# Report of APMP comparison of the activity measurements of Fe-59 (APMP.RI(II)-K2.Fe-59)

Akira Yunoki[1)], Yasushi Sato[1)], Leena Joseph[2)], Anuradha Ravindra[2)], D.B.Kulkarni[2)], Ming-Chen Yuan[3)], K. B. Lee[4)], J. M. Lee[4)], Agung Agusbudman[4)], Tae-Soon Park[4)], Paulo Alberto Lima da Cruz[5)], Carlos José da Silva[5)], Akira Iwahara[5)], Ming Zhang[6)], Jun Cheng Liang[6)], Hao Ran Liu[6)], M.J. van Staden[7)], J. Lubbe[7)], M.W. van Rooy[7)], B.R.S. Simpson[7)], Paphon Paukkachane[8)], Natnalin Sastri[8)], Thongchai Soodprasert[8)], Pujadi Marsoem[9)], Hermawan Candra Holnisar[9)] and Gatot Wurdiyanto[9)]

[1)] National Metrology Institute of Japan, Tsukuba Central 3, 305-8563 Tsukuba, Japan
[2)] Bhabha Atomic Research Centre, Trombay, Mumbai - 400 085, India
[3)] Institute of Nuclear Energy Research, No. 1000, Jia'anli Wenhua Road, Longtan District, Taoyuan City, Chinese Taipei
[4)] Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea
[5)] Laboratório Nacional de Metrologia das Radiações Ionizantes /Instituto de Radioproteção e Dosimetria, Av Salvador Allende, 3.773-Barra da Tijuca, Rio de Janeiro, Brazil
[6)] National Institute of Metrology, No. 18, Bei San Huan Dong Rd., 100029 Beijing, China
[7)] National Metrology Institute of South Africa, Lynnwood Ridge, 0040 Pretoria, South Africa
[8)] Office of Atoms for Peace, 16 Vibhavadi Rangsit Road, Ladyao Subdistrict, Chatuchak District, Bangkok 10900, Thailand
[9)] Pusat Teknologi Keselamatan Dan Metrologi Radiasi, Jl. Lebak Bulus Raya No.49, RT.5/RW.2, Lb. Bulus, Kec. Cilandak, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12440, Indonesia

**Abstract**

The international comparison of activity measurements of $^{59}$Fe, APMP.RI(II)-K2.Fe-59, was carried out within the framework of the Asia-Pacific Metrology Programme (APMP). Nine institutes took part in the comparison, and eight institutes of them undertook absolute measurements. One ampoule prepared using the same radioactive solution as that used in the comparison was sent to the BIPM/SIR [1] in order to link the comparison to the BIPM key comparison reference value (KCRV).

## 1. Introduction

The plan for a regional key comparison of activity measurement of a $^{59}$Fe solution was discussed at the eighth meeting of APMP/TCRI in Thailand. It was registered as the official Regional Metrology Organization (RMO) key comparison APMP.RI(II)-K2.Fe-59 in 2014. The pilot laboratory was the NMIJ. The ampoules of $^{59}$Fe solution were distributed in June of 2014 to all the participants. They measured the activity using their own methods and reported the results to the pilot laboratory.

## 2. Technical protocol

### 2.1 Measurement

Participants were required to report the activity concentration (in Bq $g^{-1}$) of the solution. Uncertainty estimations were performed according to GUM [2]. The reference date of the measurement was 1 June 2014 at 0:00:00 UTC.

### 2.2 Time schedule

The samples were distributed in mid-June 2014 and the deadline for the measurement reports was 15 September 2014. The NMIJ prepared a draft A report in May, 2015. After circulating it among participants of the comparison, the NMIJ revised and submitted it to the BIPM on March, 2016 as draft B. The work flow of the comparison was according to Appendix 3 of CIPM MRA-D-05 “Measurement comparisons in the context of the CIPM MRA”.

### 2.3 Estimation of the comparison results

The result of each participant was estimated by evaluating the parameter $E_n$ according to the following formula [3];

$$E_n = \frac{A_{lab} - A_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}},$$

where $A_{lab}$ and $U_{lab}$ are the activity and expanded uncertainty obtained by each participant, respectively, and $A_{ref}$ and $U_{ref}$ are the activity and an expanded uncertainty obtained by the pilot laboratory, respectively.

The results obtained from the APMP comparison will be linked to the KCRV by using the BIPM/SIR result of the NMIJ (pilot laboratory). The link between the APMP.RI(II)-K2.Fe-59 comparison and BIPM.RI(II)-K1.Fe-59 is being published in the Key Comparison Database (KCDB) in parallel with the present report.

