APMP.T-K4.2

Comparison of Realization of the Aluminum Freezing Point

Final Report

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1. Introduction

This comparison was designed to compare the realizations of the aluminum freezing point (Al FP, 660.323 °C) of the national metrology institutes (NMIs) in the Asia Pacific Metrology Programme (APMP), and to provide a linkage to the key comparison reference value (KCRV) of the CCT-K4 [1]. The first APMP follow-up comparison of CCT-K4 was APMP.T-K4 [2], in which the realization of the aluminum and silver freezing points were compared, and KRISS and NMIJ provided the link to the KCRV of the CCT-K4. However, it was able to only provide a link to the CCT-K4 KCRV at the Al FP, not at the silver freezing point (Ag FP). While an attempt to provide the link at the Ag FP is still ongoing, there were some requests from APMP NMIs to provide bilateral comparisons for the Al FP realizations. Combining these requests, the APMP have initiated another follow-up comparison of the CCT-K4, aiming to provide links to the KCRV of CCT-K4 at Al FP. KRISS piloted this comparison (APMP.T-K4.2) with National Institute of Metrology (NIM, China) as an additional linking laboratory to the CCT-K4.

The measurements for the comparison were made between 2018 and 2020. Measurements at KRISS were made between January and August of 2019, and the measurements by the other participants were made before and after the KRISS measurements within the period between 2018 and 2020.

2. Participants

Table 1 lists the laboratories that participated in this comparison. KRISS is the pilot laboratory and NIM is a co-pilot laboratory. Both laboratories provided a link to the KCRV of the CCT-K4. VMI-STAMEQ was initially included in the list of participants, but was not able to submit the measurement data in time, and, thus, was excluded from the comparison report.

Table 1. Laboratories that participated in this comparison

Laboratory	Role	Contact person	E-mail
KRISS	Pilot	Inseok Yang	iyang@kriss.re.kr
NIM	Co-pilot	Jianping Sun	sunjp@nim.ac.cn
SNSU-BSN[a]		Aditya Achmadi	aditya@bsn.go.id
SCL		Julian C. P. Cheung	cpcheung@itc.gov.hk
NMISA		Efrem Ejigu	EEjigu@nmisa.org
NMIM		Nurulaini Binti MD Ali	aini@sirim.my
MSL		Peter Saunders	peter.saunders@measurement.govt.nz
NIMT		Charuayrat Yaokulbodee	charuayrat@nimt.or.th
		Panatda Panpech	panatda@nimt.th
NMC, A*STAR		Shaochun Ye	ye_shaochun@nmc.a-star.edu.sg

[a]RCM-LIPI was renamed to SNSU-BSN after initiation of this comparison. It was indicated as RCM-LIPI in the protocol, but as SNSU-BSN in the report.

3. Comparison Pattern

The structure of the comparison was a collapsed-star type. The resistance of two standard platinum resistance thermometers (SPRTs), which were selected by each participating laboratory, were measured initially in the participating laboratory at the Al FP. Combined with a measurement of the resistance of the SPRTs at the triple point of water (TPW), *W*(Al) at the participating laboratory was obtained (pre-KRISS measurement). The SPRTs were then sent to the pilot laboratory, and *W*(Al) of each SPRTs was measured at the pilot laboratory. Finally, the SPRTs were sent back to the participating laboratory where *W*(Al) was measured again (post-KRISS measurement).

4. Travelling standards

Two SPRTs per participating laboratory were sent to KRISS and used as travelling standards for this comparison. SCL used only one SPRT in the comparison. NMC used two SPRTs initially in this comparison, but one of the SPRTs was damaged at NMC after being sent back to NMC before the post-KRISS measurement. NMC sent a detailed “Incident Report” with a photograph of the broken SPRT NMC #1, and thus the data from NMC #1 was excluded from the analysis. Table 2 lists the SPRTs used as the travelling standards in this comparison. KRISS’s SPRTs are not listed because KRISS used only the SPRTs from the participants to measure the resistance ratio (*W*) in the KRISS Al FP cell to compare the realized temperatures of KRISS and the participants via the SPRTs.

Table 2. SPRTs used as the travelling standards in this comparison.

	NIM		MSL		NMC	
	NIM #1	NIM #2	MSL #1	MSL #2	NMC #1	NMC #2
Make	NIM	NIM	Chino	Chino	NIM	Fluke
Model	586660	58660	R800-2	R800-1	58660	5681
s/n	166028	166047	RS17A-6	RS23A-6	184259	1804
Nominal *R*(TPW) (Ω)	25.5	25.5	25	25	25	25
Sheath type	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz
Tip to mid-point distance (mm)	20	20	30	30	20	20

	NMIM		NMISA		NIMT	
	NMIM #1	NMIM #2	NMISA #1	NMISA #2	NIMT #1	NIMT #2
Make	Kunming	Kunming	Chino	Chino	Fluke	Fluke
Model	High Temp	High Temp	R800-1	R800-1	5681	5681
s/n	94845	95029	RS183-02	RS183-05	1997	2000
Nominal *R*(TPW) (Ω)	2.5	2.5			25.5	25.5
Sheath type	Quartz	Quartz			Quartz	Quartz
Tip to mid-point distance (mm)	25	25			25	25

	SCL	SNSU-BSN	
	SCL	SNSU-BSN #1	SNSU-BSN #2
Make	Fluke	Fluke	Isotech
Model	5698	5681	670
s/n	985012	1870	160
Nominal *R*(TPW) (Ω)	25.5	25.5	25.5
Sheath type	Quartz	Quartz	Quartz
Tip to mid-point distance (mm)	35	40	35

5. Equipment and measuring conditions at participating laboratories

As instructed in the technical protocol, each participating laboratory measured the resistance of the SPRTs at the Al FP, then at the TPW. After necessary corrections (typically self-heating correction, hydrostatic correction, and pressure correction), this measurement gives the resistance ratio (W) of the specific SPRT at the Al FP of the participant. Similar measurements at the Al FP and at the TPW to obtain W at Al was taken at the pilot laboratory. Tables 3 to 5 list the Al FP cell and furnace, TPW cell and the resistance measurement system for the participants and the pilot laboratory.

5.1. Aluminum freezing point cell and furnace

Table 3. Aluminum freezing point cells and furnaces used at the participating laboratories.

Laboratory	KRISS	NIM	MSL	NMC	NMIM
Cell					
Cell manufacturer	KRISS	NIM	AL07 MSL	Fluke	Fluke
Open/closed?	Open	Open	Open	Closed	Open
Pressure in cell (kPa)	Corrected to 101.325	/	101.73 (Corrected to 101.325)	84.8	/
Crucible					
Crucible material	Graphite	Graphite	Graphite	Graphite	Graphite
Crucible manufacturer	Ultra Carbon	China	Isotech	Fluke	Fluke
Crucible length (mm)	255	275.5	225	N/A	195
Metal sample					
Sample source	JM	USA	Isotech	Fluke	High purity aluminum + graphite
Sample purity	99.9999 %	6N	99.99985 %+	99.9999 %	99.9999 %
Sample weight (g)	500	485	340	350	350
Thermometer well					
Well material	Quartz	Quartz	Quartz	Quartz	Quartz
Well ID (mm)	11	8.2	8.2	8	8
Immersion depth of SPRT (mm)	161	180	170	195	235
Furnace					
Manufacturer	Lab made	NIM	Isotech ITL17702	Fluke	Fluke
Control type	PID	PID	on/off	Auto	Digital controller
How many zones?	2	3	1	3	3
Heat pipe liner?	Yes	Yes	Yes	No	No
Heater current (AC/DC)?	AC	AC	AC		AC

Laboratory	NMISA	NIMT	SCL	SNSU-BSN
Cell				
Cell manufacturer	Isotech	Fluke	Fluke	Fluke
Open/closed?	Open	Open	Closed	Open
Pressure in cell	101.325	101.33	85.2	101.32
Crucible				
Crucible material	Graphite	Graphite	Graphite	Graphite
Crucible manufacturer		Fluke	Carbone of America	Carbon of America
Crucible length	460	696		250
Metal sample				
Sample source		Honeywell	Honeywell	Alfa Aesar
Sample purity	6 N	99.9999 %	99.9999 %+	99.9999 %
Sample weight	1000	350		1000
Thermometer well				
Well material	Quartz	Quartz	Quartz	Quartz
Well ID (mm)	8	8	8	8
Immersion depth of SPRT	180	195	195	195
Furnace				
Manufacturer	Isotech	Fluke	Isotech	Fluke – Hart Scientific
Control type	Eurotherm	Digital controller	PID	PID Controller
How many zones?		1	1	1
Heat pipe liner?	Yes	Yes	Yes	Yes
Heater current (AC/DC)?	DC	AC	AC	AC

5.2. Triple point of water cell

Table 4. Triple point of water cells used at the participating laboratories.

Laboratory	KRISS	NIM	MSL	NMC	NMIM
Cell manufacturer	KRISS	NIM	MSL	Hart Scientific	KRISS
Water source and purity	Filtered & distilled	Filtered & distilled	99.99999 %+	Purified ocean water	Distilled water
Well diameter	10 mm	10 mm	8 mm	12 mm	12 mm
Immersion depth	261 mm	235 mm	260 mm	265 mm	252 mm
Heat transfer liquid:	Water	Water mixed with alcohol	Ethanol	Isopropanol	Distilled water
Cell maintained in: ice bath/water bath?	Ice bath	Alcohol bath	Ice bath	Water bath	Ice bath
Ice mantle:					
Method of preparation	Dry ice	Cooling with LN2	Cold stick	Dry ice	Dry ice
Annealing time before use	10 d	7 d	5 d	7 d	3 d

Laboratory	NMISA	NIMT	SCL	SNSU-BSN
Cell manufacturer	Fluke/Isotech	Fluke	Fluke	PTB
Water source and purity		Purified ocean water, δD 4 ‰, δ^{18}O 0.1‰	Fluke	
Well diameter	10 mm	12 mm	12 mm	15 mm
Immersion depth	290 mm	264 mm	270 mm	220 mm
Heat transfer liquid:	Water/Alcohol mix	Ethanol	Water	Water mixed with alcohol
Cell maintained in: ice bath/water bath?	Triple point of Water maintenance bath	Ethanol bath	Water	Stirred water + alcohol bath
Ice mantle:				
Method of preparation	Methanol heat pipe with solid CO_2 and ethanol for heat transfer	dry ice	Filling the thermometer well with mixture of dry ice and alcohol	Using crushed dry ice
Annealing time before use	10 d	1 d	7 d	7 d

5.3. Resistance measuring device

Table 5. Resistance measuring devices used at the participating laboratories.

