# Update of the BIPM comparison BIPM.RI(II)-K1.Co-60 of activity measurements of the radionuclide $^{60}$Co to include the 2017 result of the PTB (Germany) and the 2018 result of the TAEK (Turkey)

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**Abstract** Since 1976, 28 laboratories have submitted 72 samples of $^{60}$Co to the International Reference System (SIR) for activity comparison at the Bureau International des Poids et Mesures (BIPM), with comparison identifier BIPM.RI(II)-K1.Co-60. Recently, the PTB (Germany) and the TAEK (Turkey) participated in the comparison and the key comparison reference value (KCRV) has been updated to include the PTB result. The degrees of equivalence between each equivalent activity measured in the SIR and the updated KCRV have been calculated and the results are given in the form of a table. A graphical presentation is also given.

## 1. Introduction

The SIR for activity measurements of $\gamma$-ray-emitting radionuclides was established in 1976. Each national metrology institute (NMI) may request a standard ampoule from the BIPM that is then filled with 3.6 g of the radioactive solution. For radioactive gases, a different standard ampoule is used. Each NMI completes a submission form that details the standardization method used to determine the absolute activity of the radionuclide and the full uncertainty budget for the evaluation. The ampoules are sent to the BIPM where they are compared with standard sources of $^{226}$Ra using pressurized ionization chambers. Details of the SIR method, experimental set-up and the determination of the equivalent activity $A_e$, are all given in [1].

From its inception until 31 December 2019, the SIR has been used to measure 1016 ampoules to give 771 independent results for 72 different radionuclides. The SIR makes it possible for national laboratories to check the reliability of their activity measurements at any time. This is achieved by the determination of the equivalent activity of the radionuclide and by comparison of the result with the key comparison reference value determined from the results of primary standardizations. These comparisons are described as BIPM ongoing comparisons and the results form the basis of the BIPM key comparison database (KCDB) of the Comité International des Poids et Mesures Mutual Recognition Arrangement (CIPM MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Co-60 key comparison. The results of earlier participations in this key comparison were published previously [3–8].

## 2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–8]. The dates of measurement in the SIR given in Table 1 are used in the KCDB and all references in this report. The AECL (Atomic Energy of Canada Ltd) is not part of the NMI in Canada but was an invited participant in various SIR comparisons, as in the early years, J.G.V. Taylor of the AECL was a personal member of the predecessor to the CCRI(II).

Table 1: Details of the participants in the BIPM.RI(II)-K1.Co-60.

| **NMI or laboratory** | **Previous acronyms** | **Full name** | **Country** | **RMO** | **Date of SIR measurement** yyyy-mm-dd |
|---|---|---|---|---|---|
| AECL[a] | - | Atomic Energy of Canada Ltd | Canada | SIM | 1980-04-11<br><br>1993-12-20 |
| ANSTO | AAEC | Australian Nuclear Science and Technology Organisation | Australia | APMP | 1992-05-13 |
| ASMW | - | Amt für Standardisierung, Meßwesen und Warenprüfung | former East Germany | - | 1976-09-02 |
| BARC | - | Bhabha Atomic Research Centre | India | APMP | 1981-09-03<br><br>1994-06-20<br>2001-01-10<br>2012-01-09 |
| BEV | IRK | Bundesamt fur Eich- und Vermessungswesen | Austria | EURAMET | 1998-10-14<br><br>2007-09-27 |
| BIPM | - | Bureau International des Poids et Mesures | | | 1976-07-22 |
| BKFH | OMH, MKEH | Government Office of the Capital City Budapest | Hungary | EURAMET | 1977-03-11 |

... Continuation of Table 1.

| **NMI or laboratory** | **Previous acronyms** | **Full name** | **Country** | **RMO** | **Date of SIR measurement** yyyy-mm-dd |
|---|---|---|---|---|---|
| | | | | | 1979-12-13<br>1999-06-11 |
| CIEMAT | - | Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas | Spain | EURAMET | 1999-11-30 |
| CMI-IIR | UVVVR | Czech Metrological Institute - Inspectorate for Ionizing Radiation | Czech Republic | EURAMET | 1977-03-25<br>1978-04-18 |
| CNEA | - | Comision Nacional de Energia Atomica | Argentina | SIM | 1992-01-28<br>2003-01-17<br>2011-10-24 |
| ENEA-INMRI | - | Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile - Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti | Italy | EURAMET | 1991-01-22 |
| IAEA | - | International Atomic Energy Agency | | | 1978-04-03<br>1978-05-25 |
| IFIN-HH | - | Institutul National de Cercetare - Dezvoltare in Fizica si Inginerie Nucleara- "Horia Hulubei" | Romania | EURAMET | 1983-12-15<br>2007-05-10 |
| IRA-METAS | IER | Institut de Radiophysique Appliquée - Institut fédéral de métrologie | Switzerland | EURAMET | 1979-05-17<br>2000-12-06 |
| JRC | IRMM, CBNM | EC-JRC Institute for Reference Materials and Measurements | European Union | EURAMET | 2005-01-27 |
| KRISS | KSRI | Korea Research Institute of Standards and Science | Republic of Korea | APMP | 1995-01-18 |
| LNE-LNHB | LMRI, LPRI | Laboratoire National de métrologie et d´Essais -Laboratoire National Henri Becquerel | France | EURAMET | 1978-07-17<br>1986-12-19<br>1999-10-20 |
| LNMRI-IRD | IEA, IPEN[b] | Laboratorio Nacional de Metrologia das Radiações Ionizantes | Brazil | SIM | 1976-10-07<br>1984-11-21 |

... Continuation of Table 1.

| NMI or laboratory | Previous acronyms | Full name | Country | RMO | Date of SIR measurement yyyy-mm-dd |
|---|---|---|---|---|---|
| NIM | - | National Institute of Metrology | China | APMP | 1978-10-12<br><br>2014-07-01 |
| NIST | NBS | National Institute of Standards and Technology | United States | SIM | 1980-09-03<br><br>1997-01-24<br>2007-08-07 |
| NMIJ | ETL | National Metrology Institute of Japan | Japan | APMP | 1976-11-24<br><br>2004-03-17 |
| NMISA | NAC, CSIR-NML[c] | National Metrology Institute of South Africa | South Africa | AFRIMETS | 1981-07-15<br><br><br>1992-10-27<br>2002-05-30 |
| NPL | - | National Physical Laboratory | United Kingdom | EURAMET | 1977-01-05<br><br>2000-06-30 |
| NRC | - | National Research Council | Canada | SIM | 2012-08-29 |
| POLATOM | IBJ, RC | National Centre for Nuclear Research Radioisotope Centre POLATOM | Poland | EURAMET | 2003-06-17 |
| PTB | - | Physikalisch-Technische Bundesanstalt | Germany | EURAMET | 1977-09-16<br><br>1988-01-22<br>2001-07-02<br>2017-05-10 |
| PTKMR | PDS, P3KRBiN | Pusat Teknologi Keselamatan dan Metrologi Radiasi | Indonesia | APMP | 1984-06-22 |
| TAEK | - | Turkish Atomic Energy Authority | Turkey | EURAMET | 2018-01-08 |

[a] federal Crown corporation, not part of the NMI in Canada (see text)
[b] IEA, IPEN are other institutes of the country.
[c] NAC is another institute of the country.