## 3. Source preparation

The original solution of $^{59}$Fe was provided by PerkinElmer, Inc. The chemical form was $FeCl_3$ and the activity concentration was approximately 1.2 GBq $mL^{-1}$ on 14 April 2014. After a quick activity measurement, the original solution was diluted to be approximately 500 kBq $g^{-1}$ on 1 June 2014 in a 0.1 mol $L^{-1}$ HCl solution containing 0.1 mg/g $FeCl_3$ as carrier. The diluted $^{59}$Fe solution was then transferred into the NMIJ standard type 5 mL ampoules and the BIPM/NIST - type 3.6 mL ampoule. The NMIJ standard type ampoules were sent to the participants in June 2014. The solution in the BIPM/NIST-type ampoule was sent to the BIPM/SIR [1] at the same time. The activity of the solution in each ampoule was measured in well-type pressurized ionization chambers before shipping. The relative standard deviation of the measured activities (kBq $g^{-1}$) was 0.053 %. Numbers of the ampoules, mass of the solution and the institutes where the ampoules were sent are listed in Table 1.

**Table 1 Ampoule numbers and mass of solution measured before shipping**

| Ampoule No. | Mass of solution / (g) | Institute |
|---|---|---|
| 0001 | 4.996 | ANSTO (*1) |
| 0003 | 4.995 | BARC |
| 0004 | 4.999 | INER |
| 0007 | 5.002 | KRISS |
| 0009 | 4.996 | LNMRI/IRD |
| 0010 | 4.999 | NIM |
| 0011 | 5.002 | NMISA |
| 0012 | 5.002 | OAP |
| 0013 | 5.000 | PTKMR-BATAN |
| 0014 | 4.995 | NMIJ |
| 0015 | 3.602 | BIPM |

*1 The ANSTO did not submit a result and are not mentioned further in this report.

## 4. Participants

The abbreviations, full names, countries and Regional Metrological Organizations (RMO) of the participants are listed in Table 2.

**Table 2. Acronym, full name, country and RMO of participant**

| NMI | Full name of participant | Country | RMO |
|---|---|---|---|
| BARC | Bhabha Atomic Research Centre | India | APMP |
| INER | Institute of Nuclear Energy Research | Chinese Taipei | APMP |
| KRISS | Korea Research Institute of Standards and Science | Korea | APMP |
| LNMRI/IRD | Laboratório Nacional de Metrologia das Radiações Ionizantes (LNMRI)/Instituto de Radioproteção e Dosimetria - IRD/Brazil | Brazil | SIM |
| NIM | National Institute of Metrology | China | APMP |
| NMISA | National Metrology Institute of South Africa | South Africa | AFRIMETS |
| OAP | Office of Atoms for Peace | Thailand | APMP |
| PTKMR-BATAN | Pusat Teknologi Keselamatan Dan Metrologi Radiasi | Indonesia | APMP |
| NMIJ | National Metrology Institute of Japan | Japan | APMP |

## 5. Measurement methods

The standardization methods used in the comparison of APMP.RI(II)-K2.Fe-59 are listed in Table 3.

**Table 3. The standardization methods used by participants**

| Institute | Standardization Method (see Appendix 1) |
|---|---|
| BARC | 4P-PC-BP-NA-GR-CO, 4P-LS-BP-NA-GR-CO, 4P-LS-CN-00-00-00 |
| INER | 4P-PC-BP-NA-GR-CO |
| KRISS | 4P-LS-BP-NA-GR-CO, 4P-PP-BP-NA-GR-CO |
| LNMRI/IRD | 4P-PC-BP-GH-GR-CO, 4P-LS-BP-NA-GR-CO, 4P-PC-BP-NA-GR-CO |
| NIM | 4P-PC-BP-NA-GR-CO |
| NMISA | 4P-LS-BP-NA-GR-CO |
| OAP | 4P-IC-GR-00-00-00 |
| PTKMR-BATAN | 4P-LS-BP-NA-GR-CO |
| NMIJ | 4P-PC-BP-NA-GR-CO |

## 6. Results

The standardization methods used by the participants, the measured activities, the relative uncertainties associated with the activity measurement and the date of measurements are listed in Table 4; the results are plotted in Figure 1. The half-life of $^{59}$Fe used for estimating the activity at the reference date was 44.495 days with an uncertainty of 0.008 days [4].

