

BIPM comparison BIPM.RI(II)-K1.Co-60
of the activity measurements of the radionuclide ^{60}Co

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Abstract

Since 1976, twenty national metrology institutes, the BIPM and two other laboratories have submitted fifty-eight samples of known activity of ^{60}Co to the International Reference System (SIR) for activity comparison at the Bureau International des Poids et Mesures. The activities ranged from about 0.1 MBq to 100 MBq. The degrees of equivalence between each equivalent activity measured in the SIR and the key comparison reference value (KCRV) have been calculated and the results are given in the form of a matrix. A graphical presentation is also given. The results of this comparison have been approved by Section II of the Consultative Committee for Ionizing Radiation (CCRI(II)), comparison identifier BIPM.RI(II)-K1.Co-60.

1. Introduction

The SIR for activity measurements of γ -ray-emitting radionuclides was established in 1976. Each national metrology institute (NMI) may request a standard ampoule from the BIPM that is then filled (3.6 g) with the radionuclide in liquid (or gaseous) form. The 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 are all given in [1].

Since its inception, the SIR has measured over 835 ampoules to give 606 independent results for 62 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 realizations. These comparisons are described as BIPM ongoing comparisons and the results form the basis of the BIPM key comparison database of the Mutual Recognition Arrangement (MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Co-60 key comparison.

2. Participants

The BIPM, twenty NMIs and two other laboratories have submitted fifty-eight ampoules for the comparison of ^{60}Co activity measurements since 1976. The laboratory details are given in Table 1. In cases where the laboratory has changed its name since the original submission, both the earlier and the current acronyms are given, as it is the latter that are used in the KCDB. The AECL 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

Original acronym	NMI	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
BIPM	–	Bureau International des Poids et Mesures	–	–	1976-07-22
ASMW*	PTB	Physikalisch-Technische Bundesanstalt	Germany	EUROMET	1976-09-02 1977-09-16 1988-01-22 2001-07-02
IEA* IPEN	LNMRI	Laboratorio Nacional de Metrologia das Radiações Ionizantes	Brazil	SIM	1976-10-07 1984-11-21
ETL	NMIJ	National Metrology Institute of Japan	Japan	APMP	1976-11-24
–	NPL	National Physical Laboratory	United Kingdom	EUROMET	1977-01-05 2000-06-30
–	OMH	Országos Mérésügyi Hivatal	Hungary	EUROMET	1977-03-11 1979-12-13 1999-06-11
UVVVR	CMI-IIR	Český Metrologický Institut/Czech Metrological Institute, Inspectorate for Ionizing Radiation	Czech Republic	EUROMET	1977-03-25 1978-04-18
IAEA	–	International Atomic Energy Agency	–	–	1978-04-03 1978-05-25

* another institute of the country.

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Table 1 continued

Original acronym	NMI	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
LMRI	BNM-LNHB	Bureau national de métrologie-Laboratoire national Henri Becquerel	France	EUROMET	1978-07-17 1986-12-19 1999-10-20
–	NIM	National Institute of Metrology	China	APMP	1978-10-12
IER	IRA	Institut de Radiophysique Appliquée	Switzerland	EUROMET	1979-05-17 2000-12-06
AECL	–	Atomic Energy of Canada Ltd	Canada	–	1980-04-11 1993-12-20
NBS	NIST	National Institute of Standards and Technology	United States	SIM	1980-09-03 1997-01-24
NAC*	CSIR-NML	National Metrology Laboratory	South Africa	SADCMET	1981-07-15 1992-10-27
–	BARC	Bhabha Atomic Research Centre	India	APMP	1981-09-03 1994-06-20 2001-01-10
–	IFIN	Institutul de Fizica si Inginerie Nucleara	Romania	EUROMET	1983-12-15
PDS	P3KRBiN	Pusat Penelitian & Pengembangan Keselamatan Radiasi & Biomedika Nuklir	Indonesia	APMP	1984-06-22
–	ENEA	Ente per le Nuove Tecnologie, l'Energia e l'Ambiente	Italy	EUROMET	1991-01-22
–	CNEA	Comisión Nacional de Energía Atómica	Argentina	SIM	1992-01-28

* another institute of the country.

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Table 1 continued

Original acronym	NMI	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
–	ANSTO	Australian Nuclear Science and Technology Organisation	Australia	APMP	1992-05-13
–	KRISS	Korea Research Institute of Standards and Science	Republic of Korea	APMP	1995-01-18
–	BEV	Bundesamt für Eich- und Vermessungswesen	Austria	EUROMET	1998-10-14
–	CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas	Spain	EUROMET	1999-11-30

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 any correlations are taken into account. For this comparison, the BEV ionization chamber is traceable to the NPL.

A brief description of the standardization methods for each laboratory, the activities submitted and the relative standard uncertainties ($k = 1$) are given in Table 2. Further details and an uncertainty budget are available for the CSIR-NML in [3]. Full uncertainty budgets have been requested as part of the comparison protocol only since 1998. When submitted by the NMIs, the uncertainty budgets are given in Appendix 1 attached to this report. Uncertainty budgets have been provided by the IFIN, OMH, BNM-LNHB, CIEMAT, NPL, IRA, BARC and the PTB.

The half-life used by the BIPM since 1973 is 1924.8 (1.0) days [4]. This value was measured at the BIPM and is in agreement within the uncertainties with the value currently recommended by the IAEA, 1925.5 (5) d [5]. The small difference has had no significant effect on the results to date as each measurement at the BIPM has been close to the NMI reference date but the IAEA value will be used for future measurements.

