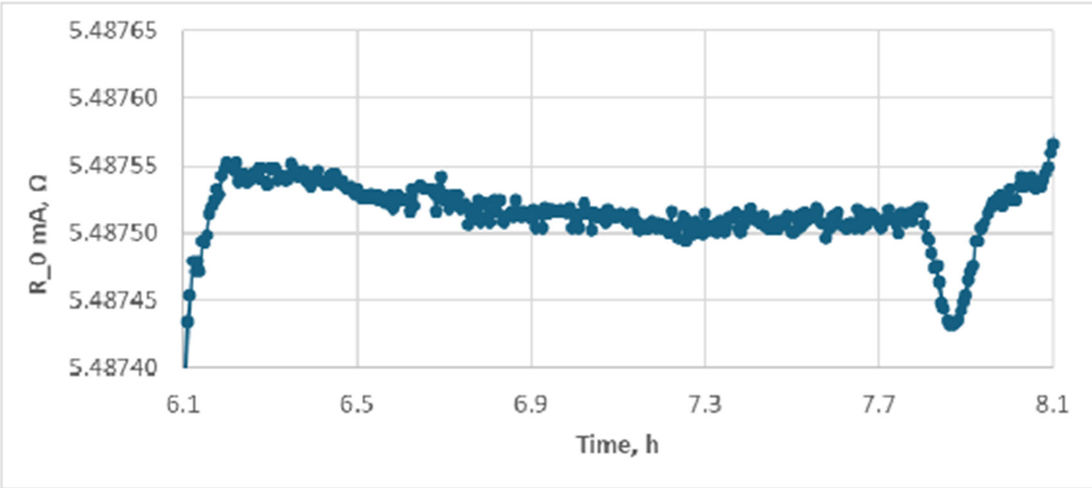
	self-heating		hydrostatic	
	correction, mK	$u_{correction}$ (k=1), mK	correction, mK	$u_{correction}$ (k=1), mK
$\bar{R}(\mathrm{Hg})$	-1.311	0.032	-1.243	0.082
$\bar{R}(\mathrm{Ar})$	-0.773	0.027	-0.314	0.038

Plateau of FP(Hg):

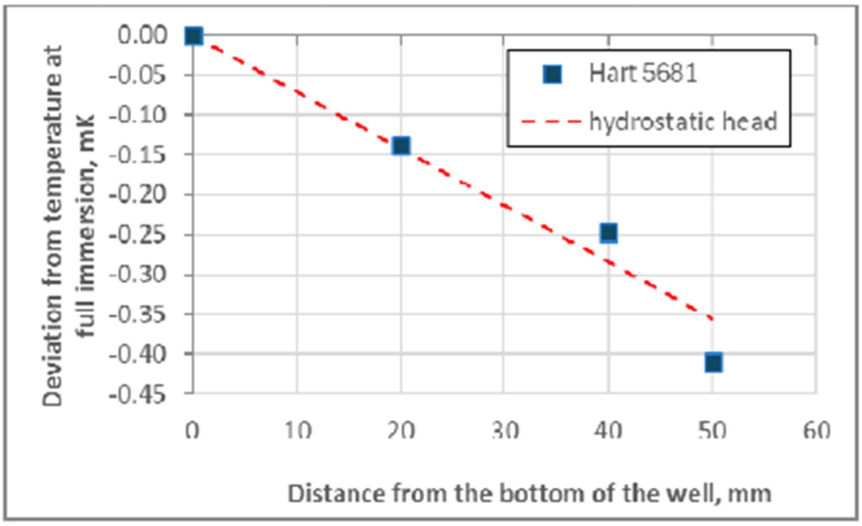


Page 1

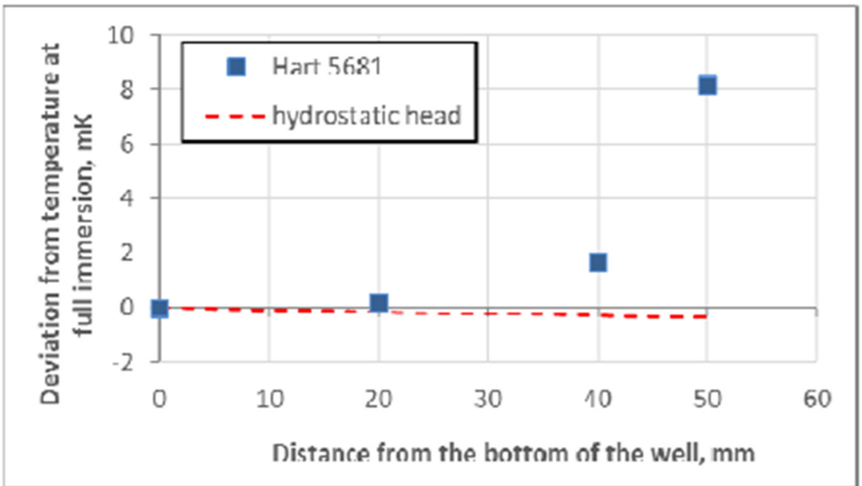
Plateau of FP(Ar):



