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NRIM-BIPM.EM-K13.a and b Key Comparisons of Electrical Resistance Standards using 1  $\Omega$  and 10 k $\Omega$  Resistors as Travelling Standards: INRIM results

*Original*

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**INRIM-BIPM.EM-K13.a and b Key Comparisons of Electrical Resistance  
Standards using 1  $\Omega$  and 10 k $\Omega$  Resistors as Travelling Standards:  
INRIM results**

T.R. 3/2023

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## Abstract

The technical report summarizes the results provided by the Resistance laboratory of the National Research Institute (INRIM) concerning the calibration of two 1  $\Omega$  and two 10 k $\Omega$  standard travelling resistors related to the comparison BIPM.EM-K13.a (1  $\Omega$  resistance standards) and BIPM.EM-K13.b (10000  $\Omega$  resistance standards) which constitute the BIPM programme of on-going bilateral comparisons of resistance standards. The chosen resistors normally assure a transfer uncertainty less than a few parts in  $10^8$ . The comparison was carried out following an initial/return measurement pattern: the BIPM travelling standards were first calibrated at the BIPM then they were sent to INRIM where they were calibrated, and finally re-calibrated after their return at the BIPM. All measurement results will be corrected to the reference temperature (23.000  $^{\circ}\text{C}$ ) and the reference pressure (1013.25 hPa). The result of the comparison will be expressed as the difference between the calibrations from the two laboratories, together with its associated uncertainty. The pilot laboratory was the BIPM.

# 1. Introduction

The National Institute of Metrological Research (INRIM), acting as National Measurement Institute (NMI, it is signatory of the CIPM Mutual Recognition Arrangement (CIPM MRA). The CIPM Mutual Recognition Arrangement is the framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available from the CIPM MRA database (the KCDB) and the results of scientific comparisons underpinning these CMCs. In this last framework, INRIM participated to the bilateral comparison BIPM.EM-K13a&b comparison with the Bureau international des poids et mesures, BIPM), acting as pilot laboratory. The INRIM measurements on the four travelling standards (two 1  $\Omega$  and two 10 k $\Omega$  took part between November and December 2022. The present document reports the details on:

- The travelling resistors to be calibrated;
- The receiving of the same standards;
- The climatic condition in which they were maintained at INRIM;
- The instrumentation and measurement system to calibrate them at INRIM;
- The INRIM results reports as measurements, tables and graphs;
- An analysis of the calibration uncertainties.

The measurements, the standards conditioning and the expression of the results with their associated uncertainties were made according to the technical protocol of the comparison [1].

## 2. Standards package

The four K13 traveling standards arrived at INRIM on 04/11/2022 inside an aluminum box. The group of standards, two resistors with nominal value 1  $\Omega$  and two 10 k $\Omega$  were identified as follows:

Table 1. Travelling resistors to be calibrated in the comparison.

| <i>Standard</i>   | <i>Manufacturer</i> | <i>Mod.</i>    | <i>no.</i>    |
|-------------------|---------------------|----------------|---------------|
| STD 1 $\Omega$    | CSIRO               | NML            | 64200         |
| STD 1 $\Omega$    | CSIRO               | NML            | 64203         |
| STD 10 k $\Omega$ | TEGAM               | SR104 - B10K09 | K205039730104 |
| STD 10 k $\Omega$ | TEGAM               | SR104 - B10K12 | K201089830104 |

The standards were carefully packed, but when the container arrived at INRIM one of the sides had been deformed during the travel (Fig. 1 a, and b). The condition of the container was promptly reported to the BIPM.



Fig. 1a, b – Unboxing and check

### 3. Climatic conditioning of the standards – oil and air baths

The 1  $\Omega$  resistors were placed in a Guildline 9732 VT no. 58.805 oil bath with a set point temperature of 23,000°C (Fig. 2). The oil temperature is measured with a calibrated Leeds & Northrup 25  $\Omega$  s/ 177 3055 thermometer. The depth of the resistors in the oil, measured between the surface and the top of the standards was 32 mm as indicated in Fig. 3.