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

NMI or laboratory	Method used and acronym (see Appendix 3)	Half-life / d	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
BIPM	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	2 611.2	73-06-06 12 h UT	0.014	0.020
PTB	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	1 867.8 1 870.0	76-06-15 12 h UT	0.04	0.10
	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	3 222.6 3 176.0	77-01-01 0 h UT	0.02	0.07
	Pressurized IC ^a 4P-IC-GR-00-00-00	-	100 020 18 272 2 036	87-09-01 0 h UT	0.02 0.02 0.03	0.07 0.06 0.09
	Pressurized IC ^b 4P-IC-GR-00-00-00	1925.3 (4)	13 760	01-01-01 0 h UT	0.03	0.22
LNMRI	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	189.4 193.8	76-06-28 0 h UT	0.14	0.04
	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	327.8 334.5	84-10-17 0 h UT	0.04	0.08
NMIJ	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	-	1 848 1 859	76-11-01 12 h UT	0.03	0.21
NPL	Pressurized IC ^a 4P-IC-GR-00-00-00	-	667 644	76-12-20 0 h UT	0.03	1.02
	$4\pi\beta(\text{PPC})-\gamma$ DCC - digital coincidence 4P-PP-BP-NA-GR-CO	-	2 290	00-02-01 12 h UT	0.10	0.27
OMH	$4\pi\beta-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	1926 (3)	1 345 1 345	77-03-01 12 h UT	0.02	0.32
	$4\pi\beta-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	1926 (3)	1 490	79-12-01 12 h UT	0.10	0.26
	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO	1925.5 (5)	1 808	99-06-01 0 h UT	0.03	0.25

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

NMI or laboratory	Method used and acronym (see Appendix 3)	Half-life / d	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
CMI-IIR	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	-	37 680	77-02-23 13 h UT	0.05	0.80
	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	1925 (4)	4 190	78-02-09 11h UT	0.1	0.3
IAEA /RCC ^c	4 $\pi\beta$ - γ coincidence and anti-coincidence 4P-00-BP-00-GR-CO 4P-00-BP-00-GR-AC	1925 (4)	1 769.8	77-04-01 12 h UT	0.07	0.13
IAEA /CMI-IIR	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	1925	3 600	78-02-09 11 h UT	0.1	0.3
BNM-LNHB	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	-	3 303.3 3 296.3	78-06-15 0 h UT	0.02	0.04
	4 $\pi\beta$ - γ (Ge(Li)) coincidence 4P-00-BP-GL-GR-CO	-	1 777.5 1 781.2	86-07-11 12 h UT	0.03	0.05
	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	1925.2 (4)	2 838.9	99-06-01 12 h UT	0.05	<0.01
NIM	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	1 746.2 1 746.4	78-08-31 4 h UT	0.05	0.20
IRA	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	3 007 2 982	79-05-01 0 h UT	0.02	0.10
	Pressurized IC ^d 4P-IC-GR-00-00-00	1925.3 (2)	2 518	00-12-01 12 h UT	0.014	0.100
AECL	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	1 183.4 1 189.3	80-02-05 17 h UT	0.02	0.02
	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	-	2 069.9	93-10-01 19 h UT	0.05	0.05

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

NMI or laboratory	Method used and acronym (see Appendix 3)	Half-life / d	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
NIST	4 $\pi\beta$ - γ coincidence and anti-coincidence 4P-00-BP-00-GR-CO 4P-00-BP-00-GR-AC	-	2 038.1	80-05-30 17 h UT	0.059	0.15
	Pressurized IC ^e 4P-IC-GR-00-00-00	-	1 402	97-01-01 12 h UT	0.03	0.23
CSIR-NML	4 $\pi\beta$ (LS)- γ coincidence 4P-LS-BP-NA-GR-CO	-	4 659 5 329	81-06-19 10 h UT	0.05	0.18
	4 $\pi\beta$ (LS)- γ coincidence [3] 4P-LS-BP-NA-GR-CO	1925.4 (2) [6]	7 066 20 525	92-09-10 12 h UT	0.014	0.133
BARC	4 $\pi\beta$ - γ coincidence 4P-PC-BP-NA-GR-CO	-	584.4	81-06-01 6 h 30 UT	0.03	0.25
		-	676.1	94-05-01 6 h 30 UT	0.04	0.11
		1922	1 072	00-12-01 6 h 30 UT	0.6	0.3
IFIN	4 $\pi\beta$ (PC)- γ coincidence, efficiency extrapolation [7] 4P-PC-BP-NA-GR-CO	-	1 444 1 424	83-09-01 12 h UT	0.05	0.09
P3KRBiN	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	1 014 1 019	84-06-01 8 h UT	0.4	-
ENEA	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	1 053	90-12-01 12 h UT	0.2	0.3
CNEA	4 $\pi\beta$ (PC)- γ coincidence 4P-PC-BP-NA-GR-CO	-	785.3	92-01-01 0 h UT	0.05	0.12
ANSTO	4 $\pi\beta$ - γ coincidence 4P-00-BP-00-GR-CO	-	1 676.0	92-04-08 23 h UT	0.10	0.08
KRISS	4 $\pi\beta$ - γ coincidence 4P-PP-BP-NA-GR-CO	-	511.6	94-10-01 0 h UT	0.24	0.19
BEV	Pressurized IC ^f 4P-IC-GR-00-00-00	1925.5	2 980	98-10-01 0 h UT	0.07	0.58

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

NMI or laboratory	Method used and acronym (see Appendix 3)	Half-life / d	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
CIEMAT	$4\pi\beta(\text{PC})-\gamma$ coincidence 4P-PC-BP-NA-GR-CO and CIEMAT /NIST ^h 4P-LS-BP-00-00-CN	1925.2	364.8 ^g	99-10-05 12 h UT	0.11	0.10

^a calibrated by $4\pi\beta(\text{PC})-\gamma$ coincidence (4P-PC-BP-NA-GR-CO) for the nuclide considered

^b calibrated on 08/06/2000 by $4\pi\beta(\text{PC})-\gamma$ coincidence using the same solution family [8]

^c the Radiochemical Centre Ltd, Amersham

^d calibrated in 1979 by $4\pi\beta-\gamma$ coincidence for the nuclide considered

^e calibrated by $4\pi\beta-\gamma$ coincidence and anti-coincidence for the nuclide considered

^f traceable to the NPL

^g weighted mean of the results obtained by the two methods

^h for the CIEMAT/NIST method, a ^3H tracer from BNM-LNHB was used.

Details regarding the solution 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. Recently the BIPM has developed a standard method for evaluating the activity of impurities using a calibrated Ge(Li) spectrometer [9]. The CCRI(II) agreed in 1999 [10] that this method should be followed according to the protocol described in [11] when an NMI makes such a request or when there appear to be discrepancies.

