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Uncertainty budgets for characteristics of SPRTs calibrated according to the ITS-90

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Introduction

According to the ITS-90, the characteristic of a standard platinum resistance thermometer (SPRT) is described by the sum of a general reference function and an individual deviation function. The coefficients of the deviation function are deduced from the results of the calibration at the defining fixed points. The users of SPRTs are interested in an information on the uncertainty, with which the characteristic of a calibrated SPRT represents temperatures on the ITS-90 in the whole calibration range. Thus, this uncertainty has to be specified in the Appendix C of the Mutual Recognition Arrangement (MRA) describing the Calibration and Measurement Capabilities (CMCs) of the different institutes.

As the basis for estimating the uncertainty of SPRT characteristics, the uncertainty of the calibration at the fixed points has to be analysed in detail. Then, the propagation of uncertainties to intermediate temperatures has to be treated. Finally, the Type 1 and Type 3 non-uniqueness has to be considered, which results from the fact that the sum of the reference function and the deviation function cannot describe ideally the complex real characteristic of a SPRT.

In this summary paper, the results of the discussions during the "Workshop of the WG3 of the CCT and EUROMET on uncertainties and CMCs in the field of thermometry" held at PTB in Berlin on February 5 and 6, 2001 are compiled. Since the documents CCT/2000-16 and CCT/2000-17 represent a good basis for preparing a guide for quoting the uncertainty of the calibration at the fixed points, a complete discussion of the mathematical model is not given. Rather only additions and improvements of details are proposed.

1. Comments on documents CCT/2000-16, CCT/2000-17

Impurities, Isotopes

Usually, the influence of impurities on the fixed-point temperature causes the main uncertainty component. Therefore, this component has to be estimated very carefully considering the fundamental crystallographic facts described in the document CCT/99-11 of Working Group 1 of the CCT (Mangum et al. 2000). Since it is principally not possible to obtain a reliable estimate for this component from the shape of the melting and freezing curves, more specific methods must be applied:

- Method 1: Sum of Individual Estimates (SIE): A detailed estimation requires to determine the concentrations of all impurities using appropriate analysis techniques and to know the concentration dependence of the fixed-point temperature for the different impurities. The estimate is the sum of the individual shifts of the fixed-point temperature due to the impurities present in the fixed-point sample. The uncertainty of the estimate then results from the uncertainty of the analysis results and of the data for the concentration dependencies.
- Method 2: Overall Maximum Estimate (OME): If the concentrations of all impurities or their individual influence on the fixed-point temperature are not known, a reliable estimate may be obtained by assuming that all impurities are not soluble in the solid phase of the fixed-point substance. Then the estimate results from the overall impurity content and the first cryoscopic

constant (see CCT/99-11). Since it can be ruled out that impurities having equilibrium distribution coefficients larger then 2 are important, a maximum estimate is obtained if the overall impurity content is estimated reliably. Method 2 yields usually larger values than Method 1.

- Method 3: Estimate based on Representative Comparisons (ERC): If the overall impurity content cannot be estimated reliably, a rough estimate can be deduced indirectly from the comparison of different fixed-point materials. But one has to ensure that the compared materials have different sources or purity. In any case, the results of this method are somewhat accidental.

All three methods yield estimates for the uncertainty component caused by the shift of the liquidus point of the fixed-point sample due to the influence of impurities (for Method 3, the plateau value has to be defined appropriately). The temperature width of the freezing or melting curves causes a further uncertainty component that can be deduced directly from the experimental data. In all cases, the estimates resulting from Methods 2 and 3 can not be used to correct for the fixed-point temperature with respect to the influence of impurities. They are only uncertainty estimates. Usually, also Method 1 does not allow calculating corrections because the uncertainty of the analysis results is comparable with the results themselves (this uncertainty may be as large as a factor of three).

It is of course possible to combine the first two methods: Application of Method 1 for the dominant impurities and Method 2 for the rest of the impurities. The isotopic composition of the sample has to be analysed if it may significantly influence the fixed-point temperature. Actually problems concerning the isotopic composition are discussed for hydrogen and water.

For the participants, valuable data for the application of Method 3 will result from the CIPM Key Comparisons in the field of thermometry. These data will yield also reasonable estimates for the levels of accuracy that can be achieved applying state-of-the-art high-purity materials. If no individual information for the used fixed-point materials is available, these estimates should be at least included in the uncertainty budgets. Until the results of the Key Comparisons will be published, we propose to accept the guideline values listed in Table 1.

Table 1: State-of-the-art estimates for the uncertainty component caused by impurities and isotopes (standard uncertainty, temperature equivalent of the quantity $C_{\mathrm{Xt/1}}$ in CCT/2000-17). Except for water, the estimates are based on the standard deviations of the results near (CCT-K2) or at the fixed points (CCT-K3, CCT-K4) obtained in the CIPM Key Comparisons. For argon, the estimate has been deduced from the results obtained in CCT-K2 for capsule-type SPRTs (CSPRTs). CCT-K3 yielded data for long-stem SPRTs that are obviously also strongly influenced by the parameters of the facilities used for the calibration at the argon triple point. Thus, the estimate based on the CSPRT data represents better the influence of impurities. Since a relatively small number of institutes took part in CCT-K2, the standard deviations obtained for H_2, Ne, O_2, and Ar have been increased by 50% to deduce the estimates. For water, the results of different comparisons have been considered.