The KRISS reported that $^{60}$Co was found in the solution, with an activity of 91 Bq g$^{-1}$ and a standard uncertainty of 7 Bq g$^{-1}$. The ratio of activity of $^{60}$Co to $^{59}$Fe at the reference date was approximately 0.02 %. The NIM reported that $^{55}$Fe and $^{60}$Co were found in the solution. The activities were less than $10^{-6}$ of $^{59}$Fe at the reference date. The NMISA, PTKMR-BATAN and NMIJ found no impurities in the solution. The KRISS, NIM, PTKMR-BATAN and NMIJ used high-purity germanium spectrometers and the NMISA used a NaI(Tl) scintillation spectrometer for assessing impurities. No correction was applied to the reported values because the activities of impurities are much smaller than uncertainties reported by the participants.

The OAP broke ampoule number 12 so weighed the mass of the solution recovered. The reported mass was 4.9991 g whereas the mass of sample which was measured before shipping was 5.002 g. The difference is only 0.06 %, therefore, no correction was applied to the result of the OAP.

The LNMRI/IRD found a problem in the computer that controlled its coincidence counting system after circulation of the Draft A report of the comparison. The problem had resulted in the counting time used being wrong by 4 %. Since the result of the LNMRI/IRD was not obtained by an instrument in full working order, the LNMRI/IRD result was not included in the calculation of the mean or in calculating the comparison reference value.

The PTKMR-BATAN investigated the reason for discrepancy with the results from the other participants, however, no clear reason could be identified.

Only one result can be submitted per laboratory for determining the mean result for the comparison; the results selected, the rationale, the measurement method, expanded uncertainties and $E_n$ values are listed in Table 5 and are plotted in Figure 2. The power-moderated mean [5] of the final results of the participants (excluding the result from the LNMRI/IRD) was 470.8 kBq $g^{-1}$ and the standard uncertainty was 1.7 kBq $g^{-1}$ at the reference date. The value obtained by the pilot laboratory is slightly lower than the other participant values and the comparison reference value. The key comparison reference value ($x_{ref}$) of the BIPM.RI(II)-K1.Fe-59 comparison as agreed by the CCRI in 2017 is 14 639(27) kBq, to which this data will be linked by using the SIR equivalent activity ($A_e$) value of the NMIJ (Pilot laboratory) of 14 576(23) kBq. The uncertainty budgets of each participant are listed in Table 6.

.

**Table 4. Standardization methods of the participants and their results**

| Institute | Method used (see Appendix 1) | Activity / (kBq $g^{-1}$) (*2) | Expanded uncertainty/ (kBq $g^{-1}$) (*2) ($k$ = 2) | Relative expanded uncertainty/ % ($k$ = 2) | Mean date of measurements |
|---|---|---|---|---|---|
| BARC | 4P-PC-BP-NA-GR-CO | 471.72 | 4.43 | 0.94 | 14 August, 2014 |
| | 4P-LS-BP-NA-GR-CO | 473.95 | 7.20 | 1.52 | |
| | 4P-LS-CN-00-00-00 | 473.05 | 2.74 | 0.58 | |
| INER | 4P-PC-BP-NA-GR-CO | 471.8 | 2.9 | 0.62 | 25 July, 2014 |
| KRISS | 4P-LS-BP-NA-GR-CO | 471.0 | 5.9 | 1.3 | 14 July, 2014 |
| | 4P-PP-BP-NA-GR-CO | 471.8 | 6.9 | 1.5 | 27 August, 2014 |
| LNMRI /IRD | 4P-PC-BP-GH-GR-CO | 501.8 | 7.0 | 1.4 | 24 September, 2014 |
| | 4P-LS-BP-NA-GR-CO | 499.4 | 4.0 | 0.8 | |
| | 4P-PC-BP-NA-GR-CO (Gamma window: 1099 keV) | 501.8 | 6.0 | 1.2 | |
| | 4P-PC-BP-NA-GR-CO (Gamma window: 1291 keV) | 497.72 | 6.0 | 1.2 | |
| NIM | 4P-PC-BP-NA-GR-CO | 471.7 | 3.2 | 0.68 | 1 August, 2014 |
| NMISA | 4P-LS-BP-NA-GR-CO | 473.6 | 2.7 | 0.57 | 22/23 July, 2014 |
| OAP | 4P-IC-GR-00-00-00 | 482 | 24 | 5.0 | --- |
| PTKMR-BATAN | 4P-LS-BP-NA-GR-CO | 458.74 | 7.44 | 1.62 | 5 September, 2014 |
| NMIJ | 4P-PC-BP-NA-GR-CO | 469.9 | 1.3 | 0.28 | 25 June, 2014 |