Table 3. Details of the solution of ^{60}Co submitted

NMI	Chemical composition	Solvent conc. / (mol dm ⁻³)	Carrier: conc. / ($\mu\text{g g}^{-1}$)	Density / (g cm ⁻³)	Relative activity of impurity *
BIPM	CoCl ₂ in HCl	0.1	CoCl ₂ : 5	1.000	–
PTB	CoCl ₂ in HCl	0.1	CoCl ₂ : 20	–	–
			CoCl ₂ : 50	–	–
			CoCl ₂ : 50	1.0	–
			CoCl ₂ : 50	1.00	–
LNMRI	CoCl ₂ in HCl	0.1	CoCl ₂ : 17.1	–	–
	Co in HCl	0.2	Co : 0.02	1.003	–
NMIJ	CoCl ₂ in HCl	0.1	CoCl ₂ : 50	–	–
NPL	CoCl ₂ in HCl	0.1	CoCl ₂ : 50	–	–
			CoCl ₂ : 25	1	–

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Table 3 continued. Details of the solution of ⁶⁰Co submitted

NMI	Chemical composition	Solvent conc. / (mol dm ⁻³)	Carrier: conc. / (μg g ⁻¹)	Density / (g cm ⁻³)	Relative activity of impurity *
OMH	Co in HCl	0.1	Co: 25	–	–
			Co: 25	–	–
	CoCl ₂ in HCl	0.1	CoCl ₂ : 25	–	–
CMI-IIR	CoCl ₂ in HCl	0.1	CoCl ₂ : 20	1	< 0.1 %
		0.08	CoCl ₂ : 20	–	< 0.1 %
IAEA/RCC	Co in HCl	0.1	Co : 100	–	–
IAEA /CMI-IIR	CoCl ₂ in HCl	0.08	CoCl ₂ : 20	–	< 0.1 %
BNM-LNHB	CoCl ₂ in HCl	0.1	CoCl ₂ : 10	0.999	< 0.02 %
					< 0.01 %
	Co in HCl	0.1	Co ⁺⁺ : 10	1.001	–
NIM	CoCl ₂ in HCl	0.1	CoCl ₂ : 100	1.0004	–
IRA	Co ⁺⁺ in HCl	0.1	Co ⁺⁺ : 30	–	–
			Co ⁺⁺ : 25	1.000 (7)	–
AECL	CoCl ₂ in HCl	0.3	Co ⁺⁺ : 10	1.0	–
	CoCl ₂ .6H ₂ O in HCl	0.1	CoCl ₂ .6H ₂ O 100	1.000	–
NIST	Co in HCl	1	Co : 50	1.015 (2)	–
	CoCl ₂ in HCl	0.1	CoCl ₂ : 100	1.000	–
CSIR-NML	CoCl ₂ in HCl	1.0	CoCl ₂ : 540	1.037	–
	CoCl ₂ .6H ₂ O in HCl	1	Co ⁺⁺ : 110	1.0183	–
BARC	CoCl ₂ in HCl	0.1	CoCl ₂ : 55	–	–
	Co(NO ₃) ₂ in HNO ₃	0.1	Co(NO ₃) ₂ : 50	1	–
	CoCl ₂ in HCl	0.1	CoCl ₂ : 25	1	–
IFIN	CoCl ₂ in HCl	0.1	Co : 50	1	–
P3KRBiN	CoCl ₂ .6H ₂ O in HCl	1	CoCl ₂ .6H ₂ O 50.5	0.990 (1)	–

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Table 3 continued. Details of the solution of ^{60}Co submitted

NMI	Chemical composition	Solvent conc. / (mol dm^{-3})	Carrier: conc. / ($\mu\text{g g}^{-1}$)	Density / (g cm^{-3})	Relative activity of impurity *
ENEA	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ in HCl	0.1	Co^{++} : 100	0.999	^{137}Cs : 0.003 (1) % ^{63}Ni : 0.026 (5) %
CNEA	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ in HCl	0.1	CoCl_2 : 10	0.999	< 0.1 %
ANSTO	CoCl_2 in HCl	0.1	Co : 47	1.00	–
KRISS	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ in HCl	0.5	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 46	1.0061	–
BEV	CoCl_2 in HCl	0.1	CoCl_2 : 50	1.0	–
CIEMAT	CoCl_2 in HCl	1	CoCl_2 : 413	1.019	^{63}Ni : 0.012 %

* 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 "mother-file". The activity measurements for ^{60}Co arise from fifty-eight ampoules and the SIR equivalent activity, A_{ei} , for each ampoule is given in Table 4 for each NMI, i . The dates of measurement in the SIR are given in Table 1. The relative standard uncertainties arising from the measurements in the SIR are also shown. This uncertainty is additional to that declared by the NMI for the activity measurement shown in Table 2. Although activities submitted are compared with a given source of ^{226}Ra , all the SIR results are normalized to the radium source number 5 [1].

The correction for impurities, when present, is negligible in all cases.

Measurements repeated at the BIPM after periods of up to 8 years later produced comparison results in agreement within two SIR standard uncertainties for the CMI-IIR (1977) and the LNMRI (1984).

The low value for the mass of solution in the ampoule from CNEA is not likely to be the cause of the high comparison result obtained. Indeed the different absorption level should decrease the equivalent activity by a few 10^{-3} in relative terms [12].

Five NMIs (the PTB, NPL, OMH, BNM-LNHB and the IRA) that have sent different ampoules over about 20 years, demonstrate consistency within statistical standard uncertainties between 4×10^{-4} and 8×10^{-4} .

As no recent submission has been identified as a pilot study, although three earlier results were withdrawn, the most recent result of each NMI is normally eligible for Appendix B of the MRA. However, the IAEA no longer undertakes the metrology of activity, the AECL is not a designated laboratory of the NRC, Canada, and Indonesia (P3KRBIN) has not signed the MRA, therefore none of these results is included in the KCDB.

No international or regional comparison for this radionuclide has been held to date so no linking data are identified.