Fixed Point	**$C_{\mathrm{Xt/1}}$ in mK**	**Fixed Point**	**$C_{\mathrm{Xt/1}}$ in mK**
H_2	0.4	Ga	0.2
Ne	0.2	In	0.8
O_2	0.2	Sn	0.5
Ar (CSPRT)	0.3	Zn	0.7
Hg	0.25	Al	1.5
H_2O	0.1	Ag	4

A simple analysis of the melting or freezing curves, assuming incorrectly that the impurities are not soluble in the solid phase of the fixed-point material and neglecting the effect of the freezing conditions, yields usually a significant underestimation of the influence of impurities on the temperature of the solid-liquid interface (see CCT/99-11). Furthermore, the shapes of these curves may also depend significantly on the temperature profile in the surroundings of the fixed-point cell. Nevertheless, their analysis including the comparison of melting and freezing may aid in ascertaining the quality of the cell. The curves may provide an order of magnitude of the effects or indicate problems. In any case, the estimate for the influence of impurities should not be smaller than the width of the curves in the range from 20% to 80% of sample melted.

Hydrostatic pressure correction

The uncertainty of the hydrostatic pressure correction that results from the uncertainties of the position of the sensor element and of the height of the fixed-point material in the cell is usually a Type B component with a symmetrical rectangular distribution.

Gas pressure correction

If sealed fixed-point cells are used, it has to be verified by comparisons with open cells that there is no considerable overpressure at the fixed-point temperature. These comparisons must be performed regularly, either by the institute itself or via comparisons with other institutes. In case that no reliable comparison data are available, a maximum estimate has to be used for the corresponding uncertainty component. The maximum estimate is obtained by assuming that the pressure at room temperature is equal to one standard atmosphere.

Possible errors due to an incorrect pressure in the fixed-point cell have to be considered in document CCT/2000-16 also for the triple point of water.

Preparation of the triple-point-of-water cell

Since the real structure of the ice mantle directly after its preparation may significantly influence the temperature of the liquid-solid interface, it is necessary to perform an appropriate annealing. To consider this influencing factor, an additional uncertainty component has to be included in document CCT/2000-16.

SPRT internal insulation leakage correction

Besides the triple point of water, insulation leakage or degradation may be of importance also at other fixed points.

2. Uncertainty budgets at the fixed points

As examples, Table 2 contains the PTB uncertainty budgets for the calibration of SPRTs at the defining fixed points of the ITS-90. These examples, together with the estimates given in the documents CCT/2000-16 and CCT/2000-17, are a reasonable starting point for establishing typical state-of-the-art uncertainty budgets as a guide for evaluating CMC uncertainty budgets. But these examples belong to the so-called “best category of uncertainty” (see Jung 1997), i.e. they can be obtained only with considerable effort by a small number of leading workers in the field.

In Table 3, uncertainty budgets are given as an alternative that represent in our opinion the “normal category of uncertainty”, which can be easily obtained at present in national metrology institutes. These budgets have been deduced from the budgets of the PTB by increasing only the estimates for three main components: influence of impurities, error in gas pressure and uncertainty propagation from the triple point of water. The estimates for the influence of impurities are deduced from the standard deviations of the results near (CCT-K2) or at the fixed points (CCT-K3, CCT-K4) obtained in the CIPM Key Comparisons (see above). For the error in gas pressure for In, Sn, Zn, Al, Ag, 30% of the maximum estimates, which would be obtained by assuming the pressure in a sealed fixed-point cell to be one standard atmosphere at room temperature, is used. The uncertainty propagated from the triple point of water is larger due to an increased uncertainty at this fixed point itself and by neglecting correlation to enable the use of different equipment for the calibration at different fixed-points.

3. Propagation of uncertainties to intermediate temperatures

Correctly the propagation of uncertainties has to be calculated as discussed for instance by White, Saunders (2000), Palencar et al. (2000), Lira et al. (1999) and Sadli et al. (1998). But considering the examples shown in the "Supplementary Information for the International Temperature Scale of 1990" (Preston-Thomas et al. 1990), in most cases, upper limits for the uncertainty would be obtained by linearly interpolating between uncertainty estimates at the fixed points that are increased compared with the original estimates discussed above by a few 10%.

4. Type 1 non-uniqueness

This type of non-uniqueness arises from the application of different deviation functions in overlapping calibration ranges. In the "Supplementary Information for the International Temperature Scale of 1990", some examples are shown and called "sub-range inconsistency". Mangum et al. (1990) and Moiseeva, Pokhodun (1992) give further examples. For a reliable estimation of the Type 1 non-uniqueness, much more experimental information is urgently necessary. On the basis of the available data, it seems to be reasonable to use 1 mK as the minimum estimate for this type of non-uniqueness in the whole temperature range from 14 K to 1235 K. Assuming a symmetrical rectangular distribution, this estimate yields a minimum standard uncertainty of about 0.3 mK. Since the non-uniqueness vanishes at the fixed points and reaches its maximum near the middle of a temperature range between the fixed points, in principle a temperature-dependent uncertainty component could be added to the uncertainty budget for SPRT characteristics. But in view of the lack of sufficient information and of the needs of the users, neglecting this temperature dependence is appropriate.

5. Type 3 non-uniqueness

This type of non-uniqueness arises from the individual differences in the detailed physical-chemical properties of the platinum wires and in the designs of the SPRTs. Most of the available data for this type of non-uniqueness concern the low-temperature range from 14 K to 273 K (see "Supplementary Information for the International Temperature Scale of 1990", Head (1997)). For temperatures above 273 K, only a few data are available: Ancsin (1984), Ancsin, Murdock (1990), Ancsin (1996), Furukawa, Strouse (2001). Considering this experimental information as well as the fact that the inclusion of further types of SPRTs may significantly increase the spread of the readings, the estimate for this type of non-uniqueness should not be smaller than 2 mK in the whole temperature range from 14 K to 1235 K. Assuming again a symmetrical rectangular distribution, this minimum value corresponds to a standard uncertainty component of about 0.6 mK. By the same reasons as for the Type 1 non-uniqueness, the temperature dependence of this component should be neglected.

