Update of the BIPM comparison BIPM.RI(II)-K1.Cs-137 of activity measurements of the radionuclide ^{137}Cs to include the 2014 result of the NRC (Canada) and the 2018 result of the TENMAK-NÜKEN (Türkiye)

C. Michotte[1], **R. Coulon**[1], **S. Courte**[1], **M. Nonis**[1], **S. Judge**[1], **G. Ratel**[1], **R. Galea**[2], **K. Moore**[2], **E. Yeltepe**[3], **A. Dirican**[3]

[1] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex, France.

[2] National Research Council (NRC), 1200 Montreal Road, ON K1A 0R6 Ottawa, Canada.

[3] Turkish Energy, Nuclear and Mineral Research Agency - Nuclear Energy Research Institute (TENMAK-NÜKEN), Lodumlu - Ankara, Türkiye.

E-mail: cmichotte@bipm.org

Abstract Since 1976, 23 laboratories have submitted 45 samples of ^{137}Cs 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.Cs-137. The NRC (Canada) and the TENMAK-NÜKEN (Türkiye) participated in the comparison and the key comparison reference value (KCRV) has been updated. The degrees of equivalence between each equivalent activity measured in the SIR or linked to the SIR from the COOMET.RI(II)-K2.Cs-137 comparison and the updated KCRV 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.Cs-137 key comparison. The results of earlier participations in this key comparison were published previously [3–5].

Successful participation in this comparison by a laboratory may provide evidential support for Calibration and Measurement Capability (CMC) claims for ^{137}Cs 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) [6]

2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–5]. 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.Cs-137.

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	1977-09-30
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1977-06-16 1994-06-03
ASMW	-	Amt für Standardisierung, Meßwesen und Warenprüfung	former East Germany	-	1978-11-07
BARC	-	Bhabha Atomic Research Centre	India	APMP	1997-04-30

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
BEV	IRK	Bundesamt fur Eich- und Vermessungswesen	Austria	EURAMET	1998-10-14 2011-09-27
BIPM	-	Bureau International des Poids et Mesures			1982-04-07
BKFH	OMH, MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1977-05-27 1997-09-25
CMI	UVVVR, CMI-IIR	Czech Metrological Institute	Czechia	EURAMET	1977-02-02 1978-11-28 1980-02-08
CNEA	-	Comision Nacional de Energia Atomica	Argentina	SIM	1992-01-28
IFIN-HH	-	Institutul National de Cercetare - Dezvoltare pentru Fizica si Inginerie Nucleara "Horia Hulubei"	Romania	EURAMET	2009-07-27
IRA	IER	Institut de Radiophysique	Switzerland	EURAMET	1996-09-20 2000-12-07
JRC	IRMM, CBNM	EC-JRC Institute for Reference Materials and Measurements	European Union	EURAMET	2004-01-20
LNE-LNHB	LMRI, LPRI, BNM-LNHB	Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel	France	EURAMET	1985-09-16 1998-12-14
NIM	-	National Institute of Metrology	China	APMP	1999-05-11
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1983-07-19 2001-11-28
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1994-12-06 2005-04-28
NMISA	NAC, CSIR-NML[b]	National Metrology Institute of South Africa	South Africa	AFRIMETS	1980-07-22 2010-08-05
NPL	-	National Physical Laboratory	United Kingdom	EURAMET	1977-05-18
NRC	-	National Research Council	Canada	SIM	2014-03-13
PTB	-	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1976-11-16

... Continuation of Table 1.

NMI or laboratory	Previous acronyms or other institutes	Full name	Country	RMO	Date of SIR measurement yyyy-mm-dd
					1997-11-13
PTKMR	PDS, PSPKR, P3KRBiN	Pusat Teknologi Keselamatan dan Metrologi Radiasi	Indonesia	APMP	1989-09-25
TENMAK-NÜKEN	TAEK	Turkish Energy, Nuclear and Mineral Research Agency - Nuclear Energy Research Institute	Türkiye	EURAMET	2018-01-11
VNIIM	-	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	2007-08-09

[a] Federal Crown corporation, not part of the NMI in Canada (see text)
[b] NAC is another institute in the country, now named iThemba LABS.