4.1 The key comparison reference value

The key comparison reference value is derived from the unweighted mean of all the results submitted to the SIR with the following provisions:

- a) only primary standardized solutions are accepted, or ionization chamber measurements that are directly traceable to a primary measurement in the laboratory;
- b) each NMI or other laboratory has only one result (normally the more recent or the mean if more than one ampoule is submitted at the same time);
- c) any outliers are identified using a reduced chi-squared test and, if necessary, excluded from the KCRV using the normalized error test with a test value of four;
- d) exclusions must be approved by the CCRI(II).

The reduced data set used for the evaluation of the KCRVs is known as the KCRV file and is the reduced data set from the SIR mother-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 only made by the CCRI(II), normally during one of its biennial meetings.

Consequently, the KCRV for ^{60}Co has been identified as 7064.6 (3.8) kBq. This value was calculated from the results of the BIPM, ASMW (1976), NMII, PTB (1977), NIM, CMI-IIR (1978), IRA (1979 was used as the subsequent ionization chamber calibrations are traceable to this primary standardization), IFIN, LNMRI (1984), P3KRBiN, ENEA, ANSTO, CSIR-NML (1992), AECL (1993), KRISS, NIST (1997), OMH (1999), BNM-LNHB (1999), CIEMAT, NPL (2000) and the BARC (2001).

Table 4. Results of SIR measurements of ⁶⁰Co

NMI	Mass of solution m_i / g	Activity submitted A_i / kBq	N° of Ra source used	SIR A_e / kBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / kBq
BIPM	3.757 9	2 611.2	4	7066	4.4×10^{-4}	4
PTB	3.601 0	1 867.8	4	7063	4×10^{-4}	8
	3.605 2	1 870.0		7061		
	3.670 0	3 222.6	4	7062	5×10^{-4}	6
	3.616 9	3 176.0		7060		
	3.599 2	100 020	5	7068	3×10^{-4}	6
	3.603 3	18 272	5	7056	3×10^{-4}	5
3.644 5	2 036	4	7056	4×10^{-4}	7	
3.600 7 (9)	13 760	5	7057	3×10^{-4}	16	
LNMRI	3.459 33	189.4	2	7062	9×10^{-4}	12
	3.539 01	193.8		7065	8×10^{-4}	
	3.468 94	327.8	2	7081 ^a	6×10^{-4}	8
	3.540 29	334.5		7073		
NMIJ	3.607 86	1 848	4	7044	4×10^{-4}	16
	3.628 78	1 859				
NPL	3.770 4	667	3	7059	5×10^{-4}	72
	3.640 7	644		7057		
	3.567 15	2 290	4	7053	4×10^{-4}	21
OMH	3.600 7	1 345	4	7048	5×10^{-4}	23
	3.600 6	1 345		7043		
	3.602 1	1 490	4	7045	4×10^{-4}	20
	3.612 2	1 808	4	7051	5×10^{-4}	18
CMI-IIR	3.568 43	37 680	5	7051	4×10^{-4}	56
	3.615 29	4 190	4	7054	4×10^{-4}	20
IAEA /RCC	3.699 3	1 769.8	4	7052	5×10^{-4}	11
IAEA /CMI-IIR	3.584 18	3 600	4	7053	4×10^{-4}	20
BNM-LNHB	3.626 37	3 303.3	4	7053	4×10^{-4}	4
	3.618 76	3 296.3		7052		
	3.592 43	1 777.5	4	7065	4×10^{-4}	5
	3.599 83	1 781.2		7063		
	3.583 06	2 838.9	4	7060	4×10^{-4}	4
NIM	3.605 25	1 746.2	4	7046 ^a	4×10^{-4}	15
	3.605 67	1 746.4		7042		

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Table 4 continued. Results of SIR measurements of ^{60}Co

NMI	Mass of solution m_i / g	Activity submitted A_i / kBq	N° of Ra source used	SIR A_e / kBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / kBq
IRA	3.629 93	3 007	4	7039	4×10^{-4}	8
	3.599 67	2 982		7042		
	3.598 0	2 518	4	7037	4×10^{-4}	8
AECL	0.941 77 ^b	1 183.4	3	7050	5×10^{-4}	4
	0.946 42	1 189.3		7051		
	0.233 20 ^b	2 069.9	4	7064	4×10^{-4}	6
NIST	3.666 88	2 038.1	4	7069	4×10^{-4}	12
	3.608 47	1 402	4	7085	4×10^{-4}	17
CSIR-NML	1.017 67 ^c	4 659	5	7064	3×10^{-4}	13
	1.164 06	5 329		7067		
	1.054 1 ^d	7 066	5	7066 ^a	3×10^{-4}	10
3.061 97	20 525	7065				
BARC	3.599 8	584.4	3	7078	6×10^{-4}	19
	3.605 8	676.1	3	7076	5×10^{-4}	9
	3.614 50	1 072	3	7099	5×10^{-4}	46
IFIN	3.533 9	1 444	4	7066 ^a	4×10^{-4}	8
	3.485 4	1 424		7068	4×10^{-4}	
P3KRBiN	3.550	1 014	3	7103 ^a	5×10^{-4}	27
	3.567	1 019		7105	6×10^{-4}	
ENEA	3.570	1 053	3	7065	6×10^{-4}	26
CNEA	2.075 43	785.3	3	7126	5×10^{-4}	10
ANSTO	3.557 10	1 676.0	4	7056	4×10^{-4}	10
KRISS	3.585 26	511.6	3	7047	7×10^{-4}	22
BEV	3.618	2 980	4	7049	4×10^{-4}	42
CIEMAT	3.682 16	364.8	2	7090	7×10^{-4}	11

^a the mean of the two A_e values is used with an averaged uncertainty as attributed to an individual entry [13]

^b mass of solution before dilution

^c mass of solution before dilution. Masses after dilution are 3.600 g and 3.613 g respectively.

^d mass of solution before dilution. Masses after dilution are 3.612 g and 3.610 g respectively.

4.2 Degrees of equivalence

Every NMI that has submitted ampoules to the SIR is entitled to have one result included in Appendix B of the KCDB as long as the NMI is a signatory or designated institute listed in the MRA. Normally, the most recent result is the one included. Any NMI may withdraw its result only if all the participants agree.