6. Consideration of correlation

Though in general the majority of the impurities decrease the fixed-point temperature, it is not reasonable to lower the corresponding uncertainty component by assuming $\rho_1 > 0$ in CCT/2000-17. First, the impurity content of the different fixed-point materials may be quite different depending on their properties, sources and preparation. Second, dominant impurities may have distribution coefficients, which are near to or even larger than one. In the end, the necessary verification of a correlation comes to the thorough analysis of the influence of impurities as discussed above.

The quantity $C_{\mathrm{Xt/l}}$ in CCT/2000-17 should be an estimate for the shift of the liquidus point by the impurities present in the fixed-point sample. (Methods 1 and 2 yield such estimates. For Method 3, the meaning of the results depend on the definition of the plateau value agreed for the comparison.) Then, there is the smallest possible correlation ρ_{int1} between the quantities $C_{\mathrm{Xt/1}}$ and $C_{\mathrm{Xt/8}}$. This is preferable because different effects (e.g. freezing conditions and thermal effects) may influence the uncertainty connected with the width of the freezing or melting curve, i.e. with the correction $C_{\mathrm{Xt/8}}$ associated with the choice of the fixed-point value.

Different types of perturbing heat exchanges have to be distinguished: Heat flowing along the parts of the SPRT causes the so-called heat-flux immersion errors. Investigating the immersion characteristic can check the magnitude of these errors. On the other hand, a non-appropriate temperature distribution in the surroundings of the fixed-point cell may cause a temperature difference between the solid-liquid interface of the fixed-point material and that part of the re-entrant thermometer well of the cell, which surrounds the sensor element of the SPRT. This temperature difference depends of course on the fraction of fixed-point material melted, i.e. it influences the shape of the freezing or melting curves. The correlation ρ_{int2} between the quantities $C_{\mathrm{Xt/3}}$, introduced in CCT/2000-17 to consider perturbing heat exchanges, and $C_{\mathrm{Xt/8}}$ would be also essentially reduced if, as it is often done, $C_{\mathrm{Xt/3}}$ would be restricted to heat-flux immersion errors.

7. Repeatability of the SPRT

The stability of the calibrated SPRT may of course significantly influence the uncertainty of the temperature measurements done by the user. It is, however, not possible to include a component in the budget for the calibration uncertainty that considers the long-term instability because the behaviour of an SPRT depends strongly on its individual design and handling. On the other hand, it seems to be reasonable to consider the information on the repeatability of the SPRT reading obtained during the calibration. The instability during its practical application is certainly larger than that caused by the careful handling during the calibration.

The instability of the SPRT at the triple point of water is included in the uncertainty of the quantity $X_{0.01^\circ\mathrm{C}}$ in CCT/2000-16 that considers the repeatability of the results at this fixed point. Evaluating the data for the instability, the following facts have to be considered:

- Each SPRT has to be appropriately annealed before it is calibrated for temperatures above 0 °C. The difference between the triple-point-of-water values obtained prior and after the last annealing is a valuable indicator of the instability, which has to be considered.
- Due to the possible oxidation and reduction of the platinum sensor above 0 °C, an information on the instability due to handling and ageing can be deduced only from the comparison of triple-point-of-water values obtained directly after calibration measurements at the same fixed point.

Considering the careful handling of the SPRT during the calibration, it is reasonable to use an uncertainty component for the instability at the triple point of water which is increased compared with that deduced directly from the spread of the triple-point-of-water values by at least a factor of three. This yields a better estimate for the real short-term instability. The resulting uncertainty component has to be propagated of course to the other fixed points.

Typically, the spread of the triple-point-of-water values may amount up to 0.2 mK. Considering the factor of three and assuming a symmetrical rectangular distribution, an additional uncertainty component of about 0.2 mK has to be added to the uncertainty budget for the calibration at the triple point of water in order to consider reliably the short-term instability of an SPRT, for which only data of one calibration exist.

The possible oxidation and reduction of the platinum sensor above 0 °C may cause an increase of the non-repeatability of the SPRT reading, i.e. a further uncertainty component has to be considered in the uncertainty budget for the application of the calibrated SPRT. Since usually the users cannot measure the resistance at the triple point of water after each temperature measurement, the estimate should be based on the possible spread of the resistance. At the triple point of water, usually a temperature equivalent of 0.5 mK seems to be a reasonable maximum estimate. Assuming again a symmetrical rectangular distribution, the resulting additional standard uncertainty component amounts to about 0.15 mK. Since oxidation and reduction change the effective cross section of the platinum wire and since the actual effective cross section depends on the application history, this component has to be propagated to temperatures up to about 600 °C. (At even higher temperatures, the oxides dissociate quickly.)

At higher temperatures (above the freezing point of zinc), a considerable drift of the SPRT resistance with time may occur due to an ageing of the platinum wire. A guideline value for the magnitude of the temperature equivalent of this drift at the freezing point of silver is 5 mK per 100 h, which yields an additional standard uncertainty component of about 1.5 mK per 100 h. Since the ageing changes the resistivity of the platinum wire, it seems to be reasonable to assume that the effect decreases with decreasing temperature proportional to the resistance.

