Update of the BIPM comparison BIPM.RI(II)-K1.Co-57 of activity measurements of the radionuclide ^{57}Co to include the 2023 result of the BEV (Austria)

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Abstract Since 1976, 20 laboratories have submitted 59 samples of ^{57}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-57. Recently, the BEV (Austria) participated in the comparison. The degrees of equivalence between each equivalent activity measured in the SIR or linked to the SIR from the CCRI(II)-S6.Co-57 comparison have been calculated and the results are given in the form of a table. A graphical representation is also given.

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 with 3.6 g of the radioactive solution. 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 2023, the SIR has been used to measure 1054 ampoules to give 807 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 continuous 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-57 key comparison. The results of earlier participations in this key comparison were published previously [3–7].

Successful participation in this comparison by a laboratory may provide evidential support for Calibration and Measurement Capability (CMC) claims for ^{57}Co measured using the laboratory's method(s) used in the comparison or methods calibrated by those used for the comparison. This comparison may also be used to support CMC claims for those radionuclides measured in the laboratory using the same method and having a degree of difficulty at or below that of the radionuclide measured in this comparison as indicated in the current Measurement Methods Matrix (MMM) [8]

2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–7]. 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 Consultative Committee for Ionizing Radiation section 2 (CCRI(II)).

Table 1: Details of the participants in the BIPM.RI(II)-K1.Co-57.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**Regional Metrology Organization (RMO)**	**Date of SIR measurement** yyyy-mm-dd
AECL[a]	-	Atomic Energy of Canada Ltd	Canada	SIM	1980-06-16 1982-05-11
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1978-01-12
BEV	IRK[d]	Bundesamt fur Eich- und Vermessungswesen	Austria	EURAMET	1998-06-24 2023-08-04
BKFH	OMH, MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1977-06-15 1983-02-09 1996-07-12
CMI	UVVVR, CMI-IIR	Czech Metrological Institute	Czechia	EURAMET	1977-02-23 1980-01-07 1991-08-20

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
					2021-12-10
IAEA	-	International Atomic Energy Agency			1979-02-09 1979-02-12
IFIN-HH	-	Institutul National de Cercetare - Dezvoltare pentru Fizica si Inginerie Nucleara "Horia Hulubei"	Romania	EURAMET	2008-07-01
IRA	IER	Institut de Radiophysique	Switzerland	EURAMET	1980-04-29 1996-09-20 2000-12-04
KRISS	KSRI	Korea Research Institute of Standards and Science	Republic of Korea	APMP	1999-01-05
LNE-LNHB	LMRI, LPRI, BNM-LNHB	Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel	France	EURAMET	1979-04-09 1985-07-09 1990-11-13 1995-07-18 1999-10-18 2007-06-20
LNMRI-IRD	IEA, IPEN[b]	Laboratorio Nacional de Metrologia das Radiações Ionizantes	Brazil	SIM	1991-02-28
NIRH	-	National Institute of Radiation Hygiene	Denmark	EURAMET	1985-04-29
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1978-07-03 1981-03-06 1985-11-13 1999-05-05 2002-04-15 2010-05-21
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1986-02-06 1996-04-05 2004-03-17 2006-09-19
NMISA	NAC, CSIR-NML[c]	National Metrology Institute of South Africa	South Africa	AFRIMETS	1985-10-08 2015-09-15
NPL	-	National Physical Laboratory	United Kingdom	EURAMET	1976-12-28

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
POLATOM	IBJ, RC	National Centre for Nuclear Research Radioisotope Centre POLATOM	Poland	EURAMET	2013-11-19
PTB	-	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1983-03-29 2005-03-31
PTKMR	PDS, PSPKR, P3KRBiN	Pusat Teknologi Keselamatan dan Metrologi Radiasi	Indonesia	APMP	1992-07-02
VNIIM	-	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	1992-07-10

[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 in the country now named iThemba LABS.
[d] other laboratory in 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 reports [3–7]. The list of acronyms used to summarize the methods is given in Appendix E.

The half life used by the BIPM is 271.80(5) days as published in BIPM Monographie 5 vol. 1 [9].

