Revised 2005/03/04

# CCT-K2.1 : NRC/VNIIFTRI bilateral comparison of capsule-type standard platinum resistance thermometers from 13.8 K to 273.16 K

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**Abstract.** A bilateral comparison of capsule-type standard platinum resistance thermometers is reported that links the VNIIFTRI realization of the International Temperature Scale of 1990 to the results of the Comité Consultatif de Thermométrie Key Comparison 2 in the temperature range 13.8033 K to 273.16 K.

## 1. Introduction

The Comité Consultatif de Thermométrie Key Comparison 2 (CCT-K2) results were published in 2002 [1]. NRC served as the pilot laboratory for CCT-K2 and remains able to provide a scale and measurement system suitable for performing bilateral comparisons linked to the original key comparison results.

In March 2003, measurements of two VNIIFTRI 100 Ω capsule-style platinum resistance thermometers (CSPRTs), S/N 356 and S/N 476, were undertaken to relate their local calibration to the results from the CCT-K2 exercise. The NRC Leeds and Northrup (L&N) CSPRT S/N 1872174 provides the link to the CCT-K2 results. The three CSPRTs were compared at the eight defining cryogenic temperatures of the International Temperature Scale of 1990 (ITS-90) in the range from 13.8033 K to 273.16 K.

## 2. Experimental details

The reader is referred to the full text of the CCT-K2 report [1] for a detailed explanation of the methodology employed for the comparison. Only the details unique to the measurements reported here will be addressed in this article.

The model PRT-5V CSPRTs contributed by VNIIFTRI were fabricated and calibrated by that institute. These CSPRTs are of compact size, with a length of 40 mm and a diameter of 3.7 mm; they have a resistance value of 100 Ω near 273 K. For comparison, the L&N CSPRT has a length of 60 mm, a diameter of 5.5 mm, and a resistance of 25 Ω at 273 K. The comparison block in the cryostat is drilled to accept L&N-style thermometers, so some means to accommodate the smaller diameter CSPRTs is required. The VNIIFTRI CSPRTs are sufficiently smaller in diameter that a copper bushing was machined to match their physical dimensions to the holes in the comparison block.

The resistance measurements were made with the same Automatic Systems Laboratories Model F18 resistance bridge used for CCT-K2. For the measurements from 13.8033 K to 83.8058 K, a 25 Ω Tinsley Model 5685A reference resistor was used, thermostatted at 25 °C ± 2 mK in a Guildline 9732VT oil bath. At 234.3156 K and 273.16 K, a 100 Ω resistor of the same make and model replaced the 25 Ω resistor to accommodate the higher resistance of the VNIIFTRI CSPRTs.

The results of this bilateral comparison are reported from one measurement run, starting at 13.8033 K and finishing at 273.16 K. With the electrical resistance of the PRT-5V VNIIFTRI CSPRTs exceeding that of the NRC L&N CSPRT by a factor of four at every temperature, power dissipation in all three thermometers was equalized by adjusting the measuring current of the resistance bridge. Excitation currents for the 100 Ω PRT-5V theremometers were set to be half (or as near as possible given the limited current settings) of that used with the 25 Ω L&N thermometer. With this scheme, change in the drift of the cryostat during the measurements is minimised. From 13.8033 K to 24.5561 K, currents of 5 mA and $5\sqrt{2}$ mA were used with the NRC thermometer, and 2 mA and $2\sqrt{2}$ mA with the VNIIFTRI thermometers. At 54.3584 K, currents of 2 mA and $2\sqrt{2}$ mA were used with the NRC thermometer, and 1 mA and $\sqrt{2}$ mA with the VNIIFTRI thermometers. From 83.8058 K to

273.16 K, currents of 1 mA and √2 mA were used with the NRC thermometer, and 0.5 mA and 0.5√2 mA with the VNIIFTRI thermometers.

## 3. Calibration values and uncertainty budgets

The calibration temperatures, resistance ratios and combined standard laboratory uncertainties ($u_L$, $k$=1) for the VNIIFTRI thermometers are listed in Table 1. The detailed uncertainty budget is included in Appendix A. The final line of the table lists the resistances at the triple point of water. The values were obtained through comparison with a group of thermometers that store the Russian version of the ITS-90.

The NRC thermometer was observed not to have remained stable since its use in the original CCT-K2 comparison [1]. The values in Table 2 reflect recent fixed-point realizations that employed the same sealed cells as were used for the calibration of the same CSPRT for the CCT-K2 exercise, so that this aspect of the NRC ITS-90 realisation is the same as carried out in 1996. On the contrary, the calibration points near 17 K and 20.3 K were obtained differently than was the case for the original exercise. A transfer CSPRT that had been compared to RhFe thermometer A140, which carries the NRC interpolating gas thermometer (IGT) scale, was used to transfer the NRC IGT-realisation of the ITS-90 to CSPRT 1872174. The uncertainty associated with this approach is only slightly larger than would be the case for a more direct calibration topology.