8. Uncertainty budgets for SPRT characteristics in different temperature ranges

Besides the estimates given in Tables 2 and 3, respectively, Tables 4 to 9 contain all uncertainty components discussed above that have to be considered additionally if the overall uncertainty of the characteristic of an SPRT is estimated. These additional components take into account the Type 1 and 3 non-uniqueness, the non-repeatability of the SPRT reading, oxidation and reduction of the platinum wire and the drift of the resistance with time at high temperatures (above the freezing point of zinc). By the reasons given above, the temperature dependence of the non-uniqueness is neglected. To obtain upper limits for the overall uncertainty including the propagation of the calibration uncertainty at the fixed points to intermediate temperatures, the estimates at the fixed points are increased by 50% compared with those given in Tables 2 and 3, respectively. Tables 4 to 6 are based on calibrations at fixed points of the best category. Tables 7 to 9 result from calibrations of the normal category.

In the narrow temperature range from the triple point of mercury to the melting point of gallium (Table 4), only the Type 1 and 3 non-uniqueness and the non-repeatability cause considerable additional components. Their estimates are of course smaller than those deduced above for the whole temperature range from 14 K to 1235 K. If the SPRT is used up to the freezing point of zinc (Table 5), also oxidation and reduction of the platinum wire have to be considered. At even higher temperatures (Table 6), the drift of the SPRT resistance with time may be important. Both oxidation and reduction and drift are taken into account only for temperatures down to the triple point of water because even long-stem SPRTs, which have been calibrated for the low-temperature range, are usually not used up to the highest temperatures. Figure 1 shows the temperature dependencies of the overall expanded uncertainty ($k = 2$) of the characteristic of an SPRT in the three calibration ranges that result from a linear interpolation between the overall estimates at the fixed points deduced in Tables 4 to 6. The diamonds represent the uncertainty of the calibration at the fixed points listed in Table 2. Tables 7 to 9 and Figure 2 contain the same information for calibrations of the normal category as Tables 4 to 6 and Figure 1 for the best category.

9. Conclusions

The documents CCT/2000-16 and CCT/2000-17 represent a good basis for preparing a guide for quoting the uncertainty of the calibration of SPRTs at the defining fixed points of the ITS-90. Some proposals for additions and/or improvements are given in this summary paper. The detailed preparation of uncertainty budgets for the characteristics of SPRTs in the whole calibration ranges, which are needed for Appendix C of the MRA, requires considerably more efforts than the estimation of the calibration uncertainty at the fixed points. First, for assessing the additional uncertainty components, the available data are not sufficient. Second, it has to be discussed in detail the best way for considering such uncertainty components as the non-uniqueness. Nevertheless, the proposed guideline values for the different uncertainty components seem to yield reasonable state-of-the-art estimates for the minimum possible uncertainty of SPRT characteristics as a guide for evaluating uncertainty budgets. Excepted narrow temperature ranges near the triple point of water (from the triple point of mercury to the melting point of gallium), the minimum overall expanded uncertainty ($k = 2$) amounts at least to about 1.5 mK between the fixed points. This level of accuracy reflects the limits of the ITS-90 itself and is compatible with the demands of the users, who are interested in reliable specifications.

10. References

Ancsin J., TEMPMEKO ’84, Suhl, October 1984, pp. 67-72

Ancsin J., *Metrologia,* 1996, **33**, 5-17

Ancsin J., Murdock E.G., *Metrologia,* 1990, **27**, 201-209

Furukawa G.T., Strouse G.F., TEMPMEKO 2001, Berlin, June 2001

Head D.I., IMEKO International Seminar on Low-Temperature Thermometry and Dynamic Temperature Measurement, Wroclaw, September 1997, pp. L-36-L-41

Jung H.J., Proceedings of TEMPMEKO ’96, edited by P. Marcarino, Levrotto & Bella, Torino, 1997, pp. 235-244

Lira I., Camarano D., Paredes Villalobos J., Santiago F., *Metrologia,* 1999, **36**, 107-111

Mangum B.W., Pfeiffer E.R., Strouse G.F., TEMPMEKO ’90, Helsinki, September 1990, pp. 17-36

Mangum B.W., Bloembergen P., Fellmuth B., Marcarino P., Pokhodun A.I., *Comments on the influence of impurities on fixed-point temperatures*, 20th Meeting of the CCT, April 2000, Document CCT/99-11

Moiseeva N.P., Pokhodun A.I., In *Temperature, Its Measurement and Control in Science and Industry*, Vol. 6 (Edited by J. F. Schooley), New York, American Institute of Physics, 1992, pp. 187-191

Palencar R., Duris S., Brdecka R., *Contribution to the Evaluation of the Uncertainties of the SPRT Calibration in the Defining Fixed Points*, 20th Meeting of the CCT, April 2000, Document CCT/2000-23

Preston-Thomas, H., Bloembergen, P., Quinn, T. J., *Supplementary Information for the International Temperature Scale of 1990*, Pavillon de Breteuil, Sèvres, Bureau International des Poids et Mesures, 1990.

Sadli M., Renaot E., Bonnier G., EUROMET Workshop Temperature, Paris, March 1998, pp. 13-18

White D.R., Saunders P., *Metrologia,* 2000, **37**, 285-293

Table 2: PTB Uncertainty budgets, corresponding to the ISO guidelines, for the calibration of SPRTs at the defining fixed points (Temperature equivalents in mK, *k*: coverage factor, 6N: 99.9999% etc.)

