Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

International Journal of Thermophysics _####################_
https://doi.org/10.1007/s10765-019-2511-7

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Procedure for an Investigation of Drift Behavior of Noble Metal Thermocouples at High Temperature

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Received: 19 December 2014 / Accepted: 22 March 2019
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Abstract

This paper presents the effects of short-term and long-term temperature exposure on noble metal thermocouples in the range from 1000 °C to 1720 °C in oxidizing atmosphere (air). As thermocouples voltage output depends on the wire material of which the sensors are constructed, high-temperature and long continuous exposure to limit temperatures can introduce changes to the materials composition and structure. This can result in drift of generated voltage independent of the thermal environment and into reduced lifetime of the sensors. The intensions of conducted measurements were to determine the drift and lifetime of commonly available alumina-sheathed noble metal thermocouples and furthermore to establish traceable techniques to enable lifetime testing and thermoelectric stability evaluation of noble metal thermocouples at high temperatures. Result presented within this paper is not intended to test the capabilities of thermocouple Types B, R and S in general, but to show a possible behavior in the above-specified temperature conditions. This work puts more emphasis on the procedures that can be used for regular checks of intensely used thermocouple. Results obtained by this study show that the long-term temperature drift of Type B thermocouples at 1600 °C, and R-, S-type thermocouples at 1000 °C are much smaller than thermoelectric stability declared by IEC 60584-1:2013 standard (International standard IEC 60584-1:2013, Thermocouples—Part 1: EMF specifications and tolerances, 2013) tolerance classes after exposure to thermal stress up to 4 months. More specifically tolerance for class 1 thermocouple Types R, S from 0 °C up to 1100 °C is ± 1 °C and for class 2 tolerance for Type B at 1600 °C is ± 1.5 °C. The short-term thermoelectric stability of R- and S-type thermocouples exposed to 1600 °C for repeated 8 h periods has been within 2 °C when measured by comparison with a reference Pt–Pd thermocouple at 960 °C. The short-term thermoelectric stability of B-type thermocouple when exposed to 1720 °C for repetition of 8 h has been within 1 °C.

Keywords Drift testing · High temperatures · Long-term stability · Noble metal · Thermoelectric stability · Thermocouple

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1 Introduction

Noble metal thermocouples were designed to perform precise measurement in laboratory and industrial applications with high precision, long lifetime and minimum drift. These thermocouples are superior in many ways to base metal thermocouples, but they are still affected by various influences. The most significant changes in the thermocouple-generated voltage (emf) are caused by altering the composition of the lead material. For example, the 0.1 % addition of Fe, Cr, Si, Ni, Rh or Cu to the pure Pt wire that is used in many noble metal thermocouples creates a change of Seebeck coefficient for the temperature range from 400 °C to 1100 °C by 1.7, 0.75, 0.64, 0.33, 0.21 or 0.15 μVK^{-1}, respectively [1]. As can be seen, the effect of contamination on the Seebeck coefficient is considerable and therefore these thermocouples should not be used in reducing oxidizing atmosphere or in the presence of metallic vapors. Low oxygen partial pressure and various refractory oxides like Al_2O_2 have an effect on the noble metal thermocouples as well [2]. Noble metal thermocouples are used in industrial conditions for long-term temperature monitoring and regulation. By this long time exposure to temperature and contaminated environment, a continuous change of the thermocouple output independent of the thermal environment may occur. This divergence due to changes within the thermocouple lead material is referred to as drift. In a majority of measurement applications, the thermoelelments are well protected from outside contamination and therefore the effects that were mentioned earlier are minimized. Beside the above-mentioned mechanisms, further effects that cause the change within the Seebeck coefficient and subsequently in generated electromotive force (emf) are mainly caused in Type R and S thermocouples by grain growth and embrittlement in the pure platinum thermoelement after a long exposure to temperatures above 1100 °C [3, 4, 13]. Furthermore, the high mobility of possible contaminants at temperatures above 1500 °C together with long exposure times affects the Seebeck coefficient of Type B thermocouples [4]. AQ1

Due to the nature of their use and high demand for more reliable and more precise measurements of temperature, it is necessary to examine the performance of these sensors in long-term application. Although the drift and thermoelectric stability measurements were performed in the past for noble metal [1, 2, 11] and base metal thermocouples [6], the used techniques vary and the results are rarely published. Furthermore, the available results are not up-to-date, and the previously stated performances may have changed due to the developments and innovation in thermocouple manufacturing. This study which is linked to the EMRP Joint Research Project "HiTeMS" (high-temperature metrology for industrial applications (> 1000 °C)) was undertaken by two national metrological institutes (NMI) CMI (CZ) and TUBITAK UME (TR). It deals with drift problematic in noble metal thermocouples. The goal of this paper is to present the drift and thermoelectric stability results obtained by the different NMI for Type S, Type B and Type R thermocouples. The study was performed on a total of ten noble metal thermocouples (3× Type S, 4× Type B and 3× Type R) which were distributed to the partners for performing short- and long-term drift testing the temperature

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Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

range from 1000 °C to 1720 °C. Thermoelectric stability measurements using fixed-point cells after the aging period were applied to all thermocouples with the exception of two R type and two S type due to occurrence of bending. This process is described in the following sections together with the results of thermoelectric stability of the tested thermocouples.

