



Investigations of Type 3 non-uniqueness in standard platinum resistance thermometers between 83 K and 353 K

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ARTICLE INFO

Keywords:

Non-uniqueness
International temperature scale 1990
Standard platinum resistance thermometers
Subrange inconsistency
Comparison calibration

ABSTRACT

A key feature of the International Temperature Scale of 1990 (ITS-90) is Type 3 non-uniqueness which arises from differences between individual Standard Platinum Resistance Thermometers (SPRTs) over a given sub-range. This can be significant in the context of the best reported uncertainties of SPRT calibrations, but it is extremely difficult to determine because it is easily obscured by the measurement uncertainties. Hence, there is little good information available, particularly over much of the temperature range commonly encountered by long-stem SPRTs, and the estimates of its magnitude are potentially overstated. This paper presents high precision comparisons at NPL and CEM of two cohorts of 8 and 6 long-stem SPRTs, by measuring the ratio of each SPRT against a common SPRT in stirred liquid baths at temperatures from 178 K to 303 K, and 274 K to 353 K, respectively. Measurements of a third cohort of 8 SPRTs were made at INTiBS in a stirred liquid bath from 198 K to 303 K and in a temperature-controlled cryostat from 84 K to 185 K. The measurements were augmented by calibrations of each SPRT at the triple points of argon and mercury, the melting point of gallium and the freezing point of indium, so extending the overall temperature range down to 84 K and up to 429 K. The three cohorts were linked by two SPRTs which were common to all of them. The comparison differences, which ideally should represent the Type 3 non-uniqueness, are presented for the specified ITS-90 interpolations, and for some alternative interpolation schemes. Specifically, it is assessed for interpolations in which the mercury triple point is replaced with the triple point of Xe, CO₂ or SF₆, which are widely considered to be potential candidates for replacing mercury in a future amendment of the ITS-90. The further alternative of using the melting point of gallium is also investigated.

1. Introduction

The currently-adopted temperature scale is the International Temperature Scale of 1990 (ITS-90) [1]. It has been in place since 1990 and has served the global temperature measurement community well, providing reliable, low uncertainty traceability for over 30 years. However, there are various potentially life-limiting issues for the ITS-90, chief among which are the impact of Types 1 and 3 non-uniqueness, which will ultimately limit the uncertainties achievable [2–6], and the need to identify an alternative to the mercury triple point (a key fixed point of the ITS-90) which could be severely restricted or even banned

by an international treaty (the UN Minamata Convention on Mercury [20]), potentially necessitating an amendment to the ITS-90 below 273.16 K.

Type 1 non-uniqueness, also known as subrange inconsistency (SRI), is associated with the difference between the interpolations over different, overlapping ITS-90 subranges for the same SPRT [2–4]. A significant amount of data exists for the assessment of the uncertainty arising from this effect [2–4,7–10], because the differences can easily be calculated, given the relevant fixed-point data. However, it is suggested [2] that much of what is apparently SRI is likely to be the result of propagated uncertainties in the data.

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<https://doi.org/10.1016/j.measurement.2023.112863>

Received 4 January 2023; Received in revised form 16 March 2023; Accepted 5 April 2023

Available online 11 April 2023

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Type 3 non-uniqueness arises from the difference between individual SPRTs over the same subrange [5,11] because their resistance characteristics are not identical, and the interpolations cannot take the detailed differences fully into account. Its assessment requires SPRT resistances to be compared at several temperatures in the subrange of interest. Because such comparisons are difficult to do precisely there is a paucity of reliable data, particularly for long-stem SPRTs at elevated temperatures, and the results necessarily overestimate the magnitude because of the effect of the comparison uncertainties.

It has been suggested that the two types of non-uniqueness are linked [11], and some inferences on Type 3 non-uniqueness can be drawn from the SPRT-dependent dispersion of data for Type 1 non-uniqueness. Data of both kinds are needed to allow reliable estimates of the intrinsic non-uniqueness of the ITS-90 to be obtained.

The three main candidates for replacing the mercury triple point (TP Hg, 234.3156 K) are the triple points of Xe (approximately 161.406 K [12,13], CO₂ (approximately 216.592 K [14,15] and SF₆ (approximately 223.555 K [16]. A further possibility is the melting point of gallium (MP Ga, 302.9146 K), even though it lies above the triple point of water (TPW). The effect on the Type 3 non-uniqueness of replacing the TP Hg with these fixed points has, to our knowledge, not so far been investigated, although interest is growing in the wider effects on the resulting uncertainties [17]. Note that the interpolations are not sensitive to the exact temperatures specified for the ‘fixed points’ (ITS-90 or otherwise) so, for investigating non-uniqueness, small temperature offsets are not important.

2. The experiments

To address these issues in the temperature range between 178 K and 353 K, the three laboratories performed precise comparison measurements of cohorts of 6 to 8 long-stem SPRTs each, drawn from a range of different manufacturers and designs. Each cohort included two SPRTs which were common to all three, to provide linkage between the three local investigations. The resistances were compared at a number of temperatures in the subrange of interest, including at the relevant fixed-point temperatures, from which the interpolations were derived. The *comparison* measurements were used, rather than actual fixed-point realizations, to avoid introducing additional unnecessary uncertainty. Exceptions to this were the TP Ar and indium freezing point (FP In), which lie outside the range of the comparison measurements. These two fixed points were used to investigate interpolations over the extended ranges. It was also important that the comparisons were made without handling or disturbing the SPRTs, in order to avoid the risk of introducing spurious changes in their characteristics.