**Table 1.** Calibration data for the VNIIFTRI thermometers. The values in italics at 273.16 K are the resistances of the thermometers (in ohms) at that temperature.

| Fixed | | 356 | | 476 | |
|---|---|---|---|---|---|
| point | $T$ / K | $W$ | $u_L$ / mK | $W$ | $u_L$ / mK |
| $H_2$ | 13.8033 | 0.00141641 | 0.63 | 0.00114565 | 0.63 |
| $H_2$ v.p. | 17.035 | 0.00253866 | 0.64 | 0.00226932 | 0.64 |
| $H_2$ v.p. | 20.271 | 0.00449308 | 0.55 | 0.00423381 | 0.55 |
| Ne | 24.5561 | 0.00872331 | 0.21 | 0.00848043 | 0.21 |
| $O_2$ | 54.3584 | 0.09203616 | 0.21 | 0.09185332 | 0.21 |
| Ar | 83.8058 | 0.21615053 | 0.17 | 0.21600300 | 0.17 |
| Hg | 234.3156 | 0.84420175 | 0.35 | 0.84417567 | 0.35 |
| $H_2O$ | 273.16 | *100.32690* | 0.16 | *100.26399* | 0.16 |

**Table 2.** Calibration data for the NRC thermometer. The value in italics is the resistance of the thermometer (ohms) at 273.16 K.

| Fixed | | 1872174 | |
|---|---|---|---|
| point | $T$ / K | $W$ | $u_L$ / mK |
| $H_2$ | 13.8033 | 0.00124018 | 0.20 |
| IGT | 17.0011 | 0.00233632 | 0.58 |
| IGT | 20.2672 | 0.00429373 | 0.58 |
| Ne | 24.5561 | 0.00851688 | 0.20 |
| $O_2$ | 54.3584 | 0.09180658 | 0.20 |
| Ar | 83.8058 | 0.21594587 | 0.20 |
| Hg | 234.3156 | 0.84416251 | 0.20 |
| $H_2O$ | 273.16 | *25.499358* | 0.15 |

The experimental measurement uncertainty budget remains 0.12 mK at 20.3 K and below and 0.09 mK above 20.3 K, the same as in the CCT-K2 report [1]. This uncertainty component, $u_{Exp}$, is summed in quadrature with each of the laboratory uncertainties, $u_L$, to form a combined uncertainty, $u_C$. The pair uncertainty for the comparison, $u_P$, is obtained by summing in quadrature the combined uncertainties for each laboratory. The justification for treating the experimental uncertainty components as completely uncorrelated when evaluating the pair uncertainty is explained in further detail in the CCT-K2 report. The relevant uncertainty equations are as follows:

$$u_C = \sqrt{u_L^2 + u_{Exp}^2} \tag{1}$$

$$u_p = \sqrt{u_{NRC}^2 + u_{VNIIFTRI}^2 + 2u_{Exp}^2} \tag{2}$$

## 4. Results

The results of the comparison are summarized in Table 3, Table 4 and Figure 1 with respect to the NRC realization of the ITS-90. Based on the results for thermometer 356, the NRC and VNIIFTRI realizations are consistent within the expanded combined uncertainties ($k$ = 2). The same cannot be said based on the results for thermometer 476, since the differences are within the expanded combined uncertainties for only three of the seven temperatures of the comparison.

Tables 1 and 2 include the triple point of water (TPW) resistances given by NRC and VNIIFTRI for their thermometers. The comparison measurements performed in the cryostat at 273.16 K, shown in Table 4, indicate an apparent TPW difference for thermometer 476 of more than 1 mK, while the TPW difference for thermometer 356 is only about 0.2 mK. This significant discrepancy suggests either that one of the original TPW calibrations was in error, or that thermometer 476 suffered a change to its TPW resistance since its calibration at VNIIFTRI. Following the return of the thermometers to VNIIFTRI, measurements at the triple point of water confirmed that thermometer 356 had remained unchanged during the Key Comparison (+0.07 mK compared to the original value), but that thermometer 476 had become substantially different (-1.52 mK compared to the original value); these results are in excellent agreement with the comparison measurements performed at NRC. Furthermore, the resistance value assigned to the VNIIFTRI standard resistor subsequent to re-calibration improves the thermometer 356 agreement with the NRC triple point of water measurement from +0.22 mK (Table 4) to -0.11 mK. Similarly, the re-calibrated, post-comparison resistance assignment for thermometer 476 reduces the -1.18 mK difference given in Table 4 to +0.09 mK. This suggests that thermometer 476, in the state received by NRC, is unrepresentative of the ITS-90 as realized at VNIIFTRI. It is likely that 476 suffered some mechanical disturbance sufficient to change both its residual resistance (significant at low temperatures) and its resistance at the triple point of water (insignificant at low temperatures). The data for thermometer 476 are therefore rejected from further analysis due to this technical failure of the transfer artifact.

**Table 3.** Zero current resistance ratio comparison data for the VNIIFTRI thermometers expressed with respect to the NRC realization of the ITS-90.

| $T_{NRC}$ / K | W(1872174) | W(356) | W(476) |
|---|---|---|---|
| 13.8028 | 0.001 240 071 | 0.001 416 012 | 0.001 144 575 |
| 17.0347 | 0.002 351 718 | 0.002 538 391 | 0.002 268 067 |
| 20.2717 | 0.004 297 175 | 0.004 493 374 | 0.004 233 164 |
| 24.5557 | 0.008 516 358 | 0.008 723 208 | 0.008 479 381 |
| 54.3577 | 0.091 803 886 | 0.092 032 136 | 0.091 848 933 |
| 83.8054 | 0.215 943 937 | 0.216 148 969 | 0.216 001 279 |
| 234.3153 | 0.844 161 420 | 0.844 200 155 | 0.844 172 695 |

**Table 4.** Comparison data for the VNIIFTRI thermometers expressed with respect to the NRC realization of the ITS-90. The table includes the expanded pair uncertainties ($k$ = 2) for these temperature differences. The values at 273.16 K express the consistency in the triple point of water realizations at the participating laboratories as carried on the thermometers. For consistency with the analysis of the original CCT-K2 report, the triple point of water values determined at NRC were used in the calculation of the resistance ratios at the various comparison temperatures from 13.8028 K to 234.3153 K.