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 budgets for the new submissions are given in Appendix D attached to this report; previous uncertainty budgets are given in the earlier reports [3–5]. The list of acronyms used to summarize the methods is given in Appendix E.

Since 2004, the half life used by the BIPM is 11 020(60) days as published in IAEA TECDOC-619 [7]. The half life of 11 020.8(12) days [8] was used for the earlier results.

Table 2: Standardization methods of the participants for ^{137}Cs.

NMI or laboratory	Method used and the acronym	Activity A_i/kBq	Relative standard uncertainty /10^{-2} A	Relative standard uncertainty /10^{-2} B	Reference date yyyy-mm-dd	Half life /d
AECL	4π(PC) β-γ coincidence using ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	2634[e]	0.16	0.16	1977-08-16 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**	
		2538	0.16	0.16		
ANSTO	Pressurized IC (4P-IC-GR-00-00-00)	1362	0.3	2.0	1977-05-01 00:00 UT	
	Pressurized IC calibrated in 1982 (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CT)[a]	4483	0.05	1.33	1994-05-18 23:00 UT	
ASMW	4π(PC) β-γ coincidence using ^{134}Cs and ^{60}Co (4P-PC-BP-NA-GR-CT)	3902[e] 3906	0.07 0.07	0.25 0.25	1978-10-01 12:00 UT	
BARC	4πβ-γ coincidence using ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	545	0.5	0.6	1997-01-01 06:30 UT	
BEV	Pressurized IC (4P-IC-GR-00-00-00)[b]	8164	0.09	0.71	1998-10-01 00:00 UT	11 020(60) [9]
	Pressurized IC (4P-IC-GR-00-00-00)[b]	3568	0.03	0.68	2011-01-01 00:00 UT	10 975.528
BIPM	4π(PC) β-γ coincidence /selective sampling with ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	2219.3[e] 2190.8 2189.9			1982-05-01 00:00 UT	11 100(100)
BKFH	4π(PC) β-γ coincidence using ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	3426[e] 3425	0.2 0.2	0.8 0.8	1977-04-30 12:00 UT	10 921 [10]
	4π(PC) β-γ coincidence using ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	1891	0.06	0.35	1997-10-01 00:00 UT	-
CMI	4π(PC) β counting (4P-PC-BP-00-00)	15 264	0.15	0.35	1976-12-15 11:00 UT	10 994
	4π(PC) β counting (4P-PC-BP-00-00)	4474	0.2	0.43	1978-10-24 11:00 UT	10 921
	4π(PC) β counting (4P-PC-BP-00-00)	4212	0.2	0.43	1979-10-24 11:00 UT	
CNEA	4π(PC) β counting using ^{134}Cs efficiency tracer, calibrated HPGe (4P-PC-BP-NA-GR-ET, UA-GH-GR-00-00-00)	1465	0.19	0.6	1992-01-01 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**	
IFIN-HH	Pressurized IC calibrated in 2003 (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CT)[a]	2730	0.32	0.74	2009-07-01 00:00 UT	10 976(29) [11]
IRA	Pressurized ionization chamber (4P-IC-GR-00-00-00)[c]	2365	0.02	0.16	1996-09-01 00:00 UT	-
	Pressurized ionization chamber (4P-IC-GR-00-00-00)[c]	2159	0.03	0.17	2000-12-01 00:00 UT	10 972(11)
JRC	4π(PPC)- γ (NaI well) coincidence using ^{134}Cs efficency tracer (4P-PP-BP-NA-GR-CT) CIEMAT/NIST method (4P-LS-BP-00-00-CN)	980.8[g] 980.8	0.5 0.10	0.4 0.69	2003-07-01 00:00 UT	11 020(60) [9]
LNE-LNHB	Pressurized IC calibrated in 1982 (4P-IC-GR-00-00-00 & 4P-PC-BP-GL-GR-CT)[a]	1047[e] 1044	0.03 0.03	0.27 0.27	1985-06-15 12:00 UT	-
	4π(PC) β-γ coincidence using ^{134}Cs efficiency tracer, LS counting (4P-PC-BP-NA-GR-CT & 4P-LS-BP-00-00-00)	3187	0.03	0.3	1998-04-06 12:00 UT	10 971(10)
NIM	Pressurized IC (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CT)[a]	5504[e] 5562	0.3 0.3	0.5 0.5	1998-11-23 00:00 UT	-
NIST	Pressurized ionization chamber calibrated in 1982 (4P-IC-GR-00-00-00 & 4P-PP-BP-NA-GR-AT)[d]	2541	0.12	0.31	1982-05-01 00:00 UT	
	Pressurized ionization chamber calibrated in 1982 (4P-IC-GR-00-00-00 & 4P-PP-BP-NA-GR-AT)[d]	1190	0.05	0.34	2001-11-15 12:00 UT	10 983(11)
NMIJ	4π(PC) β-γ coincidence using 60Co efficiency tracer (4P-PC-BP-NA-GR-CT)	4133	0.1	0.4	1994-12-01 12:00 UT	-
	$4\pi\beta$-γ coincidence using ^{134}Cs efficiency tracer (4P-PC-BP-NA-GR-CT)	2687	0.4	0.3	2005-02-15 00:00 UT	10 971.8