To achieve the required precision (repeatability), in all three laboratories the ‘method of instantaneous comparisons’ [18] was used; that is, the ratios R_x / R_{ref} were measured, where R_{ref} is the resistance of an SPRT chosen as the reference, and the R_x ($x = 2$ to 6 or 8) are the resistances of the other SPRTs. As the SPRTs have very similar characteristics, the ratios are all close to 1 and they are not sensitive to uniform changes in the bath temperature. For the NPL SPRTs the ratios changed by less than $1 \cdot 10^{-7}$ for a change in bath temperature of 0.015 K, so repeated measurements can be simply averaged, the standard deviations calculated, and self-heating corrections made, with no need for ‘drift corrections’. It is these ratios which contain the essential comparison data: R_{ref} was measured relative to a standard resistor R_s to establish the approximate temperature of the comparisons, but its exact value is not important. The key point is that, given R_{ref} , all the R_x are calculated as if the comparisons were made at this same temperature.

The NPL comparisons were carried out in a stirred silicone oil bath at ten temperatures between 178 K and 303 K, coupled with measurements at the TP Ar, 83.8058 K. Similar comparisons were made at CEM at 18 temperatures between 273 K and 353 K, coupled with measurements at the FP In, 429.7485 K. Finally comparisons were carried out at INTiBS between 84 K and 273 K, coupled with measurements at the triple points

Table 1

SPRTs used at NPL. Bold models indicate the SPRTs common to NPL, CEM and INTiBS.

Serial number	Manufacturer	Model	Country of origin
275079	Tinsley	5187SC	UK
112	Isotech	670	UK
186109	NIM	5187SC	China
186130	NIM	5187SC	China
4278	Fluke	5683	USA
108	Isotech	670	UK
RS129-03	Chino	N/A	Japan
268126	Tinsley	5187SA	UK

of argon and mercury.

In the next two sections the measurement procedures and data analysis are presented. This is followed by presentation and discussion of the comparison results interpolated over the ITS-90 subranges, and over some contrived subranges and interpolation schemes. These include the cases where the comparisons near 234 K (TP Hg) are replaced with points at 178 K, 216 K, 223 K or 302 K, to emulate the Xe point (178 K was the lowest achievable comparison temperature), and the CO₂, SF₆ and Ga points respectively. Finally, some conclusions are drawn.

3. Measurements and procedure

3.1. NPL

A set of eight long-stem SPRTs were chosen based on the design and performance; these are summarised in Table 1.

Prior to the measurements, the SPRTs were stabilised at a temperature of 720 K for about 12 h. The SPRTs were also calibrated in the temperature range from 84 K to 429 K at the TP Ar, TP Hg, TPW, MP Ga and FP In with uncertainties ($k = 1$) of ± 0.25 mK, ± 0.18 mK, ± 0.08 mK, ± 0.15 mK, and, ± 0.35 mK, respectively. However, as has been discussed, the key data were the comparison measurements.

The eight long-stem SPRTs were set up in a Kambič OB-22/2 ULT stirred silicone oil bath for precise comparisons at ten temperatures in the range from 178 K to 303 K. All eight thermometers were inserted 90 mm into a copper block (60 mm in diameter and 100 mm high) and immersed to a depth of 300 mm in the stirred oil bath. The thermometers were connected to an Isotech MicroK model 70 resistance bridge and logging system for recording the results.

The measurements were made very precisely (about 1 part in 10^7 , equivalent to about 0.025 mK) using the resistance bridge, which repeatedly scanned all the SPRTs, each cycle taking about 20 s. At each point, after the temperature had stabilised, data logging began at a current of 1 mA and blocks of 50 cycles of data were accumulated. This was then repeated at a current of $\sqrt{2}$ mA, and finally again at 1 mA. The mean and standard deviation (typically 3 to $7 \cdot 10^{-7}$, mainly due to statistical fluctuations in the bath temperature uniformity) was calculated at each current and the values were corrected to 0 mA in the usual extrapolation. Note that with this methodology, the self-heating corrections are differential, i.e. in the ratios, relative to the self-heating of the reference SPRT: absolute self-heating values are not determined or required. The reference SPRT was the Fluke model 5683, serial number 4278.

Table 2

SPRTs used at CEM. Bold models indicate the transfer SPRTs.

Serial number	Manufacturer	Model	Country of origin
275079	Tinsley	5187SC	UK
112	Isotech	670	UK
275038	Tinsley	5187SA	UK
94336	YIF	WZPB	China
1131	YSI	1131	USA
1210	Hart Scientific	5681	USA

Table 3
SPRTs measured at INTiBS.