Laboratory	KRISS	NIM	MSL	NMC	NMIM
Bridge manufacturer	ASL	ASL	MI 6015T	MI	ASL
AC/DC	AC	AC	DC	DC	AC
If AC, give					
Frequency	30 Hz	25 Hz			High
Bandwidth	0.1 Hz	0.2			0.1 Hz
Gain	10^4	10^5			10^4
Quad gain	10	/			
Output	IEEE-488	/			Ratio
Normal measuring current	Depends on SPRT	1 mA			5 mA
Self-heating current	$\sqrt{2} \times I_1$	$\sqrt{2}$ mA			5 mA × $\sqrt{2}$
Unity reading	1	1.000 000 001			Ok
Zero reading	0.000 000 001	0.000 000 000			Ok
Compliment check error	0.02 ppm	/			Ok
If DC, give					
Gain			1	Nil	
Period of reversal			4 s	8 s	
Output		IEEE-488	IEEE/GPIB		
Reference resistor					
Type	Winkins	AC/DC	100 Ω	5685A	10 Ω
Manufacturer	Tinsley 5685A	Tinsley 5658A	Tinsley	Tinsley	Tinsley
Temperature	25 °C	20°C	29.46 °C	23 °C	23 °C
Temperature coefficient	1.25 ppm/°C	α = 0.2276, β = 0.0664	−0.055 mΩ/°C	0.5 ppm/°C	2 ppm/°C
Linearity of bridge	0.03 ppm	0.02 ppm	0.01 ppm	0.177 ppm (k = 1)	0.2 ppm

Laboratory	NMISA	NIMT	SCL	SNSU-BSN
Bridge manufacturer	ASL	MI	ASL	MI
AC/DC	AC	DC	AC	DC
If AC, give				
Frequency	Low		75 Hz	
Bandwidth	0.5 Hz for Al, 0.1 for TPW		0.05 Hz	
Gain	10^4 for Al, 10^5 for TPW		10^5	
Quad gain			10	
Output				
Normal measuring current	1 mA		1 mA	
Self-heating current	$\sqrt{2}$mA		1.414 mA	
Unity reading			1.000 000 000	
Zero reading			0.000 000 000	
Compliment check error			100 ppb	
If DC, give				
Gain				
Period of reversal		10 s		4s
Output				Resistance ratio
Reference resistor				
Type	5685A	AC/DC	5685A	5685A, 25 Ω
Manufacturer	Tinsley	WIKA	Tinsley	Tinsley
Temperature	22-23	23 ± 0.5	23 ± 0.02	23
Temperature coefficient	−0.5 ppm/°C	±1ppm/°C	2 ppm/°C	1 ppm/°C
Linearity of bridge		1.274×10^{-7}	100 ppb	5.8 ppb

6. Measurement results

The following subsections list the measurement data of the participants and KRISS using the participants' SPRTs. When reporting *R*(Al), *R*(TPW), and *W* to the pilot, some participants submitted the averaged values over several realizations. In this case, only one set of values is listed. For other participants who reported individual measurement results, all of the results are listed.

In each subsection, the measurement values are followed by the uncertainty budgets submitted by each participant. In some cases, the uncertainties for the two SPRTs are slightly different, or the “pre-KRISS” and “post-KRISS” uncertainties for the same SPRT are slightly different. In these cases, only one of the representative uncertainty budgets is shown. The uncertainty budget is reported as submitted by the participants, but minimal editorial revision and rounding up to a reasonable number of significant digits were made.

Many participants reported expanded uncertainties by multiplying the standard uncertainty by the coverage factor $k = 2$, corresponding to an "approximately 95% level of confidence," as specified in the uncertainty budget template of the technical protocol. In this report, however, the standard uncertainties and degrees of freedom provided by the participants were used to calculate the uncertainties for the differences between the participant's and pilot's measurements, or between the participant's measurement and the KCRV. Consequently, the expanded uncertainties submitted by the participants were not used in this report.

6.1 KRISS

For the KRISS subsection, only the uncertainty budget is shown (without the measurement data), because the measurements at KRISS were made only with the participants' SPRTs in this comparison; these results are listed in other corresponding subsections. Table 6 is the uncertainty budget for the Al and TPW measurements at KRISS.

Table 6. KRISS uncertainty budget at Al FP and TPW

Component	Al		TPW	
	Value /mK	DF	Value /mK	DF
Type A				
Phase transition repeatability	0.38	10	0.01	10
Type B				
Long-term drift of the freezing-point cell	1.45			
Reproducibility of the plateau	0.10			
Choice of freezing-point value from the plateau	0.10			
Propagated from TPW	0.43			
Chemical impurities	0.67		0.03	
Gas pressure correction	0.05		0.005	
Resistance ratio measurement by the bridge	0.03		0.005	
Heat flux or immersion profile	0.08		0.045	
Hydrostatic-head correction	0.02		0.006	
Self-heating correction	0.11		0.033	
Insulation degradation in the transfer SPRT	0		0	
Combined standard uncertainty u	1.71	> 100	0.064	> 100
Expanded uncertainty U	3.42		0.13	> 100

6.2. NIM

Tables 7 and 8 show NIM and KRISS measurements of the two SPRTs from NIM. For each SPRT, the table starts with measurement results at NIM, measurements at KRISS, then the return measurements at NIM. Table 9 is the uncertainty budget for the Al and TPW measurements at NIM.

Table 7. NIM and KRISS measurements of NIM SPRT #1

NIM measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
85.263 487	25.256 253	3.375 935 77			
			85.262 587	25.256 173	3.375 910 74
			85.262 618	25.256 174	3.375 911 94
			85.262 557	25.256 169	3.375 910 12
85.263 290	25.256 186	3.375 936 93			

Table 8. NIM and KRISS measurements of NIM SPRT #2

NIM measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
84.614 936	25.068 329	3.375 372 05			
			84.613 965	25.068 199	3.375 350 73
			84.614 014	25.068 204	3.375 352 07
			84.614 006	25.068 207	3.375 351 33
84.614 773	25.068 268	3.375 373 75			

Table 9. NIM uncertainty budget at Al FP and TPW

Type A	Al FP		TPW		Systematic or random
	mK	DF	mK	DF	
Phase transition realization repeatability	0.65	6	0.02	6	R
Bridge repeatability	0.01	60	0.01	60	R
Total A	0.65	6	0.10	9	
Type B					
Chemical impurities or Isotope	0.55	15	0.02	8	S
Hydrostatic-head	0.08	32	0.04	8	S
Heat flux	0.24	32	0.03	18	S
Gas pressure	0.01	50	/	/	S
Slope of plateau	0.14	3	/	/	S
Propagated from TPW	0.34	12	/	/	S
Bridge nonlinearity	0.10	50	0.04	50	S
SPRT self-heating	0.03	18	0.03	18	S
R_s stability	0.01	50	0.01	50	S
Total B	0.71	35	0.07	62	
Combined standard uncertainty	0.97	23	0.08	69	
Expanded uncertainty (Approx. 95 % level of confidence, $k = 2$)	1.9	23	0.16	69	

6.3. MSL

Tables 10 and 11 show MSL and KRISS measurements of the two SPRTs from MSL. For each SPRT, the table starts with measurement results at MSL, measurements at KRISS, then the return measurements at MSL. Table 12 is the uncertainty budget for the Al and TPW measurements at MSL.

Table 10. MSL and KRISS measurements of MSL SPRT #1

MSL measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
85.718 223	25.396 657	3.375 177 41			
85.718 265	25.396 668	3.375 177 54			
85.718 161	25.396 678	3.375 172 11			
			85.718 325	25.396 634	3.375 184 46
			85.718 255	25.396 631	3.375 182 11
			85.718 241	25.396 631	3.375 181 59
			85.718 173	25.396 625	3.375 179 65
85.719 290	25.396 867	3.375 191 46			
85.719 267	25.396 861	3.375 191 39			
85.719 288	25.396 853	3.375 193 30			

Table 11. MSL and KRISS measurements of MSL SPRT #2

MSL measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
87.281 823	25.860 215	3.375 139 15			
87.281 895	25.860 214	3.375 142 10			
87.281 733	25.860 212	3.375 136 01			
			87.281 981	25.860 184	3.375 149 28
			87.281 905	25.860 180	3.375 146 84
			87.281 903	25.860 181	3.375 146 60
			87.281 899	25.860 183	3.375 146 29
87.283 612	25.860 568	3.375 162 26			
87.283 586	25.860 572	3.375 160 71			
87.283 580	25.860 557	3.375 162 39			

Table 12. MSL uncertainty budget at Al FP and TPW

	Type B	Al FP	
		mK	DF
FP realization	Chemical impurities	1.500	4
	Hydrostatic head	0.024	20
	Gas pressure	0.017	20
	Isotopic effects	0.000	20
FP use	SPRT self-heating	0.038	31
	SPRT leakage	0.100	20
	Heat-flux/thermal effects	0.100	20
	Bridge uncertainty (already included in self-heating component)	0.022	31
	Total B	**1.507**	**4.1**
TOTAL in W	**Measurement at FP**	**1.507**	**4.1**
	Measurement at TPW	**0.170**	**38.9**
	Combined standard *u*	1.517	4.2 = *v*
	Expanded *U* (95%)	4.212	2.8 = *k*

		TPW	
		mK	DF
TPW realization	Impurities	0.012	20
	hydrostatic head	0.004	20
	residual gas pressure	0.000	100
	Isotopic effects	0.002	100
	Buoyancy effect	0.000	100
	Strain/crystal size	0.005	10
TPW use	Self-heating	0.038	31
	Bridge uncertainty (already included in self-heating component)	0.022	31
	perturbing heat fluxes	0.000	100
TOTAL		**0.040**	**38.9**
	Combined standard *u*	0.040	38.9 = *v*
	Expanded *U* (95%)	0.082	2.0 = *k*

*6.4 NMC, A*STAR*

Tables 13 and 14 show NMC and KRISS measurements of the two SPRTs from NMC. For each SPRT, the table starts with measurement results at NMC, measurements at KRISS, then the return measurements at NMC. Table 15 is the uncertainty budget for the Al and TPW measurements at NMC.