## 3. NMI standardization methods

Each NMI that submits ampoules to the SIR has measured the activity either by a primary standardization method or by using a secondary method, for example a calibrated ionization chamber. In the latter case, the traceability of the calibration needs to be clearly identified to ensure that appropriate correlations are taken into account.

A brief description of the standardization methods used by the laboratories, the activities submitted, the relative standard uncertainties and the half-life used by the participants are given in Table 2. The uncertainty budget for the new submission is given in Appendix D attached to this report; previous uncertainty budgets are given in the earlier K1 reports [3–8]. The list of acronyms used to summarize the methods is given in Appendix E.

Since 2003, the half-life used by the BIPM is 1925.5(5) days as published in IAEA TECDOC-619 [9]. The half-life of 1924.8(10) days [10] was used for the earlier results.

Table 2: Standardization methods of the participants for $^{60}$Co.

| **NMI or laboratory** | **Method used and the acronym** | **Activity $A_i$/kBq** | **Relative standard uncertainty /10$^{-2}$** | | **Reference date** | **Half-life /d** |
|---|---|---|---|---|---|---|
| | | | **A** | **B** | **yyyy-mm-dd** | |
| AECL | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1183.4[j]<br>1189.3 | 0.02<br>0.02 | 0.02<br>0.02 | 1980-02-05 17:00 UT | - |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 2069.9 | 0.05 | 0.05 | 1993-10-01 19:00 UT | |
| ANSTO | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-C0) | 1676 | 0.1 | 0.08 | 1992-04-08 23:00 UT | |
| ASMW | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1867.8[j]<br>1870.0 | 0.04<br>0.04 | 0.1<br>0.1 | 1976-06-15 12:00 UT | |
| BARC | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 584.4 | 0.03 | 0.25 | 1981-06-01 06:30 UT | |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 676.1 | 0.04 | 0.11 | 1994-05-01 06:30 UT | |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1072 | 0.6 | 0.3 | 2000-12-01 06:30 UT | 1922 |
| | $4\pi\beta$(LS)-$\gamma$ coincidence (4P-LS-BP-NA-GR-CO) | 1560 | 0.29 | 0.36 | 2011-03-15 06:30 UT | 1925 |
| BEV | Ionization chamber traceable to the NPL (4P-IC-GR-00-00-00) | 2980 | 0.07 | 0.58 | 1998-10-01 12:00 UT | 1925.5 |
| | Ionization chamber traceable to the NPL (4P-IC-GR-00-00-00) | 3081 | 0.08 | 0.22 | 2007-10-01 00:00 UT | 1925.2 [14] |
| BIPM | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 2611.2 | 0.014 | 0.02 | 1973-06-06 12:00 UT | - |
| BKFH | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1345[j]<br>1345 | 0.02<br>0.02 | 0.32<br>0.32 | 1977-03-01 12:00 UT | 1926(3) |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1490 | 0.1 | 0.26 | 1979-12-01 12:00 UT | |
| | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1808 | 0.03 | 0.25 | 1999-06-01 12:00 UT | 1925.5(5) [15] |

... Continuation of Table 2.

| NMI or laboratory | Method used and the acronym | Activity $A_i$/kBq | Relative standard uncertainty /$10^{-2}$ | | Reference date | Half-life /d |
|---|---|---|---|---|---|---|
| | | | A | B | yyyy-mm-dd | |
| CIEMAT | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) CIEMAT/NIST ( 4P-LS-BP-00-00-CN) | 364.8[a] | 0.11 | 0.1 | 1999-10-05 12:00 UT | 1925.2 |
| CMI-IIR | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 37 680 | 0.05 | 0.8 | 1977-02-23 13:00 UT | - |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 4190 | 0.1 | 0.3 | 1978-02-09 11:00 UT | 1925(4) |
| CNEA | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 785.3 | 0.05 | 0.12 | 1992-01-01 12:00 UT | - |
| | CIEMAT/NIST (4P-LS-BP-00-00-CN) PPC coincidence ( 4P-PP-BP-NA-GR-CO) | 641.2[b] | 0.21 | | 2002-10-31 00:00 UT | 1925.3 |
| | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) TDCR ( 4P-LS-BP-00-00-TD) | 175.5<br>174.1 | 0.38<br>0.32 | 0.37<br>0.33 | 2010-06-27<br>2010-07-12 | 1925.2(3) [14] |
| ENEA-INMRI | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1053 | 0.2 | 0.3 | 1990-12-01 12:00 UT | - |
| IAEA | $4\pi\beta$-$\gamma$ coincidence and anti-coincidence (4P-??-BP-??-GR-CO, 4P-??-BP-??-GR-AC)[c] | 1770 | 0.07 | 0.13 | 1977-04-01 12:00 UT | 1925(4) |
| | $4\pi\beta$-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO)[d] | 3600 | 0.1 | 0.3 | 1978-02-09 11:00 UT | 1925 |
| IFIN-HH | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO)[e] | 1444[j]<br>1424 | 0.05<br>0.05 | 0.09<br>0.09 | 1983-09-01 12:00 UT | - |
| | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 2149 | 0.08 | 0.32 | 2006-10-06 00:00 UT | 1925.2(4) |
| IRA-METAS | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 3007[j]<br>2982 | 0.02<br>0.02 | 0.1<br>0.1 | 1979-05-01 12:00 UT | - |
| | Ionization chamber calibrated in 1979 by $4\pi\beta$-$\gamma$ coincidence (4P-IC-GR-00-00-00) | 2518 | 0.014 | 0.1 | 2000-12-01 12:00 UT | 1925.3(2) |
| JRC | $4\pi$(PPC)-NaI well digital coincidence (4P-PP-BP-NA-GR-CO) | 1412 | 0.17 | 0.16 | 2004-05-01 00:00 UT | 1925.2(4) [16] |
| KRISS | $4\pi\beta$-$\gamma$ coincidence (4P-PP-BP-NA-GR-C0) | 511.6 | 0.3 | | 1994-10-01 12:00 UT | - |

... Continuation of Table 2.