| $T_{NRC}$ / K | $T_{VNIIFTRI} - T_{NRC}$ / mK ± $2u_p$ / mK | |
|---|---|---|
| | **S/N 356** | **S/N 476** |
| 13.8028 | -1.16 ± 1.36 | -3.68 ± 1.36 |
| 17.0347 | -0.30 ± 1.76 | -2.47 ± 1.76 |
| 20.2717 | -0.36 ± 1.63 | -1.66 ± 1.63 |
| 24.5557 | +0.34 ± 0.63 | -0.34 ± 0.63 |
| 54.3577 | -0.34 ± 0.63 | -0.64 ± 0.63 |
| 83.8054 | +0.09 ± 0.58 | -0.16 ± 0.58 |
| 234.3153 | -0.12 ± 0.85 | -0.33 ± 0.85 |
| 273.1593 | +0.22 ± 0.51 | -1.18 ± 0.51 |

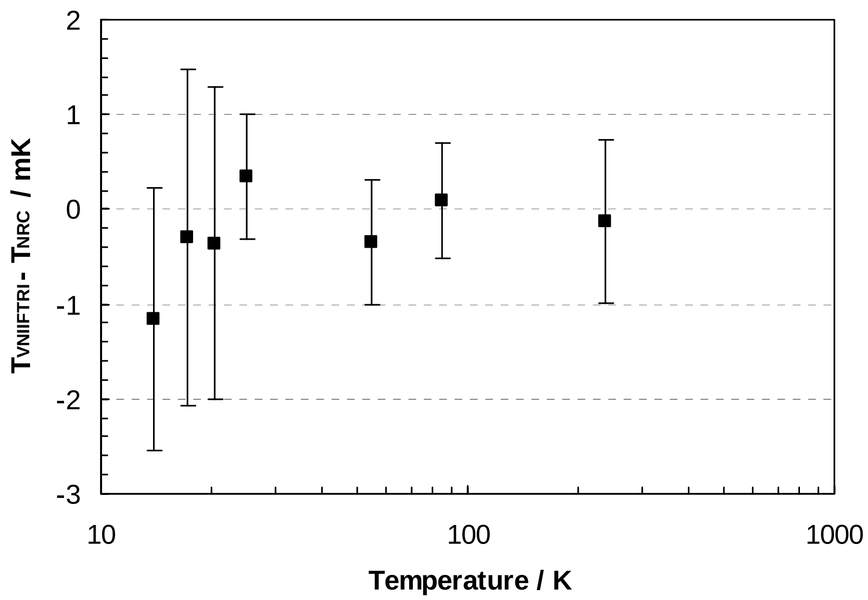


**Figure 1.** The comparison data for VNIIFTRI CSPRT 356 plotted with respect to the NRC realization of the ITS-90. The error bars represent the expanded uncertainties of the temperature differences, $2u_p$.

The VNIIFTRI data may be related to the CCT-K2 results by combining the results for thermometer 356 from Table 4 with the differences reported for the NRC thermometer with respect to the KCRV as determined by the CCT-K2 exercise. Since the NRC thermometer 1872174 was used in both Groups A and B of CCT-K2, the degrees of equivalence for VNIIFTRI with respect to the CCT-K2 KCRV were calculated for both determinations of ($T_{NRC\text{-}1996} - T_{KCRV}$) according to Equation 3. These values, together with their average, are compiled in Table 5.

$$D_{VNIIFTRI} = \left(T_{VNIIFTRI} - T_{NRC}\right) + \left(T_{NRC-1996} - T_{KCRV}\right)_{CCT-K2} \tag{3}$$

The expanded uncertainty, $U$, of the VNIIFTRI degree of equivalence (also listed in Table 5), is obtained by appropriately combining the uncertainties of the bracketed terms in Equation 3. The uncertainty of ($T_{VNIIFTRI}$ –

$T_{NRC}$) is readily identified as $u_p$ from Equation 2, and reported in Table 4. Since the CCT-K2 KCRV has zero uncertainty by definition, the uncertainty of the second term in Equation 3, ($T_{NRC-1996} - T_{KCRV}$), is determined solely by the uncertainty in $T_{NRC-1996}$. This is simply the combined standard uncertainty of the NRC calibration in 1996, $u_{NRC-1996}$, and the experimental comparison uncertainty of CCT-K2, which is equal to $u_{\mathrm{Exp}}$, calculated according to Equation 1. The NRC laboratory uncertainties for CCT-K2 are identical to those in Table 1 with the exception of the points near 17 K and 20.3 K, where the corresponding CCT-K2 uncertainties were 0.2 mK.

In combining the bracketed terms of Equation 3, we must consider the extent to which the two uncertainties for $T_{NRC}$ and $T_{NRC-1996}$ are correlated. With the exception of the 17 K and 20.3 K calibration temperatures, the 1996 and 2003 calibrations utilized the same fixed-point cells, resistance bridge, and experimental apparatus. Under the assumption that the temperatures realized by the NRC sealed cells are stable in time, the Type B components of the uncertainty budgets for CCT-K2 and this bilateral key comparison can be considered to be completely correlated, and so only the Type A repeatability component from the full laboratory uncertainty budget should be counted twice – once as the component of $u_{NRC}$ for this measurement comparison, and once to accommodate the uncorrelated component of $u_{NRC-1996}$ reported in CCT-K2. This component is $u_{TypeA}$ = 0.07 mK for all five triple point temperatures. Equation 4 summarizes the calculation of the expanded uncertainties of Table 5 for the VNIIFTRI degree of equivalence to the Key Comparison Reference Value of CCT-K2 for all but the 17 K and 20.3 K temperatures.