Fixed-point	**e-H_2**	**Ne**	**O_2**	**Ar**	**Hg**	**H_20**	**Ga**	**In**	**Sn**	**Zn**	**Al**	**Ag**
Highest purity	6N	5N	6N	6N	6N		7N	6N	6N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0	16.8	18.5
Type B uncertainty components (mK)												
1. Chemical impurities, isotopes	0.17	0.16	0.19	0.14	0.06	0.031	0.06	0.25	0.31	0.54	0.40	0.65
2. Hydrostatic head correction	0.005	0.02	0.02	0.04	0.03	0.004	0.01	0.02	0.02	0.02	0.02	0.08
3. Error in gas pressure					0.01	0.005	0.01	0.10	0.08	0.12	0.30	0.30
4. Standard resistor	0.001	0.001	0.002	0.003	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.015	0.02	0.11	0.12	0.16	0.20	0.25
6. Uncertainty propagation from TPW	<0.001	0.001	0.01	0.02	0.05		0.08	0.09	0.11	0.15	0.20	0.28
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	0.01	0.03	0.06	0.06	0.06	0.20	0.20
Type B combined (mK)	**0.18**	**0.17**	**0.20**	**0.16**	**0.12**	**0.074**	**0.12**	**0.40**	**0.43**	**0.64**	**0.65**	**0.87**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.05**	**0.20**	**0.15**	**0.15**	**0.30**	**0.30**
Standard combined uncertainty (mK)	**0.19**	**0.18**	**0.21**	**0.17**	**0.13**	**0.08**	**0.13**	**0.45**	**0.45**	**0.66**	**0.71**	**0.92**
Expanded combined uncertainty, *k* = 2 (mK)	**0.38**	**0.36**	**0.41**	**0.33**	**0.27**	**0.16**	**0.26**	**0.89**	**0.91**	**1.31**	**1.43**	**1.83**

Table 3: Uncertainty budgets of the "normal category", corresponding to the ISO guidelines, for the calibration of SPRTs at the defining fixed points. The italic font style indicates that the values are different from those in Table 2.
(Temperature equivalents in mK, *k*: coverage factor, 6N: 99.9999% etc.)

Fixed-point	**e-H_2**	**Ne**	**O_2**	**Ar**	**Hg**	**H_20**	**Ga**	**In**	**Sn**	**Zn**	**Al**	**Ag**
Highest purity	6N	5N	6N	6N	6N		7N	6N	6N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0	16.8	18.5
Type B uncertainty components (mK)												
1. Chemical impurities, isotopes	*0.42*	*0.20*	*0.20*	*0.29*	*0.25*	*0.10*	*0.20*	*0.78*	*0.52*	*0.71*	*1.50*	*3.60*
2. Hydrostatic head correction	0.01	0.02	0.02	0.04	0.03	0.00	0.01	0.02	0.02	0.02	0.02	0.08
3. Error in gas pressure					0.01	*0.15*	0.01	*0.63*	*0.70*	*1.70*	*4.30*	*5.70*
4. Standard resistor	0.001	0.001	0.002	0.003	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.02	0.02	0.11	0.12	0.16	0.20	0.25
6. Uncertainty propagation from TPW	*<0.001*	*0.002*	*0.02*	*0.04*	*0.17*		*0.22*	*0.32*	*0.38*	*0.51*	*0.67*	*0.86*
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	*0.05*	0.03	0.06	0.06	0.06	0.20	0.20
Type B combined (mK)	**0.43**	**0.20**	**0.21**	**0.30**	**0.32**	**0.20**	**0.30**	**1.09**	**0.99**	**1.93**	**4.62**	**6.81**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.05**	**0.20**	**0.15**	**0.15**	**0.30**	**0.30**
Standard combined uncertainty (mK)	**0.43**	**0.21**	**0.21**	**0.30**	**0.32**	**0.20**	**0.31**	**1.11**	**1.00**	**1.94**	**4.63**	**6.81**
Expanded combined uncertainty, *k* = 2 (mK)	**0.86**	**0.42**	**0.42**	**0.60**	**0.64**	**0.40**	**0.62**	**2.21**	**2.00**	**3.88**	**9.25**	**13.63**

Table 4: Uncertainty of the characteristic of a SPRT in the range from 234 K to 303 K after calibration at fixed points of the best category

Fixed-point	**Hg**	**H_20**	**Ga**
Highest purity	6N	0	7N
Immersion depth / cm	2.5	19.0	26.0
Type B uncertainty components (mK)			
1. Chemical impurities, isotopes	0.06	0.031	0.06
2. Hydrostatic head correction	0.03	0.004	0.01
3. Error in gas pressure	0.01	0.005	0.01
4. Standard resistor	0.01	0.05	0.01
5. Bridge measurement	0.05	0.015	0.02
6. Uncertainty propagation from TPW	0.05		0.08
7. Self-heating error	0.05	0.04	0.05
8. Heat-flux immersion error	0.02	0.01	0.01
9. Choice of fixed-point value	0.05	0.01	0.03
Type B combined (mK)	**0.12**	**0.074**	**0.12**
Type A uncertainty component (mK)	**0.05**	**0.027**	**0.05**
Standard combined uncertainty (mK)	**0.13**	**0.08**	**0.13**
Uncertainty increased by 50% (mK)	**0.20**	**0.12**	**0.19**
Additional Components			
Type 1 non-uniqueness	0.1	0.1	0.1
Type 3 non-uniqueness	0.1	0.1	0.1
Repeatability	0.08	0.1	0.11
Overall standard combined uncertainty (mK)	0.26	0.21	0.26
Expanded combined uncertainty (*k*=2) (mK)	**0.52**	**0.42**	**0.53**