Table 13. NMC and KRISS measurements of NMC SPRT #1

NMC measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
84.834 007					
	25.133 124	3.375 386 48			
84.833 992					
	25.133 112	3.375 387 50			
84.833 952					
	25.133 106	3.375 386 71			
			84.833 135		
				25.133 068	3.375 359 23
			84.833 128		
				25.133 066	3.375 359 25
			84.833 113		
				25.133 067	3.375 358 54
			84.832 994		
				25.133 094	3.375 350 23
			84.832 904		
				25.133 113	3.375 344 13
-	-	-			

Table 14. NMC and KRISS measurements of NMC SPRT #2

NMC measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
85.708 295					
	25.390 615	3.375 589 56			
85.708 273					
	25.390 609	3.375 589 49			
85.708 290					
	25.390 611	3.375 589 90			
			85.707 998		
				25.390 673	3.375 570 15
			85.707 979		
				25.390 670	3.375 569 76
			85.707 994		
				25.390 645	3.375 573 70
			85.707 869		
				25.390 669	3.375 565 58
			85.707 968		
				25.390 663	3.375 570 36
85.708 628					
	25.390 662	3.375 596 43			
85.708 631					
	25.390 668	3.375 595 75			
85.708 640					
	25.390 664	3.375 596 64			

Table 15. NMC uncertainty budget at Al FP and TPW

Uncertainty components	Type	Contribution /mK (k = 1)	
		Al	TPW
Fixed point effects			
Hydrostatic-head	B	0.016	0.010
Gas pressure	B	0.200	0.000
Chemical impurities	B	1.000	0.020
Isotopic composition	B	0.000	0.002
Slope of plateau	B	0.400	0.000
Heat Flux	B	0.300	0.010
Resistance measurement			
Standard resistor stability	B	0.084	0.025
Bridge uncertainty	B	0.011	0.003
Bridge non-linearity	B	0.149	0.044
Self-heating correction	B	0.029	0.029
Others			
Propagation from TPW	B	0.461	
Realization repeatability	A	0.160	0.040
Long term drift on TPW cell	B		0.058
Total combined uncertainty (k = 2)		**2.50**	**0.19**

*: DoF is infinity for Type B and 39 for Type A

6.5 NMIM

Tables 16 and 17 show NMIM and KRISS measurements of the two SPRTs from NMIM. For each SPRT, the table starts with measurement results at NMIM, measurements at KRISS, then the return measurements at NMIM. Table 19 is the uncertainty budget for the Al and TPW measurements at NMIM.

Table 16. NMIM and KRISS measurements of NMIM SPRT #1

NMIM measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
8.123 4600					
	2.406 3334	3.375 866 40			
8.123 4511					
	2.406 3340	3.375 861 91			
8.123 4672					
	2.406 3348	3.375 867 44			
			8.123 5768		
				2.406 3503	3.375 891 16
			8.123 5909		
				2.406 3499	3.375 897 65
			8.123 5715		
				2.406 3504	3.375 888 86
			8.123 5849		
				2.406 3500	3.375 895 06
8.123 5625					
	2.406 3786	3.375 845 55			
8.123 5719					
	2.406 3793	3.375 848 51			
8.123 5848					
	2.406 3938	3.375 833 50			

Table 17. NMIM and KRISS measurements of NMIM SPRT #2

NMIM measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
8.684 6408					
	2.572 8737	3.375 463 32			
8.684 6325					
	2.572 8810	3.375 450 45			
8.684 6298					
	2.572 8818	3.375 488 41			
			8.684 7467		
				2.572 8875	3.375 486 41
			8.684 7445		
				2.572 8872	3.375 485 87
			8.684 7422		
				2.572 8865	3.375 486 02
8.684 7109					
	2.572 9258	3.375 422 28			
8.684 7324					
	2.572 9247	3.375 431 99			
8.684 7472					
	2.572 9247	3.375 437 73			

Table 18. NMIM uncertainty budget at Al FP

	Uncertainty factor	Source	Effects	Type	$u(x_i)$ /mK	Distr	Div	$u(y_i)$ /mK	v_i(DOF)
A	**Freezing phase**								
1	Phase transition realization repeatability	Calibration data	R	A	0.428	t	1	0.603	2
B	**Fixed point effects**								
2	Hydrostatic pressure	correction	S	B	0.336	R	√3	0.194	80
3	Residual gas pressure	Max correction	S	B	1.486	R	√3	0.813	80
4	Impurities	Impurity cert	S	B	1.300	normal	2	0.650	1000
5	Thermal effects	Immersion	S	B	1.908	rect	√3	1.102	80
C	**SPRT effects**								
6	Water triple point variation	WTP stability	S	B	1.358	rect	√3	0.875	80
D	**Resistance measurement**								
7	Self-heating correction	Stdev correction	S	B	0.147	rect	√3	0.058	80
8	Bridge non-linearity (F18)	Linearity checked	R	B	0.648	rect	√3	0.374	100
9	Std resistor	Cal cert	S	B	0.259	normal	2	0.130	1000
E	**Others**								
10	Propagation (TPW)	WTP uncertainty	S	B	6.30	normal	2	3.15	1000
	Combined uncertainty (uc)				**3.68 mK**				
	Effective DOF				**936**				
	Coverage factor (k) at 95 % CL				**2.00**				
	Expanded uncertainty (k x uc)				**7.36 mK**				

Table 19. NMIM uncertainty budget at TPW

	Uncertainty factor	Source	Effects	Type	$u(x_i)$ /mK	Distr	Div	$u(y_i)$ /mK	v_i(DOF)
A	**Freezing phase**								
1	Phase transition realization repeatability	Calibration data	R	A	0.620	t	1	0.693	2
B	**Fixed point effects**								
2	Hydrostatic pressure	correction	S	B	0.106	rect	√3	0.106	80
3	Isotropic	Impurity cert	S	B	0.002	normal	2	0.002	1000
4	Thermal effects	Immersion	S	B	0.115	rect	√3	0.115	80
D	**Resistance measurement**								
5	Self-heating correction	Stdev correction	S	B	0.009	rect	√3	0.009	80
6	Bridge non-linearity (F18)	Linearity checked	R	B	0.374	rect	√3	0.374	100
7	Std resistor	Cal cert	S	B	0.130	normal	2	0.130	1000
	Combined uncertainty (uc)	**0.75 mK**							
	Effective DOF	**4.33**							
	Coverage factor (k) at 95 % CL	**2.78**							
	Expanded uncertainty (k x uc)	**2.1 mK**							

6.6 NMISA

Tables 20 and 21 show NMISA and KRISS measurements of the two SPRTs from NMISA. For each SPRT, the table starts with measurement results at NMISA, measurements at KRISS, then the return measurements at NMISA. Table 22 is the uncertainty budget for the Al and TPW measurements at NMISA.

Table 20. NMISA and KRISS measurements of NMISA SPRT #1

NMISA measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
87.637 206	25.957 332	3.376 202 34			
			87.636 908	25.957 142	3.376 215 56
			87.636 951	25.957 124	3.376 219 68
			87.636 952	25.957 101	3.376 222 59
			87.637 106	25.957 101	3.376 228 63
			87.637 080	25.957 088	3.376 229 22
			87.637 039	25.957 105	3.376 225 52
			87.637 121	25.957 099	3.376 229 36
			87.637 009	25.957 091	3.376 226 09
87.637 808	25.957 548	3.376 197 49			

Table 21. NMISA and KRISS measurements of NMISA SPRT #2

NMISA measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
86.012 096	25.475 965	3.376 205 63			
			86.012 030	25.475 742	3.376 232 53
			86.012 146	25.475 719	3.376 240 10
			86.011 879	25.475 718	3.376 229 82
			86.012 117	25.475 731	3.376 237 49
			86.012 042	25.475 730	3.376 234 64
			86.011 965	25.475 727	3.376 232 06
			86.012 111	25.475 731	3.376 237 18
			86.012 052	25.475 725	3.376 235 74
86.011 831	25.475 872	3.376 207 57			

Table 22. NMISA uncertainty budget at Al FP and TPW

Type A	Al FP		WTP	
	mK	DF	mK	DF
Phase transition realization repeatability	0.369	17	0.010	12
Bridge repeatability				
Total A	0.369		0.010	
Type B				
Chemical impurities	0.722	500		
Hydrostatic-head	0.009	500	0.004	500
Heat flux	0.958	500	0.028	500
Gas pressure	0.003	500	0.000	500
Slope of plateau	1.010	500		
Propagated from TPW	0.209	500		
Isotopic variation			0.038	500
Bridge nonlinearity	0.014	41	0.012	41
SPRT self-heating	0.000	500	0.000	500
R_s stability	0.111	500		
SPRT leakage				
Total B	1.59		0.049	
Combined standard uncertainty	1.628	1301	0.050	928
Expanded uncertainty (Approx. 95 % level of confidence, $k = 2$)	3.257	2	0.099	2

6.7. *NIMT*

Tables 23 and 24 show NIMT and KRISS measurements of the two SPRTs from NIMT. For each SPRT, the table starts with measurement results at NIMT, measurements at KRISS, then the return measurements at NIMT. Table 25 is the uncertainty budget for the Al and TPW measurements at NIMT.