Fig. 2 - Guildline 9732 VT oil bath. The short-term stability of the bath is approximately 0.001°C

The 10 k $\Omega$  resistors were housed inside a Kambic air bath mod. TK-105 US no. 15115002 set at the temperature of 23°C. The air temperature near the two resistors was measured with a calibrated 100  $\Omega$  no. 4446 FLUKE thermometer.

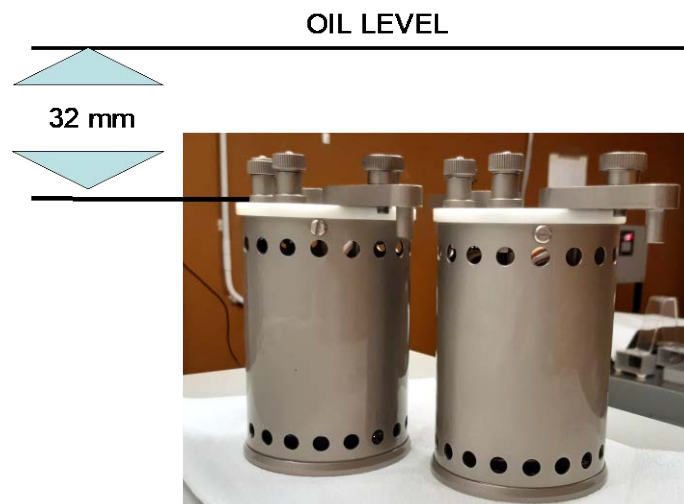
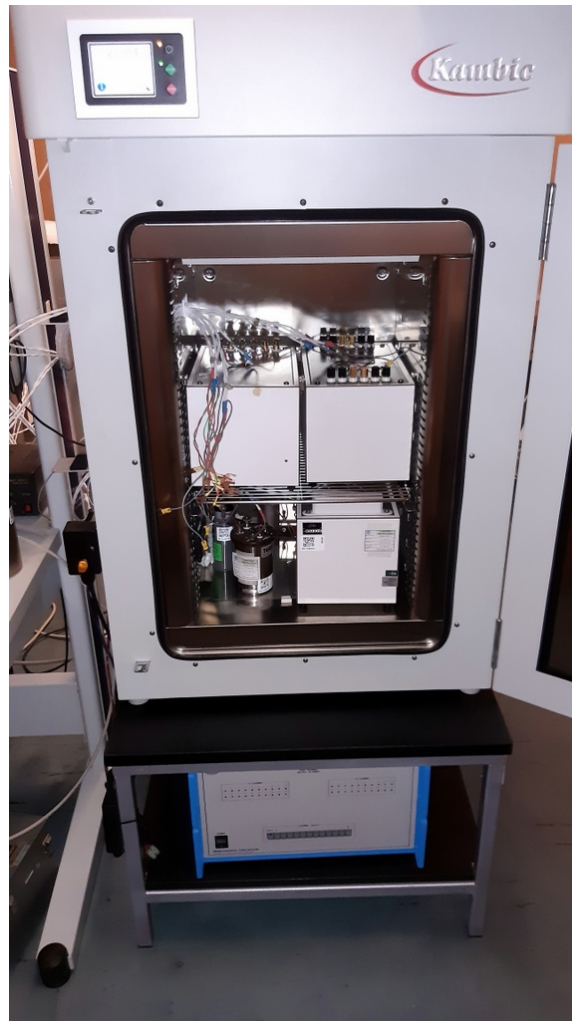


Fig. 3 - Oil immersion depth of the 1  $\Omega$  standards.



*Fig. 4 - 10 k $\Omega$  standards air-bath. The resistors were placed inside a Kambic air-bath mod. 105 with a set-point of 23.000°C and a short-term stability of approximately 0.005°C. The temperature was monitored with a PT100 platinum thermometer.*

All the resistors were connected to the measuring instrumentation by means of Teflon-insulated twisted AXON-type cables equipped with copper termination forks. The temperatures of the two baths were measured by always carrying out two series of resistance measurements in succession and at two different current values (1 mA and 1.41 mA) and making the correction due to self-heating. In correspondence with the resistance measurements of the traveling standards, the atmospheric pressure was also acquired using a Barocap-Technology instrument.