Tested thermocouples were 700 mm to 800 mm long and were housed in an alumina sheath with an outer diameter of 6 mm with a wall thickens of 1 mm. During the CMI measurements, a 10-year-old thermocouple Type B was also used for long-term drift test from local Czech manufacturer.

2 Experimental Facilities

2.1 CMI Facilities

CMI has tested four Type B, one Type R and one Type S thermocouples. These thermocouples were commercially made with an outer and inner insulation made of high-purity alumina (99.7 %), and the total length of the tested thermocouples outer insulation was 600 mm for Type R and Type S and 700 mm for Type B thermocouples. The outer diameters of the sensors were 6 mm for the Type B and 7 mm for Types R and S with a wall thickens of 1 mm. The reference junction was housed in a metal-sheathed capsule.

A three-zone horizontal furnace with sufficient homogeneity and thermal stability was used to perform the short- and long-term measurements. The furnace heating elements were constructed for continuous usage at 1800 °C. The thermal stability of the CLASIC5018T3Z furnace at 1720 °C and 1600 °C was better than 2 °C over a time span of 100 min, which was sufficient for the heat treatment of the tested thermocouples. Due to the high temperatures and the purpose of the heat treatment (the generation of drift within the thermocouples), high levels of thermal stability are not necessary. The same furnaces' thermal stability measured at 960 °C over 100 min was better than 0.1 °C. The temperature profile at 960 °C was measured, and the maximum temperature difference over 15 cm (measured from the middle of furnace) was better than 3 °C (0.5 °C over a distance of 10 cm). For the temperature of 1600 °C, the difference measured was better than 6.5 °C, and for 1720 °C, the difference did not exceed 8 °C. This has proven to be sufficient for our measurements as the tested thermocouples were placed in a static position, and the significant factor affecting the measurements was the temperature stability of the furnace. A separate furnace for the measurements at fixed point of Ag was used. This furnaces thermal characteristic (thermal stability and uniformity) was optimized for the realization of fixed point of Ag accordingly with respect to the ITS-90 [7] and its relevant supplements.

For the purpose of the initial thermocouple homogeneity measurements, a stirred vertical oil bath was used. The temperature to which the tested thermocouples were introduced to was 120 °C. The baths temperature stability at this temperature was better than 0.01 °C with a vertical overall temperature uniformity better than 0.02 °C.

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Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

To determine the long- and short-term drift, two separate measurements were done. These measurements lasted from 8 h (for the short-time exposure to higher temperature of 1720 °C) to 4 months (for the long-time exposure to lower temperature of 1600 °C), and the uncertainty of this difference is very close to the uncertainty of one measurement. The whole experiment setup for the long-term and short-term testing is represented by a three-zone horizontal furnace, tested thermocouples, Ag fixed-point cell, calibrated reference Pt/Pd thermocouple and a data recording system.

2.2 UME Facilities

UME has tested two Type R and two Type S thermocouples. These thermocouples were commercially made with an outer and inner insulation made of high-purity alumina (99.7 %), and the total length of the tested thermocouples outer insulation was 700 mm for Type R and 800 mm for Type S thermocouples. The outer diameters of sensors were 6 mm for the Type R and 7 mm for Types S with a wall thickens of 1 mm. The reference junction was housed in a metal-sheathed capsule.

Tests were performed in a commercial horizontal furnace with sufficient homogeneity and thermal stability. The horizontal profile of this furnace has been measured over a length of 5 cm; the temperature homogeneity was better than 2.5 °C. To further improve the temperature uniformity of the furnace, a cylindrical block made of isolation brick was inserted into the furnace and the thermocouples were placed inside the wells of this block. This has improved the temperature homogeneity over the same length to 1.9 °C. Silver fixed point was used to check the thermoelectric stability of the tested thermocouples after each test period. The usage of a fixed point instead of a reference thermocouple will enable us to see even the smallest differences in the emf (electro motive force) with benefit of avoiding the aging influence on the reference. The emf of the thermocouples was measured by a calibrated multimeter device. The whole experiment setup for the long-term and short-term testing is represented by a three-zone horizontal furnace, tested thermocouples, Ag fixed-point cell, calibrated reference Pt/Pd thermocouple and a data recording system.

For the purpose of the initial thermocouple homogeneity measurements, a dedicated stirred vertical oil bath was used. The temperature to which the tested thermocouples were introduced to was 100 °C. The baths temperature stability at this temperature was better than 0.01 °C with vertical overall temperature uniformity better than 0.015 °C.

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2.3 Experimental Procedures

The presented study is intended to see the short- and long-time effects of temperature exposure on new noble metal thermocouple of Types B, R and S. The thermocouples Type R and Type S were annealed for use above the temperature of 800 °C by a 2-h exposure to an isothermal temperature of 1100 °C.