Table 23. NIMT and KRISS measurements of NIMT SPRT #1

NIMT measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
86.403 019	25.601 567	3.374 911 35			
86.402 983	25.601 570	3.374 909 53			
86.402 938	25.601 554	3.374 909 86			
			86.402 539	25.601 545	3.374 895 49
			86.402 516	25.601 546	3.374 894 47
			86.402 520	25.601 515	3.374 898 75
86.403 218	25.601 547	3.374 921 71			
86.403 220	25.601 539	3.374 922 89			
86.403 191	25.601 528	3.374 923 24			

Table 24. NIMT and KRISS measurements of NIMT SPRT #2

NIMT measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
86.320 117	25.576 861	3.374 930 07			
86.320 084	25.576 863	3.374 928 52			
86.320 052	25.576 836	3.374 930 84			
			86.319 597	25.576 767	3.374 922 19
			86.319 527	25.576 769	3.374 919 08
			86.319 504	25.576 772	3.374 917 85
86.139 876	25.576 736	3.374 937 11			
86.319 882	25.576 733	3.374 937 77			
86.319 877	25.576 718	3.374 939 57			

Table 25. NIMT uncertainty budget at Al FP and TPW

Type A	Al FP		TPW		Systematic or random
	mK	DF	mK	DF	
Phase transition realization repeatability	< 0.001	2	0.049	2	R
Bridge repeatability	< 0.001	44	< 0.001	44	R
Total A	< 0.001		0.049		
Type B					
Hydrostatic-head	0.017	∞	0.015	∞	S
Heat flux	0.084	∞	0.060	∞	S
Gas pressure	1.29	∞	0.045	∞	S
Slope of plateau	0.289	∞	0.033	∞	S
Propagated from TPW	0.407	∞	0	∞	S
Bridge nonlinearity	< 0.001	∞	< 0.001	∞	S
SPRT self-heating	< 0.001	∞	< 0.001	∞	S
Rs stability	< 0.001	∞	< 0.001	∞	S
Total B	1.386		0.084		
Combined standard uncertainty	1.386	> 500	0.097	> 500	
Expanded uncertainty (Approx. 95 % level of confidence)	2.77		0.194		

6.8 SCL

Tables 26 shows SCL and KRISS measurements of the two SPRTs from SCL. For each SPRT, the table starts with measurement results at SCL, measurements at KRISS, then the return measurements at SCL. Table 27 is the uncertainty budget for the Al and TPW measurements at SCL.

Table 26. SCL and KRISS measurements of SCL SPRT #1

SCL measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
86.188 161					
	25.532 476	3.375 628 87			
86.188 143					
	25.532 473	3.375 628 50			
86.188 143					
	25.532 473	3.375 628 42			
			86.188 062		
				25.532 610	3.375 607 23
			86.188 063		
				25.532 614	3.375 606 71
			86.188 113		
				25.532 623	3.375 607 47
86.188 451					
	25.532 625	3.375 620 40			
86.188 446					
	25.532 627	3.375 619 99			
86.188 428					
	25.532 628	3.375 619 16			

Table 27. SCL uncertainty budget at Al FP and TPW

Type A	Al FP		TPW		Systematic or random
	mK	DF	mK	DF	
Phase transition realization repeatability	0.114	2	0.005	9	R
Bridge repeatability	0.001	5	0.005	5	R
Total A	0.114	2	0.007	13	
Type B					
Chemical impurities	0.519	∞	0.010	50	S
Hydrostatic-head	0.028	∞	0.004	∞	S
Heat flux	0.240	∞	0.008	∞	S
Gas pressure	0.606	∞			S
Slope of plateau	0.271	∞	0.010	∞	S
Propagated from TPW	0.224	50			S
Isotopic variation			0.045	∞	S
Bridge nonlinearity	0.210	∞	0.014	∞	S
SPRT self-heating	0.072	50	0.014	50	S
R_s stability	0.011	79	0.003	79	S
SPRT leakage	0.271	∞	0.009	∞	S
Total B	0.970	17960	0.053	7663	S
Combined standard uncertainty	0.977	6745	0.053	6712	
Expanded uncertainty (Approx. 95 % level of confidence, $k = 2$)	1.915		0.105		

6.9 SNSU-BSN

Tables 28 and 29 show SNSU-BSN and KRISS measurements of the two SPRTs from SNSU-BSN. For each SPRT, the table starts with measurement results at SNSU-BSN, measurements at KRISS, then the return measurements at SNSU-BSN. Table 30 is the uncertainty budget for the Al and TPW measurements at SNSU-BSN.

Table 28. SNSU-BSN and KRISS measurements of SNSU-BSN SPRT #1

SNSU-BSN measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
85.935 818	25.459 598	3.375 379 93			
85.935 786	25.459 542	3.375 386 22			
85.935 753	25.459 501	3.375 390 34			
			85.935 699	25.459 549	3.375 381 80
			85.935 690	25.459 541	3.375 382 49
			85.935 683	25.459 542	3.375 382 06
			85.935 581	25.459 550	3.375 377 05
85.936 086	25.459 579	3.375 393 06			
85.936 089	25.459 568	3.375 394 61			
85.936 088	25.459 574	3.375 393 73			

Table 29. SNSU-BSN and KRISS measurements of SNSU-BSN SPRT #2

SNSU-BSN measurements			KRISS measurements		
R(Al) /Ω	*R*(TPW) /Ω	*W*	*R*(Al) /Ω	*R*(TPW) /Ω	*W*
85.792 791	25.420 491	3.374 946 22			
85.792 789	25.420 538	3.374 939 97			
85.792 836	25.420 567	3.374 937 98			
			85.791 847	25.420 266	3.374 939 05
			85.791 994	25.420 314	3.374 938 37
			85.791 942	25.420 351	3.374 931 48
			85.792 035	25.420 369	3.374 932 67
			85.792 016	25.420 435	3.374 923 25
85.792 831	25.420 593	3.374 934 36			
85.792 844	25.420 618	3.374 931 52			
85.792 862	25.420 616	3.374 932 46			

Table 30. SNSU-BSN uncertainty budget at Al FP and TPW

Type A	Al FP		TPW		Systematic or random
	mK	DF	mK	DF	
Phase transition realization repeatability	0.132	5	0.200	5	R
Stability of SPRT	0.155	5	0.155	5	R
Bridge repeatability	0.092	24	0.109	24	R
Total A	0.22		0.28		
Type B					
Chemical impurities	2.397	50	0.087	50	S
Isotopic composition			0.004	50	S
Hydrostatic pressure	0.164	50	0.084	50	S
Heat flux	0.375	50	0.010	50	S
Gas pressure	0.006	50	0.000	50	S
Slope of plateau	0.300	50	0.010	50	S
Propagated from TPW	2.1	50	0.000	50	S
Bridge nonlinearity	0.354	50	0.354	50	S
SPRT self-heating	0.150	50	0.150	50	S
R_s stability	0.104	50	0.104	50	S
SPRT leakage	0.005	50	0.005	50	S
Total B	3.25		0.42		
Combined standard uncertainty	3.26	107	0.5		
Expanded uncertainty (Approx. 95 % level of confidence, $k = 2$)	6.5		1.0		

6.10. Immersion profile

Immersion profiles of the Al cells used in this comparison are shown in Figure 1. Open symbols in the plots represent measurement results and solid lines represent the theoretical slope calculated from the coefficient (0.016 mK/cm) specified in the International Temperature Scale of 1990 [3]. NMISA measured the immersion profile with the two SPRTs used in this comparison, and both results are both shown in Figure 1.