#### **4. Main instrumentation – Measurements system**

The measurement system used by INRIM for this international comparison is described in detail in the INRIM technical procedure [2]. Nevertheless, the same system is still based on the one described in [3] with only little difference as the use of a new high-performance



automated CC bridge in place of the previous manually operated bridge. The group of INRIM working standards consists of the resistors in fig. 5. The arrows indicated in the diagram show the comparisons and the direction of the traceability in the measurements for the calibration of all the INRIM standards and for the periodic checks. The origin of traceability is the QHE that is used for the calibration of a material transfer resistor, used for the calibration of a 12960  $\Omega$ /10  $\Omega$  Hamon network. Subsequently, by means of ratios 1:10 directly with a Measurements International MI 6010Q (DCC) bridge, or in ratio 1:100 with Hamon and DCC networks, all the elements of the scale are calibrated. The first step of the precision measurements was carried out during week No. 46 with a calibration of the QHE-10  $\Omega$  transfer Hamon network with an associated uncertainty equal to  $U = 7 \times 10^{-7}$  at  $2\sigma$  confidence level. The transfer of traceability from the 10  $\Omega$  Hamon network to the first element of the decade scale must take place within a short time, usually a few hours. The first group of resistors to receive traceability consists of the 10  $\Omega$ – 1  $\Omega$  – 100  $\Omega$  standards, which are calibrated and compared with each other both in a 1:10 ratio and with the 10  $\Omega$  Hamon network. Due to the impossibility of exchanging the compared resistors when they are in a ratio of 1:10, to reduce the bridge interchange error, the Hamon network is used by comparing the resistors following the diagram in Fig. 5, which allows reducing this type of systematic error. The second group of resistors consists of 100  $\Omega$ – 1k $\Omega$  – 10k $\Omega$ . Traceability is transferred to the 10 k $\Omega$  resistor via a 1k $\Omega$  step Hamon network, while the 1 k $\Omega$  resistor is calibrated against both 100  $\Omega$  and 10 k $\Omega$ , again in a 1:10 ratio. The precision measurements on the K13 traveling standards are carried out in a 1:1 ratio with 1  $\Omega$  and 10 k $\Omega$  standards of the INRIM working standard scale.