Table 2: Standardization methods of the participants for ^{57}Co.

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

... Continuation of Table 2.

NMI or laboratory	Method used and the acronym	Activity A_i/kBq	Relative standard uncertainty /10^{-2} A	B	Reference date yyyy-mm-dd	Half life /d
AECL	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	16 411[k] 15 071	0.03 0.03	0.11 0.11	1980-03-20 17:00 UT	
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	2357[k] 1662	0.08 0.08	0.15 0.15	1982-03-25 17:00 UT	
ANSTO	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	8579	0.3	0.8	1978-01-15 00:00 UT	270.9
BEV	Pressurized ionization chamber (4P-IC-GR-00-00-00)[a]	1093	0.8	0.67	1998-06-01 00:00 UT	271.79
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[a]	1256.4	0.08	0.71	2023-02-01 12:00 UT	271.81(4) [10]
BKFH	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	5516[k] 5518	0.1 0.1	0.49 0.49	1977-06-01 12:00 UT	271.4(3)
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	3726	0.03	0.29	1983-05-01 12:00 UT	
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	5065	0.03	0.3	1996-07-01 00:00 UT	271.79(9) [11]
CMI	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	35 740	0.03	1.3[m]	1977-01-20 11:00 UT	270
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	4101	0.1	0.53	1979-08-30 10:00 UT	
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	5685	0.07	0.07	1991-08-05 12:00 UT	-
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	5406	0.15	0.46	2021-12-10 11:00 UT	271.81(4) [10]
IAEA	Pressurized ionization chamber (4P-IC-GR-00-00-00)[b]	2805	0.01	0.58	1978-06-19 17:00 UT	272.4(1)
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[c]	17 230	0.07	0.3	1978-12-07 12:00 UT	270.9
IFIN-HH	4π(PC)(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	3254	0.75	0.19	2008-07-01 00:00 UT	271.80(5) [9]
IRA	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	6416[k] 6416	0.05 0.05	0.3 0.3	1980-04-01 00:00 UT	-
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[d]	2746	0.01	0.31	1996-09-01 00:00 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**	
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[d]	1955	0.04	0.31	2000-12-01 12:00 UT	271.79(9) [11]
KRISS	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	2671	0.11	0.15	1998-09-01 00:00 UT	271.77(10)
LNE-LNHB	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	1373[k] 1371	0.05 0.05	0.05 0.05	1979-02-09 00:00 UT	-
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[e]	1538[k] 1525	0.07 0.07	0.26 0.26	1985-06-25 12:00 UT	
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	4447[k] 4501	0.05 0.05	0.01 0.01	1990-10-09 12:00 UT	
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[e]	3146[k] 3141	0.02 0.02	0.15 0.15	1995-06-15 12:00 UT	
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	2160	0.5	<0.01	1999-06-25 12:00 UT	271.79(9) [11]
	4π well-type crystal (4P-NA-GR-00-00-00) 4π(LS)(e,x)-γ anti-coincidence (4P-LS-MX-NA-GR-AC)	3669[n] 3653[o] 3667[n] 3651[o]	0.06 0.06 0.21 0.21	0.46 0.46 0.11 0.11	2007-06-01-12:00 UT	271.8(5)
LNMRI-IRD	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	1497[k] 1510	0.39 0.39	0.46 0.46	1990-10-01 12:00 UT	-
NIRH	Pressurized ionization chamber (4P-IC-GR-00-00-00)	54 120	0.13	1.9	1985-05-01 00:00 UT	
NIST	Pressurized ionization chamber (4P-IC-GR-00-00-00)[f]	2867	0.01	0.58	1978-06-19 17:00 UT	272.4(1)
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[f]	1738	0.01	0.39	1981-01-16 21:00 UT	272.2(2)
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[f]	6146	0.02	0.31	1985-10-28 17:00 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	
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[f]	16 810	0.04	0.31	1999-04-22 19:00 UT	271.7(2)
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[f]	8623	0.05	0.29	2002-04-01 12:00 UT	271.74(6)
	4π(LS)(e,x)-γ anti-coincidence (4P-LS-PE-NA-GR-AC)	125 640	0.08	0.34	2008-04-01 12:00 UT	271.80(5) [9]
NMIJ	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	1913[k] 1921	0.11 0.11	0.23 0.23	1986-02-04 12:00 UT	-
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-??-GR-CO)	3632	0.12	0.28	1996-03-01 12:00 UT	
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[g]	1771.5	0.08	0.32	2004-02-01 00:00 UT	271.79
	4π(PC)(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	1684.3	0.28	0.04	2006-06-01 00:00 UT	271.4(3)
NMISA	4π(LS)(e,x)-γ coincidence (4P-LS-MX-NA-GR-CO)	58 900	0.16	0.19	1985-08-27 12:00 UT	271.77(10) [9]
	4π(LS)(e,x)-γ coincidence (4P-LS-MX-NA-GR-CO)	2220.1	0.04	0.21	2015-03-24 10:00 UT	271.80(5)
NPL	Pressurized ionization chamber (4P-IC-GR-00-00-00)[h]	428.8[k] 435.5	0.04 0.04	2.03 2.03	1976-12-20 00:00 UT	-
POLATOM	4π(LS)(e,x)-γ coincidence (4P-LS-MX-NA-GR-CO) 4π(LS)(e,x)-γ anti-coincidence (4P-LS-MX-NA-GR-AC)	17 143[l]	0.14	0.4	2013-11-01 12:00 UT	271.80(5) [9]
PTB	Pressurized ionization chamber (4P-IC-GR-00-00-00)[i]	4062	0.09	0.27	1983-03-01 00:00 UT	-
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[j]	1289.1[k] 1284.4	0.06 0.06	0.29 0.29	2005-04-01 00:00 UT	271.83(8)
PTKMR		6776[k] 6948	0.51 0.51		1992-03-01 05:00 UT	-
VNIIM	4π(PC)(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	4998	0.14	0.29	1992-06-10 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**	