| **NMI or laboratory** | **Method used and the acronym** | **Activity $A_i$/kBq** | **Relative standard uncertainty /$10^{-2}$** | | **Reference date** | **Half-life /d** |
|---|---|---|---|---|---|---|
| | | | **A** | **B** | **yyyy-mm-dd** | |
| LNE-LNHB | 4πβ-γ coincidence (4P-PC-BP-GL-GR-CO) | 3303.3[j]<br>3296.3 | 0.02<br>0.02 | 0.04<br>0.04 | 1978-06-15 12:00 UT | |
| | 4πβ-γ(Ge(Li) coincidence) (4P-PC-BP-GL-GR-CO) | 1777.5[j]<br>1781.2 | 0.03<br>0.03 | 0.05<br>0.05 | 1986-07-11 12:00 UT | |
| | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 2838.9 | 0.05 | | 1999-06-01 12:00 UT | 1925.2(4) |
| LNMRI-IRD | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 189.4[j]<br>193.8 | 0.14<br>0.14 | 0.04<br>0.04 | 1976-06-28 12:00 UT | - |
| | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 327.8[j]<br>334.5 | 0.04<br>0.04 | 0.08<br>0.08 | 1984-10-17 12:00 UT | |
| NIM | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 1746.2[j]<br>1746.4 | 0.05<br>0.05 | 0.2<br>0.2 | 1978-08-31 04:00 UT | |
| | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 1049.4 | 0.21 | 0.15 | 2014-06-07 00:00 UT | 1925.2(3) [14] |
| NIST | 4πβ-γ coincidence and anti-coincidence (4P-PC-BP-NA-GR-CO, 4P-PC-BP-NA-GR-AC) | 2038 | 0.06 | 0.15 | 1980-05-30 17:00 UT | - |
| | Ionization chamber (4P-IC-GR-00-00-00)[f] | 1402 | 0.03 | 0.23 | 1997-01-01 12:00 UT | |
| | 4πβ-γ anti-coincidence (4P-PC-BP-NA-GR-AC) | 183 | 0.03 | 0.18 | 2007-01-01 17:00 UT | 1925.2(3) [14] |
| NMIJ | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 1848[j]<br>1859 | 0.03<br>0.03 | 0.21<br>0.21 | 1976-11-01 12:00 UT | - |
| | 4πβ(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) | 1435.7 | 0.05 | 0.09 | 2004-02-01 12:00 UT | 1925.2 |
| NMISA | 4πβ(LS)-γ coincidence (4P-LS-BP-NA-GR-CO) | 4659[j]<br>5329 | 0.05<br>0.05 | 0.18<br>0.18 | 1981-06-19 10:00 UT | - |
| | 4πβ(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)[g] | 7066[j]<br>20 525 | 0.014<br>0.014 | 0.133<br>0.133 | 1992-09-10 12:00 UT | 1925.4(2) [17] |
| | 4πβ(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)[g] | 214 | 0.02 | 0.2[x] | 2002-03-28 12:00 UT | |
| NPL | Ionization chamber calibrated by 4πβ(PC)-γ coincidence (4P-IC-GR-00-00-00) | 667[j] | 0.03 | 1.02 | 1976-12-20 12:00 UT | - |

... Continuation of Table 2.

| **NMI or laboratory** | **Method used and the acronym** | **Activity** $A_i$**/kBq** | **Relative standard uncertainty /**$10^{-2}$ | | **Reference date** | **Half-life /d** |
|---|---|---|---|---|---|---|
| | | | **A** | **B** | **yyyy-mm-dd** | |
| | | 644 | 0.03 | 1.02 | | |
| | $4\pi\beta$(PPC)-$\gamma$ digital coincidence counting (4P-PP-BP-NA-GR-CO) | 2290 | 0.1 | 0.27 | 2000-02-01 12:00 UT | |
| NRC | $4\pi\beta$(PP)-$\gamma$ anti-coincidence (4P-PP-BP-NA-GR-AC) | 298.15 | 0.03 | 0.1 | 2011-11-09 17:00 UT | 1925.2(3) [14] |
| POLATOM | $4\pi\beta$(LS)-$\gamma$ coincidence and anti-coincidence (4P-LS-BP-NA-GR-CO, 4P-LS-BP-NA-GR-AC)[h] | 177.4 | 0.27 | 0.5 | 2003-04-03 12:00 UT | 1925.3 [18] |
| PTB | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 3222.6[j]<br>3176.0 | 0.02<br>0.02 | 0.07<br>0.07 | 1977-01-01 12:00 UT | - |
| | Ionization chamber calibrated by $4\pi\beta$(PC)-$\gamma$ coincidence (4P-IC-GR-00-00-00) | 100 020[j]<br>18 272<br>2036 | 0.02<br>0.02<br>0.03 | 0.07<br>0.06<br>0.09 | 1987-09-01 12:00 UT | |
| | Ionization chamber calibrated by $4\pi\beta$-$\gamma$ coincidence (4P-IC-GR-00-00-00) | 13 760 | 0.03 | 0.22 | 2001-01-01 12:00 UT | 1925.3(4) |
| | $4\pi$PC-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO)<br>$4\pi$LS-$\gamma$ coincidence ( 4P-LS-BP-NA-GR-CO)<br>CIEMAT/NIST ( 4P-LS-MX-00-00-CN)<br>TDCR ( 4P-LS-MX-00-00-TD) | 2068.7[i] | 0.05 | 0.2 | 2016-01-01 00:00 UT | 1925.3(4) |
| PTKMR | $4\pi\beta$(PC)-$\gamma$ coincidence (4P-PC-BP-NA-GR-CO) | 1014[j]<br>1019 | 0.4<br>0.4 | | 1984-06-01 08:00 UT | - |
| TAEK | Ionisation chamber calibrated at the PTB in 2012 (4P-IC-GR-00-00-00) | 888.7 | 0.49 | 1.16 | 2016-04-01 12:00 UT | 1925.3(3) |

... Continuation of Table 2.

| NMI or laboratory | Method used and the acronym | Activity $A_i$/kBq | Relative standard uncertainty /$10^{-2}$ | | Reference date | Half-life /d |
|---|---|---|---|---|---|---|
| | | | A | B | yyyy-mm-dd | |

[a] For the CIEMAT/NIST method, a $^3$H tracer from LNE-LNHB was used. The result is the weighted mean of the different methods.

[b] The activity concentrations measured are 175.6 kBq/g and 175.7 kBq/g respectively. The weighted mean result is used for the comparison.

[c] With the Radiochemical Centre, Amersham, UK

[d] With the UVVVR

[e] see details in [11]

[f] calibrated in 1980 by $4\pi\beta$-$\gamma$ coincidence and anti-coincidence

[g] see details in [12]

[h] see details in [13]

[i] The final result is the weighted mean of the results of four methods. The relative combined uncertainty (0.20 %) of the TDCR result is adopted for the final result. This is larger than the internal and external relative uncertainties of the weigthed mean. Correlations and anti-correlations between the results were not considered

[j] Several samples submitted

[x] The uncertainty of 0.08 % submitted originally has been increased to include the uncertainty of an additional correction (see section 4 of [4]).

Details regarding the solutions submitted are shown in Table 3, including any impurities, when present, as identified by the laboratories. When given, the standard uncertainties on the evaluations are shown.

Table 3: Details of each solution of $^{60}$Co submitted.

| NMI or laboratory / SIR year | Chemical composition | Solvent conc. /(mol dm$^{-3}$) | Carrier conc. /(µg g$^{-1}$) | Density /(g cm$^{-3}$) | Relative activity of any impurity[c] |
|---|---|---|---|---|---|
| AECL 1980 | $CoCl_2$ in HCl | 0.3 | $Co^{++}$: 10 | 1 | - |
| 1993 | $CoCl_2.6H_2O$ in HCl | 0.1 | $CoCl_2.6H_2O$: 100 | 1 | - |
| ANSTO 1992 | $CoCl_2$ in HCl | 0.1 | Co: 47 | 1 | - |
| ASMW 1976 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 20 | - | - |
| BARC 1981 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 55 | - | - |
| 1994 | $Co(NO_3)_2$ in $HNO_3$ | 0.1 | $Co(NO_3)_2$: 50 | 1 | - |
| 2001 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 25 | 1 | - |
| 2012 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 20 | 1 | - |
| BEV 1998 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |
| 2007 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |
| BIPM 1976 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 5 | 1 | - |
| BKFH 1977 | Co in HCl | 0.1 | Co: 25 | - | - |
| 1979 | Co in HCl | 0.1 | Co: 25 | - | - |
| 1999 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 25 | - | - |

... Continuation of Table 3.