*2 reference date = 0:00 h UTC of 1st June, 2014

Half-life of $^{59}$Fe = 44.495 d, u = 0.008 d [3]

**Table 5. Final results, method used, expanded uncertainties and $E_n$ values**

| Institute | Method used (see Appendix 1) | Activity / (kBq $g^{-1}$) (*2) | Expanded uncertainty/ (kBq $g^{-1}$) (*2) ($k$ = 2) | Relative expanded uncertainty/ % ($k$ = 2) | $E_n$ value |
|---|---|---|---|---|---|
| BARC | Arithmetric mean of the results obtained by 4P-PC-BP-NA-GR-CO and 4P-LS-BP-NA-GR-CO | 472.84 | 4.22 | 0.89 | 0.67 |
| INER | 4P-PC-BP-NA-GR-CO | 471.8 | 2.9 | 0.62 | 0.60 |
| KRISS | 4P-LS-BP-NA-GR-CO | 471.0 | 5.9 | 1.3 | 0.18 |
| LNMRI /IRD | Weighted mean of the results obtained by 4P-PC-BP-GH-GR-CO, 4P-LS-BP-NA-GR-CO, 4P-PC-BP-NA-GR-CO (Gamma window: 1099 keV) and 4P-PC-BP-NA-GR-CO (Gamma window: 1291 keV) | 499.8 | 7.0 | 1.4 | 4.2 |
| NIM | 4P-PC-BP-NA-GR-CO | 471.7 | 3.2 | 0.68 | 0.52 |
| NMISA | 4P-LS-BP-NA-GR-CO | 473.6 | 2.7 | 0.57 | 1.2 |
| OAP | 4P-IC-GR-00-00-00 | 482 | 24 | 5.0 | 0.50 |
| PTKMR-BATAN | 4P-LS-BP-NA-GR-CO | 458.74 | 7.44 | 1.62 | -1.5 |
| NMIJ | 4P-PC-BP-NA-GR-CO | 469.9 | 1.3 | 0.28 | -- |
| Arithmetic mean of values of the all participants | | 471.4 | 3.3 | 0.71 | -- |
| Power-moderated mean of values of the participants excluding the LNMRI/IRD | | 470.8 | 3.4 (*3) | 0.72 (*4) | -- |

*3 standard uncertainty

*4 relative standard uncertainty

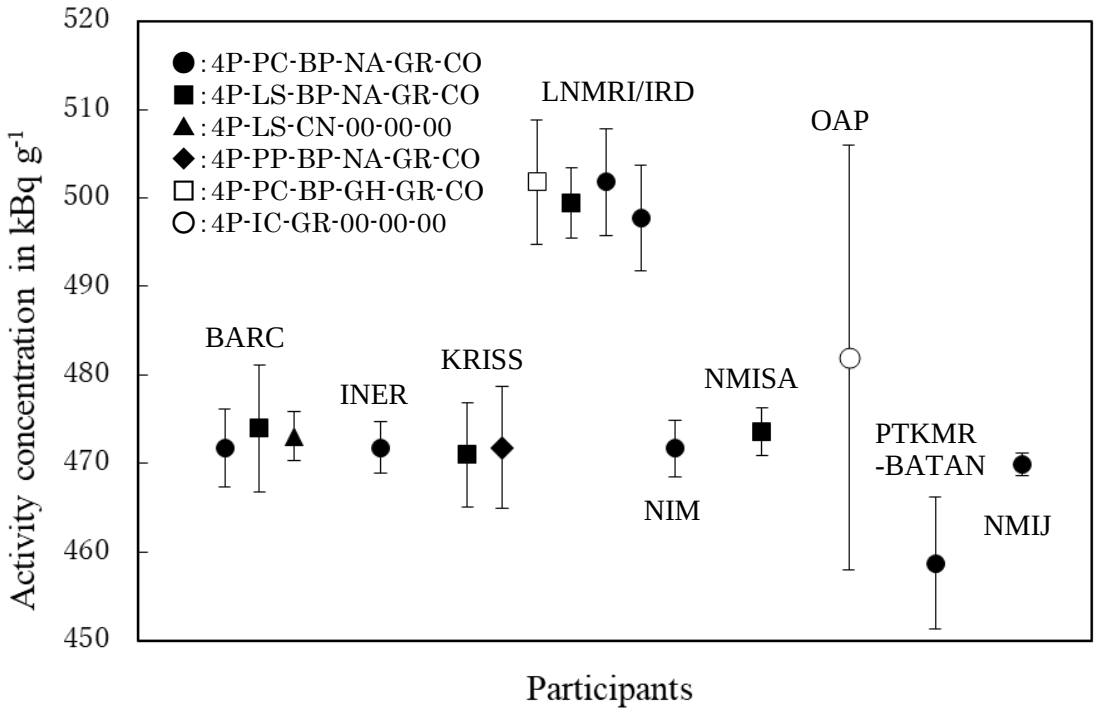


Figure 1. The measured activities with their expanded uncertainties (as listed in Table 4). The measurement method is indicated.