[a] traceable to the NPL
[b] calibrated by 4π(e,x)-γ coincidence (NBS chamber)
[c] from the The Radiochemical Centre Ltd, Amersham
[d] traceable to the 1980 primary measurement
[e] calibrated by 4π(e,x)-γ coincidence for the nuclide considered
[f] calibrated in 1978 by 4π(e,x)-γ coincidence
[g] traceable to the 1996 measurement above
[h] calibrated by 4π(e,x)-γ coincidence
[i] calibrated by 4π(PC)-γ and 4π(PPC)-γ coincidence
[j] calibrated in 2003 by 4π(PPC)ec-γ coincidence
[k] several samples submitted
[l] The result is the mean of the different methods.
[m] maximum error instead of standard uncertainty
[n] same ampoule measured by two different methods
[o] same ampoule measured by two different methods

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 ^{57}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**[a]
AECL 1980	$CoCl_2$ in HCl	0.3	$CoCl_2$:10	1	^{56}Co: 0.11 % ^{58}Co: 0.029 % ^{60}Co: <0.005 %
1982	$CoCl_2$ in HCl	0.3	$CoCl_2$:20	1	^{56}Co: 0.03(1) % ^{58}Co: 0.010(5) %
ANSTO 1978	$CoCl_2$ in HCl	0.1	$CoCl_2$:100	1	^{56}Co: 0.093(30) % ^{58}Co: 0.010(30) %
BEV 1998	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	^{56}Co: 0.000015 %
2023	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	none detected
BKFH 1977	$CoCl_2$ in HCl	0.1	$CoCl_2$:25	-	^{56}Co: 0.015(3) % ^{58}Co: 0.020(4) % ^{60}Co: 0.025(5) %
1983	$CoCl_2$ in HCl	0.1	$CoCl_2$:25	-	^{56}Co: 0.002(1) % ^{58}Co: 0.0015(8) % ^{60}Co: 0.050(15) %
1996	$CoCl_2$ in HCl	0.1	$CoCl_2$:25	-	-
CMI 1977	$CoCl_2$ in HCl	0.01	$CoCl_2$:20 000	-	^{56}Co: 0.10(5) %
1980	$CoCl_2$ in HCl	0.08	$CoCl_2$:20 000	-	^{56}Co: 0.098(10) % ^{58}Co: 0.0096(10) %