Serial number	Manufacturer	Model	Country of origin
275079	Tinsley	5187SC	UK
112	Isotech	670	UK
129-06	Chino	N/A	Japan
5452	Rosemount	162CG	USA
4113	Fluke	56831	USA
086357-3	Tinsley	5187SA	UK
461	Isotech	670Q	UK
015	Isotech	670Q	UK

3.2. CEM

A comparable procedure was used at CEM, where a set of six long-stem SPRTs were used (Table 2). Thermometers were calibrated at the TPW, TP Hg, MP Ga and FP In with the uncertainties ($k = 1$) of: ± 0.22 mK, ± 0.25 mK, ± 0.24 mK and ± 0.50 mK respectively. These thermometers were set up in a Hart Scientific 7381 stirred alcohol bath, previously characterized in terms of its stability and homogeneity. The thermometers were immersed directly into the bath to an immersion depth of 430 mm and their resistance values were measured at 18 temperatures uniformly distributed in the range 273 K to 353 K.

A resistance bridge, ASL F18, was used to measure the resistance ratio between each of the thermometers and the 275038 thermometer, considered as the reference. The reference thermometer was checked in each cycle against an external resistor, R_s (Tinsley 5685A). Each cycle consisted of measuring the resistance ratios R_x / R_{ref} of all the thermometers consecutively and with an initial and final measurement of the reference thermometer against the external resistor, R_{ref} / R_s .

Three successive cycles were performed at each point, with currents of 1 mA, $\sqrt{2}$ mA, then 1 mA again. Each individual ratio was derived from monitoring each thermometer for 4 min at 1 mA and 7 min at $\sqrt{2}$ mA. In order to ensure that the measurement conditions were stable, the mean and standard deviation (typically lower than $7 \cdot 10^{-7}$) of only the last 10 measurements in each recording period were considered in the analysis. The resistance value at 0 mA was calculated for each thermometer and each temperature.

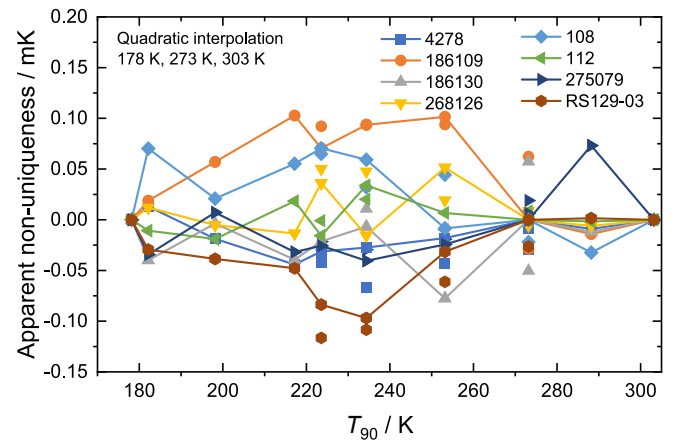
3.3. INTiBS

At INTiBS a similar measurement methodology was followed to that at NPL and CEM. Before the measurements, all SPRT were heated at 450 K for about 6 hours. Each thermometer was calibrated at the TP Ar, TP Hg, TPW, MP Ga, and again after the measurements at the TPW. Typical uncertainties ($k = 1$) for the above fixed points are ± 0.27 mK, ± 0.25 mK, ± 0.13 mK and ± 0.39 mK, respectively.

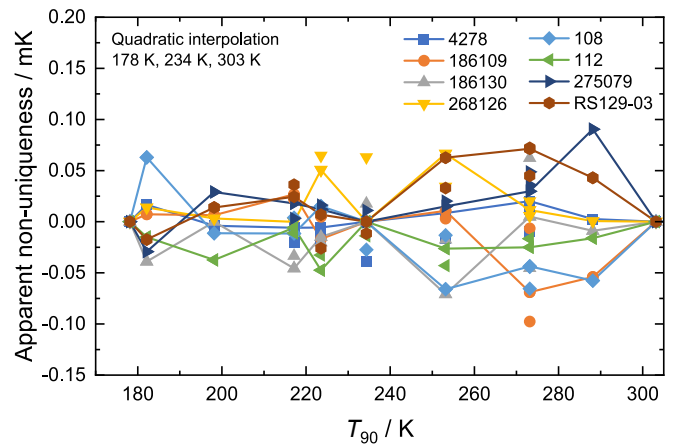
The measurements were made in a Hart Scientific 7381 stirred alcohol comparison bath from 302 K down to 198 K and then in an evacuated temperature-controlled home-made cryostat from 185 K to 84 K. The cryostat was completely immersed in a Dewar vessel with liquid nitrogen. The temperature of the comparison block was controlled by the controller LSC 340 with an accuracy of approximately 0.5 mK. The thermal contact of the comparison block and liquid nitrogen was regulated by changing the pressure in the space between the walls of the cryostat in the range from about 10 Pa to about 0.1 Pa. By choosing the pressure value, the cooling power could be regulated below 0.5 W, which allowed the temperature gradient in the comparison block to be minimized.

Two sets of 5 SPRTs (Table 3), including Chino No. 129-06 as the reference thermometer, were accommodated in the bath, and measurements were made at 9 points on cooling down and again on warming up. The thermometers were immersed directly into the bath to an immersion depth of 420 mm.