$$U = 2\sqrt{\left(u_{NRC}^2 + u_{VNIIFTRI}^2 + 2u_{Exp}^2\right) + u_{TypeA}^2 + u_{Exp}^2} \tag{4}$$

The 17 K and 20.3 K calibration temperatures were realized with different techniques and apparatus in 2003 (interpolating gas thermometer) than in 1996 (hydrogen vapor pressure measurements), so no reduction in overall uncertainty due to correlated Type B components can be claimed. The expanded uncertainties at these two temperatures are derived using Equation 5.

$$U = 2\sqrt{\left(u_{NRC}^2 + u_{VNIIFTRI}^2 + 2u_{Exp}^2\right) + u_{NRC-1996}^2 + u_{Exp}^2} \tag{5}$$

Table 5 and Figure 2 show that the differences from the KCRV for thermometer 356 agree with the CCT-K2 KCRV within the expanded combined uncertainties, $U$, and, indeed, within the combined standard uncertainties, at all temperatures *except* 13.8033 K. As much as half of the observed difference at the triple point of hydrogen may be attributable to a possible difference in the deuterium content of the respective fixed points used in the calibrations [2].

**Table 5.** The degrees of equivalence, $D$, for VNIIFTRI thermometer 356 expressed with respect to the KCRV for Groups A and B from the CCT-K2 report and their average, mediated by the NRC realization of ITS-90. To facilitate comparison with the results of CCT-K2, the temperatures in the first column are the fixed-point calibration temperatures of the ITS-90 near the actual comparison temperatures. The table includes the expanded uncertainties of the degrees of equivalence, $U$ ($k$ = 2).

| $T$ / K | $D_A$ mK | $D_B$ / mK | $D_{Avg}$ / mK | $U$ / mK |
|---|---|---|---|---|
| 13.8033 | -1.42 | -1.43 | -1.42 | 1.39 |
| 17.035 | -0.30 | -0.19 | -0.24 | 1.84 |
| 20.271 | -0.33 | -0.26 | -0.29 | 1.72 |
| 24.5561 | 0.28 | 0.22 | 0.25 | 0.67 |
| 54.3584 | -0.16 | -0.10 | -0.13 | 0.67 |
| 83.8058 | 0.27 | 0.33 | 0.30 | 0.63 |
| 234.3156 | -0.26 | -0.26 | -0.26 | 0.88 |

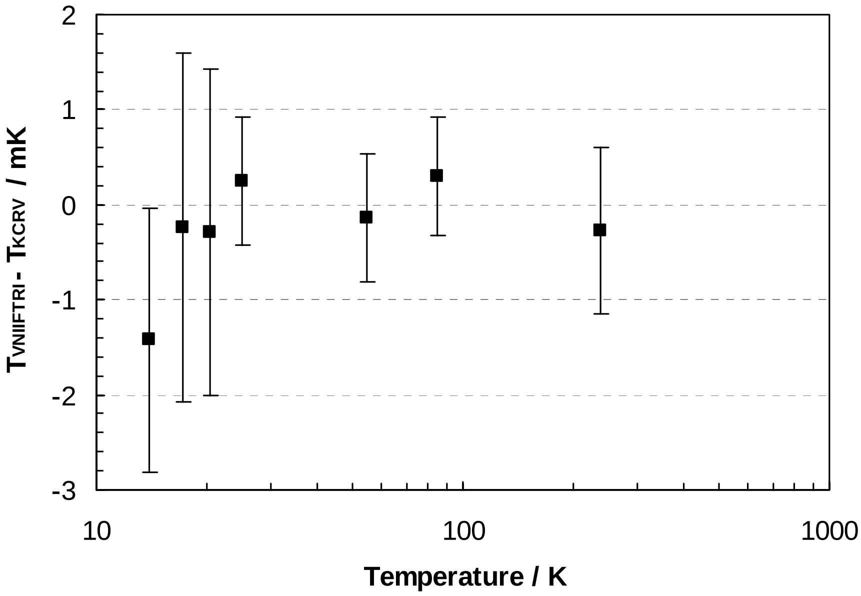


**Figure 2.** The comparison data for VNIIFTRI CSPRT 356 plotted with respect to the average KCRV determined from the two Groups of measurements from the CCT-K2 report, mediated by the NRC realization of the ITS-90. The error bars represent the expanded uncertainties, *U*.

## 5. Conclusion

The NRC/VNIIFTRI bilateral comparison of capsule-style platinum resistance thermometers over the range 13.8 K to 273.16 K has revealed calibrations at VNIIFTRI to be in agreement with the KCRV of CCT-K2 within the expanded uncertainty for all temperatures of the comparison with the exception of the triple point of hydrogen at 13.8033 K. One of the two CSPRTs supplied by VNIIFTRI was found to be discrepant as revealed by differences at the triple point of water and at the lowest temperatures of the comparison, and was therefore excluded from further analysis. The linkage to the CCT-K2 data supports the evaluation of the VNIIFTRI CMCs in Appendix C of the KCDB.