Table 5: Uncertainty of the characteristic of a SPRT in the range from 14 K to 693 K after calibration at fixed points of the best category

Fixed-point	**e-H_2**	**Ne**	**O_2**	**Ar**	**Hg**	**H_20**	**Ga**	**In**	**Sn**	**Zn**
Highest purity	6N	5N	6N	6N	6N	0	7N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0
Type B uncertainty components (mK)										
1. Chemical impurities, isotopes	0.17	0.16	0.19	0.14	0.06	0.031	0.06	0.25	0.31	0.54
2. Hydrostatic head correction	0.005	0.02	0.02	0.04	0.03	0.004	0.01	0.02	0.02	0.02
3. Error in gas pressure					0.01	0.005	0.01	0.10	0.08	0.12
4. Standard resistor	0.001	0.001	0.002	0.003	0.01	0.05	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.015	0.02	0.11	0.12	0.16
6. Uncertainty propagation from TPW	< 0.001	0.001	0.01	0.02	0.05		0.08	0.09	0.11	0.15
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	0.01	0.03	0.06	0.06	0.06
Type B combined (mK)	**0.18**	**0.17**	**0.20**	**0.16**	**0.12**	**0.074**	**0.12**	**0.40**	**0.43**	**0.64**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.027**	**0.05**	**0.20**	**0.15**	**0.15**
Standard combined uncertainty (mK)	**0.19**	**0.18**	**0.21**	**0.17**	**0.13**	**0.08**	**0.13**	**0.45**	**0.45**	**0.66**
Uncertainty increased by 50% (mK)	**0.29**	**0.27**	**0.31**	**0.25**	**0.20**	**0.12**	**0.19**	**0.67**	**0.68**	**0.98**
Additional Components										
Type 1 non-uniqueness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Type 3 non-uniqueness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Repeatability	0.1	0.1	0.1	0.1	0.13	0.15	0.17	0.24	0.28	0.39
Oxidation / Reduction						0.15	0.17	0.24	0.28	0.39
Overall standard combined uncertainty (mK)	0.74	0.73	0.75	0.72	0.71	0.71	0.74	1.01	1.04	1.31
Expanded combined uncertainty (*k*=2) (mK)	**1.47**	**1.46**	**1.49**	**1.44**	**1.42**	**1.43**	**1.47**	**2.01**	**2.07**	**2.62**

Table 6: Uncertainty of the characteristic of a SPRT in the range from 14 K to 1235 K after calibration at fixed points of the best category

Fixed-point	**e-H$_2$**	**Ne**	**O$_2$**	**Ar**	**Hg**	**H$_2$0**	**Ga**	**In**	**Sn**	**Zn**	**Al**	**Ag**
Highest purity	6N	5N	6N	6N	6N	0	7N	6N	6N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0	16.8	18.5
Type B uncertainty components (mK)												
1. Chemical impurities, isotopes	0.17	0.16	0.19	0.14	0.06	0.031	0.06	0.25	0.31	0.54	0.40	0.65
2. Hydrostatic head correction	0.005	0.02	0.02	0.04	0.03	0.004	0.01	0.02	0.02	0.02	0.02	0.08
3. Error in gas pressure					0.01	0.005	0.01	0.10	0.08	0.12	0.30	0.30
4. Standard resistor	0.001	0.001	0.002	0.003	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.015	0.02	0.11	0.12	0.16	0.20	0.25
6. Uncertainty propagation from TPW	<0.001	0.001	0.01	0.02	0.05		0.08	0.09	0.11	0.15	0.20	0.28
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	0.01	0.03	0.06	0.06	0.06	0.20	0.20
Type B combined (mK)	**0.18**	**0.17**	**0.20**	**0.16**	**0.12**	**0.074**	**0.12**	**0.40**	**0.43**	**0.64**	**0.65**	**0.87**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.05**	**0.20**	**0.15**	**0.15**	**0.30**	**0.30**
Standard combined uncertainty (mK)	**0.19**	**0.18**	**0.21**	**0.17**	**0.13**	**0.08**	**0.13**	**0.45**	**0.45**	**0.66**	**0.71**	**0.92**
Uncertainty increased by 50% (mK)	**0.29**	**0.27**	**0.31**	**0.25**	**0.20**	**0.12**	**0.19**	**0.67**	**0.68**	**0.98**	**1.07**	**1.37**
Additional Components												
Type 1 non-uniqueness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Type 3 non-uniqueness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Repeatability	0.1	0.1	0.1	0.1	0.13	0.15	0.17	0.24	0.28	0.39	0.51	0.64
Oxidation / Reduction						0.15	0.17	0.24	0.28	0.39	0.51	
Drift during use at high T (100 h)						0.35	0.39	0.56	0.66	0.90	1.18	1.50
Overall standard combined uncertainty (mK)	0.74	0.73	0.75	0.72	0.71	0.79	0.83	1.15	1.23	1.59	1.87	2.24
Expanded combined uncertainty (*k*=2) (mK)	**1.47**	**1.46**	**1.49**	**1.44**	**1.42**	**1.59**	**1.67**	**2.31**	**2.46**	**3.18**	**3.75**	**4.47**

Table 7: Uncertainty of the characteristic of a SPRT in the range from 234 K to 303 K after calibration at fixed points of the normal category