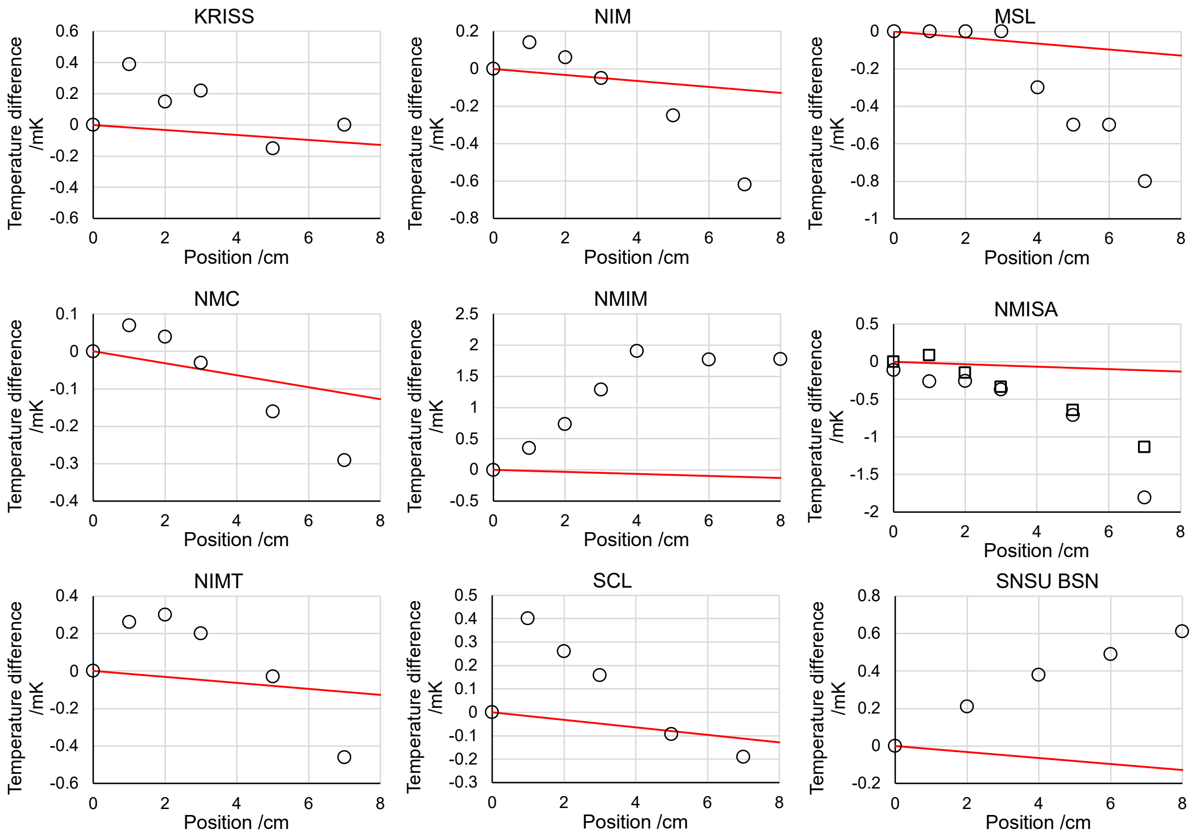

Figure 1. Immersion profiles of the Al freezing point cells used in this comparison, measured at each participant's laboratory

6.11. Summary of measurements

Table 31 shows $W_{\mathrm{NMI,before}}$ (W(Al) at the specific NMI before the KRISS measurement) and $W_{\mathrm{NMI,after}}$ (W(Al) at the specific NMI after the KRISS measurement) measured at the participants' laboratories. The average of $W_{\mathrm{NMI,before}}$ and $W_{\mathrm{NMI,after}}$ is $W_{\mathrm{NMI,avg}}$. Together with W_{KRISS}, $\Delta T(\mathrm{NMI_{APMP.T\text{-}K4.2}} - \mathrm{KRISS_{APMP.T\text{-}K4.2}})$ is calculated as

$$\Delta T(\mathrm{NMI_{APMP.T\text{-}K4.2}} - \mathrm{KRISS_{APMP.T\text{-}K4.2}}) = (W_{\mathrm{NMI,avg}} - W_{\mathrm{KRISS}}) / (dW_{\mathrm{r}} / dT)_{\mathrm{Al}} . \quad (1)$$

In Table 31, this difference is simply denoted as ΔT_{NMI}. $u_{\mathrm{NMI},i}$ is the standard uncertainty of the W(Al) measurement, converted to temperature, when the participant's Al FP was realized with the participant's SPRT #i (i = 1 or 2). When the two uncertainties $u_{\mathrm{NMI},i}$ before and after the KRISS measurement reported by the participants were different, a single representative value was used for $u_{\mathrm{NMI},i}$.

Table 31. Resistance ratio measured at participating laboratories and KRISS, and the temperature difference calculated from them. The last column indicates the expanded uncertainty claimed by the participants. ΔT_{NMI} is short for $\Delta T(\mathrm{NMI_{APMP.T\text{-}K4.2}} - \mathrm{KRISS_{APMP.T\text{-}K4.2}}) = (W_{\mathrm{NMI,avg}} - W_{\mathrm{KRISS}}) / (dW_{\mathrm{r}} / dT)_{\mathrm{Al}}$.

artefact	$W_{\mathrm{NMI,before}}$	$W_{\mathrm{NMI,after}}$	$W_{\mathrm{NMI,avg}}$	W_{KRISS}	ΔT_{NMI} /mK	$u_{\mathrm{NMI},i}$ /mK
NIM #1	3.375 935 77	3.375 936 93	3.375 936 35	3.375 910 93	+7.93	0.97
NIM #2	3.375 372 05	3.375 373 75	3.375 372 90	3.375 351 38	+6.72	0.97
MSL #1	3.375 175 69	3.375 192 05	3.375 183 87	3.375 181 96	+0.60	1.52
MSL #2	3.375 139 09	3.375 161 79	3.375 150 44	3.375 147 25	+0.99	1.52
NMC #1	3.375 386 90	-	-	3.375 354 28	-	-
NMC #2	3.375 589 65	3.375 596 27	3.375 592 96	3.375 569 91	+7.19	1.25
NMIM #1	3.375 865 25	3.375 842 52	3.375 853 88	3.375 893 18	–12.26	3.91
NMIM #2	3.375 454 06	3.375 430 67	3.375 442 36	3.375 486 10	–13.65	3.65
NMISA #1	3.376 202 34	3.376 197 49	3.376 199 92	3.376 224 58	–7.70	1.62
NMISA #2	3.376 205 63	3.376 207 57	3.376 206 60	3.376 234 95	–8.84	1.63
NIMT #1	3.374 910 25	3.374 922 62	3.374 916 43	3.374 896 24	+6.30	1.40
NIMT #2	3.374 929 81	3.374 938 15	3.375 933 98	3.374 919 71	+4.45	1.39
SCL	3.375 628 60	3.375 619 90	3.375 624 25	3.375 607 14	+5.34	0.98
SNSU-BSN #1	3.375 385 50	3.375 393 80	3.375 389 65	3.375 380 85	+2.75	3.23
SNSU-BSN #2	3.374 941 39	3.374 932 78	3.374 937 08	3.374 932 97	+1.28	3.70

Table 32 shows ΔT_{NMI}, averaged for two SPRTs (if applicable) and one representative uncertainty u_{NMI} in the Al FP realization at each NMI. $u_{\mathrm{A,pilot}}$ is the standard deviation of the mean of W measured at KRISS, converted to temperature. When two SPRTs were measured at KRISS, $u_{\mathrm{A,pilot}}$ was evaluated assuming equal weight and no correlation between the measurements of the two SPRTs. $u(C_{\mathrm{SPRT}})$ is the standard uncertainty due to the instability of the artefact during the comparison, calculated from the two values of $u(C_{\mathrm{SPRT},i})$ (i = 1 or 2) as defined in the comparison protocol (using the symbols defined in this report):

$$u(C_{\mathrm{SPRT},i}) = \frac{\left| W_{\mathrm{NMI},i,\mathrm{before}} - W_{\mathrm{NMI},i,\mathrm{after}} \right|}{(dW_{\mathrm{r}} / dT) \cdot \sqrt{12}} . \quad (2)$$

For most participants who used two SPRTs in this comparison, $u(C_{\mathrm{SPRT}})$ was calculated as follows:

$$u(C_{\mathrm{SPRT}}) = \sqrt{\frac{u^2(C_{\mathrm{SPRT},1}) + u^2(C_{\mathrm{SPRT},2})}{4}} \; . \qquad (3)$$

The uncertainty $u(\Delta T_{\mathrm{NMI}})$ of ΔT_{NMI} is calculated by combining u_{NMI}, $u_{\mathrm{A,pilot}}$, and $u(C_{\mathrm{SPRT}})$:

$$u(\Delta T_{\mathrm{NMI}}) = \sqrt{u_{\mathrm{NMI}}^2 + u_{\mathrm{A,pilot}}^2 + u^2(C_{\mathrm{SPRT}})} \; . \qquad (4)$$

Table 32. Measured temperature difference $\Delta T_{\mathrm{NMI}} = \Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}})$ of each participant averaged over two artifacts (one artifact each in case of NMC and SCL) used in this comparison. The table also includes the standard uncertainty u_{NMI} of the Al FP at each participant's laboratory, the type A uncertainty $u_{\mathrm{A,pilot}}$ of the Al FP measurement at the pilot, and the uncertainty $u(C_{\mathrm{SPRT}})$ due to the instability of the artefact during the comparison. The last column shows the combined uncertainty derived from u_{NMI}, $u_{\mathrm{A,pilot}}$, and $u(C_{\mathrm{SPRT}})$.

Laboratory	ΔT_{NMI} /mK	u_{NMI} /mK	$u_{\mathrm{A,pilot}}$ /mK	$u(C_{\mathrm{SPRT}})$ /mK	$u(\Delta T_{\mathrm{NMI}})$ /mK
NIM	+7.3	1.0	0.1	0.1	1.0
MSL	+0.8	1.5	0.2	1.3	2.0
NMC	+7.2	1.2	0.5	0.6	1.5
NMIM	–13.0	3.7	0.3	1.5	3.9
NMISA	–8.3	1.6	0.3	0.2	1.7
NIMT	+5.4	1.4	0.3	0.7	1.6
SCL	+5.3	1.0	0.1	0.8	1.3
SNSU-BSN	+2.0	3.2	0.5	0.5	3.3

7. Analysis of the results

The temperature difference between the realized Al FP at each NMI in this comparison and the corresponding KCRV of the CCT-K4 is

$$\begin{aligned}&\Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}}) \\ &\quad = \Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}}) + \Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS\text{-}NIM}}. \qquad (5)\end{aligned}$$

The first half of the right-hand side of (5), $\Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}})$, is as calculated in the second column of Table 32. The second half, $\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS\text{-}NIM}}$, represents the difference between the KRISS measurement in APMP.T-K4.2 and the KCRV of the CCT-K4 through the simple average of the two available links, i.e., via KRISS and via NIM, and can be written as

$$\begin{aligned}&\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS\text{-}NIM}} \\ &\quad = \frac{1}{2}\left[\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS}} + \Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{NIM}}\right]. \qquad (6)\end{aligned}$$