| **NMI or laboratory / SIR year** | **Chemical composition** | **Solvent conc. / (mol dm$^{-3}$)** | **Carrier conc. / (µg g$^{-1}$)** | **Density / (g cm$^{-3}$)** | **Relative activity of any impurity[c]** |
|---|---|---|---|---|---|
| CIEMAT 1999 | $CoCl_2$ in HCl | 1 | $CoCl_2$: 413 | 1.019 | $^{63}$Ni: 0.012 % |
| CMI-IIR 1977 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 20 | 1 | <0.1 % |
| 1978 | $CoCl_2$ in HCl | 0.08 | $CoCl_2$: 20 | - | <0.1 % |
| CNEA 1992 | $CoCl_2.6H_2O$ in HCl | 0.1 | $CoCl_2$: 10 | 0.999 | <0.1 % |
| 2003 | $CoCl_2.6H_2O$ in HCl | 1 | $CoCl_2.6H_2O$: 150 | 1.015 | <0.01 % |
| 2011 | $CoCl_2.6H_2O$ in HCl | 0.1 | $CoCl_2.6H_2O$: 90 | 1 | - |
| ENEA-INMRI 1991 | $CoCl_2.6H_2O$ in HCl | 0.1 | $Co^{++}$: 100 | 0.999 | $^{137}$Cs: 0.003(1) % <br> $^{63}$Ni:0.026(5) % |
| IAEA 1978 | Co in HCl | 0.1 | Co: 100 | - | - |
| 1978 | $CoCl_2$ in HCl | 0.08 | $CoCl_2$: 10 | - | <0.1 % |
| IFIN-HH 1983 | $CoCl_2$ in HCl | 0.1 | Co: 50 | 1 | - |
| 2007 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 100 | 1 | <0.01 % |
| IRA-METAS 1979 | $Co^{++}$ in HCl | 0.1 | $Co^{++}$: 30 | - | - |
| 2000 | $Co^{++}$ in HCl | 0.1 | $Co^{++}$: 25 | 1.000(7) | - |
| JRC 2005 | $CoCl_2$ in HCl | 0.1 | Co: 50 | - | -[a] |
| KRISS 1995 | $CoCl_2.6H_2O$ in HCl | 0.5 | $CoCl_2.6H_2O$: 46 | 1.0061 | - |
| LNE-LNHB 1978 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 10 | 0.999 | <0.02 % |
| 1986 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 10 | 0.999 | <0.01 % |
| 1999 | Co in HCl | 0.1 | $Co^{++}$: 10 | 1.001 | - |
| LNMRI-IRD 1976 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 17.1 | - | - |
| 1984 | Co in HCl | 0.2 | Co: 0.02 | 1.003 | - |
| NIM 1978 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 100 | 1.0004 | - |
| 2014 | $Co^{++}$ in HCl | 0.1 | $Co^{++}$: 10 | 1.006 | - |
| NIST 1980 | Co in HCl | 1 | Co: 50 | 1.015(2) | - |
| 1997 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 100 | 1 | - |
| 2007 | $CoCl_2$ in HCl | 1.1 | $CoCl_2$: 130 | 1.017 | $^{57}$Co: 1.5(2)x10$^{-5}$ |
| NMIJ 1976 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$:50 | - | - |
| 2004 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 100 | 1.002 | - |
| NMISA 1981 | $CoCl_2$ in HCl | 1 | $CoCl_2$: 540 | 1.037 | - |
| 1992 | $CoCl_2.6H_2O$ in HCl | 1 | $Co^{++}$: 110 | 1.0183 | - |
| 2002 | $CoCl_2.6H_2O$ in HCl | - | $Co^{++}$: 110 | 1.0183 | - |
| NPL 1977 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | - | - |
| 2000 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 25 | 1 | - |

... Continuation of Table 3.

| **NMI or laboratory / SIR year** | **Chemical composition** | **Solvent conc. /(mol dm$^{-3}$)** | **Carrier conc. /(µg g$^{-1}$)** | **Density /(g cm$^{-3}$)** | **Relative activity of any impurity**[c] |
|---|---|---|---|---|---|
| NRC 2012 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 230 | 1.000(3) | -[b] |
| POLATOM 2003 | $CoCl_2$ in HCl | 0.1 | Co: 25 | 1 | <0.1 % |
| PTB 1977 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | - | - |
| 1988 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |
| 2001 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |
| 2017 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |
| PTKMR 1984 | $CoCl_2.6H_2O$ in HCl | 1 | $CoCl_2.6H_2O$: 50.5 | 0.990(1) | - |
| TAEK 2018 | $CoCl_2$ in HCl | 0.1 | $CoCl_2$: 50 | 1 | - |

[a] Confirmed by measurements carried out at the BIPM
[b] None detected
[c] the ratio of the activity of the impurity to the activity of $^{60}$Co at the reference date

## 4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a database known as the "master-file". The latest submission has added 2 ampoules for the activity measurements for $^{60}$Co giving rise to 72 ampoules in total. The SIR equivalent activity, $A_{ei}$, for each ampoule received from each NMI, $i$, including both previous and new results, is given in Table 4.

The relative standard uncertainties arising from the measurements in the SIR are also shown. This uncertainty is additional to that declared by the NMI ($u(A_i)$) for the activity measurement shown in Table 2. Although submitted activities are compared with a given source of $^{226}$Ra, all the SIR results are normalized to the radium source number 5 [1]. No recent submission has been identified as a pilot study so the most recent result of each NMI is normally eligible for Appendix B of the MRA [2].

Table 4: Results of SIR measurement of $^{60}$Co.

| **NMI or laboratory / SIR year** | $m_i$ **/g** | $A_i$ **/kBq** | $^{226}$**Ra source** | $A_{ei}$ **/kBq** | **Relative uncert. from SIR /10$^{-4}$** | $u_{ci}$ **/kBq** | $A_{ei}$ **for KCRV /kBq** |
|---|---|---|---|---|---|---|---|
| AECL 1980 | 0.941 77[a] | 1183.4 | 3 | 7050 | 5 | 4 | - |
| | 0.946 42 | 1189.3 | 3 | 7051 | 5 | 4 | - |
| 1993 | 0.233 2[a] | 2069.9 | 4 | 7064 | 4 | 6 | 7064(6) |
| ANSTO 1992 | 3.557 1 | 1676 | 4 | 7056 | 4 | 10 | 7056(10) |
| ASMW 1976 | 3.601 0 | 1867.8 | 4 | 7063 | 4 | 8 | 7062(8)[d] |
| | 3.605 2 | 1870.0 | 4 | 7061 | 4 | 8 | - |
| BARC 1981 | 3.599 8 | 584.4 | 3 | 7078 | 6 | 19 | - |
| 1994 | 3.605 8 | 676.1 | 3 | 7076 | 5 | 9 | - |

... Continuation of Table 4.