## References

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**Appendix A**

The detailed uncertainty budget for the VNIIFTRI thermometers.

| Fixed point | $H_2$ | 17 K | 20.3 K | Ne | $O_2$ | Ar | Hg | $H_2O$ |
|---|---|---|---|---|---|---|---|---|
| Substance purity | 6N | | | 5N | 6N | 6N | | |
| *Uncertainty components* (mK) | | | | | | | | |
| Chemical impurities | 0.18 | | | 0.2 | 0.2 | 0.15 | | 0.05 |
| Reference scale (NS VNIIFTRI) | | 0.2 | 0.2 | | | | 0.3 | |
| Hydrostatic head correction | 0.005 | | | 0.03 | 0.03 | 0.05 | | 0.005 |
| Error in gas pressure | | | | | | | | 0.05 |
| Standard resistor | 0.01 | 0.015 | 0.015 | 0.02 | 0.02 | 0.03 | 0.06 | 0.1 |
| Bridge measurement | 0.05 | 0.05 | 0.05 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 |
| Self-heating error | 0.6 | 0.6 | 0.5 | 0.05 | 0.05 | 0.05 | 0.1 | 0.1 |
| Heat-flux error | 0.05 | | | 0.04 | 0.04 | 0.03 | | 0.02 |
| Temperature inhomogeneity | | 0.1 | 0.1 | | | | 0.1 | |
| Drift correction | | 0.06 | 0.06 | | | | 0.1 | |
| Standard combined uncertainty (mK) | 0.63 | 0.64 | 0.55 | 0.21 | 0.21 | 0.17 | 0.35 | 0.16 |
| Expanded uncertainty ($k$ = 2) (mK) | 1.26 | 1.28 | 1.10 | 0.42 | 0.42 | 0.34 | 0.70 | 0.32 |

## Appendix B

Tables of bilateral equivalence, including links to the original CCT-K2 data. The elements above the diagonal are the pair differences (in mK) and their expanded ($k$=2) uncertainty. The $QDE_{0.95}$ confidence intervals for pairwise agreement are given below the diagonal. Further information is found in the CCT-K2 report. The linked results for VNIIFTRI are shown in green.

| $H_2$ Group A | BNM | IMGC | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|
| BNM | - | -2.39 ± 4.17 | -3.13 ± 4.17 | -2.78 ± 4.18 | -2.45 ± 4.19 | -2.71 ± 4.16 | -1.29 ± 4.39 |
| IMGC | *5.83* | - | -0.74 ± 0.47 | -0.39 ± 0.53 | -0.06 ± 0.56 | -0.32 ± 0.32 | 1.10 ± 1.43 |
| NIST | *6.56* | *1.12* | - | 0.35 ± 0.54 | 0.68 ± 0.57 | 0.42 ± 0.34 | 1.84 ± 1.43 |
| NPL | *6.22* | *0.82* | *0.79* | - | 0.33 ± 0.62 | 0.07 ± 0.42 | 1.49 ± 1.45 |
| NRC | *5.90* | *0.56* | *1.15* | *0.84* | - | -0.26 ± 0.46 | 1.16 ± 1.46 |
| KCRV | *6.14* | *0.58* | *0.70* | *0.43* | *0.64* | - | 1.42 ± 1.39 |
| VNIIFTRI | *4.96* | *2.27* | *3.02* | *2.68* | *2.36* | *2.56* | - |

| $H_2$ Group B | BNM | IMGC | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|
| BNM | - | -2.43 ± 4.17 | -3.02 ± 4.17 | -2.55 ± 4.18 | -2.33 ± 4.19 | -2.58 ± 4.18 | -2.60 ± 4.16 | -1.17 ± 4.39 |
| IMGC | *5.87* | - | -0.59 ± 0.47 | -0.12 ± 0.48 | 0.10 ± 0.56 | -0.15 ± 0.54 | -0.17 ± 0.32 | 1.26 ± 1.43 |
| NIST | *6.45* | *0.97* | - | 0.47 ± 0.50 | 0.69 ± 0.57 | 0.44 ± 0.56 | 0.42 ± 0.34 | 1.85 ± 1.43 |
| NPL | *5.99* | *0.53* | *0.88* | - | 0.22 ± 0.58 | -0.03 ± 0.57 | -0.05 ± 0.36 | 1.38 ± 1.44 |
| NRC | *5.78* | *0.58* | *1.16* | *0.70* | - | -0.25 ± 0.64 | -0.27 ± 0.46 | 1.16 ± 1.46 |
| PTB | *6.03* | *0.61* | *0.90* | *0.56* | *0.78* | - | -0.02 ± 0.44 | 1.41 ± 1.46 |
| KCRV | *6.03* | *0.43* | *0.70* | *0.37* | *0.65* | *0.43* | - | 1.43 ± 1.39 |
| VNIIFTRI | *4.86* | *2.43* | *3.03* | *2.56* | *2.36* | *2.61* | *2.57* | - |

Table B.1: Linked bilateral equivalence matrix for comparison measurements near the hydrogen triple point.

| 17 K Group A | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|
| NIST | - | -0.07 ± 0.58 | -0.06 ± 0.55 | -0.01 ± 0.30 | 0.29 ± 1.86 |
| NPL | *0.59* | - | 0.01 ± 0.68 | 0.06 ± 0.50 | 0.36 ± 1.91 |
| NRC | *0.55* | *0.67* | - | 0.05 ± 0.46 | 0.35 ± 1.90 |
| KCRV | *0.29* | *0.50* | *0.46* | - | 0.30 ± 1.84 |
| VNIIFTRI | *1.91* | *2.00* | *1.98* | *1.89* | - |

| 17 K Group B | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|
| NIST | - | 0.10 ± 0.55 | -0.17 ± 0.55 | -0.20 ± 0.67 | 0.01 ± 0.30 | 0.20 ± 1.86 |
| NPL | *0.57* | - | -0.27 ± 0.65 | -0.30 ± 0.76 | -0.09 ± 0.46 | 0.10 ± 1.90 |
| NRC | *0.63* | *0.81* | - | -0.03 ± 0.76 | 0.18 ± 0.46 | 0.37 ± 1.90 |
| PTB | *0.76* | *0.93* | *0.74* | - | 0.21 ± 0.60 | 0.40 ± 1.94 |
| KCRV | *0.29* | *0.48* | *0.56* | *0.71* | - | 0.19 ± 1.84 |
| VNIIFTRI | *1.86* | *1.86* | *1.99* | *2.05* | *1.83* | - |