Here, the term $\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS}}$ represents the difference between the KRISS measurement in APMP.T-K4.2 and the KCRV of the CCT-K4 estimated via the KRISS link, and the term $\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{NIM}}$ represents the same temperature difference estimated via the NIM link. The first term is calculated to be

$$\begin{aligned}
&\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS}} \\
&\quad = \Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KRISS}_{\mathrm{CCT\text{-}K4}}) + \Delta T(\mathrm{KRISS}_{\mathrm{CCT\text{-}K4}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}}) \\
&\quad = 0 + (-2.26\ \mathrm{mK}) \\
&\quad = -2.26\ \mathrm{mK},
\end{aligned} \tag{7}$$

where $\Delta T(\mathrm{KRISS}_{\mathrm{APMP\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})$ is set to zero because KRISS used the same Al cell in the APMP.T-K4.2 and CCT-K4 comparisons. The second term in (6) is calculated to be

$$\begin{aligned}
&\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{NIM}} \\
&\quad = \Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{NIM}_{\mathrm{APMP.T\text{-}K4.2}}) + \Delta T(\mathrm{NIM}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{NIM}_{\mathrm{CCT\text{-}K4}}) \\
&\qquad + \Delta T(\mathrm{NIM}_{\mathrm{CCT\text{-}K4}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}}) \\
&\quad = -7.32\ \mathrm{mK} + 0.8\ \mathrm{mK} + (-0.13\ \mathrm{mK}) \\
&\quad = -6.65\ \mathrm{mK}.
\end{aligned} \tag{8}$$

Here, $\Delta T(\mathrm{NIM}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{NIM}_{\mathrm{CCT\text{-}K4}})$ is set to be +0.8 mK, which is the estimated temperature difference between the two Al cells used in the APMP.T-K4.2 and CCT-K4 at NIM [4]. Applying (7) and (8), (6) can be simplified to

$$\begin{aligned}
\Delta T(\mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})_{\mathrm{KRISS\text{-}NIM}} &= \frac{1}{2}(-2.26\ \mathrm{mK} - 6.65\ \mathrm{mK}) \\
&= -4.46\ \mathrm{mK}
\end{aligned} \tag{9}$$

and (5) can be rewritten as

$$\Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}}) = \Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T\text{-}K4.2}}) - 4.46\ \mathrm{mK}. \tag{10}$$

Table 33 lists $\Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})$ calculated for participants who did not participate in the CCT-K4. This difference is denoted as $\Delta T_{\mathrm{NMI,CCT\text{-}K4}}$ in Table 33. The uncertainty associated with this difference, $u(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$, is calculated by

$$u(\Delta T_{\mathrm{NMI,CCT\text{-}K4}}) = \sqrt{u^2(\Delta T_{\mathrm{NMI}}) + \left(\frac{u(\Delta T_{\mathrm{KRISS}})}{2}\right)^2 + \left(\frac{u(\Delta T_{\mathrm{NIM}})}{2}\right)^2 + u^2_{\mathrm{NIM,KRISS}}}\ . \tag{11}$$

$u(\Delta T_{\mathrm{KRISS}})$ represents the uncertainty of the value in equation (7), and was assigned based on the long-term drift of the KRISS's Al FP cell. $u(\Delta T_{\mathrm{NIM}})$ represents the uncertainty of the value in equation (8) and was determined as the square root of the quadrature sum of (i) the standard uncertainty of the mean of KRISS measurement of NIM's SPRTs in APMP.T-K4.2, (ii) the $u(C_{\mathrm{SPRT}})$ term of the NIM

SPRTs, and (iii) the standard uncertainty of the mean of NIM measurements when comparing NIM's cells used in the CCT-K4 and this comparison [4]. $u_{\mathrm{NIM,KRISS}}$ is the standard uncertainty arising from the discrepancy between the links to the KCRV of the CCT-K4 via KRISS and NIM, with the discrepancy assumed to be the width of the rectangular distribution. From $u(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$, the expanded uncertainty $U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ was calculated for a coverage of probability of 95 %.

Table 33. $\Delta T(\mathrm{NMI}_{\mathrm{APMP.T\text{-}K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})$ indicated as $\Delta T_{\mathrm{NMI,CCT\text{-}K4}}$ in the second column, and its related uncertainties.

Laboratory	$\Delta T_{\mathrm{NMI,CCT\text{-}K4}}$ /mK	$u(\Delta T_{\mathrm{NMI}})$ /mK	$u(\Delta T_{\mathrm{KRISS}})$ /mK	$u(\Delta T_{\mathrm{NIM}})$ /mK	$u_{\mathrm{NIM,KRISS}}$ /mK	$u(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ /mK	$U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ /mK
MSL	−3.7	2.0	1.5	0.3	1.3	2.5	5.0
NMC	2.7	1.5	1.5	0.3	1.3	2.1	4.1
NMIM	−17.4	3.9	1.5	0.3	1.3	4.2	8.3
NMISA	−12.7	1.7	1.5	0.3	1.3	2.2	4.4
NIMT	0.9	1.6	1.5	0.3	1.3	2.1	4.2
SCL	0.9	1.3	1.5	0.3	1.3	1.9	3.8
SNSU-BSN	−2.4	3.3	1.5	0.3	1.3	3.6	7.2

Figure 2 shows the temperature differences of the participants from the KCRV of the CCT-K4, and the expanded uncertainties $U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ as error bars.

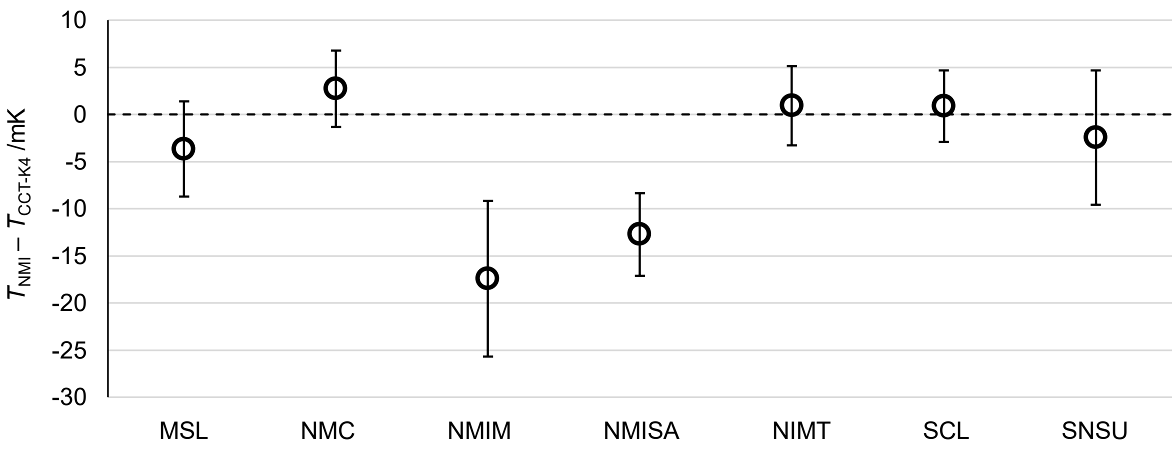

Figure 2. Temperature difference between the participants and the KCRV of the CCT-K4 at the Al freezing point. The error bars represent the expanded uncertainty of the difference, with a coverage probability of 95 %.

8. Conclusions

Five out of seven participating laboratories in this report have shown consistent results at Al FP within the expanded uncertainty of the temperature difference. The results of NMIM and NMISA deviated from the KCRV of the CCT-K4 by −17.4 mK and −12.7 mK, respectively. NMIM has participated in the APMP.T-K4 and the deviation was similar (−14.5 mK) in both its direction and magnitude.

The key limitation of the comparison result is the discrepancy between the KRISS and NIM links to the KCRV of the CCT-K4. In this comparison, the measured difference between NIM and KRISS was 7.32 mK. In the CCT-K4, the NIM result was lower than the KCRV of the CCT-K4 by 0.13 mK, while the KRISS result was lower than the KCRV of the CCT-K4 by 2.26 mK. Considering that the NIM Al cell used in this comparison was estimated to be higher than the NIM cell used in the CCT-K4 by 0.8 mK [4], KRISS was *expected* to be lower than NIM value by −2.26 − (−0.13) − 0.8 mK = 2.93 mK. Therefore, the discrepancy in the NIM-KRISS difference between this comparison and the CCT-K4 is 7.32 − 2.93 = 4.39 mK. This discrepancy is smaller than the simple sum of the two U_{NMI}'s of KRISS and NIM, but larger than the combined uncertainty of the two U_{NMI} 's under the assumption of no correlation: $\sqrt{U_{\mathrm{KRISS}}{}^2 + U_{\mathrm{NIM}}{}^2}$. As a result, $u_{\mathrm{NIM,KRISS}}$ had to be included in the uncertainty of the temperature difference between the participants and the KCRV of the CCT-K4, leading to a larger $U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ for all participants of this comparison. This, in turn, limits the usefulness of this comparison in supporting small CMCs at the Al FP.
The measurements of the CCT-K4 are now older than 20 years, and in this comparison, KRISS included a long-term stability term in the uncertainty of the Al FP considering this. To fully resolve this issue, another CCT key comparison of the Al FP (and Ag FP) is necessary.

Another limitation of the comparison is the observed instability of some SPRTs used as travelling artifacts. The change of the SPRT from the pre-KRISS measurements to the post-KRISS measurements, calculated from the change in W(Al) converted to the temperature difference, is larger than 5 mK for both SPRTs used by MSL and larger than 7 mK for both SPRTs used by NMIM. This also resulted in large $U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$ for the two participants.

Unlike in the CCT-K4, in which fixed point cells along with the high-temperature SPRTs were circulated, in APMP.T-K4 and in this comparison only SPRTs were circulated as transfer standards, not fixed-point cells. Some SPRTs suffered large change during the comparison, which is shown by large difference in the measurement results of the participating laboratories before and after the pilot lab measurement. The typical stability of the SPRTs at high temperatures, considering that they have to be transported to different laboratories by hand or in some cases by courier, is not good enough to support the comparison of the realization of fixed-point cells. For comparison of the calibration at Al and Ag, circulating the cells, optionally with SPRTs, might be a better scheme than just circulating thermometers.