... 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[a]
1991	$CoCl_2$ in HCl	0.1	$CoCl_2$:20	1	^{56}Co: 0.090(9) % ^{58}Co: 0.050(5) % ^{60}Co: 0.0003(2) %
2021	$CoCl_2$ in HCl	0.1	$CoCl_2$:20	1	^{56}Co: 0.0390(31) % ^{58}Co: 0.0150(18) %
IAEA 1979	Solvent: HCl	1	Co:110	1.016(2)	^{56}Co: 0.128(6) % ^{58}Co: 0.032(2) %
1979	-	-	Co:100	-	^{56}Co: 0.011(1) % ^{58}Co: 0.0010(5) %
IFIN-HH 2008	$CoCl_2$ in HCl	0.1	$CoCl_2$:20	1	^{56}Co: 0.065(36) % ^{58}Co: 0.026(18) %
IRA 1980	$CoCl_2$ in HCl	0.1	$CoCl_2$:25	-	^{56}Co: 0.030(5) % ^{58}Co: 0.0028(5) %
1996	$CoCl_2$ in HCl	-	$CoCl_2$:60	-	^{56}Co: 4.1(8)x10^{-4} % ^{58}Co: 5.6(11)x10^{-5} % ^{60}Co: 1.3(4)x10^{-3} %
2000	$CoCl_2$ in HCl	-	$CoCl_2$:25	1.000(7)	^{56}Co: 7.0(13)x10^{-4} % ^{58}Co: 1.2(2)x10^{-4} %
KRISS 1999	$CoCl_2$ in HCl	0.1	$CoCl_2$:60	1.0015	-
LNE-LNHB 1979	$CoCl_2$ in HCl	0.1	$CoCl_2$:10	0.999	^{56}Co: 0.055(5) % ^{58}Co: 0.092(7) % ^{60}Co: 0.012(2) %
1985	$CoCl_2$ in HCl	0.1	$CoCl_2$:10	0.999	^{56}Co: 0.025(2) % ^{58}Co: 0.015(1) %
1990	$CoCl_2$ in HCl	0.1	$CoCl_2$:10	0.999	^{56}Co: 0.113(2) % ^{58}Co: 0.050(1) %
1995	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	^{56}Co: 0.089(3) % ^{58}Co: 0.019(1) %
1999	Co^{++} in HCl	0.1	Co:10	1.001	^{56}Co: 0.047(5) % ^{58}Co: 0.008(1) %
2007	$CoCl_2$ in HCl[b]	0.1	$CoCl_2$:60	1.0001	^{56}Co: 0.0226(6) % ^{58}Co: 0.0060(4) %
LNMRI-IRD 1991	$CoCl_2$ in HCl	0.1	$CoCl_2$:100	1.003	^{56}Co: <0.3 %
NIRH 1985	$CoCl_2$ in HCl	0.1	-	-	^{56}Co: 0.098(2) % ^{58}Co: 0.021(1) %
NIST 1978	Solvent: HCl	1	Co:110	1.016(2)	^{56}Co: 0.128(6) % ^{58}Co: 0.032(2) %
1981	Solvent: HCl	1	Co:100	1.016(2)	^{56}Co: 0.0995(30) % ^{58}Co: 0.0285(14) %
1985	$CoCl_2$ in HCl	1	$CoCl_2$:480	1.016	^{56}Co: 8.2(8)x10^{-3} % ^{58}Co: 9.9(5)x10^{-4} % ^{65}Zn: 5.5(3)x10^{-4} %
1999	$CoCl_2$ in HCl	1	$CoCl_2$:1000	1.016(1)	^{56}Co: 0.035(4) %

... Continuation of Table 3.