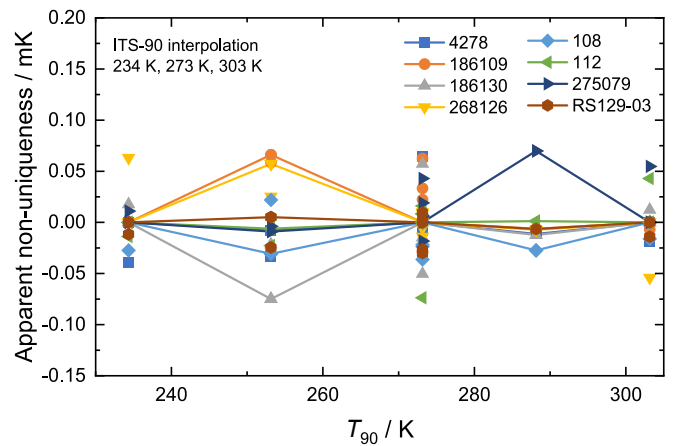
Due to the large temperature difference between the room temperature and the measurement temperature and the symmetry of the



(a)



(b)



(c)

Fig. 1. The general consistency of the NPL data for the comparison of SPRTs, which ran from 273 K to 303 K, then down to 178 K and back up to 273 K. Note that points taken on cooling are linked by lines, but repeat points taken on warming are not. All plots are on the same vertical scale and the data lie mostly within ± 0.1 mK.

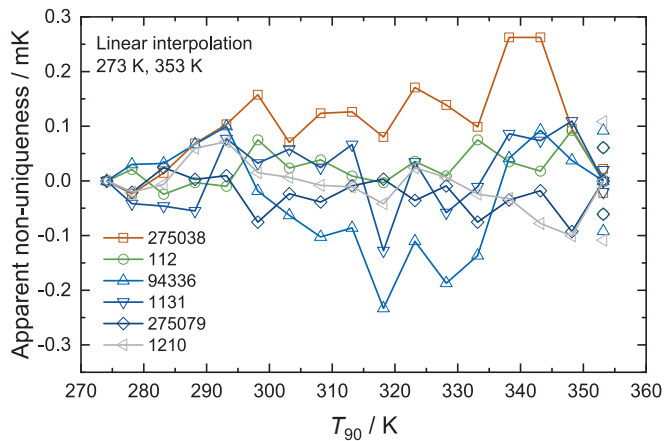


Fig. 2. Comparison data for six SPRTs at CEM between 273 K and 353 K. The linear interpolations are fitted to the mean of the two comparisons at 353 K.

measuring system the cryostat could only accommodate 3 SPRTs without overloading the control: consequently, the SPRTs were divided into 4 pairs, with the same Chino SPRT (129-06) as the reference. The sets of SPRTs were selected so that each pair comprised of thermometers with a similar design. Measurements were made at 10 points on cooling down and again on warming up. All measurements were made using a Fluke Super-Thermometer resistance bridge, type 1595A, which was used to scan across all the SPRTs.

4. Data analysis

Having measured the ratios R_x / R_{ref} at 0 mA and the resistance R_{ref} at 0 mA, the resistances, and hence the ratios $W(T) = R(T) / R(TPW)$, and the differences (deviations) $W(T) - W_{ref}(T)$, can all be calculated. These deviations from $W_{ref}(T)$ can now be compared with deviations interpolated using the relevant equations (or the equivalent Lagrange functions) and the deviations at the chosen fixed points.

The differences between the interpolated deviations and the deviations determined in the experiment can then be plotted, relative to the reference SPRT as the baseline. However, this is in reality just another SPRT, and the differences are best presented relative to the mean of the set. The figures in this paper show the results. Ideally they should represent the Type 3 non-uniqueness of the set of SPRTs over the particular subrange, but in reality, even though the comparisons were very precise, the extent to which they do this is limited by the residual statistical uncertainties in the measurements.

5. Results

The following figures show the ‘apparent’ non-uniqueness as determined experimentally: in other words, it includes the experimental errors and uncertainties, so the results shown in the figures are upper limits for the non-uniqueness. The repeatability of the comparisons is evidenced by the dispersion of the data at 273 K and at other repeated points.

Fig. 1a to 1c show the general consistency of the NPL data for the comparison of SPRTs, which ran from 273 K to 303 K, then in steps down to 178 K and back up to 273 K. Fig. 1a shows that the interpolations in the whole range, using a quadratic in $(W - 1)$, deviated from the means by less than ± 0.12 mK. The repeat (warming-up) data are closely consistent with the initial (cooling) data. The data suggest that the non-uniqueness is bounded by SPRTs 186109 and RS129-03 at about ± 0.1 mK in this subrange. However, this is not borne out in Fig. 1b, where the mid-range point is more central, at 234 K rather than 273 K: the resulting ‘non-uniqueness’ is somewhat smaller and the positions of these two SPRTs are different (what were positive differences at 234 K

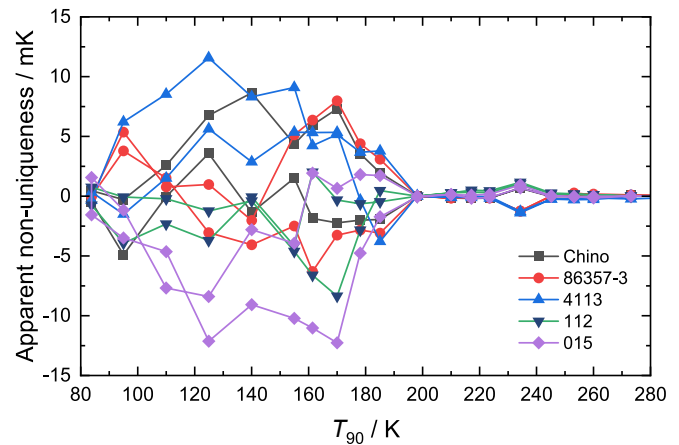


Fig. 3. Comparison data for five SPRTs at INTiBS between 273 K and 198 K in the liquid bath, and from 185 K to 84 K in the cryostat. The data are fitted in two parts, using the ITS-90 Eq. 13.