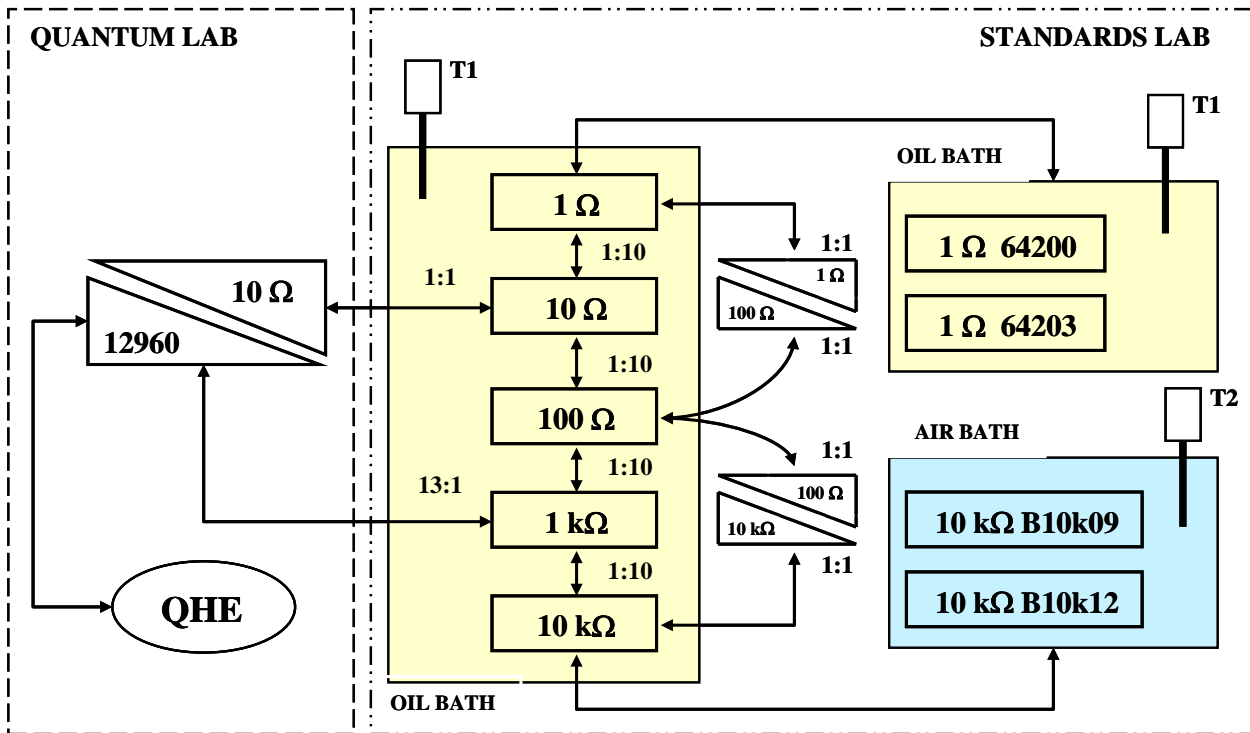
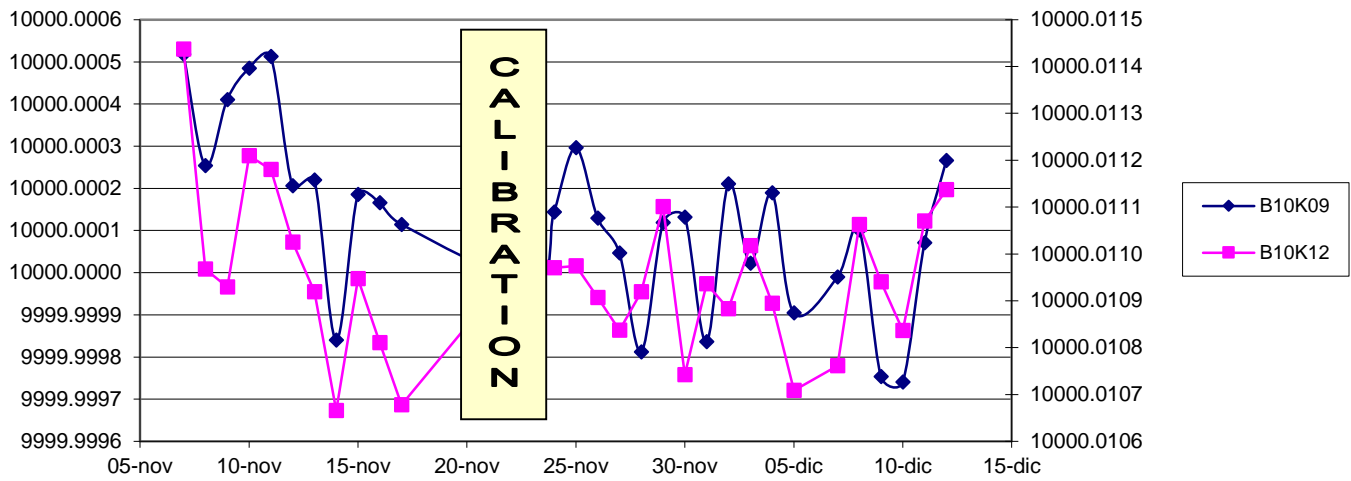
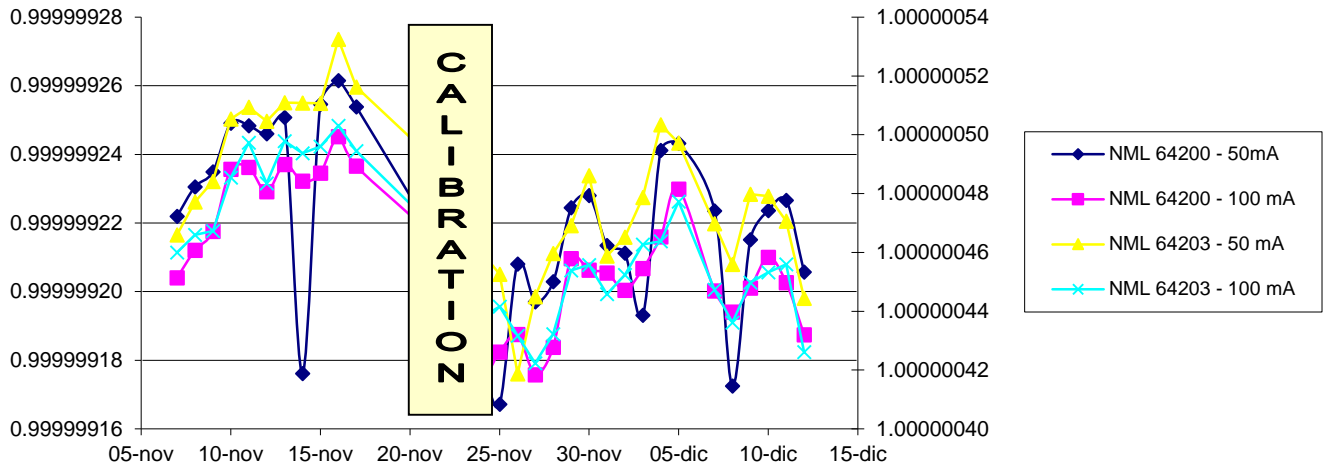