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the key comparison reference value [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 with the KCRV

The degree of equivalence of a particular NMI, i , with the key comparison reference value is expressed as the difference between the results

$$D_i = A_{e_i} - \text{KCRV} \quad (1)$$

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

$$U_i = 2u_{D_i}, \quad (2)$$

taking correlations into account as appropriate (see Appendix 2).

4.2.2 Comparison of any two NMIs with each other

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

$$D_{ij} = D_i - D_j = A_{e_i} - A_{e_j} \quad (3)$$

and the expanded uncertainty of this difference U_{ij} where

$$u_{D_{ij}}^2 = u_i^2 + u_j^2 - \sum_k (f_k \text{ucorr}_k)_i^2 - \sum_k (f_k \text{ucorr}_k)_j^2 \quad (4)$$

and any obvious correlations in the standard uncertainties for a given component, ucorr_k , between the NMIs (such as a traceable calibration) are subtracted using an appropriate correlation coefficient, f_k , as are normally those correlations coming from the SIR.

The uncertainties of the differences between the values assigned by individual NMIs and the key comparison reference value (KCRV) are not necessarily the same uncertainties that enter into the calculation of the uncertainties in the degrees of equivalence between a pair of participants. Consequently, the uncertainties in the table of degrees of equivalence cannot be generated from the column in the table that gives the uncertainty of each participant with respect to the KCRV. However, the effects of correlations have been treated in a simplified way as the degree of confidence in the uncertainties themselves does not warrant a more rigorous approach.

Table 5 shows the matrix of all the degrees of equivalence as they will appear in Appendix B of the KCDB. It should be noted that for consistency within the KCDB, a simplified level of nomenclature is used with A_{e_i} replaced by x_i . The introductory text is that agreed for the comparison. The graph of the first column of 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 1. This representation indicates in part the degree of equivalence between the NMIs but does not take into account the correlations between the different NMIs. However,

the matrix of degrees of equivalence shown in yellow in Table 5 does take the known correlations into account.

Conclusion

The BIPM ongoing key comparison for ^{60}Co , BIPM.RI(II)-K1.Co-60 currently comprises twenty results. These have been analysed with respect to the KCRV determined for this radionuclide, and with respect to each other. The matrix of degrees of equivalence has been approved by the CCRI(II) and will be published in the BIPM key comparison database. Other results may be added as and when other NMIs contribute ^{60}Co activity measurements to this comparison.

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Table 5. Table of degrees of equivalence and introductory text for ⁶⁰Co

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

MEASURAND : Equivalent activity of ⁶⁰Co

Key comparison reference value: the SIR reference value x_R for this radionuclide is 7065 kBq, with a standard uncertainty u_R of 4 kBq (see Section 4.1 of the Report).

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms:

$D_i = (x_i - x_R)$ and U_i , its expanded uncertainty ($k = 2$), both expressed in kBq, and $U_i = 2((1 - 2/n)u_i^2 + (1/n^2)\sum u_i^2)^{1/2}$ when each laboratory has contributed to the calculation of x_R , with n the number of laboratories (see Appendix 2 of the Report).

The degree of equivalence between two laboratories is given by a pair of terms:

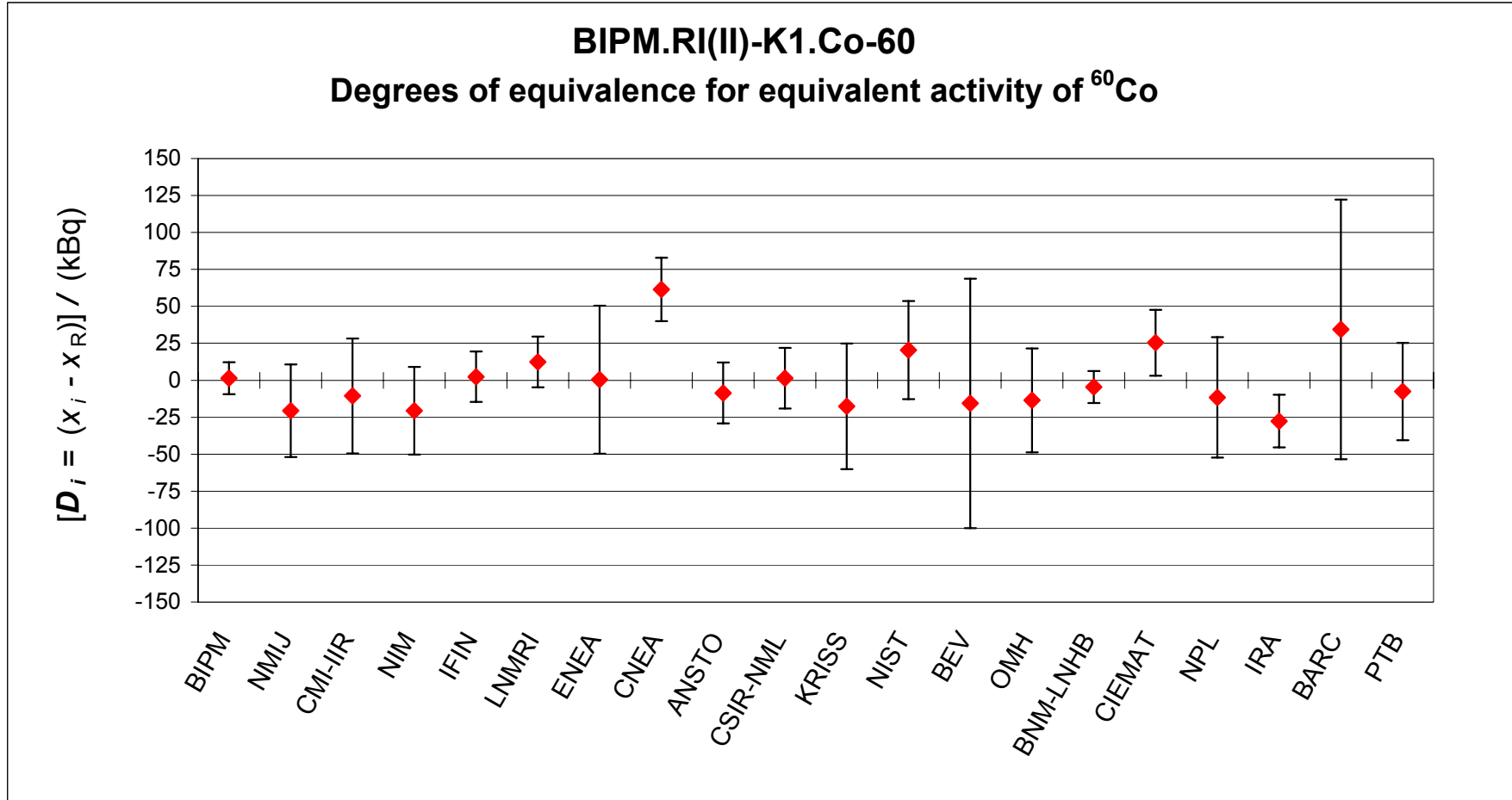
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij} , its expanded uncertainty ($k = 2$), both expressed in kBq.