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

The bases for protocol testing are described in [9]. Two different tests were considered:

- Procedure for testing short-term drift
- Procedure for testing long-term drift

It is expected that these tests will be performed at different temperatures.

Drift: short-term

This test should be applied to a calibrated and properly annealed thermocouple. For the Types R and S, thermocouples are intended to be used above 800 °C, and these should be exposed to a stable and homogenous temperature field for at least 2 h and passively cooled at room temperature [10–12]. This is also the case for Type B thermocouples although currently there is no representative information regarding the effectiveness of this procedure. Recommended procedure for determining thermocouple short-term drift/thermoelectric stability is as follows:

1. Calibration of the tested thermocouple at the maximum temperature of intended use and a homogeneity check. (The homogeneity check should be performed by introducing a steep moving temperature gradient along the measuring junction of the thermocouple. This can be realized by emerging the thermocouple from an isothermal environment with a temperature and homogeneity that will not introduce any alternations to the thermoelements.)
2. Testing the thermocouples at the desired temperature.
3. The duration of the test is 8 h maximum
4. Calibration of the thermocouple at the maximum temperature of intended use.
5. Repeat steps 3–4 three times.

The calibration drift is determined as the voltage change (or its temperature equivalent) between the first calibration and the final calibration.

Drift: long-term

This test should be applied to a calibrated and properly annealed thermocouple. Recommended procedure for determining thermocouple long-term drift/thermoelectric stability is as follows:

1. Calibration of the tested thermocouple at the maximum temperature of intended use and a homogeneity check.
2. Testing of the thermocouples at the desired temperature.
3. The duration of the test is 4 months at minimum.
4. Calibration of the tested thermocouple at the maximum temperature of intended use every week during the first month and every 2 weeks for the following months.
5. The test(s) are finished if

   (a) The agreed final time is reached, or
   (b) There is no output from the thermocouple, or

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Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

(c) The deviation of the tested thermocouple from standard ENIEC 60584-1 exceeds 3 times the desired tolerance.

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The calibration drift is determined as the voltage change (or its temperature equivalent) from the first measurement to the termination.

2.3.1 Drift Measurements CMI

The drift measurements were performed with four Type B thermocouples. The tested thermocouples homogeneity was initially measured in an oil bath with a set temperature of 120 °C from which it was slowly withdrawn from the maximum emersion. The length of the thermocouple that was measured in this manner was 300 mm from the tip of the thermocouple (excluding the first 70-mm segment from the tip due to large heat dissipation with low emersion). The purpose of these homogeneity measurements was to detect possible severe defects without the risk of altering the thermocouple homogeneity by high-temperature exposure before the testing cycles. The measured values were only indicative in nature and were not used to form the final uncertainty budget. After these initial measurements, the thermocouples were calibrated in a silver fixed-point cell. After this step, one thermocouple was selected for a short-term drift test. The initially calibrated thermocouple was exposed to a temperature of 1720 °C for a time period of 8 h. After this temperature exposure, a repeated calibration was performed to see the influence of the high-temperature exposure and the possible level of EMF (electromotive force) drift. The calibration was done in the same furnace by comparison with a Pt–Pd reference thermocouple in a furnace set to 960 °C. The calibration temperature was set to minimize the introduction of an additional drift to the tested and reference thermocouple. This procedure was repeated three times. The other three thermocouples were investigated for long-term drift at 1600 °C for 4 months. The calibrations at fixed point of silver were performed as well. Second run of measurements was performed with one piece of Type R and one piece of Type S thermocouples. The same procedure for short-term drift testing was applied. The temperature used for these tests was set for 1600 °C.

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2.3.2 Drift Measurements UME

A number of four noble metal thermocouples (2× R-type and 2× S-type) have been measured for long-term drift (at 1000 °C) and short-term drift (at 1600 °C) tests. The thermocouples dimensions were 880 mm in length with an outer diameter of 7 mm with a wall thickens of 1 mm. The thermocouple protective sheath was made out of alumina material.

The tested thermocouple homogeneity was initially measured in an oil bath with a set temperature of 100 °C from which it was slowly withdrawn from the maximum emersion. The length of the thermocouple that was measured in this way was 320 mm from the tip of the thermocouple (excluding the first 80-mm segment from the tip due to large heat dissipation with low emersion).

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

For long-term drift testing, these thermocouples were first checked at Ag fixed point and then exposed to a temperature of 1000 °C in a commercial 3-zone Carbolite furnace. During this temperature exposure, the thermocouple voltage was not measured. The thermocouples were kept at 1000 °C for 1 week and then removed and checked at Ag fixed point. This process was repeated eleven times. For short-term drift testing, the thermocouples were kept at 1600 °C for 8 h. Since there was significant bending in the 30-cm front region of the thermocouples after exposing to 1600 °C, testing at Ag fixed-point was not possible after they were removed. So a comparison with a Pt–Pd reference thermocouples in a furnace set to 960 °C was performed to keep track of any drift. This procedure was repeated three times. The voltage output from the tested thermocouples was measured by a calibrated multimeter.