... 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**	
NMISA	4π(LS) β-γ coincidence using 60Co efficiency tracer (4P-LS-BP-NA-GR-CT)	66 760[e] 60 690	0.04 0.04	0.99 0.99	1980-05-21 10:00 UT	-
	4π LS β-γ coincidence using 60Co efficiency tracer (4P-LS-BP-NA-GR-CT)	1471.8	0.04	0.3	2009-11-26 10:00 UT	10 964(9)
NPL	Pressurized ionization chamber traceable to NPL primary standards (4P-IC-GR-00-00-00)	566[e] 554	0.05 0.05	1.92 1.92	1977-06-01 00:00 UT	-
NRC	4π(PPC) β-γ anti-coincidence using ^{134}Cs efficency tracer (4P-PP-BP-NA-GR-AT)	2338.37	0.2	0.57	2013-10-07 17:00 UT	10 976(29) [11]
PTB	Pressurized ionization chamber calibrated by 4π(PC) β-γ coincidence with efficiency tracing and by 4π(PC) β counting (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CT & 4P-PC-BP-00-00-00)	2043[e] 2039	0.16 0.16	0.3 0.3	1976-10-01 00:00 UT	-
	Pressurized ionization chamber calibrated in 1982 by 4πβ-γ PC/PPC coincidence using ^{134}Cs efficiency tracer (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CT & 4P-PP-BP-NA-GR-CT)	19 734[f]	0.05	0.36	1998-01-01 00:00 UT	-
PTKMR	4πβ-γ coincidence using ^{134}Cs efficiency tracer. (4P-PC-BP-NA-GR-CT)	2462[e] 2629	0.07 0.07		1989-08-01 15:00 UT	
TENMAK-NÜKEN	Pressurized ionization chamber traceable to the PTB (4P-IC-GR-00-00-00)	609.373	0.79	1.3	2016-04-01 12:00 UT	10 976(29) [11]
VNIIM	4π(PC) β counting (4P-PC-BP-00-00-00)	3385	0.35	0.25	2007-06-01 00:00 UT	10 969

... 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] IC calibrated by 4π(PC) β-γ coincidence using ^{134}Cs efficiency tracer
[b] Traceable to primary standards of ^{137}Cs at the NPL
[c] Traceable to the SIR in 1982
[d] IC calibrated by 4π(PPC) β-γ anti-coincidence with ^{134}Cs efficiency tracer
[e] Several samples submitted
[f] The result is the mean of the different methods.
[g] The mean activity value and standard uncertainty of the two results submitted as evaluated by the JRC is 980.8(58) kBq