now often appear as negative differences at 273 K and *vice versa*). This illustrates the sensitivity of the interpolations to the distribution of the points and the errors in the data used to generate them. The statistical uncertainties are also evident in Fig. 1c (which is based on the ITS-90 Eq 14 [11] in the subrange from 234 K to 303 K). In spite of the rugged appearance of the figures, comparisons of long-stem SPRT resistances have rarely if ever been done at these levels of precision. The repeatability is compounded of the bridge statistical uncertainty, fluctuations in the bath temperature uniformity and (for repeat points) SPRT instability; its magnitude may be seen in the Figures.

The results for the CEM comparison data, using a linear interpolation between 273 K and 353 K, are shown in Fig. 2. Here the differences (apparent non-uniqueness) rise to ± 0.2 mK, and some effect due to the break in the measurement sequence between 333 K and 338 K can be seen. The two measurements at 353 K were repeatable within ± 0.11 mK, and the averages were used for deriving the interpolations.

The results at INTiBS were analysed in two parts: the data taken in the bath and those taken in the cryostat. In both cases the ITS-90 Eq. 13 is used for interpolation between 84 K and 273 K, but for the bath data the mid-point uses the lowest comparison point in the bath, 198 K, while the cryostat data uses the highest comparison point in the cryostat, 185 K, taking the mean of the cooling and warming measurements. The data are plotted in Fig. 3, for the set of 5 SPRTs. The data in the bath are consistent within ± 0.3 mK, apart from exceptional differences at 234 K. However, the cryostat data are clearly seen to diverge in the interval below 185 K. Here the cooling and warming data generally repeated within a few mK, but the differences between the SPRTs abruptly increased (compared with the results in the bath), in the worst cases up to ± 12 mK. These differences are too large to associate with SPRT non-uniqueness and it seems likely that they are due to systematic but quite repeatable temperature gradients between the SPRTs in the cryostat.

6. Additional interpolations

In Fig. 4a to 4d, the NPL data are extended to 84 K using the triple point of argon (TP Ar), as no comparison data could be taken below 178 K. Although the argon points were not necessarily compatible with the comparisons, the effect of any incompatibility is much attenuated, by a factor of about 10, at 178 K and above. These four graphs, plotted on the same scale, show the effect on the interpolations of replacing the TP Hg at 234 K by a point at 223 K (for TP SF₆), by 216 K (for TP CO₂), and by 178 K (in place of TP Xe), all using the interpolating equation, Eq. 13, as specified in the ITS-90. Most of the data are bunched within ± 0.07 mK. To some extent the dispersion is reduced as the mid-range comparison point moves toward the centre of the interval, as would be expected