9. References

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10. Appendices

10.1 Approved protocol

Key Comparison APMP.T-K4.2 – Draft Protocol **2017-12-19**

Comparison of Realization of the Aluminum Freezing Point

Objective: This comparison is designed to compare the realizations of the aluminum freezing point (Al FP) of the national metrology institutes (NMIs) in the Asia Pacific Metrology Programme (APMP), and to provide a linkage to the KCRV of the CCT-K4. The transfer standards will be long-stem SPRTs.

NMI Participants:

Pilot: Korea Research Institute of Standards and Science (KRISS)
- Wukchul Joung, wukchul.joung@kriss.re.kr

Co-pilot: National Institute of Metrology (NIM)
- Jianping Sun, sunjp@nim.ac.cn

Participating NMIs:

Measurement Standards Laboratory (MSL)
- Rod White, rod.white@measurement.govt.nz

National Metrology Centre, Agency for Science, Technology and Research (NMC, A*STAR)
- Shaochun Ye, ye_shaochun@nmc.a-star.edu.sg

National Metrology Institute of Malaysia (NMIM)
- Hafidzah Othman, hafidzah@sirim.my

National Metrology Institute of South Africa (NMISA)
- Efrem Ejigu, EEjigu@nmisa.org

National Institute of Metrology (Thailand) (NIMT)
- Charuayrat Yaokulbodee, charuayrat@nimt.or.th

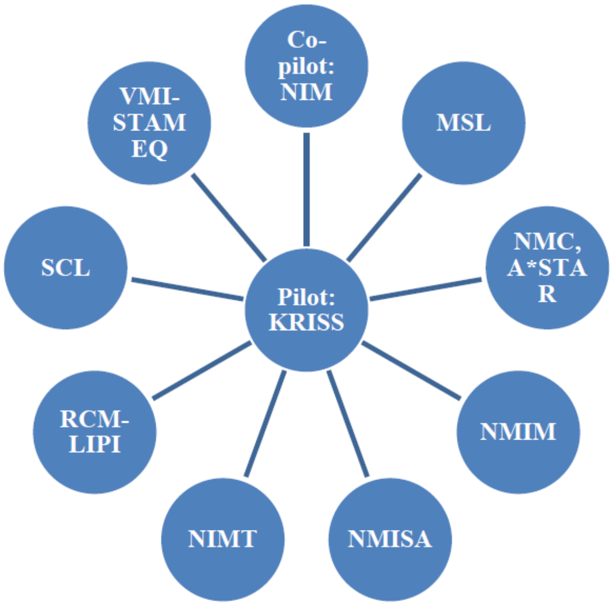
Research Center for Metrology-LIPI (RCM-LIPI)
- Suherlan Abu Hanifa, suherlan75@yahoo.com

Standards and Calibration Laboratory (SCL)
- Julian C. P. Cheung, cpcheung@itc.gov.hk

Vietnam Metrology Institute, Directorate for Standards and Quality (VMI-STAMEQ)
- Do Van Hong, hongdv@vmi.gov.vn

Page 1 of 14

Comparison scheme: Collapsed star



Projected Timeline:

Protocol Agreement	December 31, 2017
Transfer Standards Sent to KRISS	March 31, 2018
Transfer Standards Returned to participants	December 31, 2018
Transfer Standards Re-measured by participants	March 31, 2019
Draft A Report Completed	July 31, 2019

Participants will supply the following information:

- Two SPRTs
  - NMI participants will select their own SPRTs (preferably 25 Ω SPRTs) based on their own criteria.
    - NMI participants will inform the pilot of the selection criteria and information on the artefacts (e.g. manufacturer, model, serial number, nominal TPW resistance, sheath type, sensing element length, etc.)
    - In the CCT-K4, a transfer cell (i.e. a sealed aluminum fixed-point cell) was used as the artefact. The consequence of using SPRTs as the artefacts, instead of the cell, is the addition of the measurement uncertainties related with the measurement of the resistances and the stability of the thermometers. However,

as this indicates the measurement capability of the participant more properly, it is expected to be more beneficial for the participants to claiming their CMCs.

- The participants must calibrate SPRTs at Al FP before sending the artefacts to the pilot and again on return from the pilot.
- The participants are required to hand-carry their SPRTs to and from the pilot. However, if hand carrying the artefacts is not possible due to some reasons, the participant can use a parcel delivery service with a careful packaging, but this may result in a significant change in the resistance of the SPRT; thus, this is not a recommended way to transport the artefact.
  - All the costs including the insurance on the artefacts will be paid by the participants.
  - When requested, the pilot provide proper documentation for custom formalities.

- Calibration results supplied in three resistances at Al FP and TPW (i.e. $R_{\mathrm{Al\,FP}}$ and R_{TPW}) and the resistance ratio at Al FP (i.e. W) with all corrections applied by the NMIs such that the W values are equivalent to the ITS-90 assigned temperature values for 0 mA; the calibration results should be based on at least 3 repeated measurements at Al FP (including the subsequent measurement at TPW).
  - Appendix A gives a reporting worksheet.
- The measurement equation used to compute each calibration result including the hydrostatic head and gas pressure corrections.
- Uncertainty budgets compliant with CCT WG-KC (CCT/08-19/rev) that includes degrees of freedom associated each component. Separate uncertainty budgets for each SPRT before and after the measurement at KRISS should be submitted.
  - A suggested uncertainty budget is given in Appendix B.
    - A participant can add or delete sources of uncertainty as needed.
    - A participant may choose to supply their own uncertainty budget (CCT WG-KC compliant) that includes degrees of freedom for each source of uncertainty.
    - Please identify which components of the uncertainty budget are associated with random effects and which are associated with systematic effects within this comparison.
- Immersion profile for the Al FP cell used.
  - [R(FP), 0 mA] and corresponding [immersion depth (sensor midpoint), cm].
- Information on instrumentation used in the comparison.
  - Tables for reporting the instrumentation are given in Appendix C.

Reporting the calibration results:

The participants should send all the results and required information to the pilot laboratory (Wukchul Joung, wukchul.joung@kriss.re.kr) after completing the 2nd round measurement at the participating NMIs without informing the results to the other participating laboratory. If there are any questions about any aspects of the protocol or about how to report something that is requested, please contact the pilot laboratory prior to submitting the report. In case of unexpected delay, the participant is also required to contact the pilot for rearrangement of the schedule; if a significant delay is expected or if it is requested by the participant, the pilot can cancel the participation of the participant. After reviewing all submitted reports, the pilot will contact the participant if there is anything that is unclear or if any additional information is needed to complete the analysis of the data.

Method of Measurement:

The following procedures are only for reference. The participating NMIs are recommended to follow their own procedures practiced for calibration of an SPRT.

1. Measure *R*(TPW) of the transfer SPRTs.
2. Insert the SPRTs into an annealing furnace preheated to 500 °C and wait for 30 minutes. Heat the annealing furnace to 670 °C for 1 hour.
3. Anneal the SPRTs for 2 hours.
4. Lower the furnace temperature down to 500 °C for 4 hours. After stabilization at 500 °C for an hour, quickly remove the SPRT to the ambient air.
5. Measure *R*(TPW) of the transfer SPRTs.
6. If the change in the resistance of the SPRTs at the TPW before and after the annealing is smaller than 0.5 mK proceed to step 7, otherwise repeat the steps from 2 to 5. In case of not fulfilling this criterion even after repeated annealing, contact the pilot.
7. Melt the sample completely by setting the furnace set value 10 K above the freezing temperature of aluminum. The sample is recommended to be molten at this temperature for more than 10 hours. After completing the melt, stabilize the molten sample at 2 K above the freezing temperature.
8. Insert the fully annealed SPRT into the annealing furnace preheated to 500 °C. Heat the annealing furnace to 660 °C for 1 hour.
9. Nucleate the sample by lowering the furnace temperature below the freezing temperature. Specific temperature difference can be different for different samples at different NMIs.

After nucleation, remove a monitor SPRT in the cell and slowly increase the furnace set value to a temperature at which the freezing temperature of aluminum is to be measured.

10. Induce an inner liquid-solid interface around the thermometer well by inserting two fused silica rods successively for 2 minutes. Specific methods can also differ from NMIs to NMIs.
11. Insert the transfer SPRT and measure *R*(Al FP) of the SPRT at two measuring currents.
12. After the calibration at the Al FP, quickly remove the SPRT from the cell and place it into the annealing furnace at 660 °C. Annealing the SPRT for an hour and lower the furnace temperature to 500 °C for 4 hours. After stabilization at 500 °C for an hour, quickly remove the SPRT to the ambient air.
13. Measure *R*(TPW) of the transfer SPRT.
14. Repeat the procedure from 7 to 13 at least 3 times for each artefact. Measurements of resistances of both the SPRTs in the same plateau is possible as long as the measurements are sufficiently fast to ensure that significant segregation of impurities does not occur during the measurements.
15. Immersion characteristics can be measured following the steps from 7 to 13 with additional measurements of the aluminum freezing temperatures at different immersion depths. A table for reporting the immersion characteristics is given in Appendix A.