The approximation $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$ is used in the following table.

Lab i ↓	D_i / kBq		U_i / kBq		Lab j →																			
	D_i / kBq	U_i / kBq	BIPM		NMIJ		CMI-IIR		NIM		IFIN		LNMRI		ENEA		CNEA		ANSTO		CSIR-NML			
			D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq		
BIPM	1	11			22	33	12	41	22	31	-1	18	-11	18	1	53	-60	22	10	22	0	22		
NMIJ	-21	31	-22	33			-10	51	0	44	-23	36	-33	36	-21	61	-82	38	-12	38	-22	38		
CMI-IIR	-11	39	-12	41	10	51			10	50	-13	43	-23	43	-11	66	-72	45	-2	45	-12	45		
NIM	-21	30	-22	31	0	44	-10	50			-23	34	-33	34	-21	60	-82	36	-12	36	-22	36		
IFIN	2	17	1	18	23	36	13	43	23	34			-10	23	2	54	-59	26	11	26	1	26		
LNMRI	12	17	11	18	33	36	23	43	33	34	10	23			12	54	-49	26	21	26	11	26		
ENEA	0	50	-1	53	21	61	11	66	21	60	-2	54	-12	54			-61	56	9	56	-1	56		
CNEA	61	21	60	22	82	38	72	45	82	36	59	26	49	26	61	56			70	28	60	28		
ANSTO	-9	21	-10	22	12	38	2	45	12	36	-11	26	-21	26	-9	56	-70	28			-10	28		
CSIR-NML	1	21	0	22	22	38	12	45	22	36	-1	26	-11	26	1	56	-60	28	10	28				
KRISS	-18	43	-19	45	3	54	-7	59	3	53	-20	47	-30	47	-18	68	-79	48	-9	48	-19	48		
NIST	20	33	19	35	41	47	31	52	41	45	18	38	8	38	20	62	-41	39	29	39	19	39		
BEV	-16	84	-17	84	5	90	-5	93	5	89	-18	86	-28	86	-16	99	-77	86	-7	86	-17	86		
OMH	-14	35	-15	37	7	48	-3	54	7	47	-16	39	-26	39	-14	63	-75	41	-5	41	-15	41		
BNM-LNHB	-5	11	-6	11	16	33	6	41	16	31	-7	18	-17	18	-5	53	-66	22	4	22	-6	22		
CIEMAT	25	22	24	23	46	39	36	46	46	37	23	27	13	27	25	56	-36	30	34	30	24	30		
NPL	-12	41	-13	23	9	39	-1	46	9	37	-14	45	-24	27	-12	56	-73	30	-3	30	-13	30		
IRA	-28	18	-29	18	-7	36	-17	43	-7	34	-30	23	-40	23	-28	54	-89	26	-19	26	-29	26		
BARC	34	88	33	92	55	97	45	100	55	97	32	93	22	93	34	106	-27	94	43	94	33	94		
PTB	-8	33	-9	33	13	45	3	51	13	44	-10	36	-20	36	-8	61	-69	38	1	38	-9	38		

Lab i ↓	D_i / kBq		U_i / kBq		Lab j →																	
	D_i / kBq	U_i / kBq	KRISS		NIST		BEV		OMH		BNM-LNHB		CIEMAT		NPL		IRA		BARC		PTB	
			D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq	D_{ij} / kBq	U_{ij} / kBq
BIPM	1	11	19	45	-19	35	17	84	15	37	6	11	-24	23	13	23	29	18	-33	92	9	33
NMIJ	-21	31	-3	54	-41	47	-5	90	-7	48	-16	33	-46	39	-9	39	7	36	-55	97	-13	45
CMI-IIR	-11	39	7	59	-31	52	5	93	3	54	-6	41	-36	46	1	46	17	43	-45	100	-3	51
NIM	-21	30	-3	53	-41	45	-5	89	-7	47	-16	31	-46	37	-9	37	7	34	-55	97	-13	44
IFIN	2	17	20	47	-18	38	18	86	16	39	7	18	-23	27	14	45	30	23	-32	93	10	36
LNMRI	12	17	30	47	-8	38	28	86	26	39	17	18	-13	27	24	27	40	23	-22	93	20	36
ENEA	0	50	18	68	-20	62	16	99	14	63	5	53	-25	56	12	56	28	54	-34	106	8	61
CNEA	61	21	79	48	41	39	77	86	75	41	66	22	36	30	73	30	89	26	27	94	69	38
ANSTO	-9	21	9	48	-29	39	7	86	5	41	-4	22	-34	30	3	30	19	26	-43	94	-1	38
CSIR-NML	1	21	19	48	-19	39	17	86	15	41	6	22	-24	30	13	30	29	26	-33	94	9	38
KRISS	-18	43			-38	56	-2	95	-4	57	-13	45	-43	49	-6	49	10	47	-52	102	-10	54
NIST	20	33	38	56			36	91	34	50	25	35	-5	40	32	40	48	38	-14	98	28	47
BEV	-16	84	2	95	-36	91			-2	91	-11	84	-41	87	-4	77	12	86	-50	125	-8	90
OMH	-14	35	4	57	-34	50	2	91			-9	37	-39	42	-2	42	14	39	-48	99	-6	48
BNM-LNHB	-5	11	13	45	-25	35	11	84	9	37			-30	23	7	23	23	18	-39	92	3	33
CIEMAT	25	22	43	49	5	40	41	87	39	42	30	23			37	31	53	27	-9	95	33	39
NPL	-12	41	6	49	-32	40	4	77	2	42	-7	23	-37	31			16	27	-46	95	-4	39
IRA	-28	18	-10	47	-48	38	-12	86	-14	39	-23	18	-53	27	-16	27			-62	93	-20	36
BARC	34	88	52	102	14	98	50	125	48	99	39	92	9	95	46	95	62	93			42	97
PTB	-8	33	10	54	-28	47	8	90	6	48	-3	33	-33	39	4	39	20	36	-42	97		