NMI or laboratory / SIR year	**Chemical composition**	**Solvent conc.** $/(\mathrm{mol\,dm^{-3}})$	**Carrier conc.** $/(\mathrm{\mu g\,g^{-1}})$	**Density** $/(\mathrm{g\,cm^{-3}})$	**Relative activity of any impurity**[a]
					^{58}Co: 0.0093(9) %
2002	$CoCl_2$ in HCl	1	$CoCl_2$:200	1.016(1)	^{56}Co: 0.0132(2) % ^{58}Co: 0.0019(4) %
2010[c]	$CoCl_2$ in HCl	0.1	$CoCl_2$:44	1	^{56}Co: 0.056(4) % ^{58}Co: 0.021(3) %
NMIJ 1986	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	-
1996	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	-
2004	$CoCl_2$ in HCl	0.1	$CoCl_2$:100	1.002	-
2006	$CoCl_2$ in HCl	0.1	$CoCl_2$:100	-	-
NMISA 1985	$CoCl_2$ in HCl	1	Co:223	1.0169	^{56}Co: 0.0620(5) % ^{58}Co: 0.0130(4) %
2015	$CoCl_2$ in HCl	0.1	Co:10	1	-
NPL 1976	$CoCl_2$ in HCl	0.1	$CoCl_2$:100	-	-
POLATOM 2013	$CoCl_2$ in HCl	0.1	$CoCl_2$:55	1	< 0.1 %
PTB 1983	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	^{56}Co: 5.1(5)x10^{-3} % ^{58}Co: 0.5(2)x10^{-3} % ^{60}Co: 0.5(2)x10^{-3} %
2005	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	^{56}Co: 1.94(4)x10^{-4} % ^{58}Co: 4.59(9)x10^{-5} % ^{65}Zn: 6.9(21)x10^{-4} %
PTKMR 1992	$CoCl_2$ in HCl	1	$CoCl_2$:10	1	-
VNIIM 1992	$CoCl_2$ in HCl	0.1	Co:10	1.001	^{56}Co: 0.010(2) % ^{58}Co: 0.030(3) %

[a] The ratio of the activity of the impurity to the activity of ^{57}Co at the reference date
[b] for the two ampoules
[c] same solution as for the CCRI(II)-S6.Co-57 comparison

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a dedicated database based on CSV formatted files controlled by the Git version control system [12]. Machine-readable versions of this report (XML and JSON documents) are attached to this document [13]. The latest submission has added 1 ampoule for the activity measurements of ^{57}Co giving rise to 59 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 any of five sources of ^{226}Ra, all the SIR results are normalized to the radium source number 5 [1]. Table 4 also shows the comparison results selected for the KCRV as explained in section 4.1.

Table 4: Results of SIR measurement of ^{57}Co.

NMI or laboratory / SIR year	Mass 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	0.293 35[a]	16 411	3	170 440	21	410	-
	0.269 41	15 071	3	170 470	21	410	-
1982	0.177 194[a]	2357	1	168 840	29[c]	560	168 980(560)[j]
	0.124 928	1662	1	169 130	28	560	-
ANSTO 1978	3.591 23	8579	2	165 900	110[c]	2300	165 900(2300)
BEV 1998	3.642	1093	1	168 800	19	1800	-
2023	3.611 3	1256.4	1	174 100	12	1300	-
BKFH 1977	3.602 6	5516	2	168 830	19	900	-
	3.604 0	5518	2	168 740	19	900	-
1983	3.603	3726	2	168 890	32[c]	730	-
1996	3.612 6	5065	2	169 290	10	540	169 290(540)
CMI 1977	0.957 41[d]	35 740	4	168 600	130[c]	3100	-
1980	3.603 9	4101	2	168 570	18	960	-
1991	3.603 5	5685	2	169 960	29[c]	530	-
2021	3.595 7	5406	2	168 620	15	850	168 620(850)
IAEA 1979[m]	3.670 63	2805	1	169 750	14	1000	-
1979[n]	3.557 5	17 230	3	168 640	9	540	-
IFIN-HH 2008	3.602 64	3254	1	171 200	105[c]	2200	169 500(1400)[l]
IRA 1980	3.602 0	6416	2	167 730	17	590	167 700(590)[j]
	3.601 8	6416	2	167 660	18	590	-
1996	3.641	2746	1	168 490	12	560	-
2000	3.588 9(1)	1955	1	168 020	16	590	-
KRISS 1999	3.608 16	2671	1	169 710	13	390	169 710(390)
LNE-LNHB 1979	3.621 40	1373	1	168 550	21	460	-
	3.616 79	1371	1	168 160	23	470	-
1985	3.600 58	1538	1	168 030	16	520	-
	3.570 64	1525	1	167 950	16	520	-
1990	3.575 17	4447	2	169 210	12	210	-
	3.618 68	4501	2	169 118	12	220	-
1995	3.627 1	3146	2	168 980	13	340	-
	3.621 7	3141	2	168 820	14	350	-
1999	3.587 49	2160	1	167 430	16	880	-
2007	3.590 2	3669	2	168 690[f]	11	800	-
		3667		168 590[g]	11	430	-
	3.574 6	3653	2	168 640[f]	11	800	168 570(430)[j]
		3651		168 540[g]	11	430	-
LNMRI-IRD 1991	3.606 28	1497	1	169 400	13	1000	169 350(1000)[j]
	3.624 70	1510	1	169 300	14	1000	-
NIRH 1985	3.425 5	54 120	4	170 400	11	3200	-
NIST 1978	3.751 63	2867	2	170 100	22[c]	1100	-