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 ^{137}Cs 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 1977	CsCl in HCl	0.3	Cs:10	1	^{134}Cs:0.03(1) %
ANSTO 1977	CsCl in HCl	0.1	-	1	^{134}Cs:0.09(2) %
1994	CsCl in HCl	2	-	-	-
ASMW 1978	$CsNO_3$ in HNO_3	0.1	$CsNO_3$:20	1.0001	^{134}Cs:0.35(2) %
BARC 1997	$CsNO_3$ and $Ba(NO_3)_2$ in HNO_3	0.01	$CsNO_3$ $Ba(NO_3)_2$:37	-	-
BEV 1998	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	1	-
2011	CsCl in HCl	0.1	CsCl:50	1	-
BIPM 1982 [a]	CsCl in HCl	0.2	CsCl:20	-	^{134}Cs:0.004 %
BKFH 1977	Cs in HCl	0.1	Cs:10	1	^{60}Co:0.003(1) % ^{134}Cs:0.021(5) %
1997	CsCl in HCl	0.1	CsCl:25	-	^{134}Cs:0.005(1) %
CMI 1977	CsCl in HCl	0.01	CsCl:20	-	<0.03 %
1978	CsCl in HCl	0.08	CsCl:20	-	^{134}Cs:0.16(2) %
1980	CsCl in HCl	0.08	CsCl:20	-	^{134}Cs:0.040(8) %
CNEA 1992	CsCl in HCl	0.1	CsCl:50	1	^{134}Cs:0.10(5) %
IFIN-HH 2009	CsCl in HCl	1	CsCl:100	1	-
IRA 1996	CsCl in HCl	1	CsCl:30	-	^{60}Co<0.00033 %
2000	CsCl in HCl	1	CsCl:30	1.015	-
JRC 2004	CsCl in HCl	0.1	CsCl:50	-	^{134}Cs:0.013(1) %
LNE-LNHB 1985	CsCl and $BaCl_2$ in HCl	0.1	CsCl:10 $BaCl_2$:10	0.999	-
1998	CsCl in HCl	0.1	CsCl:10	1.0001	-

... 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]
NIM 1999	Cs,Ba in HCl	0.1	Cs Ba:50	1.008	-
NIST 1983	CsCl in HCl	1	CsCl:19	1.015	^{134}Cs:0.00106(53) %
2001	CsCl in HCl	1	CsCl:30	1.015(1)	-
NMIJ 1994	CsCl in HCl	0.1	CsCl:50	1	-
2005	CsCl in HCl	0.1	CsCl:50 CsCl:100	1.00 1.002	-
NMISA 1980	CsCl in HCl	1	Cs:789	1.037	-
2010	CsCl in HCl	1	$CsCl_2$:1000	1.02	-
NPL 1977	CsCl in HCl	0.1	CsCl:100	1.001	^{134}Cs<0.01 %
NRC 2014	HCl	0.1	-	1	None detected
PTB 1976	CsCl in HCl	0.1	CsCl:50	-	^{134}Cs:0.02 %
1997	CsCl in HCl	0.1	CsCl:50	1	-
PTKMR 1989	CsCl in HCl	2.7	CsCl:28	1.0920(3)	-
TENMAK-NÜKEN 2018	CsCl in HCl	0.1	CsCl:50	1	None detected
VNIIM 2007 [b]	Cs in HNO_3	0.5	-	1.015	^{90}Sr/^{90}Y<0.018 % γ emitters < 0.007 %

[a] solution used to make the link of the 1982 CCRI(II)-K2 comparison
[b] solution used to make the link of the 2007 COOMET.RI(II)-K2 comparison
[c] The ratio of the activity of the impurity to the activity of ^{137}Cs at the reference date

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 2 ampoules for the activity measurements of ^{137}Cs giving rise to 45 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]. Table 4 also shows the comparison results selected for the KCRV as explained in section 4.1.

Table 4: Results of SIR measurement of ^{137}Cs.