3 Results

3.1 Drift Testing CMI

The calibration results of Type B thermocouples at fixed point of silver were the fallowing: TC-B I (4497.8 μV), TC-B II (4494.1 μV), TC-B III (4498.0 μV) and TC-B07/II (4494.0 μV). The first set of short-term test measurements performed on B I thermocouple is shown in Fig. 1. The two black lines in the figure indicate the class 2 tolerance limits according to the European standard for thermocouples [8]. The dotted line indicates linear approximation of the drift. The drift rate observed in our measurements was of − 0.27 °C per day at 1720 °C. The several-day exposure to temperature around 1720 °C has caused a deformation of the ceramic sheath of the tested thermocouple. This mechanical issue did not influence the behavior of

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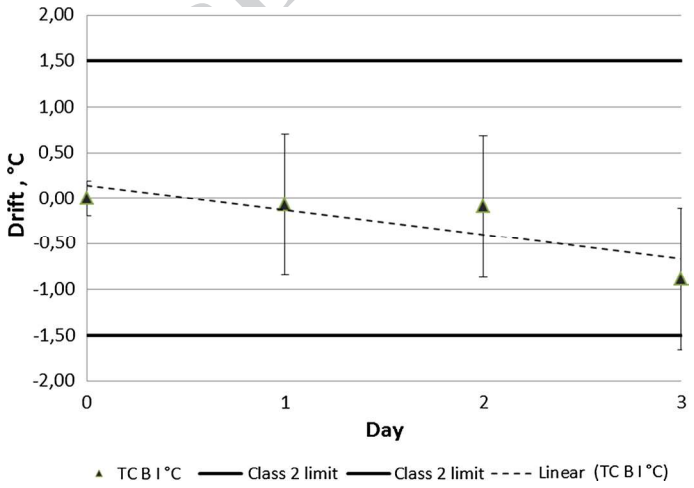


Fig. 1 Short-term drift of Type B thermocouple (exposed to 1720 °C). Drift data obtained by repeated comparison calibration against a Pt/Pd thermocouple at 960 °C

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

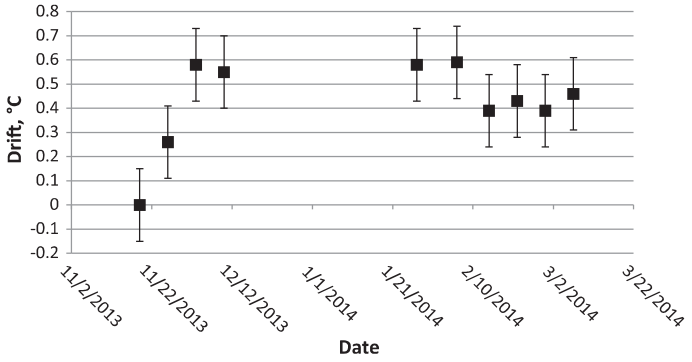


Fig. 2 Long-term drift of Type B II thermocouple (exposed to 1600 °C). Drift data obtained by repeated calibration at fixed point of silver

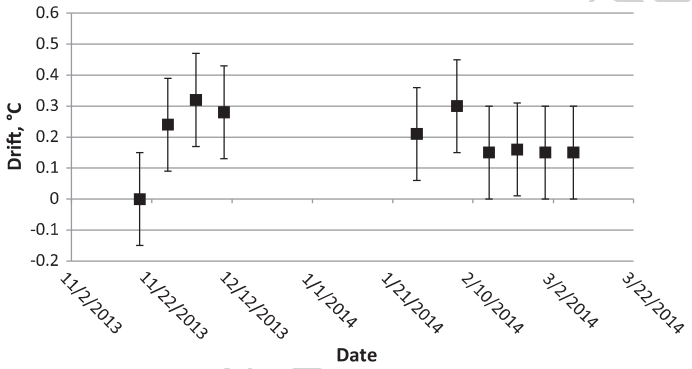


Fig. 3 Long-term drift of Type B III thermocouple (exposed to 1600 °C). Drift data obtained by repeated calibration at fixed point of silver

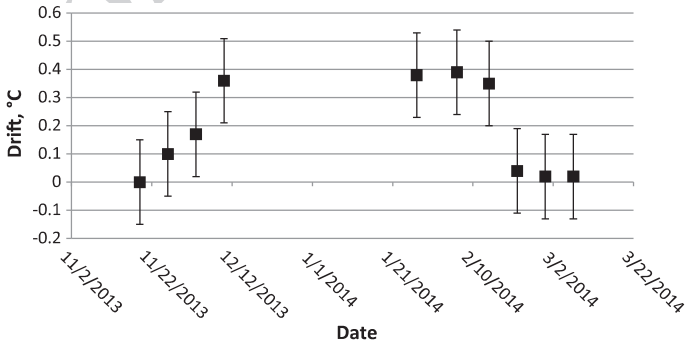


Fig. 4 Long-term drift of Type B 07/II thermocouple (exposed to 1600 °C). Drift data obtained by repeated calibration at fixed point of silver