... 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	$A_{\mathbf{e}i}$ **for KCRV /kBq**
1981	3.660 5	1738	1	169 720	15	710	-
1985	3.602 74	6146	2	170 250	11	550	-
1999	3.758 6(2)	16 810	3	171 390	14	590	-
2002	3.609 5(2)	8623	3	171 270	11	540	-
2010	3.570 3	125 640	3	168 920[h]	10	610	168 920(610)
NMIJ 1986	3.608 1	1913	1	169 500	13	480	-
	3.623 1	1921	1	169 150	15	490	-
1996	3.584	3632	2	167 900	10	530	-
2004	3.750 74	1771.5	1	165 200	17	610	-
2006	3.619 79	1684.3	1	168 480	14	530	168 480(530)
NMISA 1985	2.777 5[i]	58 900	4	170 770	8	450	-
2015	3.523 19	2220.1	1	170 640	15	450	170 640(450)
NPL 1976	3.624 9	428.8	1	168 000	15	3400	167 800(3400)[j]
	3.681 2	435.5	1	167 600	18	3400	-
POLATOM 2013	3.664 29	17 143	3	170 180	9	730	170 180(730)
PTB 1983	3.713 2	4062	2	168 850	11	520	-
2005	3.635 4(9)	1289.1	1	169 490	18	580	169 420(560)[j]
	3.622 2(9)	1284.4	1	169 340	14	540	-
PTKMR 1992	3.575	6776	2	152 420	10	800	-
	3.666	6948	2	152 250	10	800	-
VNIIM 1992	3.562 4	4998	2	167 290	12	570	167 290(570)

[a] mass of solution before dilution
[c] the uncertainty from the SIR reflects the NMI uncertainty of the impurities
[d] mass and activity after transfer to a NBS-type ampoule at the BIPM, with addition of HCl (0.01 mol/dm^3)
[f] activity measurement using 4P-NA-GR-00-00-00
[g] activity measurements using 4P-LS-MX-NA-GR-AC, used for the KCRV and the KCDB
[h] used to link the comparison CCRI(II)-S6.Co-57
[i] mass of solution before dilution. Mass after dilution = 3.59975 g
[j] An average value and average uncertainty between all submitted samples is used for the KCDB [14].
[l] result of a further SIR measurement carried about one year later when the impurity correction in the SIR is reduced by a factor 10. Result used for the KCRV. See [6] for more detail.
[m] calibrated by NIST
[n] calibrated by Amersham

The BEV measurement was repeated after 178 days, giving a result in line with the standard uncertainty and confirming the absence of impurities in the solution. Also, a second ampoule containing an aliquot of the same ^{57}Co solution was measured in the SIR and confirmed that the BEV result is an outlier.