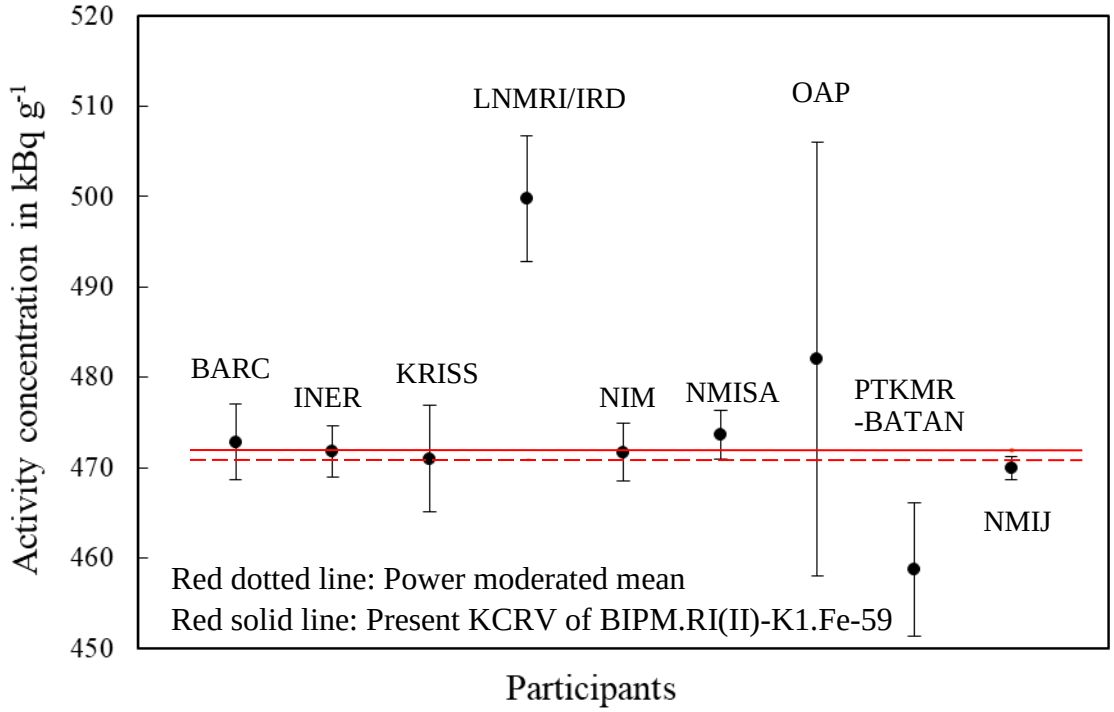


Figure 2. Laboratory final results with their expanded uncertainties listed in Table 5. Vertical solid lines indicate expanded uncertainties ($k$=2) of each result. A dotted red horizontal line indicates the power-moderated mean [5] of the final results of the participants, excluding the LNMRI/IRD. A solid red horizontal line indicates the present KCRV of BIPM.RI(II)-K1.Fe-59 as agreed by the CCRI in 2017 of 14 639(27) kBq.