Table B.2: Linked bilateral equivalence matrix for comparison measurements near 17 K.

| 20.3 K Group A | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|
| NIST | - | 0.06 ± 0.57 | -0.06 ± 0.54 | 0.00 ± 0.28 | 0.33 ± 1.74 |
| NPL | *0.57* | - | -0.12 ± 0.68 | -0.06 ± 0.50 | 0.27 ± 1.79 |
| NRC | *0.54* | *0.71* | - | 0.06 ± 0.46 | 0.39 ± 1.78 |
| KCRV | *0.28* | *0.50* | *0.46* | - | 0.33 ± 1.72 |
| VNIIFTRI | *1.83* | *1.83* | *1.90* | *1.80* | - |

| 20.3 K Group B | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|
| NIST | - | -0.06 ± 0.54 | -0.19 ± 0.54 | -0.48 ± 0.66 | -0.06 ± 0.28 | 0.20 ± 1.74 |
| NPL | *0.54* | - | -0.13 ± 0.65 | -0.42 ± 0.76 | 0.00 ± 0.46 | 0.26 ± 1.78 |
| NRC | *0.64* | *0.69* | - | -0.29 ± 0.76 | 0.13 ± 0.46 | 0.39 ± 1.78 |
| PTB | *1.02* | *1.04* | *0.92* | - | 0.42 ± 0.60 | 0.68 ± 1.82 |
| KCRV | *0.30* | *0.45* | *0.52* | *0.91* | - | 0.26 ± 1.72 |
| VNIIFTRI | *1.75* | *1.81* | *1.90* | *2.19* | *1.76* | - |

Table B.3: Linked bilateral equivalence matrix for comparison measurements near 20.3 K.

| Ne Group A | BNM | IMGC | KRISS | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|
| BNM | - | -0.13 ± 1.12 | -0.03 ± 1.15 | 0.11 ± 1.13 | 0.08 ± 1.17 | 0.04 ± 1.17 | -0.02 ± 1.08 | -0.30 ± 1.27 |
| IMGC | *1.12* | - | 0.10 ± 0.49 | 0.24 ± 0.43 | 0.21 ± 0.52 | 0.17 ± 0.52 | 0.11 ± 0.28 | -0.17 ± 0.73 |
| KRISS | *1.13* | *0.52* | - | 0.14 ± 0.51 | 0.11 ± 0.59 | 0.07 ± 0.59 | 0.01 ± 0.40 | -0.27 ± 0.78 |
| NIST | *1.12* | *0.59* | *0.57* | - | -0.03 ± 0.54 | -0.07 ± 0.54 | -0.13 ± 0.32 | -0.41 ± 0.74 |
| NPL | *1.15* | *0.64* | *0.62* | *0.53* | - | -0.04 ± 0.62 | -0.10 ± 0.44 | -0.38 ± 0.80 |
| NRC | *1.14* | *0.61* | *0.60* | *0.55* | *0.61* | - | -0.06 ± 0.44 | -0.34 ± 0.80 |
| KCRV | *1.06* | *0.34* | *0.39* | *0.40* | *0.47* | *0.45* | - | -0.28 ± 0.67 |
| VNIIFTRI | *1.38* | *0.79* | *0.92* | *1.02* | *1.04* | *1.00* | *0.83* | - |

| Ne Group B | BNM | IMGC | KRISS | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|---|
| BNM | - | -1.99 ± 2.81 | -1.73 ± 2.83 | -1.92 ± 2.82 | -1.69 ± 2.83 | -1.76 ± 2.83 | -2.14 ± 2.83 | -1.88 ± 2.80 | -2.10 ± 2.88 |
| IMGC | *4.31* | - | 0.26 ± 0.49 | 0.07 ± 0.43 | 0.30 ± 0.47 | 0.23 ± 0.52 | -0.15 ± 0.49 | 0.11 ± 0.28 | -0.11 ± 0.73 |
| KRISS | *4.06* | *0.66* | - | -0.19 ± 0.51 | 0.04 ± 0.55 | -0.03 ± 0.59 | -0.41 ± 0.57 | -0.15 ± 0.40 | -0.37 ± 0.78 |
| NIST | *4.24* | *0.44* | *0.62* | - | 0.23 ± 0.50 | 0.16 ± 0.54 | -0.22 ± 0.51 | 0.04 ± 0.32 | -0.18 ± 0.74 |
| NPL | *4.02* | *0.69* | *0.54* | *0.64* | - | -0.07 ± 0.58 | -0.45 ± 0.55 | -0.19 ± 0.38 | -0.41 ± 0.77 |
| NRC | *4.09* | *0.66* | *0.58* | *0.62* | *0.58* | - | -0.38 ± 0.59 | -0.12 ± 0.44 | -0.34 ± 0.80 |
| PTB | *4.47* | *0.56* | *0.88* | *0.64* | *0.90* | *0.87* | - | 0.26 ± 0.40 | 0.04 ± 0.78 |
| KCRV | *4.19* | *0.34* | *0.48* | *0.32* | *0.50* | *0.49* | *0.59* | - | -0.22 ± 0.67 |
| VNIIFTRI | *4.47* | *0.74* | *1.01* | *0.81* | *1.05* | *1.00* | *0.77* | *0.78* | - |