Fig. 5 - Complete diagram of the measurement system used for the K13 a&b key comparison. The traceability derives from the QHE realized in the INRIM Quantum laboratory and transferred to the decade scale in two ways: through a specifically designed Hamon network and by 1:13 ratio direct comparison, with a MI 6010Q DCC bridge. The working references and the two 1 Ω traveling resistors (k13) are kept at  $T = 23.000 \pm 0.001^\circ\text{C}$  in a Guildline oil bath. All ESI resistors and 10 kΩ (K13) resistors were kept at  $23.000 \pm 0.005^\circ\text{C}$  in a Kambic US-105 air bath.

## 5. Measurements, tables and graphs

The measurements were carried out every day, starting at 5:00 am when low level electrical and thermal noise and drift usually occur. The data of the measurements are contained in table 2. The data making up the average are those included between 10 November and 12 December. The measurements of the first few days were removed from the average because they were considered unstable, furthermore in the period between 18 and 23 November no measurements were made on the K13 standards due to the calibration of the INRIM working standards. The reference date of the k13 INRIM measurements is Monday November 21.



The final resistance values of the 1 and 10 kΩ standards are:

Table 2. Resistance values for the 1 Ω and 10 kΩ travelling resistors.

**1 Ω**

| Standard | no.            | Value      | $U$ (nΩ/ Ω) |
|----------|----------------|------------|-------------|
| STD 1 Ω  | 64200 – 50 mA  | 0.99999922 | 139.0       |
| STD 1 Ω  | 64200 – 100 mA | 0.99999921 | 139.0       |
| STD 1 Ω  | 64203 – 50 mA  | 1.00000048 | 139.0       |
| STD 1 Ω  | 64203 – 100 mA | 1.00000046 | 139.0       |

**10 kΩ**

| <i>Standard</i> | No.           | Value      | U (nΩ/Ω) |
|-----------------|---------------|------------|----------|
| STD 10 k Ω      | K205039730104 | 10000.0001 | 170.4    |
| STD 10 k Ω      | K201089830104 | 10000.0109 | 170.4    |

## 6. Uncertainties analysis

Tables 3 and 4 report, for the 1 Ω and 10 kΩ respectively, the uncertainties budget taking into account the main components and following [4]. The highest type A uncertainty values, evaluated for the two resistors at each resistance level, were assigned to both of them.