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$.**

●: 4P-PC-BP-NA-GR-CO

| Item No. | Function | BARC | INER | LNMRI/ IRD (*5) | LNMRI/ IRD (*6) | NIM | NMIJ |
|---|---|---|---|---|---|---|---|
| 1 | counting statistics | 0.39 | 0.14 | 0.180 | 0.180 | 0.19 | 0.04(*7) |
| 2 | weighing | 0.05 | 0.02 | 0.050 | 0.050 | 0.10 | 0.08 |
| 3 | dead time | 0.10 | 0.01 | 0.003 | 0.006 | 0.05 | < 0.01 |
| 4 | background | 0.13 | 0.06 | 0.490 | 0.478 | 0.05 | 0.01 |
| 5 | pile up | -- | -- | -- | -- | -- | -- |
| 6 | resolving time | 0.18 | 0.01 | 0.009 | 0.016 | 0.05 | 0.03 |
| 7 | Gandy effect | -- | 0.06 | 0.068 | 0.068 | 0.10 | 0.02 |
| 8 | counting time | -- | 0.01 | -- | -- | 0.01 | 0.02 |
| 9 | adsorption | -- | -- | -- | -- | 0.06 | -- |
| 10 | impurities | -- | -- | -- | -- | < 0.01 | -- |
| 11 | tracer | -- | -- | -- | -- | | -- |
| 12 | input parameters and statistical model | -- | -- | -- | -- | | -- |
| 13 | quenching | -- | -- | -- | -- | | -- |
| 14 | interpolation from calibration curve | -- | -- | -- | -- | | -- |
| 15 | decay-scheme parameters | -- | -- | -- | -- | | -- |
| 16 | half-life $T_{1/2}$ = 44.495 d | 0.02 | 0.02 | 0.025 | 0.024 | 0.04 | 0.01 |
| 17 | self-absorption | -- | -- | -- | -- | -- | -- |
| 18 | extrapolation of efficiency curve | 0.07 | 0.25 | 0.276 | 0.270 | 0.22 | 0.1 |
| 19 | other effects | -- | -- | -- | -- | | -- |
| combined uncertainty (1σ) | | 0.47 | 0.31 | 0.60 | 0.59 | 0.34 | 0.14 |

*5 gamma window: 1099 keV.

*6 gamma window: 1291 keV.

*7 Included in a component of extrapolation of efficiency curve.

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$ (continued).**

◆: 4P-PP-BP-NA-GR-CO

| Item No. | Function | KRISS |
|---|---|---|
| 1 | counting statistics | 0.71 |
| 2 | weighing | 0.1 |
| 3 | dead time | 0.01 |
| 4 | background | 0.1 |
| 5 | pile up | -- |
| 6 | resolving time | 0.02 |
| 7 | Gandy effect | -- |
| 8 | counting time | 0.01 |
| 9 | adsorption | -- |
| 10 | impurities | 0.02(*8) |
| 11 | tracer | -- |
| 12 | input parameters and statistical model | -- |
| 13 | quenching | -- |
| 14 | interpolation from calibration curve | -- |
| 15 | decay-scheme parameters | -- |
| 16 | half-life $T_{1/2}$ = 44.495 d | 0.03 |
| 17 | self-absorption | -- |
| 18 | extrapolation of efficiency curve | 0.1 |
| 19 | other effects | -- |
| combined uncertainty (1σ) | | 0.73 |

*8 Considering the impurity of $^{60}$Co found in the solution.

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$ (continued).**

■: 4P-LS-BP-NA-GR-CO

| Item No. | Function | BARC | KRISS | LNMRI /IRD | NMISA | PTKMR-BATAN |
|---|---|---|---|---|---|---|
| 1 | counting statistics | 0.19(*9) | 0.14(*10) | 0.180 | 0.06(*15) | 0.25 |
| 2 | weighing | 0.02 | 0.05(*11) | 0.050 | 0.01 | 0.5 |
| 3 | dead time | 0.12 | -- | 0.002 | 0.002 | 0.05 |
| 4 | background | 0.70 | -- | 0.327 | 0.1 | 0.01 |
| 5 | pile up | -- | -- | -- | -- | -- |
| 6 | resolving time | 0.1 | 0.30(*12) | 0.012 | 0.001 | 0.02 |
| 7 | Gandy effect | -- | -- | 0.095 | -- | -- |
| 8 | counting time | -- | -- | -- | 0.001 | -- |
| 9 | adsorption | -- | -- | -- | 0.01 | -- |
| 10 | impurities | -- | 0.02(*13) | -- | -- | -- |
| 11 | tracer | -- | -- | -- | -- | -- |
| 12 | input parameters and statistical model | -- | -- | -- | -- | -- |
| 13 | quenching | -- | -- | -- | -- | -- |
| 14 | interpolation from calibration curve | -- | -- | -- | -- | 0.05 |
| 15 | decay-scheme parameters | -- | -- | -- | -- | 0.3 |
| 16 | half-life $T_{1/2}$ = 44.495 d | 0.02 | 0.01 | 0.023 | 0.02 | 0.02 |
| 17 | self-absorption | -- | -- | -- | -- | -- |
| 18 | extrapolation of efficiency curve | 0.14 | 0.54(*14) | 0.112 | 0.25(*16) | 0.5 |
| 19 | other effects - satellite pulses | -- | -- | -- | 0.03(*17) | -- |
| combined uncertainty (1σ) | | 0.76 | 0.63 | 0.40 | 0.28 | 0.81 |

*9 Included in a component of extrapolation of efficiency curve.