| **NMI or laboratory / SIR year** | $m_i$ /g | $A_i$ /kBq | $^{226}$**Ra source** | $A_{\mathbf{e}i}$ /kBq | **Relative uncert. from SIR** $/10^{-4}$ | $u_{\mathbf{c},i}$ /kBq | $A_\mathbf{e}$ **for KCRV** /kBq |
|---|---|---|---|---|---|---|---|
| 2001 | 3.614 5 | 1072 | 3 | 7099 | 5 | 46 | 7099(46) |
| 2012 | 3.603 23 | 1560 | 4 | 7184 | 5 | 33 | - |
| BEV 1998 | 3.618 | 2980 | 4 | 7049 | 4 | 42 | - |
| 2007 | 3.606 9 | 3081 | 4 | 7057 | 4 | 17 | - |
| BIPM 1976 | 3.757 9 | 2611.2 | 4 | 7066 | 4 | 4 | 7066(4) |
| BKFH 1977 | 3.600 7 | 1345 | 4 | 7048 | 5 | 23 | - |
| | 3.600 6 | 1345 | 4 | 7043 | 5 | 23 | - |
| 1979 | 3.602 1 | 1490 | 4 | 7045 | 4 | 20 | - |
| 1999 | 3.612 2 | 1808 | 4 | 7051 | 5 | 18 | 7051(18) |
| CIEMAT 1999 | 3.682 16 | 364.8 | 2 | 7090 | 7 | 11 | 7090(11) |
| CMI-IIR 1977 | 3.568 43 | 37 680 | 5 | 7051 | 4 | 56 | - |
| 1978 | 3.615 29 | 4190 | 4 | 7054 | 4 | 20 | 7054(20) |
| CNEA 1992 | 2.075 43 | 785.3 | 3 | 7126 | 5 | 10 | - |
| 2003 | 3.650 37 | 641.2 | 3 | 7050 | 5[b] | 15 | - |
| 2011 | 3.606 43 | 175.5 | 2 | 7079 | 9 | 38 | 7070(26)[e] |
| | | 174.1 | | 7060 | | 33 | - |
| ENEA-INMRI 1991 | 3.57 | 1053 | 3 | 7065 | 6 | 26 | 7065(26) |
| IAEA 1978 | 3.699 3 | 1770 | 4 | 7052 | 5 | 11 | - |
| 1978 | 3.584 18 | 3600 | 4 | 7053 | 4 | 20 | - |
| IFIN-HH 1983 | 3.533 9 | 1444 | 4 | 7066 | 4 | 8 | - |
| | 3.485 4 | 1424 | 4 | 7068 | 4 | 8 | - |
| 2007 | 3.617 39 | 2149 | 4 | 7101 | 4 | 24 | 7101(24) |
| IRA-METAS 1979 | 3.629 93 | 3007 | 4 | 7039 | 4 | 8 | 7041(8)[d] |
| | 3.599 67 | 2982 | 4 | 7042 | 4 | 8 | - |
| 2000 | 3.598 | 2518 | 4 | 7037 | 4 | 8 | - |
| JRC 2005 | 3.497 98 | 1412 | 4 | 7039 | 4 | 17 | 7039(17) |
| KRISS 1995 | 3.585 26 | 511.6 | 3 | 7047 | 7 | 22 | 7047(22) |
| LNE-LNHB 1978 | 3.626 37 | 3303.3 | 4 | 7053 | 4 | 4 | - |
| | 3.618 76 | 3296.3 | 4 | 7052 | 4 | 4 | - |
| 1986 | 3.592 43 | 1777.5 | 4 | 7065 | 4 | 5 | - |
| | 3.599 83 | 1781.2 | 4 | 7063 | 4 | 5 | - |
| 1999 | 3.583 06 | 2838.9 | 4 | 7060 | 4 | 4 | 7060(4) |
| LNMRI-IRD 1976 | 3.459 33 | 189.4 | 2 | 7062 | 9 | 12 | - |
| | 3.539 01 | 193.8 | 2 | 7065 | 8 | 12 | - |
| 1984 | 3.468 94 | 327.8 | 2 | 7081 | 6 | 8 | 7077(8)[d] |
| | 3.540 29 | 334.5 | 2 | 7073 | 6 | 8 | - |
| NIM 1978 | 3.605 25 | 1746.2 | 4 | 7046 | 4 | 15 | - |
| | 3.605 67 | 1746.4 | 4 | 7042 | 4 | 15 | - |
| 2014 | 3.611 28 | 1049.4 | 3 | 7052 | 5 | 19 | 7052(19) |
| NIST 1980 | 3.666 88 | 2038 | 4 | 7069 | 4 | 12 | - |
| 1997 | 3.608 47 | 1402 | 4 | 7085 | 4 | 17 | - |

... Continuation of Table 4.

| **NMI or laboratory / SIR year** | $m_i$ /g | $A_i$ /kBq | $^{226}$**Ra source** | $A_{ei}$ /kBq | **Relative uncert. from SIR** /$10^{-4}$ | $u_{c,i}$ /kBq | $A_e$ **for KCRV** /kBq |
|---|---|---|---|---|---|---|---|
| 2007 | 3.659 57 | 183 | 2 | 7083 | 8 | 14 | 7083(14) |
| NMIJ 1976 | 3.607 86 | 1848 | 4 | 7044 | 4 | 16 | - |
| | 3.628 78 | 1859 | 4 | 7044 | 4 | 16 | - |
| 2004 | 3.633 75 | 1435.7 | 4 | 7050 | 4 | 8 | 7050(8) |
| NMISA 1981 | 3.600 | 4659 | 5 | 7064 | 3 | 13 | - |
| | 3.613 | 5329 | 5 | 7067 | 3 | 13 | - |
| 1992 | 3.612 | 7066 | 5 | 7066 | 3 | 10 | 7066(10)[d] |
| | 3.610 | 20 525 | 5 | 7065 | 3 | 10 | - |
| 2002 | 3.596 | 214 | 2 | 7098[c] | 10 | 16 | - |
| NPL 1977 | 3.770 4 | 667 | 3 | 7059 | 5 | 72 | - |
| | 3.640 7 | 644 | 3 | 7057 | 5 | 72 | - |
| 2000 | 3.567 15 | 2290 | 4 | 7053 | 4 | 21 | 7053(21) |
| NRC 2012 | 3.605 6 | 298.15 | 2 | 7065 | 8 | 9 | 7065(9) |
| POLATOM 2003 | 3.699 87 | 177.4 | 2 | 7040 | 8 | 40 | 7040(40) |
| PTB 1977 | 3.670 0 | 3222.6 | 4 | 7062 | 5 | 6 | - |
| | 3.616 9 | 3176.0 | 4 | 7060 | | 6 | - |
| 1988 | 3.599 2 | 100 020 | 5 | 7068 | 3 | 6 | - |
| | 3.603 3 | 18 272 | 5 | 7056 | 3 | 5 | - |
| | 3.644 5 | 2036 | 4 | 7056 | 4 | 7 | - |
| 2001 | 3.600 7(9) | 13 760 | 5 | 7057 | 3 | 16 | - |
| 2017 | 3.600 56 | 2068.7 | 4 | 7057 | 4 | 15 | 7057(15) |
| PTKMR 1984 | 3.550 | 1014 | 3 | 7103 | 5 | 27 | 7104(27)[d] |
| | 3.567 | 1019 | 3 | 7105 | 6 | 27 | - |
| TAEK 2018 | 3.584 | 888.7 | 3 | 7048 | 5 | 89 | - |

[a] mass of solution before dilution
[b] solution contained in a CNEA-type ampoule (see section 4 of [4])
[c] not representative of the activity presently disseminated by NMISA (see section 4 of [4])
[d] An average value and average uncertainty between all submitted samples is used for the KCDB [19].
[e] An average value between all methods has been done.