Fixed-point	**Hg**	**$H_2$0**	**Ga**
Highest purity	6N		7N
Immersion depth / cm	2.5	19.0	26.0
Type B uncertainty components (mK)			
1. Chemical impurities, isotopes	0.25	0.10	0.20
2. Hydrostatic head correction	0.03	0.00	0.01
3. Error in gas pressure	0.01	0.15	0.01
4. Standard resistor	0.01	0.05	0.01
5. Bridge measurement	0.05	0.02	0.02
6. Uncertainty propagation from TPW	0.17		0.22
7. Self-heating error	0.05	0.04	0.05
8. Heat-flux immersion error	0.02	0.01	0.01
9. Choice of fixed-point value	0.05	0.05	0.03
Type B combined (mK)	**0.32**	**0.20**	**0.30**
Type A uncertainty component (mK)	**0.05**	**0.03**	**0.05**
Standard combined uncertainty (mK)	**0.32**	**0.20**	**0.31**
Uncertainty increased by 50% (mK)	**0.48**	**0.30**	**0.46**
Additional Components			
Type 1 non-uniqueness	0.1	0.1	0.1
Type 3 non-uniqueness	0.1	0.1	0.1
Repeatability	0.08	0.1	0.11
Overall standard combined uncertainty (mK)	0.51	0.35	0.50
Expanded combined uncertainty (*k*=2) (mK)	**1.02**	**0.69**	**0.99**

Table 8: Uncertainty of the characteristic of a SPRT in the range from 14 K to 693 K after calibration at fixed points of the normal category

Fixed-point	**e-H_2**	**Ne**	**O_2**	**Ar**	**Hg**	**H_20**	**Ga**	**In**	**Sn**	**Zn**
Highest purity	6N	5N	6N	6N	6N	0	7N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0
Type B uncertainty components (mK)										
1. Chemical impurities, isotopes	0.42	0.20	0.20	0.29	0.25	0.10	0.20	0.78	0.52	0.71
2. Hydrostatic head correction	0.01	0.02	0.02	0.04	0.03	0.00	0.01	0.02	0.02	0.02
3. Error in gas pressure					0.01	0.15	0.01	0.63	0.70	1.70
4. Standard resistor	0.00	0.00	0.00	0.00	0.01	0.05	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.02	0.02	0.11	0.12	0.16
6. Uncertainty propagation from TPW	< 0.001	0.00	0.02	0.04	0.17		0.22	0.32	0.38	0.51
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.06	0.06	0.06
Type B combined (mK)	**0.43**	**0.20**	**0.21**	**0.30**	**0.32**	**0.20**	**0.30**	**1.09**	**0.99**	**1.93**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.05**	**0.20**	**0.15**	**0.15**
Standard combined uncertainty (mK)	**0.43**	**0.21**	**0.21**	**0.30**	**0.32**	**0.20**	**0.31**	**1.11**	**1.00**	**1.94**
Uncertainty increased by 50% (mK)	**0.64**	**0.32**	**0.32**	**0.45**	**0.48**	**0.30**	**0.46**	**1.66**	**1.50**	**2.91**
Additional Components										
Type 1 non-uniqueness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Type 3 non-uniqueness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Repeatability	0.1	0.1	0.1	0.1	0.13	0.15	0.17	0.24	0.28	0.39
Oxidation / Reduction						0.15	0.17	0.24	0.28	0.39
Overall standard combined uncertainty (mK)	0.93	0.75	0.75	0.81	0.84	0.77	0.85	1.82	1.69	3.03
Expanded combined uncertainty (*k*=2) (mK)	**1.87**	**1.50**	**1.50**	**1.63**	**1.67**	**1.53**	**1.70**	**3.65**	**3.38**	**6.07**

Table 9: Uncertainty of the characteristic of a SPRT in the range from 14 K to 1235 K after calibration at fixed points of the normal category

Fixed-point	**e-H_2**	**Ne**	**O_2**	**Ar**	**Hg**	**H_20**	**Ga**	**In**	**Sn**	**Zn**	**Al**	**Ag**
Highest purity	6N	5N	6N	6N	6N	0	7N	6N	6N	6N	6N	6N
Immersion depth / cm	2.5	2.5	2.5	2.5	2.5	19.0	26.0	16.0	15.0	16.0	16.8	18.5
Type B uncertainty components (mK)												
1. Chemical impurities, isotopes	0.42	0.20	0.20	0.29	0.25	0.10	0.20	0.78	0.52	0.71	1.50	3.60
2. Hydrostatic head correction	0.01	0.02	0.02	0.04	0.03	0.00	0.01	0.02	0.02	0.02	0.02	0.08
3. Error in gas pressure					0.01	0.15	0.01	0.63	0.70	1.70	4.30	5.70
4. Standard resistor	0.00	0.00	0.00	0.00	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01
5. Bridge measurement	0.04	0.01	0.01	0.01	0.05	0.02	0.02	0.11	0.12	0.16	0.20	0.25
6. Uncertainty propagation from TPW	< 0.001	0.00	0.02	0.04	0.17		0.22	0.32	0.38	0.51	0.67	0.86
7. Self-heating error	0.02	0.02	0.02	0.02	0.05	0.04	0.05	0.15	0.20	0.20	0.20	0.20
8. Heat-flux immersion error	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.20	0.10	0.10	0.10	0.10
9. Choice of fixed-point value	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.06	0.06	0.06	0.20	0.20
Type B combined (mK)	**0.43**	**0.20**	**0.21**	**0.30**	**0.32**	**0.20**	**0.30**	**1.09**	**0.99**	**1.93**	**4.62**	**6.81**
Type A uncertainty component (mK)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.05**	**0.20**	**0.15**	**0.15**	**0.30**	**0.30**
Standard combined uncertainty (mK)	**0.43**	**0.21**	**0.21**	**0.30**	**0.32**	**0.20**	**0.31**	**1.11**	**1.00**	**1.94**	**4.63**	**6.81**
Uncertainty increased by 50% (mK)	**0.64**	**0.32**	**0.32**	**0.45**	**0.48**	**0.30**	**0.46**	**1.66**	**1.50**	**2.91**	**6.94**	**10.22**
Additional Components												
Type 1 non-uniqueness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Type 3 non-uniqueness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Repeatability	0.1	0.1	0.1	0.1	0.13	0.15	0.17	0.24	0.28	0.39	0.51	0.64
Oxidation / Reduction						0.15	0.17	0.24	0.28	0.39	0.51	
Drift during use at high *T* (100 h)						0.35	0.39	0.56	0.66	0.90	1.18	1.50
Overall standard combined uncertainty (mK)	0.93	0.75	0.75	0.81	0.84	0.84	0.93	1.91	1.81	3.16	7.11	10.37
Expanded combined uncertainty (*k*=2) (mK)	**1.87**	**1.50**	**1.50**	**1.63**	**1.67**	**1.68**	**1.87**	**3.82**	**3.63**	**6.33**	**14.22**	**20.75**