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

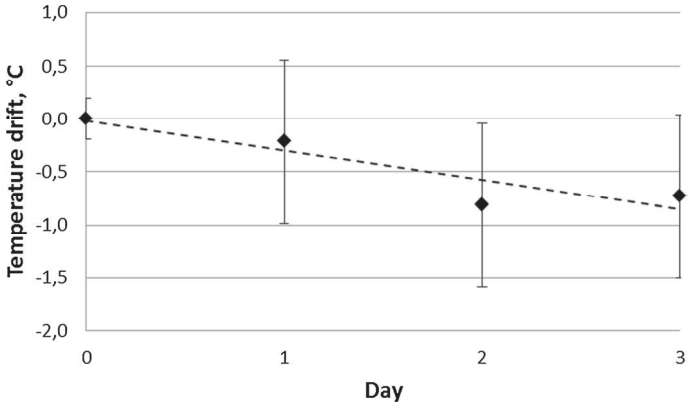


Fig. 5 Short-term drift of Type R thermocouple (exposed to 1600 °C). Drift data obtained by repeated comparison calibration against a Pt/Pd thermocouple at 960 °C

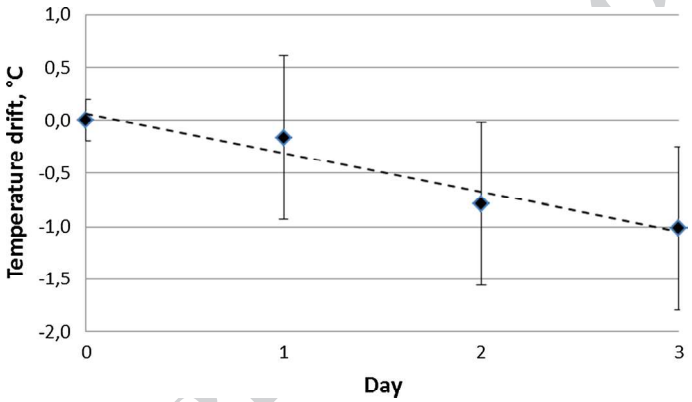


Fig. 6 Short-term drift of Type S thermocouple (exposed to 1600 °C). Drift data obtained by repeated comparison calibration against a Pt/Pd thermocouple at 960 °C

the sensor. After these measurements, the long-term investigation was performed on three Type B thermocouples. The results are shown in Figs. 2, 3, 4. It is necessary to mention that the class 2 tolerance limit of ± 1.5 °C was not reached after this test.

The first calibration of Type R and S thermocouples at fixed point of silver has given the following results: TC R (9985.3 μV) and TC S (9143.3 μV). The short-term drift test procedure was applied on these Type R and S thermocouples at 1600 °C. At every 8 h, a calibration by comparison at 960 °C was performed with a calibrated Pt–Pd thermocouple as a standard. The results of these short-term drift investigation measurements for Type R and S thermocouples are presented in Figs. 5 and 6.

The dotted lines indicate linear approximation of the drift at the value of − 0.28 °C (Type R thermocouple) and − 0.37 °C (Type S thermocouple) per day at

Journal : SmallExtended 10765 | Article No : 2511 | Pages : 18 | MS Code : IJOT-D-14-00319 | Dispatch : 26-3-2019

Author Proof

Table 1 Type R thermocouple (1) thermoelectric stability at Ag fixed point after testing

Weeks	Average emf (mV)	Average t (°C)
0[a]	9.9730	959.440
1[a]	9.9897	960.719
2[a]	9.9814	960.084
3	10.0037	961.801
4	10.0032	961.760
5	10.0025	961.711
6	10.0040	961.822
8	10.0037	961.798
10	10.0019	961.666

[a]Measurement influenced by the nanovoltmeter thermoelectric stability

Table 2 Type R thermocouple (2) thermoelectric stability at Ag fixed point after testing

Weeks	Average emf (mV)	Average t (°C)
0[a]	10.0046	961.861
1[a]	10.0039	961.814
2[a]	10.0137	962.565
3	10.0025	961.711
4	10.0031	961.756
5	10.0032	961.763
6	10.0055	961.935
8	10.0044	961.851
10	10.0033	961.771

[a]Measurement influenced by the nanovoltmeter thermoelectric stability

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1600 °C, respectively. During these short-term drift measurements, a deformation of the ceramic sheath of the thermocouples occurred due to temperature exposure. This mechanical issue did not influence the behavior of the sensors.

3.2 Drift Testing UME

The data presented in this section were obtained by using the procedures described in Sect. 2.3. The total length of the long-term testing was reduced to 10 week. For long-term drift test, the thermoelectric stability of Type S and R thermocouples before and after the temperature exposure is presented in Tables 1 and 2. The first three measurements at Ag cell presented in these tables were not considered due to a thermoelectric stability problem of the measurement instrument which can also be seen from the provided data. This faulty nanovoltmeter was replaced with another calibrated multimeter, and much stable results were obtained. The first three measurements are marked and not included in Figs. 7, 8, 9, 10. Each measurement

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

presented within the previously mentioned figures represents the measured value at the solidification temperatures of Ag fixed point. In order to calculate uncertainty of measurement, typical standard deviation of the plateau readings (during 20 min or more) and the standard deviation of melt and freeze average values were quadratically summed and expanded by a factor of 2 ($k = 2$). Uncertainty values are given as y-axis error bars. The graphical interpretation of these results can be found in Figs. 7, 8, 9, 10.