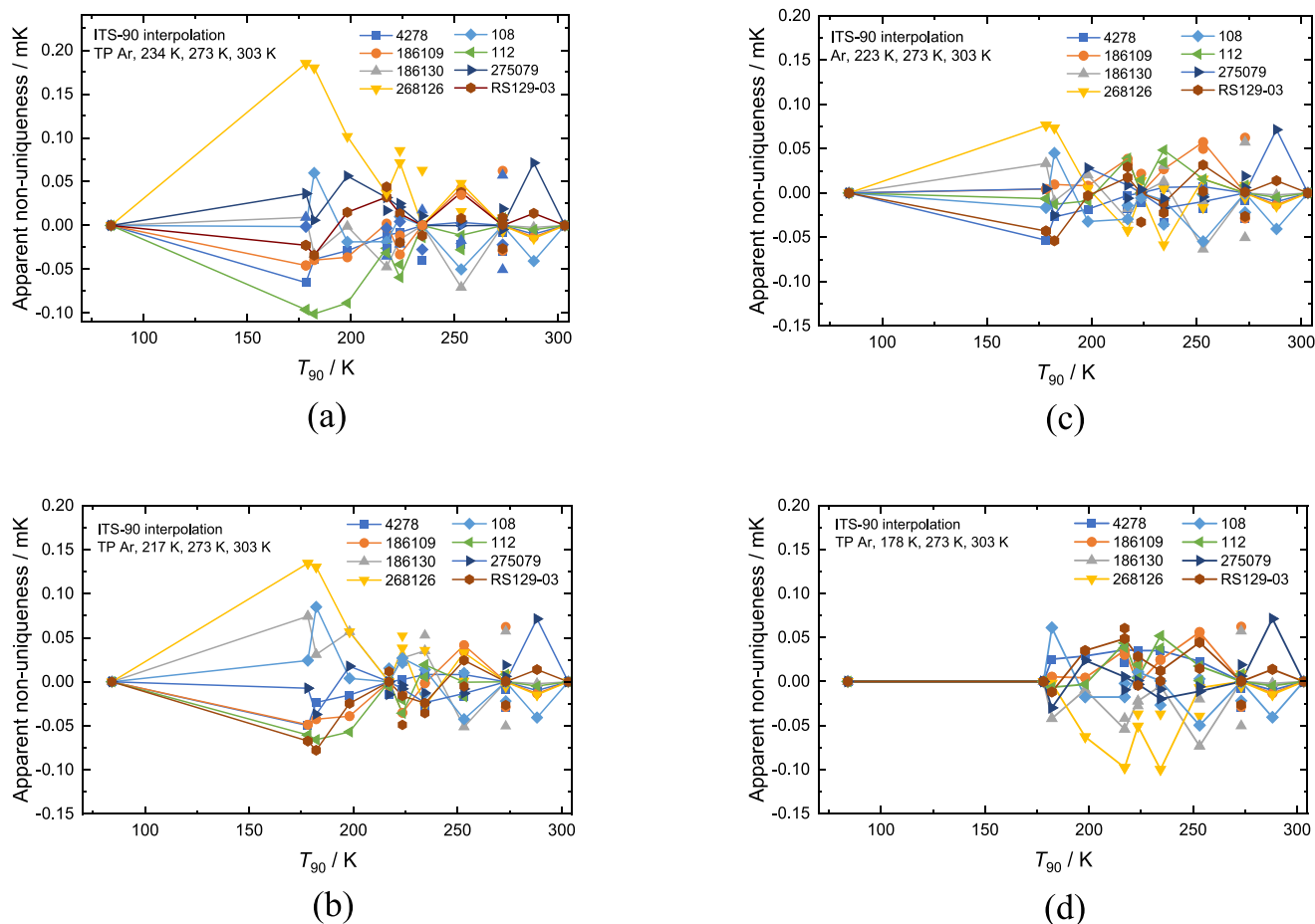


Fig. 4. The NPL data extended to 84 K using values of $W(\text{TP Ar})$ and at comparison temperatures approximating four alternative triple points: ‘Hg’ (a), ‘CO₂’ (b), ‘SF₆’ (c), ‘Xe’ (d). Note that no comparison data could be taken below 178 K, and all the plots are on the same scale (ordinate range 0.35 mK).

from the improved distribution of the points. However, this trend is upset by the propagation of random errors, notably in the case of SPRT 268126.

In Fig. 5, the graphs are four further NPL interpolations for Ar—Hg—TPW—Ga, plotted on the similar scales. Fig. 5a uses the repeat comparisons at 234 K taken on warming, which suggests that the poor result in Fig. 4a for SPRT 268126 was due to the propagation of an offset of ~ 0.06 mK in the cooling comparison at that point. Fig. 5b shows the result of using a quadratic in $(W - 1)$, in place of the ITS-90 Equation 13: with this interpolation SPRT 268126 is again less discrepant, but the overall dispersion of the interpolations is slightly larger than in Fig. 4a, being ± 0.15 mK at 178 K. Fig. 5c is Fig. 5b with Ga in place of Hg: that is, the quadratic interpolation extends from Ar to Ga, without Hg. Although the dispersion of the results at 178 K is now increased to ± 0.3 mK, it is still small, and may be of interest to users of long-stem SPRTs as it does not require any fixed point between the Ar point and the triple point of water. Fig. 5d is Fig. 4a with the baseline changed to the mean of the two circulating SPRTs (dashed lines), rather than the mean of all eight: the range of the dispersion is unchanged.

In Fig. 6 the NPL results (Fig. 5d, from TP Ar to 303 K) are merged with those of CEM (Fig. 2, from 273 K to 353 K), both with the new baseline of the mean of the two common SPRTs, 112 and 275079. As these two SPRTs agree well with each other, the two sets of results are simply plotted together. ‘N’ against the SPRT serial number refers to NPL, ‘C’ to CEM.

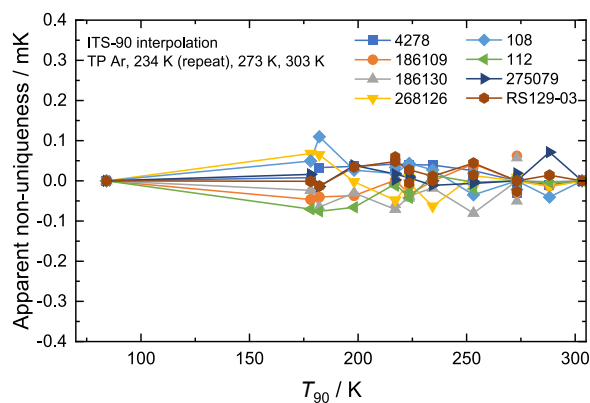
Finally, Fig. 7 shows the effect of extending the range to FP In. Although the two common reference SPRTs agree well, the interpolations to the indium point are inconsistent with the comparison data at 353 K by amounts ranging from -0.8 mK to $+0.4$ mK.

Specifically, the indium point for SPRT 275038 would need to be increased by about 1.2 mK to bring the differences to within about 0.1 mK of the baseline, and two other SPRTs show inconsistencies which are about half this amount. We note that the inconsistencies with the In freezing points are only attenuated linearly in these interpolations, not as strongly as was the case for the triple point of Ar.