Table B.4: Linked bilateral equivalence matrix for comparison measurements near the neon triple point.

| $O_2$ Group A | BNM | IMGC | KRISS | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|
| BNM | - | 0.13 ± 0.57 | -0.16 ± 0.62 | -0.14 ± 0.56 | -0.09 ± 0.63 | -0.25 ± 0.68 | -0.07 ± 0.52 | 0.09 ± 0.85 |
| IMGC | *0.62* | - | -0.29 ± 0.42 | -0.27 ± 0.31 | -0.22 ± 0.43 | -0.38 ± 0.50 | -0.20 ± 0.24 | -0.04 ± 0.71 |
| KRISS | *0.68* | *0.63* | - | 0.02 ± 0.39 | 0.07 ± 0.50 | -0.09 ± 0.56 | 0.09 ± 0.34 | 0.25 ± 0.75 |
| NIST | *0.61* | *0.53* | *0.39* | - | 0.05 ± 0.41 | -0.11 ± 0.48 | 0.07 ± 0.20 | 0.23 ± 0.70 |
| NPL | *0.64* | *0.58* | *0.50* | *0.41* | - | -0.16 ± 0.57 | 0.02 ± 0.36 | 0.18 ± 0.76 |
| NRC | *0.82* | *0.79* | *0.57* | *0.52* | *0.64* | - | 0.18 ± 0.44 | 0.34 ± 0.80 |
| KCRV | *0.53* | *0.40* | *0.38* | *0.24* | *0.35* | *0.54* | - | 0.16 ± 0.67 |
| VNIIFTRI | *0.85* | *0.70* | *0.88* | *0.81* | *0.82* | *1.00* | *0.73* | - |

| $O_2$ Group B | BNM | IMGC | KRISS | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|---|
| BNM | - | 0.17 ± 0.55 | -0.09 ± 0.60 | 0.06 ± 0.55 | -0.05 ± 0.58 | -0.23 ± 0.67 | -0.17 ± 0.68 | 0.01 ± 0.50 | 0.11 ± 0.84 |
| IMGC | *0.63* | - | -0.26 ± 0.42 | -0.11 ± 0.34 | -0.22 ± 0.38 | -0.40 ± 0.50 | -0.34 ± 0.52 | -0.16 ± 0.24 | -0.06 ± 0.71 |
| KRISS | *0.62* | *0.60* | - | 0.15 ± 0.42 | 0.04 ± 0.45 | -0.14 ± 0.56 | -0.08 ± 0.57 | 0.10 ± 0.34 | 0.20 ± 0.75 |
| NIST | *0.55* | *0.39* | *0.50* | - | -0.11 ± 0.38 | -0.29 ± 0.50 | -0.23 ± 0.52 | -0.05 ± 0.24 | 0.05 ± 0.71 |
| NPL | *0.58* | *0.54* | *0.45* | *0.43* | - | -0.18 ± 0.53 | -0.12 ± 0.55 | 0.06 ± 0.30 | 0.16 ± 0.73 |
| NRC | *0.78* | *0.81* | *0.61* | *0.70* | *0.62* | - | 0.06 ± 0.64 | 0.24 ± 0.44 | 0.34 ± 0.80 |
| PTB | *0.74* | *0.77* | *0.58* | *0.66* | *0.59* | *0.63* | - | 0.18 ± 0.46 | 0.28 ± 0.81 |
| KCRV | *0.49* | *0.36* | *0.38* | *0.25* | *0.32* | *0.60* | *0.56* | - | 0.10 ± 0.67 |
| VNIIFTRI | *0.85* | *0.70* | *0.83* | *0.70* | *0.78* | *1.00* | *0.96* | *0.68* | - |

Table B.5: Linked bilateral equivalence matrix for comparison measurements near the oxygen triple point.

| Ar Group A | BNM | IMGC | KRISS | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|
| BNM | - | 0.27 ± 0.45 | -0.48 ± 0.52 | 0.07 ± 0.45 | 0.10 ± 0.52 | -0.11 ± 0.59 | 0.07 ± 0.40 | -0.20 ± 0.75 |
| IMGC | *0.64* | - | -0.75 ± 0.39 | -0.20 ± 0.28 | -0.17 ± 0.39 | -0.38 ± 0.48 | -0.20 ± 0.20 | -0.47 ± 0.66 |
| KRISS | *0.91* | *1.07* | - | 0.55 ± 0.39 | 0.58 ± 0.48 | 0.37 ± 0.56 | 0.55 ± 0.34 | 0.28 ± 0.72 |
| NIST | *0.46* | *0.43* | *0.87* | - | 0.03 ± 0.39 | -0.18 ± 0.48 | 0.00 ± 0.20 | -0.27 ± 0.66 |
| NPL | *0.55* | *0.50* | *0.98* | *0.39* | - | -0.21 ± 0.56 | -0.03 ± 0.34 | -0.30 ± 0.72 |
| NRC | *0.62* | *0.78* | *0.83* | *0.58* | *0.67* | - | 0.18 ± 0.44 | -0.09 ± 0.77 |
| KCRV | *0.41* | *0.36* | *0.83* | *0.20* | *0.34* | *0.54* | - | -0.27 ± 0.63 |
| VNIIFTRI | *0.83* | *1.01* | *0.87* | *0.82* | *0.89* | *0.77* | *0.79* | - |