For short-term drift test, the thermoelectric stability of Type S and R thermocouples was measured as the difference between the tested thermocouples temperature indication and reference Pt–Pd thermocouple temperature indication at 960 °C before and after a testing process. The results of these measurements are shown

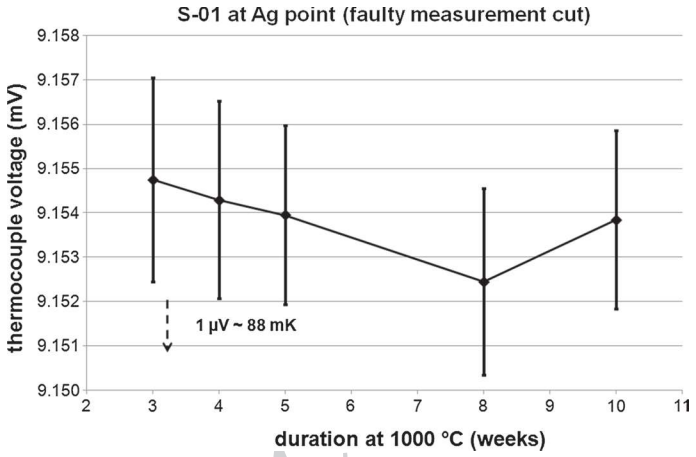


Fig. 7 Type S thermocouple thermoelectric stability (1) at Ag fixed point after testing process

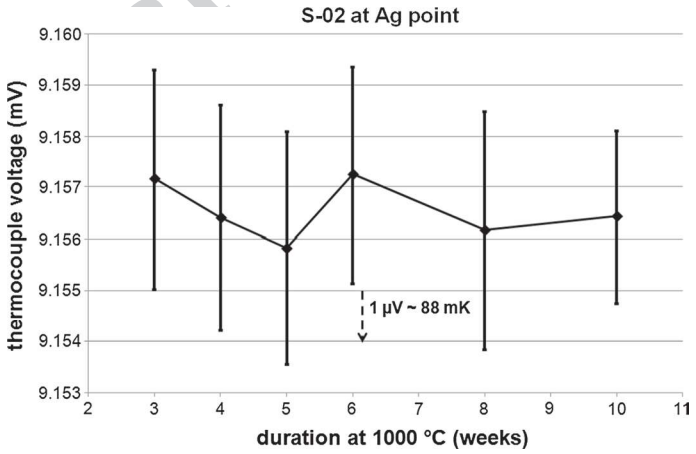


Fig. 8 Type S thermocouple thermoelectric stability (2) at Ag fixed point after testing process

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

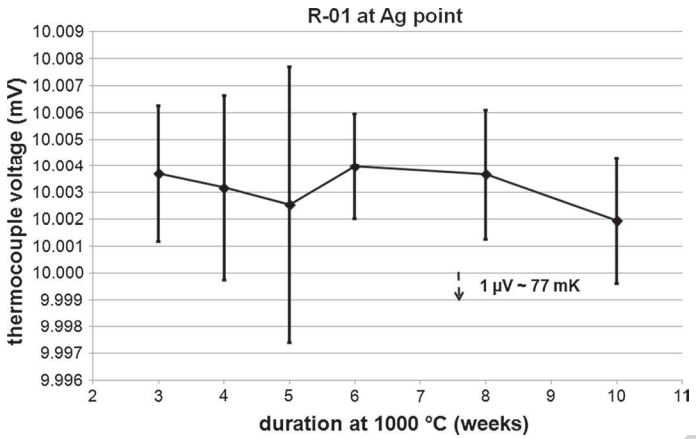


Fig. 9 Type R thermocouple thermoelectric stability (1) at Ag fixed point after testing process

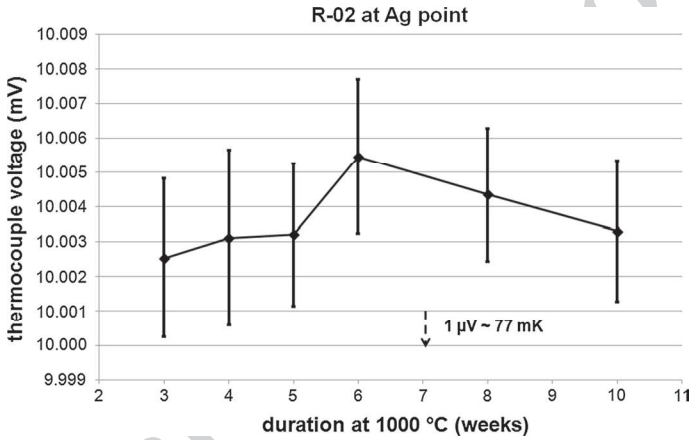


Fig. 10 Type R thermocouple thermoelectric stability (2) at Ag fixed point after testing process

in Fig. 11. Here, the zeroth measurement is the initial measurement performed at 960 °C (without any exposure to 1600 °C). The following three measurements were performed at 960 °C, after 8 h of exposures to 1600 °C.