Figure 1. Graph of degrees of equivalence with the KCRV for ^{60}Co
 (as it appears in Appendix B of the MRA)



Appendix 1. Uncertainty budgets for the activity of ^{60}Co submitted to the SIR

Uncertainty evaluation by the IFIN (1983 solution)

For comparison, the uncertainties have also been evaluated according to the GUM [14] and it is interesting to note that this gives a smaller combined standard uncertainty when compared with the earlier method for $k = 1$.

Uncertainty component evaluation	1983 formula $\varepsilon = (t \cdot S_x^- + \sum \delta_i) \cdot 10^{-2}$	GUM formula, 2002 $u_c = \sqrt{u_A^2 + \frac{\sum U_{Bi}^2}{9}} \cdot 10^{-2}$
Statistical evaluation u_A	$S_x^- = 0.048$; $t = 3.355$ ($\nu = 8$) $t \cdot S_x^- = 0.161 \cong \mathbf{0.2}$	0.048
Type B evaluation of other components	δ_i	U_{Bi} ($k = 3$)
Extrapolation correction	0.078	0.078
Dead time correction	0.085	0.085
Accidental coincidences	0.018	0.018
Background	0.027	0.027
Weighing	0.05	0.05
Decay correction	0.013	0.013
	$\sum \delta_i = 0.271 \cong \mathbf{0.3}$	
Combined uncertainty $\times 10^2$	$\varepsilon(p^* = 99.7\%) = 0.432 \cong 0.5$	$u_c = 0.065$

**Uncertainty evaluation of the massic activity of IRA solution
(Reference of the measurement: M60Co5A9_26102000)**

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Current of the first long lived reference source $\nu = 3$ *	1.2	–
Current of the second long lived reference source; $\nu = 7$	0.6	–
Current of the ampoule of ^{60}Co under measurement; $\nu = 5$	0.9	–
Substitution factor of the reference source	–	2.4
Equivalent activity (calibration for ^{60}Co)	–	10
Decay correction for the reference sources	–	2
Decay correction for ^{60}Co	–	0.01
Gravimetric measurements	–	0.3
Background	–	0.2
Quadratic summation	1.6 †	10.5
Total relative combined uncertainty u_c	11	

* number of degrees of freedom

† quadratic sum of 1.2 and 0.9 only

Uncertainty evaluation of the BNM-LNHB entry - 1999

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics, $\nu^* = 16$	5	–
Weighing, dilution **	–	–
Dead time	–	<1
Coincidence resolving time	–	–
Background	<1	–
Timing	–	<0.1
Half-life	–	0
Delay mismatch	–	–
Scheme corrections	–	<0.1
Radionuclide impurities	–	<1
Jitter	–	<0.1
Quadratic summation	5	<1
Total relative combined uncertainty u_c	5	

* number of degrees of freedom

** included in counting statistics

Uncertainty evaluation of the massic activity of BARC solution 5501

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics	20	–
Extrapolation of efficiency curve	54	–
Gravimetric measurements	–	4
Dead time	–	20
Timing (accuracy of the crystal)	–	1
Resolving time	–	17
Background	–	0.4
Quadratic summation	58	27
Total relative combined uncertainty u_c	63	

Uncertainty evaluation of the OMH solution - 1999

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics, $\nu^* = 14$	3.4	–
Weighing, dilution	–	7
Dead time	–	0.5
Coincidence resolving time	–	1
Background	–	0.5
Timing	–	0.5
Half-life	–	<0.1
Delay mismatch	–	15
Extrapolation	–	15
Radionuclide impurities	–	<11
Quadratic summation	3.4	24.9
Total relative combined uncertainty u_c	25	

*number of degrees of freedom

Uncertainty evaluation of the CIEMAT solution – reference AB991

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics	10.6	–
Gamma efficiency of beta channel	–	3
Resolving time	–	5
Dead time	–	7
Background	–	2
Impurities	–	0.5
Gravimetry	–	3
Quadratic summation	10.6	9.8
Total relative combined uncertainty u_c	14	

Uncertainty evaluation of the NPL solution for 2000

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics	10	–
Pulse pile up (dead times in series)	–	1
Timing calibration	–	1
Weighing	–	3
Dead times (± 50 ns) (beta channel)	–	1
Resolving times (± 50 ns) (beta channel)	–	10
Background	–	10
Extrapolation	–	20
Choice of fit	–	10
Gamma gate setting	–	1
Half-life	–	1
Choice of correction formula	–	5
Quadratic summation	10	27
Total relative combined uncertainty u_c	29	

Uncertainty evaluation of the PTB solution in ampoule 2000-1395 (2001)

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
Counting statistics for one foil	3	–
Events in the beta channel	–	6
Events in the gamma channel	–	15
Events in the coincidence channel	–	15
Background in the beta channel	–	1
Background in the gamma channel	–	5
Background in the coincidence channel	–	1
Mass of the solution dispensed to a carrier foil	–	12
Extrapolation polynomial	–	4
Dilution factor	–	4
Correction for dilution factor and non-homogeneity	–	4
Quadratic summation	3	22*
Total relative combined uncertainty u_c	22	

* the correlation coefficients are taken into account [8] in the summation.