| Ar Group B | BNM | IMGC | KRISS | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|---|
| BNM | - | 0.20 ± 0.48 | 0.10 ± 0.56 | 0.07 ± 0.49 | 0.15 ± 0.51 | -0.13 ± 0.62 | -0.11 ± 0.61 | 0.11 ± 0.44 | -0.22 ± 0.77 |
| IMGC | *0.60* | - | -0.10 ± 0.39 | -0.13 ± 0.30 | -0.05 ± 0.33 | -0.33 ± 0.48 | -0.31 ± 0.47 | -0.09 ± 0.20 | -0.42 ± 0.66 |
| KRISS | *0.58* | *0.43* | - | -0.03 ± 0.40 | 0.05 ± 0.43 | -0.23 ± 0.56 | -0.21 ± 0.54 | 0.01 ± 0.34 | -0.32 ± 0.72 |
| NIST | *0.50* | *0.38* | *0.40* | - | 0.08 ± 0.34 | -0.20 ± 0.49 | -0.18 ± 0.47 | 0.04 ± 0.22 | -0.29 ± 0.67 |
| NPL | *0.58* | *0.34* | *0.43* | *0.37* | - | -0.28 ± 0.51 | -0.26 ± 0.49 | -0.04 ± 0.26 | -0.37 ± 0.68 |
| NRC | *0.66* | *0.73* | *0.69* | *0.61* | *0.70* | - | 0.02 ± 0.61 | 0.24 ± 0.44 | -0.09 ± 0.77 |
| PTB | *0.63* | *0.69* | *0.66* | *0.57* | *0.67* | *0.60* | - | 0.22 ± 0.42 | -0.11 ± 0.76 |
| KCRV | *0.48* | *0.26* | *0.33* | *0.23* | *0.27* | *0.60* | *0.57* | - | -0.33 ± 0.63 |
| VNIIFTRI | *0.86* | *0.96* | *0.91* | *0.84* | *0.93* | *0.77* | *0.77* | *0.85* | - |

Table B.6: Linked bilateral equivalence matrix for comparison measurements near the argon triple point.

| Hg Group A | BNM | IMGC | KRISS | NIST | NPL | NRC | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|
| BNM | - | -0.17 ± 0.59 | -0.11 ± 0.76 | -0.35 ± 0.63 | -0.34 ± 0.68 | -0.09 ± 0.71 | -0.23 ± 0.56 | 0.03 ± 1.04 |
| IMGC | *0.67* | - | 0.06 ± 0.56 | -0.18 ± 0.34 | -0.17 ± 0.43 | 0.08 ± 0.48 | -0.06 ± 0.20 | 0.20 ± 0.90 |
| KRISS | *0.78* | *0.56* | - | -0.24 ± 0.59 | -0.23 ± 0.64 | 0.02 ± 0.68 | -0.12 ± 0.52 | 0.14 ± 1.02 |
| NIST | *0.87* | *0.46* | *0.73* | - | 0.01 ± 0.47 | 0.26 ± 0.52 | 0.12 ± 0.28 | 0.38 ± 0.92 |
| NPL | *0.90* | *0.53* | *0.77* | *0.46* | - | 0.25 ± 0.58 | 0.11 ± 0.38 | 0.37 ± 0.96 |
| NRC | *0.72* | *0.50* | *0.67* | *0.69* | *0.73* | - | -0.14 ± 0.44 | 0.12 ± 0.98 |
| KCRV | *0.69* | *0.23* | *0.56* | *0.35* | *0.43* | *0.51* | - | 0.26 ± 0.88 |
| VNIIFTRI | *1.02* | *0.97* | *1.04* | *1.14* | *1.17* | *0.99* | *1.00* | - |

| Hg Group B | BNM | IMGC | KRISS | NIST | NPL | NRC | PTB | KCRV | VNIIFTRI |
|---|---|---|---|---|---|---|---|---|---|
| BNM | - | -0.80 ± 0.59 | -1.10 ± 0.76 | -0.96 ± 0.61 | -0.85 ± 0.66 | -0.73 ± 0.71 | -0.93 ± 0.68 | -0.87 ± 0.56 | -0.61 ± 1.04 |
| IMGC | *1.29* | - | -0.30 ± 0.56 | -0.16 ± 0.31 | -0.05 ± 0.39 | 0.07 ± 0.48 | -0.13 ± 0.43 | -0.07 ± 0.20 | 0.19 ± 0.90 |
| KRISS | *1.73* | *0.76* | - | 0.14 ± 0.57 | 0.25 ± 0.62 | 0.37 ± 0.68 | 0.17 ± 0.64 | 0.23 ± 0.52 | 0.49 ± 1.02 |
| NIST | *1.46* | *0.42* | *0.62* | - | 0.11 ± 0.42 | 0.23 ± 0.50 | 0.03 ± 0.45 | 0.09 ± 0.24 | 0.35 ± 0.91 |
| NPL | *1.39* | *0.40* | *0.76* | *0.46* | - | 0.12 ± 0.56 | -0.08 ± 0.51 | -0.02 ± 0.34 | 0.24 ± 0.94 |
| NRC | *1.32* | *0.49* | *0.93* | *0.64* | *0.59* | - | -0.20 ± 0.58 | -0.14 ± 0.44 | 0.12 ± 0.98 |
| PTB | *1.49* | *0.49* | *0.71* | *0.44* | *0.52* | *0.68* | - | 0.06 ± 0.38 | 0.32 ± 0.96 |
| KCRV | *1.33* | *0.24* | *0.66* | *0.29* | *0.33* | *0.51* | *0.39* | - | 0.26 ± 0.88 |
| VNIIFTRI | *1.47* | *0.96* | *1.33* | *1.11* | *1.04* | *0.99* | *1.12* | *1.00* | - |

Table B.7: Linked bilateral equivalence matrix for comparison measurements near the mercury triple point.