During the testing of the thermocouples at 1600 °C, it was observed that the test thermocouples were bent at 30-cm front region. This corresponds with the length of ceramic block which was used to establish better temperature uniformity in the furnace. If a larger block was utilized over a larger area, this bending would not

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

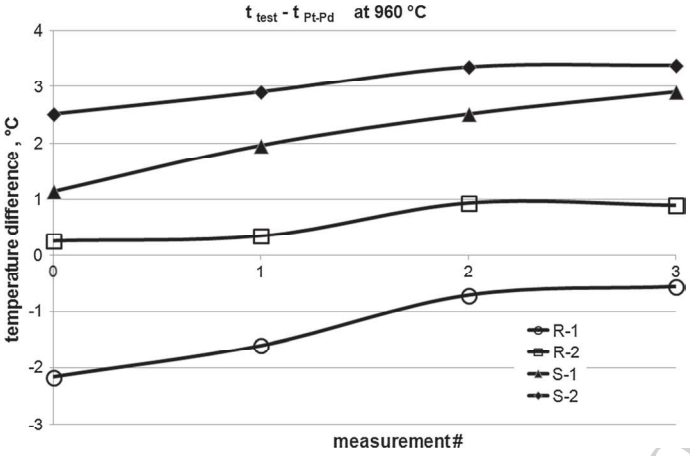


Fig. 11 Thermoelectric stability of R- and S-type thermocouples at 960 °C (as difference from the reference Pt–Pd thermocouple)

possibly occur or occur at a larger distance from the tip of thermocouple, and this would make it possible to have measurements at Ag fixed point. Despite the bending, the thermoelectric stability of R- and S-type thermocouples after exposing to 1600 °C is quite good (within 2 °C both at 960 °C and at 1600 °C).

4 Measurement Uncertainty

Within this section, a detailed uncertainty budget of each individual measuring techniques used for the determination of tested thermocouple emf drift by the national metrological institutes CMI and UME is presented. The uncertainty of the silver fixed-point measurement performed by CMI can be seen in Table 3, and the uncertainty budget for calibration by comparison at 960 °C is shown in Table 4. The two calibration methods were used for the long-term tests performed at 1720 °C and short-term tests performed at 1600 °C, respectively. The overall uncertainty of the measurement performed by UME, consisting of two different calibration methods for long- and short-term measurements, can be seen in Table 5. AQ2

5 Conclusion

This paper shows the results of drift and thermoelectric stability measurements obtained by the different NMI for Type S, B and R thermocouples. The study was performed on multiple thermocouples which were exposed to temperatures from 1000 °C to 1720 °C. Their thermoelectric stability was checked using fixed-point

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Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

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Table 3 Uncertainty budget of silver fixed-point measurements

Source	z_{max}	Distribution	κ	u_x	k	u_y	u_y
Realization of fixed point	1 µV	Normal	2.000	0.500 µV	1 µV·µV^{-1}	0.500 µV	0.044 °C
Temperature profile	0.05 °C	Rectangular	1.732	0.029 °C	11.4 µV·°C^{-1}	0.329 µV	0.029 °C
Heat conduction	0.05 °C	Rectangular	1.732	0.029 °C	11.4 µV·°C^{-1}	0.329 µV	0.029 °C
Multimeter measurement	0.3 µV	Rectangular	1.732	0.173 µV	1 µV·µV^{-1}	0.173 µV	0.015 °C
Parasitic thermovoltage. incl. switch	0.2 µV	Rectangular	1.732	0.115 µV	1 µV·µV^{-1}	0.115 µV	0.010 °C
Cold junction	0.05 °C	Rectangular	1.732	0.029 °C	5.4 µV·°C^{-1}	0.156 µV	0.029 °C
Thermocouple homogeneity	0.1 °C	Rectangular	1.732	0.058 °C	11.4 µV·°C^{-1}	0.658 µV	0.058 °C
Thermocouple hysteresis	0.1 °C	Rectangular	1.732	0.058 °C	11.4 µV·°C^{-1}	0.658 µV	0.058 °C
Type A	0.05 °C	Rectangular	1.732	0.029 °C	11.4 µV·°C^{-1}	0.329 µV	0.029 °C
Combined uncertainty						1.695 µV	0.152 °C
Coverage factor						2	2
Expanded uncertainty						3.40 µV	0.30 °CC

z_{max}—uncertainty component value, κ—value pertaining to a given probability distribution, u_x—standard uncertainty for respective distribution, k—sensitivity coefficient, u_y—respective standard uncertainty converted into µV and °C