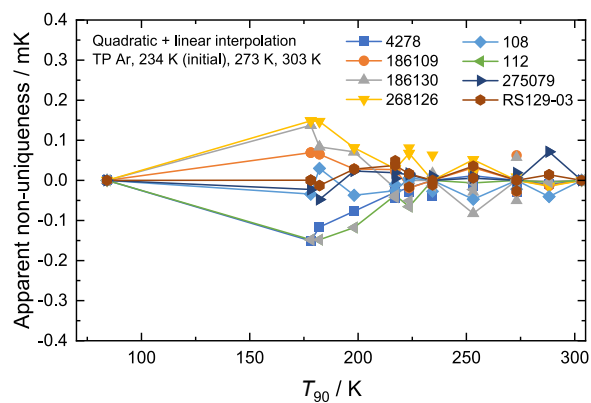
7. Conclusions

NPL and CEM have performed comparison measurements of cohorts of eight and six local long-stem SPRTs respectively, drawn from a range of different manufacturers and designs. Each cohort included two SPRTs which were common to both, to provide linkage between the two local investigations. The temperature range of the comparisons was from 178 K to 353 K, and this is augmented by calibration of each SPRT, at NPL using the triple point of argon, 84 K, and at CEM using the freezing point of indium, 429 K.

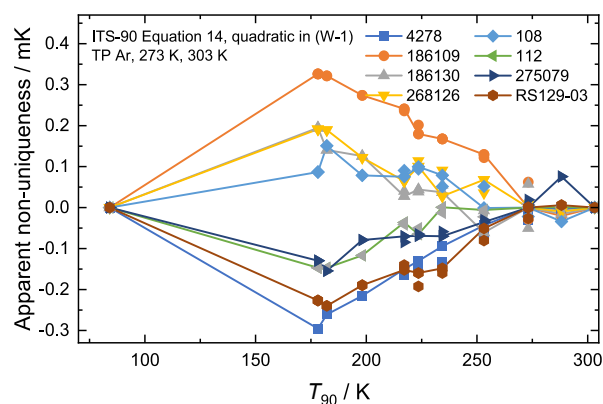
Few, if any, comparisons of long-stem SPRTs have previously been made so precisely, and they will be a useful reference for users needing to incorporate the uncertainty contribution from Type 3 non-uniqueness into their uncertainty budget. The measurements reported here represent upper limits, because, in addition to the Type 3 non-uniqueness, they incorporate experimental measurement uncertainty, but they suggest that an assessment of the Type 3 non-uniqueness uncertainty need be no higher than ± 0.1 mK, at least between 178 K and 303 K (Fig. 1), rising to ± 0.2 mK at 353 K (Fig. 2). The results of comparison measurements at INTiBS in a cryostat between 84 K and 185 K showed significant differences which are more likely to be due temperature gradients between the SPRTs than to Type 3 non-uniqueness.



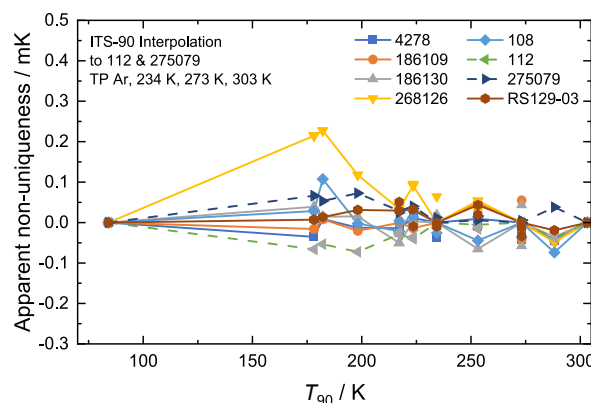
(a)



(b)



(c)



(d)

Fig. 5. Four further NPL interpolations for subranges Ar-Hg-TPW-Ga. In 5a the repeat ‘Hg’ point is used; 5b and 5c use ITS-90 Eq. 14 (quadratic in $(W-1)$). Fig. 5b uses the initial comparison at 234 K, but with this interpolation 268126 is no longer an outlier; 5c shows the effect of using the ‘Ga’ point in place of the ‘Hg’ point, there then being no fixed point between Ar and TPW; and 5d shows the non-uniqueness relative to the mean of the two common SPRTs, cf Fig. 4a. All the figures are on the same vertical scale.

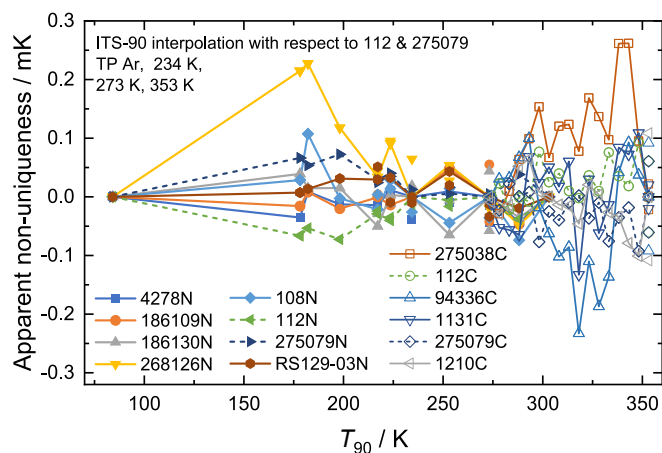


Fig. 6. . Combined results of NPL (from TP Ar to 303 K) and CEM (from 273 K to 353 K).