The CCRI(II)-S6.Co-57 comparison was held in 2008 [15]. The results were linked to the BIPM.RI(II)-K1.Co-57 comparison through the measurement in the SIR of at least one ampoule of the CCRI(II)-S6 comparison as explained in [5].

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 [16] 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 chi-squared value is one. In addition, it allows for a power α smaller than two in the weighting factor. As proposed in [16], α 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) results for solutions standardized by only 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 use only 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.

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 new BEV (Austria) result from an ionization chamber measurement cannot be used in the calculation of the reference value. Consequently, the reference value has not been updated and is equal to **168 990(250) kBq** (see report [7]).

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). No recent submission has been identified as a pilot study so the most recent result of each NMI is normally eligible for inclusion on the KCDB platform of the CIPM MRA [2]. 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

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

The introductory text in Appendix A is the one agreed by the CCRI(II) for all the K1 comparisons.

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, 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 [17] 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.

Appendix B 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 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 continuous key comparison for ^{57}Co, BIPM.RI(II)-K1.Co-57, currently comprises 8 valid results. The SIR results, together with the previously published CCRI(II)-S6.Co-57 results, have been analyzed providing degrees of equivalence for 11 national metrology institutes. Other results may be added when other NMIs contribute ^{57}Co activity measurements to this comparison or take part in other linked comparisons.

6. References

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Appendix A. Introductory text for ^{57}Co degrees of equivalence

Key comparison BIPM.RI(II)-K1.Co-57

MEASURAND: Equivalent activity of ^{57}Co

Key comparison reference value: the SIR reference value x_{R} for this radionuclide is 168 990 kBq , with a standard uncertainty, u_{R} equal to 250 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 MBq, 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_{R}.

Appendix B. Table of degrees of equivalence for BIPM.RI(II)-K1.Co-57

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Co-57

NMI i	D_i /**MBq**	U_i /**MBq**
PTB	0.4	1.1
NMIJ	-0.5	1.1
LNE-LNHB	-0.42	0.93
NIST	-0.1	1.2
POLATOM	1.2	1.5
NMISA	1.65	0.96
CMI	-0.4	1.7
BEV	5.1	2.6

Table B2: The table of degrees of equivalence for the CCRI(II)-S6.Co-57(2008) comparison

NMI i	D_i /**MBq**	U_i /**MBq**
BARC	3.6	1.3
IFIN-HH	0.2	2.6
LNMRI-IRD	3.5	1.3

Appendix C. Graph of degrees of equivalence with the KCRV for ^{57}Co (as it appears in Appendix B of the CIPM MRA)