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cells after a certain aging period was reached. It was clearly shows that the methodology used is suitable for this type of exploration and can be done not only at level of NMI. The results are not indication of any thermocouple capabilities of Types R, S and B, but can be used as one example of the thermocouple behavior. Long-term drift and short-term drift tests have been performed on R-, S- and B-type thermocouples by different metrology institutes. The main results are that the long-term drift of Type B thermocouples at 1600 °C and R-, S-type thermocouples at 1000 °C are much smaller than thermoelectric stability declared by EN 60584-1 standard tolerance classes after 10-week and 4-month exposure. The short-term thermoelectric stability of R- and S-type thermocouples when exposed to 1600 °C for a repetition of 8-h periods has been within 2 °C when measured by comparison with a reference Pt–Pd thermocouple at 960 °C. The short-term thermoelectric stability of R- and S-type thermocouples when exposed to 1600 °C for a repetition of 8-h periods has been within 1 °C when measured by comparison with a reference Pt–Pd thermocouple at 960 °C. The short-term thermoelectric stability of B-type thermocouple when exposed to 1720 °C for repetition of 8 h has been within 1 °C.

This works goal was to define a procedure for an investigation of drift behavior of noble metal thermocouples at high temperature.

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

Author Proof

Table 4 Uncertainty budget of a calibration by comparison at 960 °C

Source	z_{max}	Distribution	κ	u_x	k	u_y	u_y
Calibration temperature	0.3 °C	Normal	2.000	0.150 °C	11.4 μV·°C^{-1}	1.710 μV	0.150 °C
Temperature profile and thermal stability	0.6 °C	Rectangular	1.732	0.346 °C	11.4 μV·°C^{-1}	3.949 μV	0.346 °C
Heat conduction	0.05 °C	Rectangular	1.732	0.029 °C	11.4 μV·°C^{-1}	0.329 μV	0.029 °C
Multimeter measurement	0.3 μV	Rectangular	1.732	0.173 μV	1 μV·μV^{-1}	0.173 μV	0.015 °C
Parasitic thermovoltage, incl. switch	0.2 μV	Rectangular	1.732	0.115 μV	1 μV·μV^{-1}	0.115 μV	0.010 °C
Cold junction	0.05 °C	Rectangular	1.732	0.029 °C	5.4 μV·°C^{-1}	0.156 μV	0.029 °C
Thermocouple homogeneity	0.1 °C	Rectangular	1.732	0.058 °C	11.4 μV·°C^{-1}	0.658 μV	0.058
Thermocouple hysteresis	0.1 °C	Rectangular	1.732	0.058 °C	11.4 μV·°C^{-1}	0.658 μV	0.058 °C
Type A	0.05 °C	Rectangular	1.732	0.029 °C	11.4 μV·°C^{-1}	0.329 μV	0.029 °C
Combined uncertainty						5.044 μV	0.444 °C
Coverage factor						2	2
Expanded uncertainty						10.09 μV	0.88 °C

z_{max}—uncertainty component value, κ—value pertaining to a given probability distribution, u_x—standard uncertainty for respective distribution, k—sensitivity coefficient, u_y—respective standard uncertainty converted into μV and °C

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Journal : SmallExtended 10765 | Article No : 2511 | Pages : 18 | MS Code : IJOT-D-14-00319 | Dispatch : 26-3-2019

Author Proof

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Table 5 Overall uncertainty for long- and short-term measurements performed by UME

Measurement type	Uncertainty component	Value (μv)	Value (mK)
Typical uncertainty budget for long-term drift tests (measurements performed at Ag fixed point)	Typical thermoelectric stability of a single plateau (maximum of melt and drift)	2.08	160
	Typical repeatability of plateaus (standard deviation of melt and freeze)	2.27	175
	Cell uniformity	2.60	200
	Multimeter calibration	0.25	19
	Total uncertainty ($k = 1$)	4.04[a]	311[a]
	Expanded uncertainty ($k = 2$)	8.08[a]	622[a]
Uncertainty budget for short-term drift tests (measurements performed at furnace at 960 °C)	Typical thermoelectric stability during a single measurement	2.72	200
	Furnace uniformity	8.17	600
	Multimeter calibration	0.25	19
	Total uncertainty ($k = 1$)	8.62[a]	633[a]
	Expanded uncertainty ($k = 2$)	17.23[a]	1266[a]

[a]The presented uncertainty values represent a typical uncertainty for the performed measurements. For each individual measurement and sensor, this value may vary due to the changing budget components like thermoelectric stability which depend on individual sensors. The specific values of uncertainty are presented within Figs. 7, 8, 9, 10

Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

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Acknowledgments The work presented was made thanks to the joint research project IND01 High Temperature Metrology for Industrial Application (HiTeMS) funded by the European Metrology Research Program (EMRP) and the European NMIs. This work is part funded by the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. The authors would like to thank the Slovak University of Technology in Bratislava and the Slovak Institute of Metrology, the grant agency VEGA (Project Numbers VEGA 1/0748/15, VEGA 1/0164/15, VEGA 1-0610-17), the agency APVV (Project Number APVV-15-0164, APVV-15-0704, APVV 15-0295) and the agency KEGA (Project Numbers KEGA039STU-4/2017, KEGA014STU-4/2015) for their support.

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Journal : SmallExtended 10765	Article No : 2511	Pages : 18	MS Code : IJOT-D-14-00319	Dispatch : 26-3-2019

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