Linkage Mechanism:

KRISS and NIM participated in the CCT-K4, and both NMIs will serve as the linking laboratories in this comparison. The linkage will be from the fixed-point resistance ratio for the participating NMIs to the KCRV of the CCT-K4 through the mean difference between the fixed-point temperatures of the linking laboratories and the KCRV of the CCT-K4.

$$\Delta T(\mathrm{NMI}_{\mathrm{APMP.T-K4.2}} - \mathrm{KCRV}_{\mathrm{CCT-K4}}) = \Delta T(\mathrm{NMI}_{\mathrm{APMP.T-K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T-K4.2}}) + \Delta T(\mathrm{KRISS}_{\mathrm{APMP.T-K4.2}} - \mathrm{KCRV}_{\mathrm{CCT-K4}})_{\mathrm{KRISS\text{-}NIM}}$$

Where

$\Delta T(\mathrm{NMI}_{\mathrm{APMP.T-K4.2}} - \mathrm{KCRV}_{\mathrm{CCT\text{-}K4}})$ is the temperature difference between the fixed-point resistance ratio of the participating NMI in the APMP.T-K4.2 and the KCRV of the CCT-K4,

$\Delta T(\mathrm{NMI}_{\mathrm{APMP.T-K4.2}} - \mathrm{KRISS}_{\mathrm{APMP.T-K4.2}})$ is the fixed-point temperature difference between the participating NMI and KRISS measured in the APMP.T-K4.2,

$\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{KRISS-NIM}}$ is the temperature difference between the fixed-point resistance ratio of KRISS in the APMP.T-K4.2 and the KCRV of the CCT-K4 through the simple average of the deviations of the linking laboratories from the KCRV of the CCT-K4.

The fixed-point temperature difference between the participating NMI and KRISS, $\Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}})$, is defined as the average of the measured difference from the two artefacts.

$$\Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}}) = \frac{1}{2}\left\{\Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}})_1 + \Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}})_2\right\}$$

The temperature difference between the participating NMI and KRISS for each artefact is defined as the average of the measurement results before and after the measurement at KRISS.

$$\Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}})_i = \left\{W(\text{NMI}_{\text{APMP.T-K4.2}})_i - W(\text{KRISS}_{\text{APMP.T-K4.2}})_i\right\} \Big/ \frac{\mathrm{d}W_r}{\mathrm{d}T}$$

Here, the subscript, i refers to each artefact. The resistance ratio of the participating NMI for an artefact is the average of the measurement results before and after the measurement at KRISS.

$$W(\text{NMI}_{\text{APMP.T-K4.2}})_i = \frac{1}{2}\left\{W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{pre}} + W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{post}}\right\}$$

Here, the resistance ratios $W(\text{NMI}_{\text{APMP.T-K4.2}})_i$ and $W(\text{KRISS}_{\text{APMP.T-K4.2}})_i$ are the averages from the 3 repeated measurements.

The temperature difference between the fixed-point resistance ratio of KRISS in the APMP.T-K4.2 and the KCRV of the CCT-K4, $\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{KRISS-NIM}}$, is defined as a simple average of the deviations of the linking laboratories (i.e. KRISS and NIM) from the KCRV of the CCT-K4.

$$\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{KRISS-NIM}} = \frac{1}{2}\left\{\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{KRISS}} + \Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{NIM}}\right\}$$

Where

$$\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{KRISS}}$$
$$= \Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{CCT-K4}}) + \Delta T(\text{KRISS}_{\text{CCT-K4}} - \text{KCRV}_{\text{CCT-K4}})$$

$$\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KCRV}_{\text{CCT-K4}})_{\text{NIM}}$$
$$= \Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{NIM}_{\text{APMP.T-K4.2}}) + \Delta T(\text{NIM}_{\text{APMP.T-K4.2}} - \text{NIM}_{\text{CCT-K4}})$$
$$+ \Delta T(\text{NIM}_{\text{CCT-K4}} - \text{KCRV}_{\text{CCT-K4}})$$

Here, the temperature differences of the between the fixed-point cells of KRISS and NIM in the APMP.T-K4.2 and those in the CCT-K4, which are $\Delta T(\text{KRISS}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{CCT-K4}})$ and $\Delta T(\text{NIM}_{\text{APMP.T-K4.2}} - \text{NIM}_{\text{CCT-K4}})$, account for any changes in the fixed-point cells between these two comparisons. If the same fixed-point cell is to be used, this difference vanishes but only has uncertainty.

In this comparison, SPRT cutoff criteria will be used to ensure that uncertainty associated with the travel, handling, or stability of either SPRT will not dominate the standard uncertainty of the temperature difference. In this regard, the test for the stability of the travelling artefacts will be based on measurements done by the participants before and after the travel to KRISS. Following inequalities show the cutoff criteria used in this comparison, and an artefact, which meets both the two criteria, will not be included in the calculation. In case of failure of both the SPRTs, the participant will be informed of the failure of the two artefacts by the pilot and asked to repeat the measurements (possibly with different SPRTs).

$$\frac{\left|W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{pre}} - W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{post}}\right|}{(\mathrm{d}W_{\mathrm{r}}/\mathrm{d}T)\sqrt{u_{\mathrm{R}}^{2}\{W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{pre}}\} + u_{\mathrm{R}}^{2}\{W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{post}}\}}} > t_{0.95,\nu_{\text{eff}}}$$

$$u(C_{\text{SPRT},i}) > \frac{\sqrt{u^{2}(\Delta T(\text{NMI}_{\text{APMP.T-K4.2}} - \text{KRISS}_{\text{APMP.T-K4.2}})_{i} - u^{2}(C_{\text{SPRT},i}))}}{3}$$

Where

$$u(C_{\text{SPRT},i}) = \frac{\left|W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{pre}} - W(\text{NMI}_{\text{APMP.T-K4.2}})_{i,\text{post}}\right|}{(\mathrm{d}W_{\mathrm{r}}/\mathrm{d}T)\sqrt{12}}$$

In the cutoff criteria above, $u_{\mathrm{R}}\{W(\text{NMI}_{\text{APMP.T-K4.2}})_{i}\}$ is the combined standard uncertainty from all sources of random uncertainty for each SPRT, and $t_{0.95,\nu_{\text{eff}}}$ is the appropriate quantile of the

Student's t distribution with degrees of freedom, ν_{eff} needed to compute an approximate 95 % level of confidence for the temperature differences observed after travel to and from KRISS for each SPRT.

Appendix A: Measurement Reporting Worksheet

1. Measurement data

Participating NMI [ ]

Before sending SPRTs to pilot laboratory

Fixed-point	Artefact 1		Artefact 2	
	R_{FP} / Ω	R_{TPW} / Ω	R_{FP} / Ω	R_{TPW} / Ω
	W		W	
Al FP 1				
Al FP 2				
Al FP 3				
Average				
	U / mK		U / mK	

Final R(TPW) [ ] [ ]

On return to participating laboratory

Fixed-point	Artefact 1		Artefact 2	
	R_{FP} / Ω	R_{TPW} / Ω	R_{FP} / Ω	R_{TPW} / Ω
	W		W	
Al FP 1				
Al FP 2				
Al FP 3				
Average				
	U / mK		U / mK	

Final R(TPW) [ ] [ ]

2. Corrections

Before sending SPRTs to pilot laboratory

Fixed-point	Hydrostatic head		Gas pressure	
	Correction / mK	$u_{correction}$ / mK	Correction / mK	$u_{correction}$ / mK
Al FP				

On return to participating laboratory

Fixed-point	Hydrostatic head		Gas pressure	
	Correction / mK	$u_{correction}$ / mK	Correction / mK	$u_{correction}$ / mK
Al FP				

3. Immersion characteristics

Distance from the bottom / cm	0	1	2	3	5	7
Deviation from the bottom / mK						

Appendix B: Suggested Uncertainty Budget

Participating NMI

Type A	Al FP		TPW		Systematic or random
	mK	DF	mK	DF	
Phase transition realization repeatability					
Bridge repeatability					
Total A					
Type B					
Chemical impurities					
Hydrostatic-head					
Heat flux					
Gas pressure					
Slope of plateau					
Propagated from TPW					
Isotopic variation					
Bridge nonlinearity					
SPRT self-heating					
R_s stability					
SPRT leakage					
Total B					
Combined standard uncertainty					
Expanded uncertainty (Approx. 95 % level of confidence)					

Appendix C: Table for Instrumentation

1. Fixed-point (Al FP) cell and furnace

Laboratory	
Cell Cell manufacturer Open/closed? Pressure in cell	
Crucible Crucible material Crucible manufacturer Crucible length	
Metal sample Sample source Sample purity Sample weight	
Thermometer well Well material Well ID (mm)	
Immersion depth of SPRT[1]	
Furnace Manufacturer Control type How many zones? Heat pipe liner? Heater current (AC/DC)?	

[1] The distance from the surface of the ingot to the bottom of the thermometer well

2. Triple point of water cell

Laboratory	
Cell manufacturer	
Water source and purity	
Well diameter	
Immersion depth	
Heat transfer liquid:	
Cell maintained in: ice bath/water bath?	
Ice mantle:	
Method of preparation	
Annealing time before use	

3. Resistance measuring device

Laboratory	
Bridge manufacturer AC/DC	
If AC, give Frequency Bandwidth Gain Quad gain Output Normal measuring current Self-heating current Unity reading Zero reading Compliment check error	
If DC, give Gain Period of reversal Output	
Reference resistor Type Manufacturer Temperature Temperature coefficient	
Linearity of bridge	

4. Artefacts

Laboratory		
Artefact	Artefact 1	Artefact 2
Manufacturer		
Model		
Serial number		
Nominal resistance at TPW		
Sheath type		
Sensing element length[2]		

[2] The distance from the tip of the sheath to the mid-point of the sensing element

10.2 Document control history

2024-10-02 Sent to the APMP TCT Chair with a request to forward it to the CCT-WG-KC for CCT review.

2025-12-08 Following the comments from the CCT-WG-KC reviewers, the uncertainty term "Propagation from TPW" at the Al FP was reevaluated. This resulted in a slight increase in $u_{\mathrm{NMI},i}$ for some participants, as well as a subsequent increase in both $u(\Delta T_{\mathrm{NMI}})$ and $U(\Delta T_{\mathrm{NMI,CCT\text{-}K4}})$.
2026-01-07 Approved by the CCT-WG-KC