### *4.1. The key comparison reference value*

In May 2013, the CCRI(II) decided to calculate the key comparison reference value (KCRV) by using the power-moderated weighted mean [20] rather than an unweighted mean, as had been the policy. This type of weighted mean is similar to a Mandel-Paule mean in that the NMIs' uncertainties may be increased until the reduced chisquared value is one. In addition, it allows for a power $\alpha$ smaller than two in the weighting factor. As proposed in [20], $\alpha$ is taken as $2 - 3/N$ where $N$ is the number of results selected for the KCRV. Therefore, all SIR key comparison results can be selected for the KCRV with the following provisions:

(a) only results for solutions standardized by primary techniques are accepted, with the exception of radioactive gas standards (for which results from transfer instrument measurements that are directly traceable to a primary measurement in the laboratory may be included);

(b) each NMI or other laboratory may only use one result (normally the most recent result or the mean if more than one ampoule is submitted);

(c) results more than 20 years old are included in the calculation of the KCRV but are not included in data shown in the KCDB or in the plots in this report, as they have expired;

(d) possible outliers can be identified on a mathematical basis and excluded from the KCRV using the normalized error test with a test value of 2.5 and using the modified uncertainties;

(e) results can also be excluded for technical reasons; and

(f) the CCRI(II) is always the final arbiter regarding excluding any data from the calculation of the KCRV.

The data set used for the evaluation of the KCRVs is known as the KCRV file and is a reduced data set from the SIR master-file. Although the KCRV may be modified when other NMIs participate, on the advice of the Key Comparison Working Group of the CCRI(II), such modifications are made only by the CCRI(II) during one of its biennial meetings, or by consensus through electronic means (e.g., email) as discussed at the CCRI(II) meeting in 2013.

The BARC (2012) result is considered as an outlier so that their earlier result in 2001 is eligible to be kept in the KCRV. Consequently, using the recent result produces an updated KCRV for $^{60}$Co in 2020 of **7062.7(27) kBq** with the power $\alpha$ =1.88 that has been calculated using the previously published results, selected as shown in Table 4, for the ASMW (1976), BIPM (1976), CMI-IIR (1978), IRA-METAS (1979), PTKMR (1984), LNMRI-IRD (1984), ENEA-INMRI (1991), ANSTO (1992), NMISA (NAC, 1992), AECL (1993), KRISS (1995), CIEMAT (1999), LNE-LNHB (1999), BKFH (1999), NPL (2000), BARC (2001), POLATOM (2003), NMIJ (2004), JRC (2005), IFIN-HH (2007), NIST (2007), CNEA (2011), NRC (2012), NIM (2014), and the PTB (2017) result. This can be compared with the previous KCRV values of 7064.6(38) kBq published in 2003 [3] , 7061.3(35) kBq published in 2006 [6] , 7063.3(40) kBq published in 2010 [7] and 7062.7(27) kBq published in 2017 [8].

### *4.2. Degrees of equivalence*

Every participant in a comparison is entitled to have one result included in the KCDB as long as the NMI is a signatory or designated institute listed in the CIPM MRA, and the result is valid (i.e., not older than 20 years). Normally, the most recent result is the one included. An NMI may withdraw its result only if all other participants agree.

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the KCRV [2]. The degree of equivalence is expressed quantitatively in terms of the deviation from the key comparison reference value and the expanded uncertainty of this deviation ($k = 2$). The degree of equivalence between any pair of national measurement standards is expressed in terms of their difference and the expanded uncertainty of this difference and is independent of the choice of key comparison reference value.

### *4.2.1. Comparison of a given NMI result with the KCRV*

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

$$D_i = A_{\mathrm{e}i} - \mathrm{KCRV} \tag{1}$$

and the expanded uncertainty ($k = 2$) of this difference, $U_i$, known as the equivalence uncertainty; hence

$$U_i = 2u(D_i) \tag{2}$$

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

$$u^2(D_i) = (1 - 2w_i)u_i^2 + u^2(\mathrm{KCRV}) \tag{3}$$

However, when the result of the NMI $i$ is not included in the KCRV, then

$$u^2(D_i) = u_i^2 + u^2(\mathrm{KCRV}) \tag{4}$$

### *4.2.2. Comparison between pairs of NMI results*

The degree of equivalence between the results of any pair of NMIs, $i$ and $j$, is expressed as the difference $D_{ij}$ in the values

$$D_{ij} = D_i - D_j = A_{\mathrm{e}i} - A_{\mathrm{e}j} \tag{5}$$

and the expanded uncertainty ($k = 2$) of this difference, $U_{ij} = 2u(D_{ij})$, where

$$u^2(D_{ij}) = u_i^2 + u_j^2 - 2u(A_{\mathrm{e}i}, A_{\mathrm{e}j}) \tag{6}$$

where any obvious correlations between the NMIs (such as a traceable calibration, or correlations normally coming from the SIR or from the linking factor in the case of linked comparison) are subtracted using the covariance $u(A_{\mathrm{e}i}, A_{\mathrm{e}j})$ (see [21] for more detail). However, the CCRI decided in 2011 that these pair-wise degrees of equivalence no longer need to be published as long as the methodology is explained.

Table B1 shows the matrix of all the degrees of equivalence as they will appear in the KCDB. It should be noted that for consistency within the KCDB, a simplified level of nomenclature is used with $A_{ei}$ replaced by $x_i$. The introductory text is that agreed for the comparison. The graph of the results in Table 5, corresponding to the degrees of equivalence with respect to the KCRV (identified as $x_R$ in the KCDB), is shown in Figure C1. This graphical representation indicates in part the degree of equivalence between the NMIs but obviously does not take into account the correlations between the different NMIs. It should be noted that the final data in this paper, while correct at the time of publication, will become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA [2] are those available in the KCDB.

## 5. Conclusion

The BIPM ongoing key comparison for $^{60}$Co, BIPM.RI(II)-K1.Co-60, currently comprises 14 results. The KCRV has been recalculated including the result from the PTB (Germany). The results have been analyzed with respect to the updated KCRV, providing degrees of equivalence for 14 national metrology institutes. The degrees of equivalence have been approved by the CCRI(II) and are published in the BIPM key comparison database. Other results may be added when other NMIs contribute $^{60}$Co activity measurements to this comparison or take part in other linked comparisons.

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**Appendix A. Introductory text for $^{60}$Co degrees of equivalence**

**Key comparison BIPM.RI(II)-K1.Co-60**

**MEASURAND: Equivalent activity of $^{60}$Co**

Key comparison reference value: the SIR reference value $x_{\mathrm{R}}$ for this radionuclide is 7062.7 kBq , with a standard uncertainty, $u_{\mathrm{R}}$ equal to 2.7 kBq (see Section 4.1 of the Final Report). The value $x_i$ is taken as the equivalent activity for a laboratory $i$.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms: $D_i = (x_i - x_{\mathrm{R}})$ and $U_i$, its expanded uncertainty ($k = 2$), both expressed in kBq, and $U_i = 2((1 - 2w_i)u_i^2 + u_{\mathrm{R}}^2)^{1/2}$, where $w_i$ is the weight of laboratory $i$ contributing to the calculation of $x_{\mathrm{R}}$.