Table 3 – Uncertainty budget for the 1 Ω resistors

|   | Source of uncertainties  | Type | $u_r (\times 10^{-9})$ | $\nu$    |
|---|--|------|------------------------|----------|
| Transfer<br>$H_{SS} \rightarrow H_{SP}$       | Link from $R_{K-90}$ to Hamon 36×360 Ω ( $H_{SS} = 12960 \Omega$ ) | B    | 35                     | $\infty$ |
|   | $H_{SS}/H_{SP}$ (10 Ω) ratio correction                            | B    | 17                     | $\infty$ |
|   | $H_{SP}$ temperature coefficient                                   | B    | 0.03                   | $\infty$ |
|   | temperature difference $H_{SS}$ and $H_{SP}$                       | B    | 0.58                   | $\infty$ |
|   | $H_{SP}$ drift (1 day)   | B    | 0.69                   | $\infty$ |
|   | <b><math>u_c(R_{HSP})</math></b>                                   |      | <b>39.1</b>            |          |
|   | Ratio noise $H_{SP} - 1 \Omega$                                    | A    | 3.14                   | 50       |
| Transfer<br>$H_{SP} \rightarrow R_x 1 \Omega$ | Bridge ratio error correction                                      | B    | 46.2                   | $\infty$ |
|   | Effect due to $H_{SP}$ temperature coefficient                     | B    | 5.8                    | $\infty$ |
|   | $H_{SP}$ drift (1 day)   | B    | 0.3                    | $\infty$ |
|   | Emf  | B    | 9.99                   | $\infty$ |
|   | Temperature instability on $R_x$                                   | B    | 7.1                    | $\infty$ |
|   | Resistors Johnson noise  | B    | 0.74                   | $\infty$ |
|   | <b><math>u_c(R_x)</math></b>                                       |      | <b>69.5</b>            |          |

Table. 4 - Uncertainty budget for the 10 kΩ resistors

| Source of uncertainties                         | Type | $u_r (\times 10^{-9})$ | $\nu$ |
|---|------|------------------------|-------|
| Link from $R_{K-90}$ to standard 100 Ω ESI      | B    | 61.7                   | 50    |
| Ratio noise 100 Ω ESI/Hamon LN <sub>100 Ω</sub> | A    | 1.9                    | 50    |
| Ratio noise Hamon LN <sub>10 kΩ</sub> /10kΩ     | A    | 5.9                    | 50    |
| Bridge ratio error correction                   | B    | 8.0                    | ∞     |
| Hamon ratio transfer error                      | B    | 57.7                   | ∞     |
| Temperature coefficient                         | B    | 0.23                   | ∞     |
| Hamon drift                                     | B    | negl.                  | ∞     |
| Emf   | B    | 0.02                   | ∞     |
| Temperature instability on $R_x$                | B    | 3.12                   | ∞     |
| Resistors Johnson noise                         | B    | 0.74                   | ∞     |
| <b><math>u_c(R_x)</math></b>                    |      | <b>85.2</b>            |       |

## Acknowledgment

We would like to thank the BIPM team for the technical, scientific and logistical organization of the K13 comparison.

## References

- [1] R. Goebel, Technical protocol for BIPM.EM-K13a&b comparisons, BIPM/ELEC-T-17, rev. 1.1, December 2015.
- [2] PT-EM.2.1-07, Calibration of 1 Ω ÷ 10 kΩ INRIM standard resistors rev.03, 2021.
- [3] G. Boella and G. Marullo Reedtz, "A Room Temperature Setup to Compare the Quantized Hall Resistance with 1 Ω Standards, IEEE Trans Instrum Meas, 41. I, February 1992.
- [4] JCGM 100:2008 Evaluation of measurement data - Guide to the expression of uncertainty in measurement First edition.

## Annex

In table 5 the measurement results provided by INRIM to the BIPM for the comparison are listed along with the corresponding dates, temperature and pressure values.

