Update of the BIPM comparison BIPM.RI(II)-K1.Cr-51 of activity measurements of the radionuclide ^{51}Cr to include the 2012 result of the KRISS (Rep. of Korea), the 2022 result of the POLATOM (Poland), and to link the 2022 EURAMET.RI(II)-K2.Cr-51 comparison

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Abstract

Two new participations in the BIPM.RI(II)-K1.Cr-51 comparison have been added to the previous results and this has produced a revised value for the key comparison reference value (KCRV), calculated using the power-moderated weighted mean. A link has been made to the EURAMET.RI(II)-K2.Cr-51 comparison piloted by the POLATOM in 2022, who sent an ampoule from the EURAMET comparison to the International Reference System (SIR). The LNE-LNHB (France) used the EURAMET comparison to update its degree of equivalence. The degrees of equivalence between each equivalent activity measured in the SIR and the KCRV have been calculated and the results are given in the form of a table for the latest results in the BIPM.RI(II)-K1.Cr-51, and the linked EURAMET.RI(II)-K2.Cr-51. A graphical presentation 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. For radioactive gases, a different standard ampoule is used. Each NMI completes a 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 measured 1054 ampoules to provide 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 ongoing comparisons and the results form the basis of the BIPM key comparison database (KCDB) of the CIPM Mutual Recognition Arrangement (CIPM MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Cr-51 key comparison and includes results published previously [3 - 5].

In addition, a bilateral comparison, EURAMET.RI(II)-K2.Cr-51, piloted by the National Centre for Nuclear Research Radioisotope Centre POLATOM, Laboratory of Radioactivity Standards (POLATOM, Poland) was held in 2022 for this radionuclide [6]. A link to the SIR has been evaluated thanks to the participation of the POLATOM in both comparisons.

One further international comparison linked to the SIR, APMP.RI(II)-K2.Cr-51 was held in 2004. Linked degrees of equivalence were already published in [4].

Successful participation in this comparison by a laboratory may provide evidential support for Calibration and Measurement Capability (CMC) claims for ^{51}Cr 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)[1,2].

2. Participants in the BIPM.RI(II)-K1.Cr-51

The KRISS and the POLATOM have submitted ampoules for inclusion in this comparison. The details of the laboratories that have participated in the BIPM.RI(II)-K1.Cr-51 comparison are given in Table 1a, with the earlier submissions being taken from [3 - 5]. 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 is used in the KCDB. The date of measurement in the SIR is also given in Table 1a and is used in the KCDB and all references in this report.

[1] International Rules for CMC Claims in Ionizing Radiation Metrology Doc 3 March 16 2021 (Sept 2020), Consultative Committee for Ionizing Radiation metrology (CCRI), https://www.bipm.org/documents/20126/54619299/Rules+for+entering+CMC+claims+in+ionizing+radiation+metrology/c0b97b77-99e1-4abb-1d10-9a90a35fc9bf

[2] Guidance on Applying the Measurement Methods Matrix (MMM) in Using Comparison Results to Support CMCs, https://www.bipm.org/documents/20126/72227223/MMM+and+supporting+docs.pdf/3e2bc3be-ce68-591f-a4f5-fce0c3aedefc

Table 1a. Details of the participants in the BIPM.RI(II)-K1.Cr-51

NMI	**Original acronym**	**Full name**	**Country**	**Regional metrology organization**	**Date of measurement at the BIPM**
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1977-01-24 1978-12-15 1981-08-12 1999-05-03
CMI	UVVVR	Český Metrologický Institut/Czech Metrological Institute, Inspectorate for Ionizing Radiation	Czech Republic	EURAMET	1978-04-13 1982-06-30
–	IAEA**	International Atomic Energy Agency	–	–	1978-05-19
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1978-08-30
PTB	ASMW *	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1979-03-01 1983-01-14 1995-03-24 1998-04-24
BFKH	OMH MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1980-05-22 1989-10-09
–	AECL***	Atomic Energy of Canada Ltd	Canada	–	1980-07-09
NPL	–	National Physical Laboratory	United Kingdom	EURAMET	1980-12-01 2004-05-28
–	CBNM now JRC	Joint Research Centre, European Union	European Union	EURAMET	1981-06-17
LNE-LNHB	LMRI LPRI BNM-LNHB	Laboratoire national de métrologie et d’essais -Laboratoire national Henri Becquerel	France	EURAMET	1984-12-20 1994-04-15 2006 -07-17
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1993-11-24 2004-03-15