## Appendix B. Table of degrees of equivalence for BIPM.RI(II)-K1.Co-60

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Co-60

| **NMI** $i$ | $D_i$ **/kBq** | $U_i$ **/kBq** |
|---|---|---|
| IRA-METAS | -26 | 17 |
| NMISA | 35 | 32 |
| POLATOM | -23 | 80 |
| NMIJ | -13 | 16 |
| JRC | -24 | 34 |
| IFIN-HH | 38 | 48 |
| NIST | 20 | 28 |
| BEV | -6 | 34 |
| CNEA | 7 | 52 |
| BARC | 121 | 66 |
| NRC | 2 | 18 |
| NIM | -11 | 38 |
| PTB | -6 | 30 |
| TAEK | -15 | 178 |

## Appendix C. Graph of degrees of equivalence with the KCRV for $^{60}$Co (as it appears in Appendix B of the MRA)

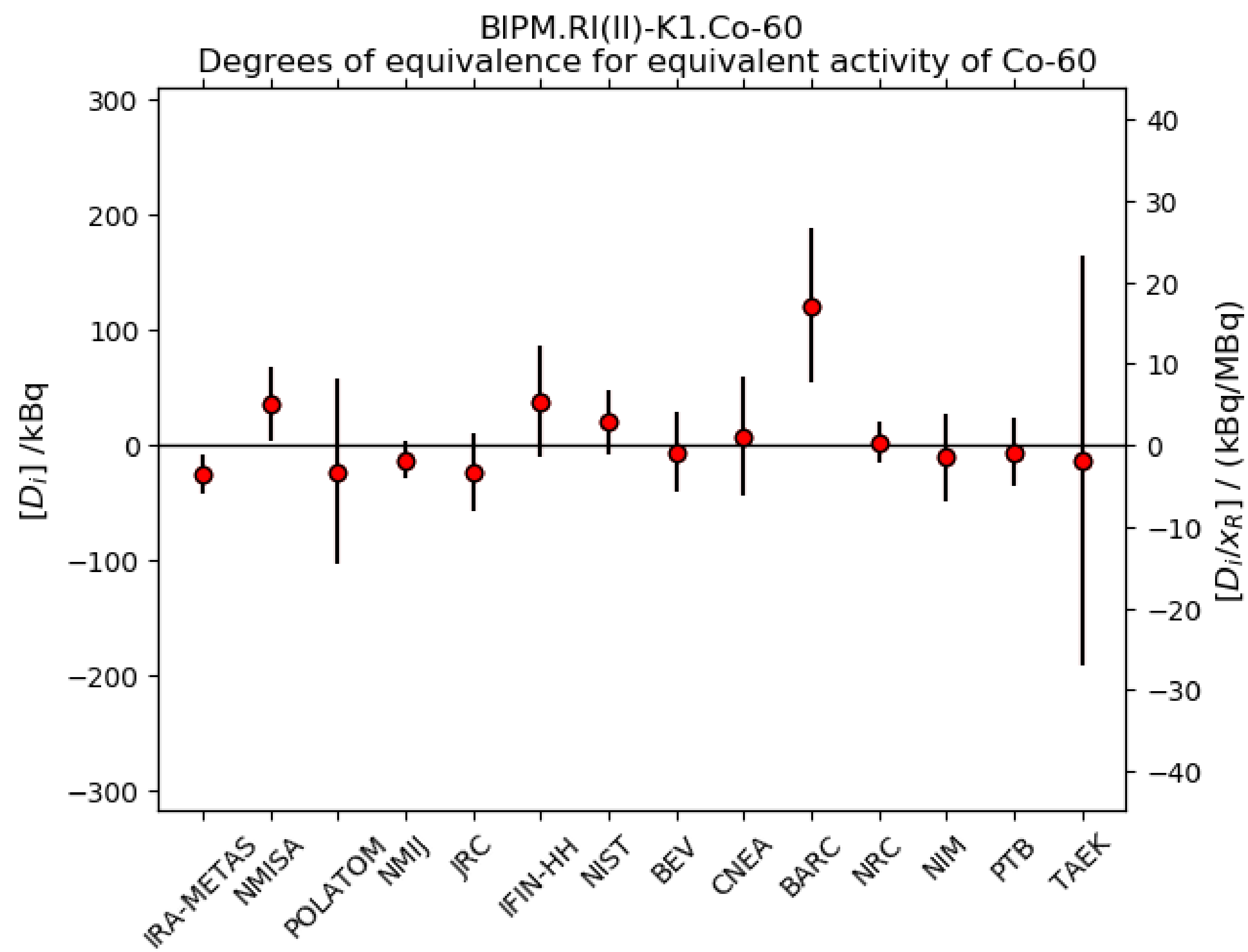


**Figure C1.** Degrees of equivalence for equivalent activity of $^{60}$Co.

## Appendix D. Uncertainty budgets for the activity of $^{60}$Co submitted to the SIR

**Detailed Uncertainty Budget (4P-PC-BP-NA-GR-CO)**

Laboratory: **PTB**; Radionuclide: **Co-60**; Ampoule number: **2016-1384**.

*Uncertainty components**, in % of the activity concentration, due to

| | | Remarks | Evaluation type (A or B) | Relative sensitivity Factor |
|---|---|---|---|---|
| counting statistics | **0.105** | | **A** | |
| weighing | **0.05** | | **B** | |
| dead time | **negligible** | | **B** | |
| background | **0.03** | | **A** | |
| pile-up | **n.a.** | | | |
| counting time | **negligible** | | **B** | |
| adsorption | **0.05** | | **B** | |
| impurities | **<0.03** | **no impurities detected** | **B** | |
| model and decay data | **negligible** | | **B** | |
| decay correction | **<0.01** | | **B** | |
| resolving time | **negligible** | | **B** | |
| extrapolation of efficiency curve | **0.026** | | **B** | |
| fitting uncertainty | **0.196** | | **B** | |
| dilution | **0.02** | **two dilution steps** | **B** | |
| combined uncertainty (as quadratic sum of all uncertainty components) | **0.24** | | | |

* The uncertainty components are to be considered as approximations of the corresponding standard deviations (see also *Metrologia*, 1981, **17**, 73 and *Guide to expression of uncertainty in measurement*, http://www.bipm.org/en/publications/guides/

**Detailed Uncertainty Budget (4P-LS-BP-NA-GR-CO)**

Laboratory: **PTB**; Radionuclide: **Co-60**; Ampoule number: **2016-1384**.

*Uncertainty components**, in % of the activity concentration, due to

| | | Remarks | Evaluation type (A or B) | Relative sensitivity Factor |
|---|---|---|---|---|
| counting statistics | **0.06** | | **A** | |
| weighing | **0.03** | | **B** | |
| dead time | **0.20** | | **B** | |
| background | **0.03** | | **A** | |
| pile-up | **n.a.** | | | |
| counting time | **negligible** | | **B** | |
| adsorption | **0.05** | | **B** | |
| impurities | **<0.03** | **no impurities detected** | **B** | |
| model and decay data | **negligible** | | **B** | |
| decay correction | **<0.01** | | **B** | |
| resolving time | **0.20** | | **B** | |
| extrapolation of efficiency curve | **0.01** | | **B** | |
| fitting uncertainty | **0.14** | | **B** | |
| dilution | **0.02** | **two dilution steps** | **B** | |
| combined uncertainty (as quadratic sum of all uncertainty components) | **0.33** | | | |

* The uncertainty components are to be considered as approximations of the corresponding standard deviations (see also *Metrologia*, 1981, **17**, 73 and *Guide to expression of uncertainty in measurement*, http://www.bipm.org/en/publications/guides/

**Detailed Uncertainty Budget (4P-LS-MX-00-00-CN)**

Laboratory: **PTB**; Radionuclide: **Co-60**; Ampoule number: **2016-1384**.