Appendix 2. Evaluation of the uncertainty of the degree of equivalence

Table 5 indicates for each laboratory the degree of equivalence D_i with its associated uncertainty U_i . This appendix presents the procedure used to evaluate these uncertainties.

The degree of equivalence of one laboratory is defined as the difference between the individual value of the equivalent activity A_{ei} for an NMI i and a suitable reference value which has been evaluated by the KCDB Working Group and the expanded uncertainty of this difference. Currently, the reference value, KCRV, for a given radionuclide is calculated as the arithmetic mean value of the SIR experimental entries for this radionuclide. Briefly at least four situations can occur depending on the consistency of the experimental SIR data sets :

1. All data are consistent and contribute to the reference value; this is the general case;
2. The value obtained by a laboratory that no longer exists, is used as long as it fits the usual quality criteria; it is taken into account when evaluating the reference value but does not appear in the matrices of results;
3. A value, that has been identified for example as an outlier, is not taken into account for the evaluation of the reference value but, nevertheless, the corresponding laboratory appears in the matrices of results.

The situation where a laboratory that no longer exists but contributes to the reference value and where an outlier has been identified in the data set can occur. This is a combination of both situation 2) and situation 3). The results, deduced from these two preceding cases, are also presented here, case 4.

In the following, the expression of the uncertainty for these four cases is considered on the assumption that the uncertainties of the different equivalent activities A_{ei} are not correlated. For the sake of coherence with the definition of the variables used in the text, the following notation is used :

$x_i = A_{ei}$ and $u_i = u_{A_{ei}}$ its uncertainty.

Case 1. All n laboratories contribute to the reference value, and appear in Table 5. In this case obviously we have

$$x_{\text{ref}} = \bar{x} = \frac{\sum_{j=1}^n x_j}{n} \quad (\text{A-1})$$

$$D_i = x_i - x_{\text{ref}} \quad (\text{A-2})$$

$$D_i = x_i - \frac{\sum_{j=1}^n x_j}{n} = x_i \left(1 - \frac{1}{n}\right) - \frac{\sum_{j \neq i} x_j}{n} \quad (\text{A-3})$$

At this stage the uncertainty of D_i has to be calculated. Applying the method of Gauß for the propagation of the uncertainties it is necessary to calculate the partial derivatives of D_i with respect to the x_i .

$$\text{So } \frac{\partial D_i}{\partial x_i} = \left(1 - \frac{1}{n}\right), \text{ and} \quad (\text{A-4})$$

$$\frac{\partial D_i}{\partial x_j} = -\frac{1}{n}, (j \neq i). \quad (\text{A-5})$$

Then the total combined uncertainty becomes

$$u_{c_i}^2 = \left(\frac{\partial D_i}{\partial x_i}\right)^2 u_i^2 + \sum_{j \neq i} \left(\frac{\partial D_i}{\partial x_j}\right)^2 u_j^2 \quad (\text{A-6})$$

$$= \left(1 - \frac{1}{n}\right)^2 u_i^2 + \frac{1}{n^2} \sum_{j \neq i} u_j^2 \quad (\text{A-7})$$

or, after recombination

$$= \left(1 - \frac{2}{n}\right) u_i^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2. \quad (\text{A-8})$$

When a coverage factor of 2 is used (A-8) becomes

$$U_i^2 = 2^2 \left[\left(1 - \frac{2}{n}\right) u_i^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2 \right]. \quad (\text{A-9})$$

Case 2. A laboratory was used to evaluate the reference value but does not appear in Table 5.

Let us assign the subscript n to the additional laboratory that contributes to the reference value. The uncertainty of this laboratory will appear only in the second part of equation (A-9). Accordingly, equation (A-9) becomes

$$U_i^2 = 2^2 \left[\left(1 - \frac{2}{n}\right) u_i^2 + \frac{1}{n^2} \left(\sum_{j=1}^n u_j^2\right) \right], \text{ for } i = 1, n - 1. \quad (\text{A} - 10)$$

Case 3. The reference value was evaluated with all reported values except one.

For the sake of simplicity let us assign the subscript $n + 1$ to the ineligible laboratory so that the subscript for the other laboratories will run from 1 to n . Under this assumption the treatment of the ineligible laboratory will be slightly different and two formulae are deduced.

The ineligible laboratory does not contribute to the reference value, so the term $(1 - 2/n)$ in (A-9) reduces to 1 and the uncertainty is simply given by

$$U_{n+1}^2 = 2^2 \left[u_{n+1}^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2 \right]. \quad (\text{A} - 11)$$

In the evaluation of the uncertainty related to the n other laboratories the contribution from laboratory $n + 1$ disappears totally and the uncertainty remains given by the expression (A-10) without restriction over the subscript range i. e.

$$U_i^2 = 2^2 \left[\left(1 - \frac{2}{n}\right) u_i^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2 \right]. \quad (\text{A} - 12)$$

Case 4. A laboratory that no longer exists contributes to the reference value and an outlier has been identified for another laboratory.

Let us assign the subscript n to the defunct existing laboratory so that the expression for the mean (A-1) remains applicable. In addition the outlier will be labelled by $n + 1$. For the $(n - 1)$ first laboratories which contribute to the mean value and appear in Table 5 the uncertainty of D_i is given by

$$U_i^2 = 2^2 \left[\left(1 - \frac{2}{n}\right) u_i^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2 \right], \text{ for } i = 1, n - 1. \quad (\text{A} - 13)$$

For the laboratory $n + 1$ that is ineligible for the KCRV, its coefficient $(1 - 2/n)$ in (A-13) reduces to 1 and the expression of the uncertainty in Table 5 becomes

$$U_{n+1}^2 = 2^2 \left[u_{n+1}^2 + \frac{1}{n^2} \sum_{j=1}^n u_j^2 \right], \quad (\text{A} - 14)$$

similar to (A-11).

Appendix 3. 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	SA

Examples	method	acronym
4π (PC) β - γ -coincidence counting		4P-PC-BP-NA-GR-CO
4π (PPC) β - γ -coincidence counting eff. trac.		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