We suggest that the range of comparisons could usefully be extended to investigate the Type 3 non-uniqueness up to 505 K, given a comparison bath with good temporal and spatial uniformity. Coupled with a

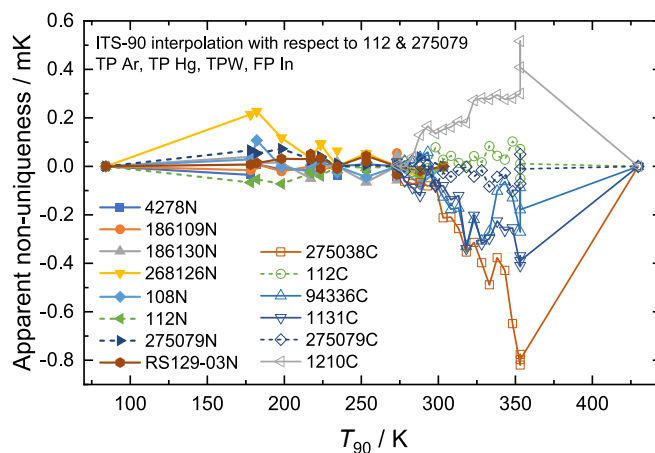


Fig. 7. Composite figure of NPL and CEM data for differences between SPRTs, the apparent Type 3 non-uniqueness of the ITS-90 between 178 K and 353 K, for interpolations from the TP Ar to MP Ga and TPW to FP In. The inconsistency in SPRT 268126 at 178 K is discussed in the text. The large divergences above 273 K arise mainly from inconsistencies between the FP In and the comparison data.

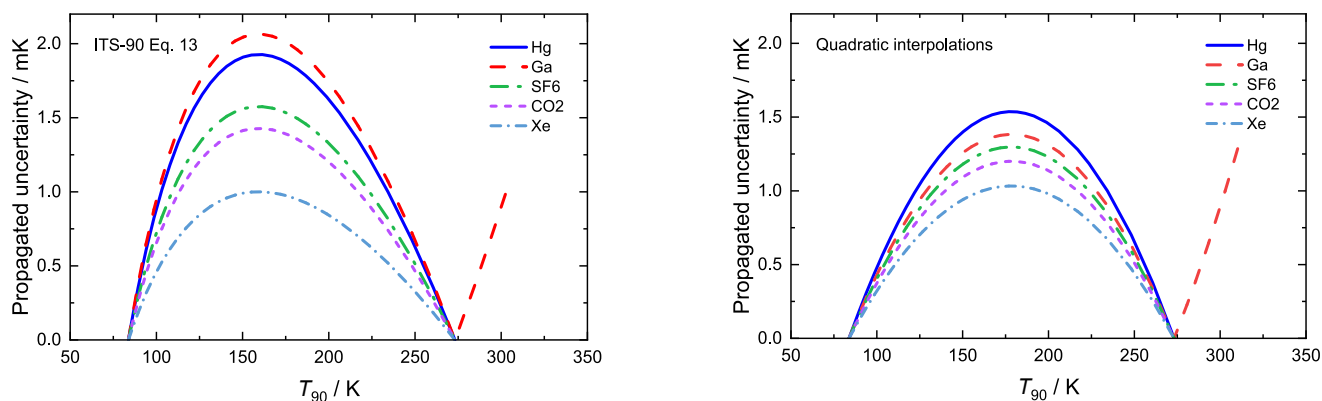


Fig. 8. Propagation of 1 mK errors at the triple point of mercury and at possible replacement points, the triple points of SF₆, CO₂, Xe, and the melting point of Ga, using the ITS-90 Eq. 13 (left) and Eq. 14 (a simple quadratic, right). In each case the modulus of the error is shown.

measurement at the freezing point of zinc, interpolations in subranges to the indium, tin and zinc points could then be investigated, following the principles of this work, as far as the comparison measurements allow.

A key conclusion arising from this study is that any of the Xe, CO₂ or SF₆ triple points could successfully replace the mercury point, and the choice should be based on their utility, realization uncertainty, and their location in the subrange. The realization uncertainties of the alternative fixed points are likely to be larger than those for the mercury point, but the propagation of the uncertainties would in all cases be somewhat lower [3,19]. On the other hand, very low uncertainties can be achieved at the melting point of gallium but, being an out-of-range point close to TPW, the interpolations are less satisfactory (Fig. 5c) and the uncertainty propagates poorly: more strongly than for TP Hg if the ITS-90 Eq. 13 is used, but slightly less if the quadratic Eq. 14 is used (the dispersion of the data in Fig. 5c would be caused if the Ga points were inconsistent by $\sim \pm 0.2$ mK).

Fig. 8 shows how errors of 1 mK in each of the alternative points propagate, for interpolations using the ITS-90 equations 13 and 14.

CRedit authorship contribution statement

Radka Veltcheva: Investigation, Data curation, Writing – review & editing. **Carmen Garcia Izquierdo:** Investigation, Data curation. **Richard Rusby:** Writing – review & editing. **Jonathan Pearce:** Writing – review & editing. **Elena Gómez:** Investigation, Data curation. **Aleksandra Kowal:** Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgments

This work was funded by the EU EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme, specifically from the EMPIR project 18SIB02 "Realising the redefined kelvin".

The authors are grateful to Jianping Sun (NIM, China) for contributing two locally manufactured SPRTs to the study.

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