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 1977	0.526 80[a]	2634	3	27 596	8	66	27 590(66)[e]
	0.507 58	2538	3	27 583	7	65	-
ANSTO 1977	3.593	1362	3	27 460	9	540	-
1994	3.711	4483	3	27 470	6	370	27 470(370)
ASMW 1978	3.644 22	3902	3	27 914	8	76	27 922(76)[e]
	3.647 83	3906	3	27 930	8	76	-
BARC 1997	3.642 2	545	2	27 380	9	220	27 380(220)
BEV 1998	3.611	8164	4	27 320	5	200	-
2011	3.602 6	3568	3	27 400	6	190	-
BIPM 1982	3.657 94	2219.3	3	27 613	6	123	27 610(120)[e]
	3.611 08	2190.8	3	27 601	6	123	-
	3.609 48	2189.9	3	27 615		123	-
BKFH 1977	3.604 3	3426	3	27 386	6	230	-
	3.603 2	3425	3	27 395	6	230	-
1997	3.624 6	1891	3	27 628	7	99	27 628(99)
CMI 1977	0.957 64[b]	15 264	4	27 490	5	110	-
1978	3.590 34	4474	3	27 730	8	130	-
1980	3.592 6	4212	3	27 530	7	130	-
CNEA 1992	2.029 65	1465	3	27 450	15	180	-
IFIN-HH 2009	3.609 67	2730	3	27 610	6	220	-
IRA 1996	3.591 1(1)	2365	3	27 552	6	47	-
2000	3.626 5(1)	2159	3	27 458	6	50	-
JRC 2004	3.632 55	980.8	2	27 340	9	160	27 340(160)[f]
		980.8		27 340		160	-
LNE-LNHB 1985	3.561 31	1047	2	27 561	9	79	-
	3.571 45	1044	2	27 500	8	78	-
1998	3.595	3187	3	27 514	6	84	27 514(84)
NIM 1999	3.616 48	5504	4	27 255	5	170	27 260(170)[e]
	3.654 61	5562	4	27 270	5	170	-
NIST 1983	3.615 39	2541	3	27 577	6	93	27 577(93)
2001	3.649 1(2)	1190	2	27 634	8	98	-
NMIJ 1994	3.612 2	4133	3	27 750	6	120	-
2005	3.621 22	2687	3	27 720	6	140	27 720(140)
NMISA 1980	3.601	66 760	5	27 658	5	280	-
	3.603	60 690	5	27 653	5	280	-
2010	3.632 13	1471.8	2	27 710	10	90	27 710(90)
NPL 1977	3.617 8	566	2	27 307	9	530	27 290(520)[e]
	3.543 7	554	2	27 269	9	520	-
NRC 2014	3.608 6	2338.37	3	27 908	6	169	27 910(170)
PTB 1976	3.618 3(2)	2043	3	27 289	6	94	-
	3.611 6(2)	2039	3	27 286	6	94	-
1997	3.657 33	19 734	5	27 600	5	100	27 600(100)
PTKMR 1989	3.556	2462	3	27 966	6	26	-
	3.797	2629	3	27 962	6	25	-

... 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_{ei} for KCRV /kBq
TENMAK-NÜKEN 2018	3.615 6	609.373	2	27 687	8.9	422	-
VNIIM 2007	3.593 42	3385	3	27 450 [d]	6	120	-

[a] mass of standardized solution before dilution
[b] mass measured at the BIPM after transfer into NBS/BIPM ampoule
[d] result used to link the COOMET.RI(II)-K2.Cs-137 comparison
[e] An average value and average uncertainty between all submitted samples is used for the KCDB [14].
[f] The result was obtained using an average between methods.

The COOMET.RI(II)-K2.Cs-137 comparison was held in 2007 [15]. The results were linked to the BIPM.RI(II)-K1.Cs-137 comparison through the measurement in the SIR of at least one ampoule of the COOMET 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.