Table. 5 –INRIM measurement results in Excel format along with the corresponding dates, temperature and pressure values.

| INRIM<br>EM.K13 a & b<br>2022 |             |             |             |             |             |             |             |             |             |             |             |             |             |             |             |             |
|-------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
|                               | 07-nov      | 08-nov      | 09-nov      | 10-nov      | 11-nov      | 12-nov      | 13-nov      | 14-nov      | 15-nov      | 16-nov      | 17-nov      | 23-nov      | 24-nov      | 25-nov      | 26-nov      | 27-nov      |
| NML 64200 - 50mA              | 0.999999222 | 0.999999231 | 0.999999235 | 0.999999249 | 0.999999248 | 0.999999246 | 0.999999251 | 0.999999176 | 0.999999255 | 0.999999262 | 0.999999254 | 0.999999201 | 0.999999181 | 0.999999167 | 0.999999208 | 0.999999197 |
| NML 64200 - 100 mA            | 0.999999204 | 0.999999212 | 0.999999218 | 0.999999236 | 0.999999236 | 0.999999229 | 0.999999237 | 0.999999232 | 0.999999235 | 0.999999245 | 0.999999237 | 0.999999206 | 0.999999177 | 0.999999182 | 0.999999187 | 0.999999176 |
| NML 64203 - 50 mA             | 1.000000466 | 1.000000477 | 1.000000484 | 1.000000505 | 1.000000509 | 1.000000505 | 1.000000511 | 1.000000511 | 1.000000511 | 1.000000532 | 1.000000516 | 1.000000482 | 1.00000046  | 1.000000453 | 1.000000419 | 1.000000445 |
| NML 64203 - 100 mA            | 1.00000046  | 1.000000466 | 1.000000467 | 1.000000485 | 1.000000497 | 1.000000483 | 1.000000498 | 1.000000494 | 1.000000496 | 1.000000503 | 1.000000494 | 1.000000459 | 1.000000438 | 1.000000442 | 1.000000432 | 1.000000422 |
| T oil bath (°C)               | 23.001      | 23.001      | 23.001      | 23.000      | 23.001      | 23.001      | 23.002      | 23.001      | 23.002      | 23.001      | 23.001      | 23.001      | 23.001      | 22.999      | 22.998      | 22.999      |
| P (hPa)                       | 991.4       | 988.0       | 990.0       | 992.0       | 1005.0      | 1003.5      | 995.5       | 993.7       | 989.9       | 978.1       | 974.0       | 972.8       | 983.7       | 989.5       | 995.4       | 1000.0      |
|                               |             |             |             |             |             |             |             |             |             |             |             |             |             |             |             |             |
|                               | 07-nov      | 08-nov      | 09-nov      | 10-nov      | 11-nov      | 12-nov      | 13-nov      | 14-nov      | 15-nov      | 16-nov      | 17-nov      | 23-nov      | 24-nov      | 25-nov      | 26-nov      | 27-nov      |
| B10K09                        | 10000.00052 | 10000.00025 | 10000.00041 | 10000.00048 | 10000.00051 | 10000.00021 | 10000.00022 | 9999.99984  | 10000.00019 | 10000.00017 | 10000.00011 | 9999.999979 | 10000.00014 | 10000.0003  | 10000.00013 | 10000.00005 |
| B10K12                        | 10000.01144 | 10000.01097 | 10000.01093 | 10000.01121 | 10000.01118 | 10000.01103 | 10000.01092 | 10000.01067 | 10000.01095 | 10000.01081 | 10000.01068 | 10000.01102 | 10000.01097 | 10000.01097 | 10000.01091 | 10000.01084 |
| T air bath (°C)               | 22.959      | 22.960      | 22.980      | 22.980      | 22.981      | 22.980      | 22.981      | 22.980      | 22.980      | 22.979      | 22.979      | 22.976      | 22.980      | 22.979      | 22.979      | 22.980      |
| P (hPa)                       | 991.91      | 990.60      | 990.50      | 994.00      | 1005.81     | 1003.42     | 998.37      | 995.31      | 989.52      | 977.52      | 974.93      | 975.06      | 985.56      | 991.23      | 997.57      | 1000.08     |