*Uncertainty components**, in % of the activity concentration, due to

| | | Remarks | Evaluation type (A or B) | Relative sensitivity Factor |
|---|---|---|---|---|
| counting statistics | **0.07** | | **A** | |
| weighing | **0.03** | | **B** | |
| dead time | **0.10** | | **B** | |
| background | **0.03** | | **A** | |
| pile-up | **n.a.** | | | |
| counting time | **0.01** | | **B** | |
| adsorption | **0.05** | | **B** | |
| impurities | **<0.03** | **no impurities detected** | **B** | |
| tracer and interpolation of efficiency curve | **0.05** | | **B** | |
| model and decay data | **0.16** | | **B** | |
| ionization quenching and *kB* value | **0.07** | | **B** | |
| TDCR value and interpolation of efficiency curve | **n.a.** | | | |
| decay correction | **<0.01** | | **B** | |
| PMT asymmetry | **0.05** | | **B** | |
| resolving time | **n.a.** | | | |
| extrapolation of efficiency curve | **n.a.** | | | |
| fitting uncertainty | **n.a.** | | | |
| dilution | **0.02** | **two dilution steps** | **B** | |
| combined uncertainty (as quadratic sum of all uncertainty components) | **0.24** | | | |

* The uncertainty components are to be considered as approximations of the corresponding standard deviations (see also *Metrologia*, 1981, **17**, 73 and *Guide to expression of uncertainty in measurement*, http://www.bipm.org/en/publications/guides/

**Detailed Uncertainty Budget (4P-LS-MX-00-00-TD)**

Laboratory: **PTB**; Radionuclide: **Co-60**; Ampoule number: **2016-1384**.

*Uncertainty components**, in % of the activity concentration, due to

| | | Remarks | Evaluation type (A or B) | Relative sensitivity Factor |
|---|---|---|---|---|
| counting statistics | **0.04** | | **A** | |
| weighing | **0.03** | | **B** | |
| dead time | **0.03** | | **B** | |
| background | **0.03** | | **A** | |
| pile-up | **n.a.** | | | |
| counting time | **0.01** | | **B** | |
| adsorption | **0.05** | | **B** | |
| impurities | **<0.03** | **no impurities detected** | **B** | |
| tracer and interpolation of efficiency curve | **n.a.** | | | |
| model and decay data | **0.12** | | **B** | |
| ionization quenching and *kB* value | **0.07** | | **B** | |
| TDCR value and interpolation of efficiency curve | **0.10** | | **B** | |
| decay correction | **<0.01** | | **B** | |
| PMT asymmetry | **0.05** | | **B** | |
| resolving time | **n.a.** | | | |
| extrapolation of efficiency curve | **n.a.** | | | |
| fitting uncertainty | **n.a.** | | | |
| dilution | **0.02** | **two dilution steps** | **B** | |
| combined uncertainty (as quadratic sum of all uncertainty components) | **0.20** | | | |

* The uncertainty components are to be considered as approximations of the corresponding standard deviations (see also *Metrologia*, 1981, **17**, 73 and *Guide to expression of uncertainty in measurement*, http://www.bipm.org/en/publications/guides/

**Detailed Uncertainty Budget**

Laboratory: _ _ TAEK _ _ _; Radionuclide: _ _ Co-60 _ _; Ampoule number: _ _ 2 _ _.

*Uncertainty components**, in % of the activity concentration, due to

| | | Remarks | Evaluation type (A or B) | Relative sensitivity Factor |
|---|---|---|---|---|
| counting statistics | 0.42 | current measurement | A | 1 |
| weighing | 0.003 | 2 µg precision microbalance | B | 1 |
| dead time | | | | |
| background | | included in counting statistics | | |
| pile-up | | | | |
| counting time | | | | |
| adsorption | | Negligible (counting rinsed ampoules with HPGe detector) | | |
| impurities | | Negligible (not detectable at 20 cm with a HPGe detector) | | |
| tracer | | | | |
| input parameters and statistical model | | | | |
| quenching | | | | |
| interpolation from calibration curve | | | | |
| decay-scheme parameters | 0.0028 | decay correction unc. | B | 1 |
| half life ($T_{1/2}$ = 10975.8 d ; $u$ = 29.2 d) | ~ 0 | decay correction during measurement period unc. | | |
| self absorption | | | | |
| extrapol.of efficiency curve | | | | |
| other effects (if relevant) (explain) | 0.25 | Cs-137 ref source current meas. unc. | A | 1 |
| | 1.16 | Ionization chamber cal. factor unc. | B | 1 |
| combined uncertainty (as quadratic sum of all uncertainty components) | 1.26 | equation used is shown below | | |

$$a = \frac{A}{m} = k_{IK} \cdot C_{geom} \cdot C_{impurity} \cdot C_{Decay} \cdot C_{Duration} \cdot \frac{I}{I_R} \cdot \frac{A_R}{m}$$

* The uncertainty components are to be considered as approximations of the corresponding standard deviations (see also *Metrologia*, 1981, **17**, 73 and *Guide to expression of uncertainty in measurement*, JCGM 100:2008

## Appendix E. 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** |
|---|---|---|---|
| 4 $\pi$ | 4P | proportional counter | PC |
| defined solid angle | SA | press. Prop. Counter | PP |
| 2 $\pi$ | 2P | liquid scintillation counting | LS |
| undefined solid angle | UA | NaI(Tl) | NA |
| | | Ge(HP) | GH |
| | | Ge(Li) | GL |
| | | Si(Li) | SL |
| | | CsI(Tl) | CS |
| | | ionization chamber | IC |
| | | grid ionization chamber | GC |
| | | Cerenkov detector | CD |
| | | calorimeter | CA |
| | | solid plastic scintillator | SP |
| | | 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 |
| mixed electrons | ME | coincidence | CO |
| bremsstrahlung | BS | anti-coincidence | AC |
| gamma rays | GR | coincidence counting with efficiency tracing | CT |
| x-rays | XR | anti-coincidence counting with efficiency tracing | AT |
| photons $(x + \gamma)$ | PH | triple-to-double coincidence ratio counting | TD |
| photons + electrons | PE | selective sampling | SS |
| alpha particle | AP | high efficiency | HE |
| mixture of various radiation | MX | digital coincidence counting | DC |

| **Examples of methods** | **acronym** |
|---|---|
| $4\pi$(PC)$\beta$-$\gamma$ coincidence counting | 4P-PC-BP-NA-GR-CO |
| $4\pi$(PPC)$\beta$-$\gamma$ coincidence counting eff. trac | 4P-PP-MX-NA-GR-CT |
| defined solid angle $\alpha$-particle counting with a PIPS detector | SA-PS-AP-00-00-00 |
| $4\pi$(PPC)AX-$\gamma$(GeHP)-anticoincidence counting | 4P-PP-MX-GH-GR-AC |
| $4\pi$CsI-$\beta$,AX,$\gamma$ counting | 4P-CS-MX-00-00-HE |
| calibrated IC | 4P-IC-GR-00-00-00 |
| internal gas counting | 4P-PC-BP-00-00-IG |