Consequently, using the recent result produces an updated KCRV for ^{137}Cs in 2018 of **27 613(47) kBq** with the power α =1.8 that has been calculated using the previously published results, selected as shown in Table 4, for the AECL (1977), NPL (1977), ASMW (1978), BIPM (1982), NIST (1983), ANSTO (1994), BARC (1997), BKFH (1997), PTB (1997), LNE-LNHB (1998), NIM (1999), JRC (2004), NMIJ (2005), NMISA (2010), and the NRC (2014) result. This can be compared with the previous KCRV values of 27 549(44) kBq published in 2003 [3], 27 534(42) kBq published in 2005 [4] and 27 544(49) kBq published in 2013 [5].

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

$$D_i = A_{\mathrm{e}i} - \mathrm{KCRV} \qquad (1)$$

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

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

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

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

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 $A_{\mathrm{e}i}$ 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 ^{137}Cs, BIPM.RI(II)-K1.Cs-137, currently comprises 7 valid results. The KCRV has been recalculated to include the latest result from the NRC (Canada). The SIR results, together with the previously published COOMET.RI(II)-K2.Cs-137 results, have been analyzed with respect to the updated KCRV, providing degrees of equivalence for 9 national metrology institutes. Other results may be added when other NMIs contribute ^{137}Cs activity measurements to this comparison or take part in other linked comparisons.

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Appendix A. Introductory text for ^{137}Cs degrees of equivalence

Key comparison BIPM.RI(II)-K1.Cs-137

MEASURAND: Equivalent activity of ^{137}Cs

Key comparison reference value: the SIR reference value x_{R} for this radionuclide is 27 613 kBq , with a standard uncertainty, u_{R} equal to 47 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.Cs-137

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Cs-137

NMI i	D_i /**MBq**	U_i /**MBq**
NMIJ	0.11	0.28
VNIIM	-0.16	0.26
IFIN-HH	-0.00	0.45
NMISA	0.10	0.19
BEV	-0.21	0.39
NRC	0.29	0.33
TENMAK-NUKEN	0.07	0.85

Table B2: The table of degrees of equivalence for the COOMET.RI(II)-K2.Cs-137(2007) comparison

NMI i	D_i /**MBq**	U_i /**MBq**
BelGIM	-0.39	0.55
SMU	0.16	0.63

Appendix C. Graph of degrees of equivalence with the KCRV for ^{137}Cs (as it appears in Appendix B of the MRA)