Heat-flux (immersion) test results during realization of the FP(Hg):

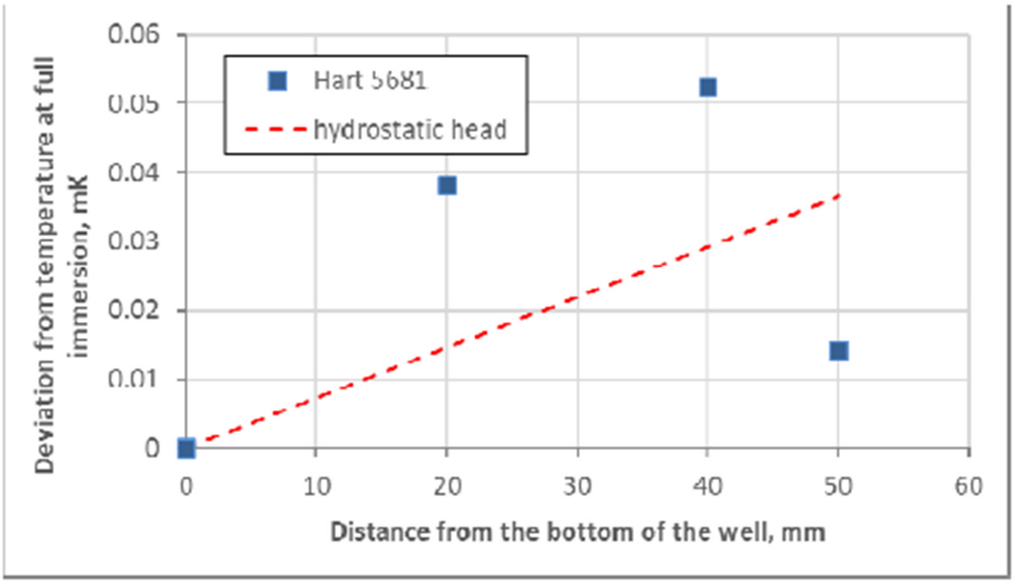


Heat-flux (immersion) test results during realization of the FP(Ar):



Page 2

Heat-flux (immersion) test results during realization of the TPW:



APPENDIX III – Uncertainty budgets

The following tables contain detailed uncertainties supplied by each participating laboratory using the "Appendix B: Suggested Uncertainty Budget for the Determination of the W-Value of an SPRT" from the original technical protocol. The columns named "Type" provide indication about the classification of the uncertainty (either Type A or Type B).

Participating NMI: MIRS/UL-FE/LMK

	Ar		Hg		
	mK	df	mK	df	Type A or B(*)
Phase Transition Realization Repeatability	0.038	5	0.041	5	A
Bridge (repeat., non-linearity, AC quadrature)	0.027	60	0.027	60	A
Reference resistor stability	0.001	180	0.001	180	A
Chemical Impurities	0.03		0.01		B
Hydrostatic-head	0.016		0.035		B
Propagated TPW	0.02		0.06		B
SPRT self-heating	0.02		0.02		B
Heat Flux	0.11		0.055		A
Insulation leakage	0		0		B
SPRT Pt Oxydation	0		0.015		B
Gas pressure	0		0		B
Combined Standard Uncertainty	0.127		0.105		
Expanded Uncertainty (k=2, using effective df)	**0.255**		**0.210**		

(*) write A or B depending on the method used

df: degree of freedom

Participating NMI Faculty of Mechanical Engineering and Naval Architecture - Laboratory for Process Measurements (FSB-LPM), Croatia

	Ar		Hg		
	mK	df	mK	df	Type A or B(*)
Phase Transition Realization Repeatability	0.154	2	0.012	2	A
Bridge (repeat., non-linearity, AC quadrature)	0.230	57	0.633	38	B
Reference resistor stability	0.004	50	0.017	50	B
Chemical Impurities	0.312	87	0.333	71	B
Hydrostatic-head	0.038	50	0.082	50	B
Propagated TPW	0.058	77	0.225	77	B
SPRT self-heating	0.027	50	0.032	50	B
Heat Flux	0.600	3	0.040	3	A
Insulation leakage	0.002	50	0.008	50	B
SPRT Pt Oxydation	0.005	2	0.000	2	A
Gas pressure	0.000	50	0.000	50	B

Combined Standard Uncertainty	0.735		0.756	
Expanded Uncertainty (*k* =2, using effective df)	1.852		1.536	

(*) write A or B depending on the method used

df: degree of freedom