*10 Standard deviation of the mean for the activity determinations for 10 sources and 2 background measurements method.

*11 Gravimetric mass determination uncertainty 0.09% subtracted out the repeatability that was already taken into account in the measurement variability.

*12 Difference of activity values obtained using different resolving times.

*13 Measured concentration fraction of $^{60}$Co impurity.

*14 Standard deviation of the distribution obtained with different efficiency ranges.

*15 Statistical analysis of 16 values.

*16 Alternative fits and gamma-ray windows were used to estimate the extrapolation range, assumed uniform, range/(2√3).

*17 Satellite pulses varied by 10%.

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$ (continued).**

▲: 4P-LS-CN-00-00-00

| Item No. | Function | BARC |
|---|---|---|
| 1 | counting statistics | 0.28 |
| 2 | weighing | 0.03 |
| 3 | dead time | -- |
| 4 | background | 0.01 |
| 5 | pile up | -- |
| 6 | resolving time | -- |
| 7 | Gandy effect | -- |
| 8 | counting time | -- |
| 9 | adsorption | -- |
| 10 | impurities | -- |
| 11 | tracer | 0.06 |
| 12 | input parameters and statistical model | -- |
| 13 | quenching | -- |
| 14 | interpolation from calibration curve | -- |
| 15 | decay-scheme parameters | -- |
| 16 | half-life $T_{1/2}$ = 44.495 d | 0.02 |
| 17 | self-absorption | -- |
| 18 | extrapolation of efficiency curve | -- |
| 19 | other effects | -- |
| combined uncertainty (1σ) | | 0.29 |

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$ (continued).**

□: 4P-PC-BP-GH-GR-CO

| Item No. | Function | LNMRI /IRD |
|---|---|---|
| 1 | counting statistics | 0.180 |
| 2 | weighing | 0.050 |
| 3 | dead time | 0.004 |
| 4 | background | 0.478 |
| 5 | pile up | -- |
| 6 | resolving time | 0.016 |
| 7 | Gandy effect | 0.081 |
| 8 | counting time | -- |
| 9 | adsorption | -- |
| 10 | impurities | -- |
| 11 | tracer | -- |
| 12 | input parameters and statistical model | -- |
| 13 | quenching | -- |
| 14 | interpolation from calibration curve | -- |
| 15 | decay-scheme parameters | -- |
| 16 | half- life $T_{1/2}$ = 44.495 d | 0.022 |
| 17 | self-absorption | -- |
| 18 | extrapolation of efficiency curve | 0.275 |
| 19 | other effects | |
| combined uncertainty (1σ) | | 0.70 |

**Table 6. Uncertainty components and estimated relative values / $10^{-2}$ (continued).**

○: 4P-IC-GR-00-00-00

| Item No. | Function | OAP |
|---|---|---|
| 1 | counting statistics | 0.1 |
| 2 | weighing | 0.1 |
| 3 | dead time | -- |
| 4 | background | -- |
| 5 | pile up | -- |
| 6 | resolving time | -- |
| 7 | Gandy effect | -- |
| 8 | counting time | -- |
| 9 | adsorption | -- |
| 10 | impurities | -- |
| 11 | tracer | -- |
| 12 | input parameters and statistical model | -- |
| 13 | quenching | -- |
| 14 | interpolation from calibration curve | 0.5 |
| 15 | decay-scheme parameters | -- |
| 16 | half- life<br>$T_{1/2}$ = 44.495 d | 0.02 |
| 17 | self-absorption | -- |
| 18 | extrapolation of efficiency curve | -- |
| 19 | other effects<br>- reference source stability<br>- electrometer accuracy<br>- calibration factor | <br>0.3<br>0.2<br>2.2 |
| combined uncertainty (1σ) | | 2.29 |

## 6. Preliminary degrees of equivalence

The degree of equivalence of the result of a particular NMI, *i*, with the key comparison reference value is expressed as the difference $D_i$ between the values

$$D_i = x_i - x_{ref}$$

where $x_i$ and $x_{ref}$ are each participant's result and the comparison reference value obtained by the power moderated mean [5], respectively. The expanded uncertainty ($k$ = 2) of this difference $U_i$, known as the equivalence uncertainty; hence:

$$U_i = 2u(D_i)$$

When the result of the NMI *i* is included in the KCRV with a weight $w_i$, then

$$u^2(D_i) = (1\text{-}2w_i)\, u_i^2 + u^2(x_{ref}) \ .$$

where $u_i$ is the combined standard uncertainties as reported by each laboratory.
However, when the result of the NMI *i* is not included in the KCRV, then

$$u^2(D_i) = u_i^2 + u^2(x_{ref}).$$

The preliminary degrees of equivalence for participants in the comparison are presented in Table 7. Final degrees of equivalence, as well as the final Key Comparison Reference Value (KCRV) will be calculated using measurements made in the International Reference System (SIR).