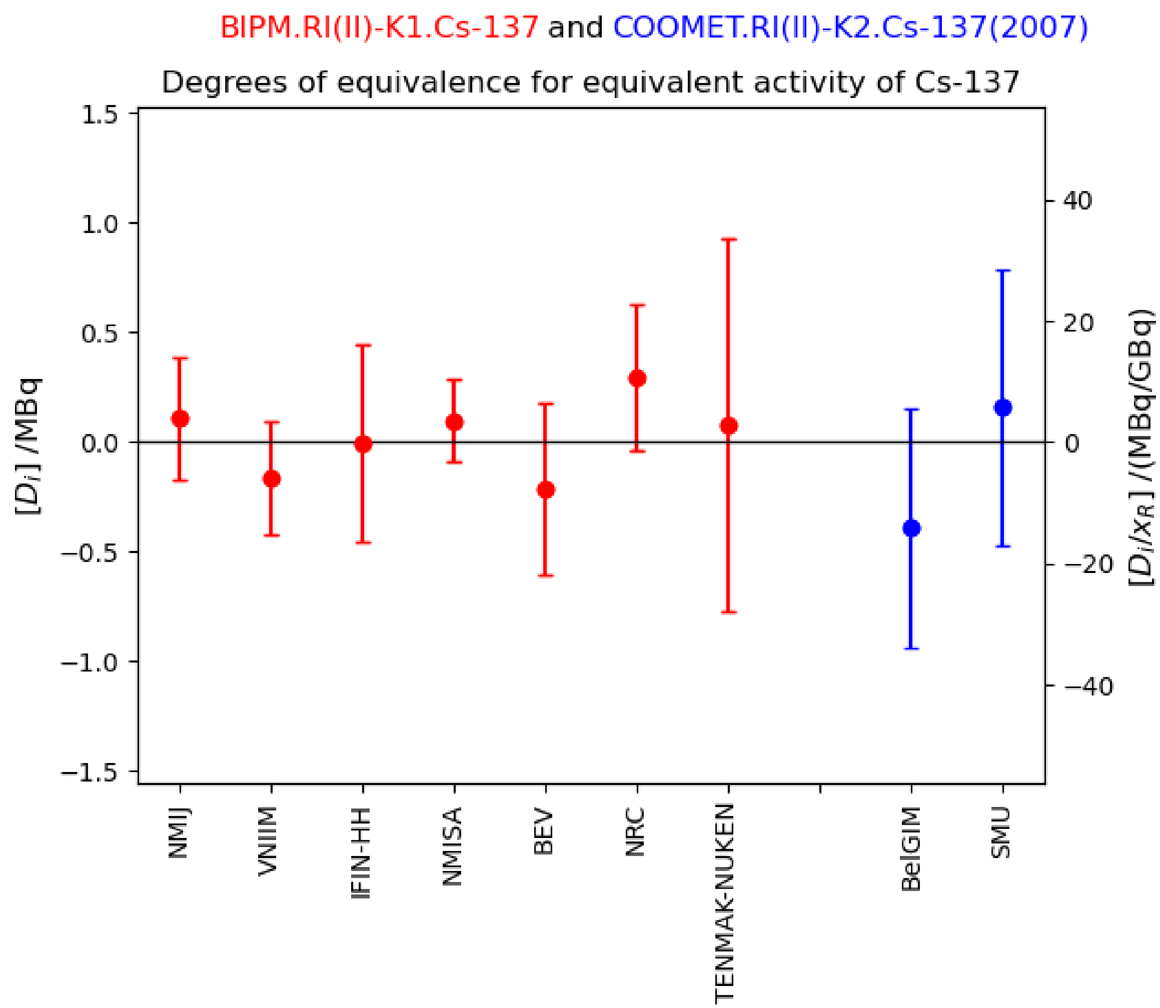

Figure C1. Degrees of equivalence for equivalent activity of ^{137}Cs.

Appendix D. Uncertainty budgets for the activity of ^{137}Cs submitted to the SIR

The NRC (2014) has submitted a detailed uncertainty budget as follows:

Relative standard uncertainties **Contributions due to**	$u_{rel,i}$ **/ 10^{-4}**	**Method of evaluation**	**Comments**
counting statistics	20	A	internal uncertainty of the weighted average of 9 sources
weighing	< 3	B	balance calibration
live time	< 0.1	B	
background	1	B	see below *
tracer	40	B	^{134}Cs tracer uncertainty
decay corrections	–		
extrapolation of efficiency curve	40	B	maximum standard error on N_0
correction factor due to non-beta triggered events $1 + b(\alpha\epsilon_{ce} + \epsilon_{\beta\gamma})/(1+\alpha)$	5	B	b = β branching ratio of ^{137}Cs
Relative combined standard uncertainty, u_c	**60**		

* equation is $ma_1 \frac{(N_\gamma - Y)}{N_\gamma N_\beta} \frac{\Delta B_\gamma}{N_\gamma}$ where,

a_1 ≡ fit coefficient
Y ≡ γ counting rate
N_β ≡ β counting rate in the A/C channel
N_γ ≡ gamma counting rate
ΔB_γ ≡ uncertainty of background rate

The TENMAK-NUKEN has submitted a detailed uncertainty budget as follows:

Relative standard uncertainties	Comment	$u_{rel,i} \times 10^4$ evaluated by method	
Contributions due to		**A**	**B**
Ampoule current meas.	–	75	–
Cs-137 ref. source current meas.	–	25	–
IC calibration factor	–	–	130
Background	included in contribution from current measurement	–	–
Weighing	2 μg precision microbalance	–	0.3
Adsorption	counting of rinsed ampoule with HPGe detector	–	negl.
Decay correction	uncertainty of decay correction during measurement is negl.	–	0.84
Radionuclide impurities	not detectable at 20 cm with HPGe detector	–	negl.
Quadratic summation		**79**	**130**
Relative combined standard uncertainty, u_c		**150**	

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