| INRIM<br>EM.K13 a & b<br>2022 |             |             |             |             |             |             |             |             |             |             |             |             |             |             |  |  |
|-------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--|--|
|                               | 28-nov      | 29-nov      | 30-nov      | 01-dic      | 02-dic      | 03-dic      | 04-dic      | 05-dic      | 07-dic      | 08-dic      | 09-dic      | 10-dic      | 11-dic      | 12-dic      |  |  |
| NML 64200 - 50mA              | 0.999999203 | 0.999999224 | 0.999999228 | 0.999999213 | 0.999999211 | 0.999999193 | 0.999999241 | 0.999999243 | 0.999999224 | 0.999999172 | 0.999999215 | 0.999999224 | 0.999999227 | 0.999999206 |  |  |
| NML 64200 - 100 mA            | 0.999999184 | 0.99999921  | 0.999999206 | 0.999999205 | 0.9999992   | 0.999999207 | 0.999999216 | 0.99999923  | 0.9999992   | 0.999999194 | 0.999999201 | 0.99999921  | 0.999999203 | 0.999999187 |  |  |
| NML 64203 - 50 mA             | 1.00000046  | 1.000000469 | 1.000000486 | 1.000000459 | 1.000000465 | 1.000000479 | 1.000000503 | 1.000000497 | 1.00000047  | 1.000000456 | 1.00000048  | 1.000000479 | 1.000000471 | 1.000000444 |  |  |
| NML 64203 - 100 mA            | 1.000000432 | 1.000000454 | 1.000000456 | 1.000000446 | 1.000000452 | 1.000000463 | 1.000000464 | 1.000000477 | 1.000000447 | 1.000000436 | 1.00000045  | 1.000000453 | 1.000000456 | 1.000000426 |  |  |
| T oil bath (°C)               | 22.998      | 22.995      | 22.996      | 22.996      | 22.997      | 22.996      | 22.998      | 22.998      | 22.999      | 22.998      | 22.998      | 22.998      | 22.998      | 22.999      |  |  |
| P (hPa)                       | 991.5       | 897.3       | 989.0       | 989.9       | 989.3       | 989.0       | 984.5       | 988.3       | 986.5       | 982.0       | 976.3       | 970.5       | 970.2       | 978.0       |  |  |
|                               |             |             |             |             |             |             |             |             |             |             |             |             |             |             |  |  |
|                               | 28-nov      | 29-nov      | 30-nov      | 01-dic      | 02-dic      | 03-dic      | 04-dic      | 05-dic      | 07-dic      | 08-dic      | 09-dic      | 10-dic      | 11-dic      | 12-dic      |  |  |
| B10K09                        | 9999.999812 | 10000.00012 | 10000.00013 | 9999.999836 | 10000.00021 | 10000.00002 | 10000.00019 | 9999.999904 | 9999.999989 | 10000.0001  | 9999.999754 | 9999.99974  | 10000.00007 | 10000.00027 |  |  |
| B10K12                        | 10000.01082 | 10000.0111  | 10000.01074 | 10000.01094 | 10000.01088 | 10000.01102 | 10000.01089 | 10000.01071 | 10000.01076 | 10000.01106 | 10000.01084 | 10000.01084 | 10000.01107 | 10000.01114 |  |  |
| T air bath (°C)               | 22.979      | 22.980      | 22.979      | 22.979      | 22.979      | 22.979      | 22.980      | 22.980      | 22.979      | 22.979      | 22.980      | 22.979      | 22.979      | 22.978      |  |  |
| P (hPa)                       | 990.87      | 998.17      | 989.50      | 990.59      | 989.94      | 989.15      | 984.44      | 989.34      | 987.00      | 982.00      | 975.50      | 970.50      | 972.00      | 980.00      |  |  |