**Table 7. Preliminary degrees of equivalence**

| Institute | Difference, $D_i$ (kBq g$^{-1}$) | Expanded uncertainty ($k$=2) of the difference, $U_i$ (kBq g$^{-1}$) |
|---|---|---|
| BARC | 2.1 | 4.9 |
| INER | 1.0 | 4.2 |
| KRISS | 0.2 | 6.2 |
| LNMRI/IRD | 29.0 | 7.8 |
| NIM | 0.9 | 4.3 |
| NMISA | 2.8 | 4.1 |
| OAP | 11.2 | 23.7 |
| PTKMR-BATAN | -12.0 | 7.5 |
| NMIJ | -0.9 | 3.6 |

## 7. Conclusion

The APMP key comparison of APMP.RI(II)-K2.Fe-59 radionuclide activity measurements was completed. In total, nine institutes participated in the comparison. The comparison reference value and preliminary degrees of equivalence have been evaluated. The measurement results of eight institutes are linked to the KCRV of the BIPM.RI(II)-K1.Fe-59 through the result of the pilot laboratory.

**Acknowledgements**

The authors would like to thank all participants in this comparison and the BIPM staff for their continuous efforts in maintaining the SIR.

**References**

[1] G. Ratel, The Système International de Référence and its application in key comparisons, *Metrologia* **44(4)** (2007) S7-S16.

[2] JCGM, *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, JCGM 100:2008

[3] ISO, Statistical methods for use in proficiency testing by interlaboratory comparisons, ISO 13528:2005.

[4] M. -M. Be et al. Monographie BIPM-5, BPM, 2004, Vol. 1 – A = 1 to 150, pp.99-103.

[5] S. Pommé and J Keightley, Determination of a reference value and its uncertainty through a power-moderated mean, *Metrologia* 52 (2015) S200-S212.

**Appendix 1 Acronyms used to identify different measurement methods**

Each acronym has six components, geometry-detector (1)-radiation (1)-detector (2)-radiation (2)-mode. When a component is unknown, ?? is used and when it is not applicable 00 is used.

| **Geometry** | **acronym** | **Detector** | **acronym** |
|---|---|---|---|
| 4π | 4P | proportional counter | PC |
| defined solid angle | SA | press. prop counter | PP |
| 2π | 2P | liquid scintillation counting | LS |
| undefined solid angle | UA | NaI(Tl) | NA |
| | | Ge(HP) | GH |
| | | Ge-Li | GL |
| | | Si-Li | SL |
| | | CsI | CS |
| | | ionization chamber | IC |
| | | grid ionization chamber | GC |
| | | bolometer | BO |
| | | calorimeter | CA |
| | | PIPS detector | PS |
| **Radiation** | **acronym** | **Mode** | **acronym** |
| positron | PO | efficiency tracing | ET |
| beta particle | BP | internal gas counting | IG |
| Auger electron | AE | CIEMAT/NIST | CN |
| conversion electron | CE | sum counting | SC |
| bremsstrahlung | BS | coincidence | CO |
| gamma ray | GR | anti-coincidence | AC |
| X-rays | XR | coincidence counting with efficiency tracing | CT |
| alpha - particle | AP | anti-coincidence counting with efficiency tracing | AT |
| mixture of various radiation e.g. X and gamma | MX | triple-to-double coincidence ratio counting | TD |
| | | selective sampling | SS |

| **Examples method** | **acronym** |
|---|---|
| 4π(PC)β−γ-coincidence counting | 4P-PC-BP-NA-GR-CO |
| 4π(PPC)β−γ-coincidence counting eff. tracing | 4P-PP-MX-NA-GR-CT |
| defined solid angle α-particle counting with a PIPS detector | SA-PS-AP-00-00-00 |
| 4π(PPC)AX-γ(GeHP)-anticoincidence counting | 4P-PP-MX-GH-GR-AC |
| 4π CsI-β,AX,γ counting | 4P-CS-MX-00-00-00 |
| calibrated IC | 4P-IC-GR-00-00-00 |
| internal gas counting | 4P-PC-BP-00-00-IG |