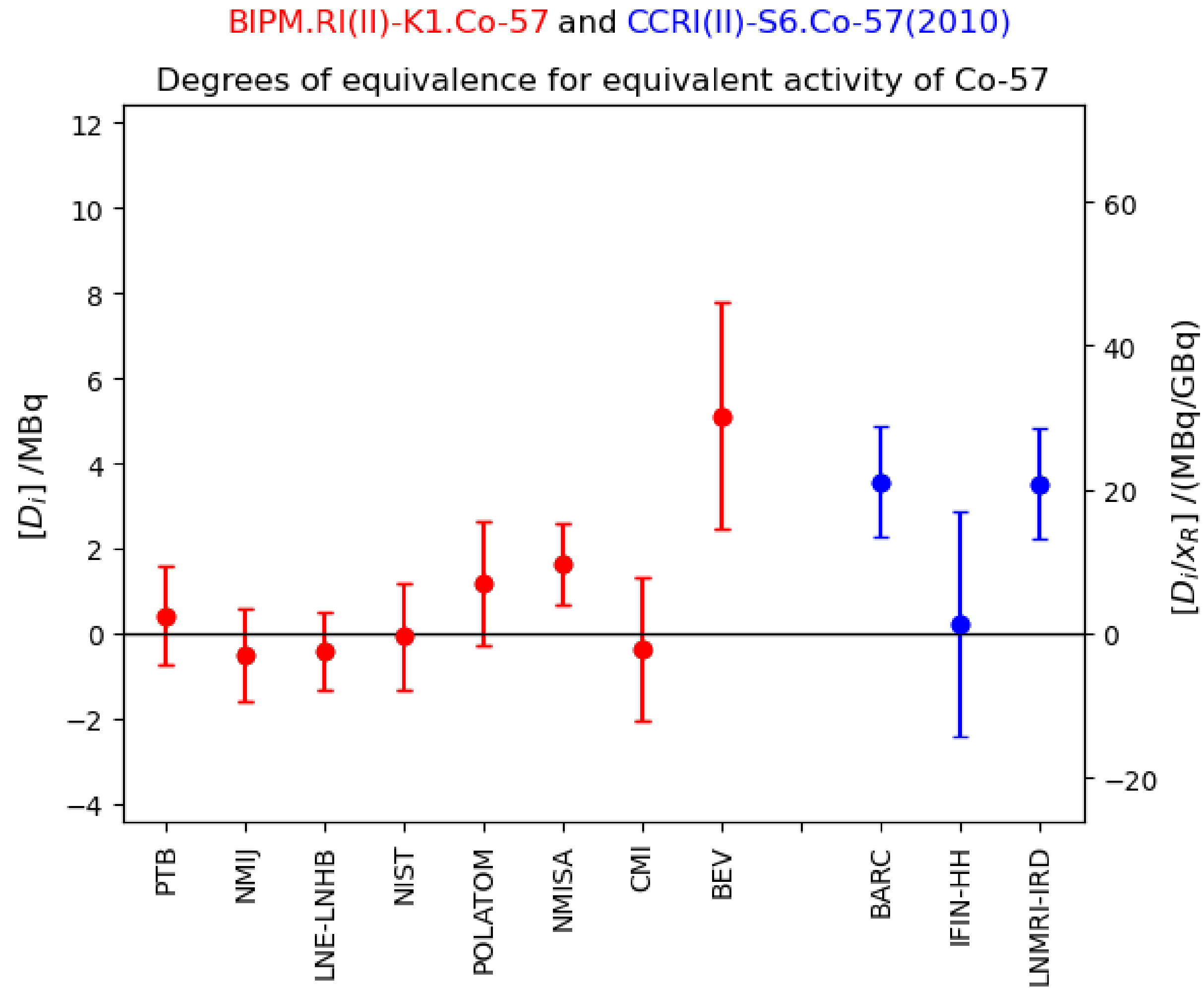

Figure C1. Degrees of equivalence for equivalent activity of ^{57}Co.

Appendix D. Uncertainty budgets for the activity of ^{57}Co submitted to the SIR

Uncertainty budget from BEV

SIR/SIRTI reporting form - radioactive solution V2.2 page 3a

BIPM.RI(II)-K1 or BIPM.RI(II)-K4

Measurement method	Pressurized Ionisation chamber	
ACRONYM	4P IC GR	**Comments:**
Activity concentration at reference date / kBq g^{-1}	347.9	
Relative standard uncertainty / 10^{-2}	0.72	
Date of measurement at the NMI (YYYY-MM-DD)	2023-03-21	

For relative methods:

Primary methods or standards used for calibration	I-125, Am-241, Co-57, Cs-137, Co-60
Date of calibration	4.2.2004
Date of primary measurement	

Uncertainty budget

Uncertainty component	Relative uncertainty / 10^{-2}	Evaluation type (A or B)	Comment
Counting statistics	0.076	A	
Background			included in counting statistics
Weighing	0.022	B	
current measurement	0.12	B	
chamber correction	0.12	B	gas pressure, temperature, position of source
filling height	0.12	B	
Decay data	0.015	B	
calibration factor	0.68	B	
Combined standard uncertainty	**0.72**		

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 π	4P	proportional counter	PC
defined solid angle	SA	press. Prop. Counter	PP
2 π	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
		CeBr3	CB

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	anticoincidence	AC
gamma rays	GR	coincidence counting with efficiency tracing	CT
x-rays	XR	anticoincidence 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**
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
4πCsI-β,AX,γ counting	4P-CS-MX-00-00-HE
calibrated IC	4P-IC-GR-00-00-00
internal gas counting	4P-PC-BP-00-00-IG