Figure 1: Expanded Uncertainty (k = 2) of the Characteristic of an SPRT calibrated on the ITS-90 at Fixed Points of "Best Category"

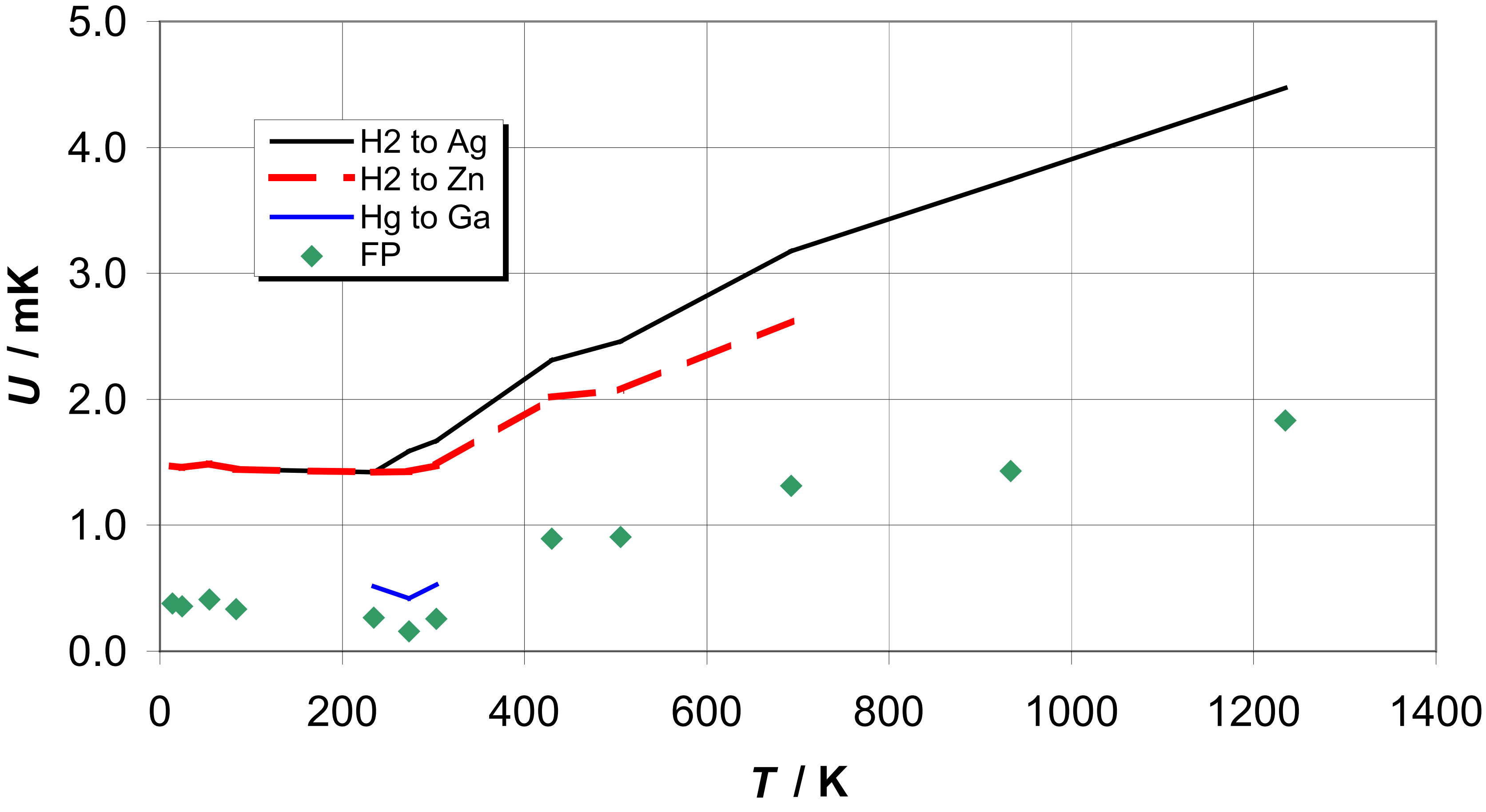

Figure 2: Expanded Uncertainty ($k = 2$) of the Characteristic of an SPRT calibrated on the ITS-90 at Fixed Points of "Normal Category"