Table 1a continued. Details of the participants in the BIPM.RI(II)-K1.Cr-51

NMI	Original acronym	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
KRISS	–	Korea Research Institute of Standards and Science	Rep. of Korea	APMP	2012-01-27
POLATOM	–	National Centre for Nuclear Research Radioisotope Centre POLATOM, Laboratory of Radioactivity Standards	Poland	EURAMET	2022-06-03

* Another laboratory in the country
** In collaboration with UVVVR
*** Federal Crown corporation, not part of the NMI in Canada

The two NMIs that took part in the bilateral comparison, EURAMET.RI(II)-K2.Cr-51 piloted by the POLATOM in 2022 are shown in Table 1b including the POLATOM, the linking laboratory.

Table 1b. Details of the participants in the 2022 EURAMET.RI(II)-K2.Cr-51 eligible for linking to BIPM.RI(II)-K1.Cr-51 comparison

NMI	**Full name**	**Country**	**Regional metrology organization**
LNE-LNHB	Laboratoire national de métrologie et d’essais - Laboratoire national Henri Becquerel	France	EURAMET
POLATOM	National Centre for Nuclear Research Radioisotope Centre POLATOM, Laboratory of Radioactivity Standards	Poland	EURAMET

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.

A brief description of the standardization methods, the activities submitted, the relative standard uncertainties and the half-life used by the participants in the SIR are given in Table 2. The uncertainty budgets for the two new submissions are given in Appendix 1, previous uncertainty budgets are given in the earlier K1 reports [3–5]. The uncertainty budgets for the eligible participants in the EURAMET.RI(II)-K2.Cr-51 comparison are given in the EURAMET comparison report [6]. The acronyms used for the measurement methods are given in Appendix 2.

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 2. Standardization methods of the SIR participants for ^{51}Cr

NMI	Method used and acronym (see Appendix 2)	Half-life / d	Activity A_i / kBq	Reference date YYYY-MM-DD	Relative standard uncertainty × 100 by method of evaluation	
					A	B
NIST 1977	Pressurized IC* 4P-IC-GR-00-00-00	–	10 260	1976-12-07 17 h UT	0.05	1.35
1978		27.73	3 936	1978-12-06 17 h UT	0.01	0.64
1981	Pressurized IC ** 4P-IC-GR-00-00-00	27.73	6 082	1981-07-28 16 h UT	0.01	0.34
1999		27.702(4)	24 449	1999-04-22 19 h UT	0.10	0.24
CMI 1978	4π x-γ coincidence 4P-PC-MX-NA-GR-CO	27.75	3 570	1978-02-23 11 h UT	0.20	0.47
1982	4π(PC)-γ coincidence 4P-PC-MX-NAGR-CO	27.71	7 233	1982-06-09 12 h UT	0.10	0.23
IAEA 1978	x-γ coincidence 00-00-XR-00-GR-CO	27.75	3 781	1978-02-23 11 h UT	0.20	0.47
ANSTO 1978	4πx-γ coincidence 4P-PC-XR-NA-GR-CO	–	7 368	1978-08-01	0.1	0.1
PTB 1979	Pressurized IC † 4P-IC-GR-00-00-00	–	15 428	1979-03-01	0.02	0.15
1983	4π(e_A,x)-γ coincidence 4P-PP-MX-NAGR-CO	–	13 984 14 041	1982-11-29 12 h UT	0.26	0.36
1995	Pressurized IC ‡ 4P-IC-GR-00-00-00	–	8 425 8 403	1995-04-01	0.03	0.40
1998	4π(PPC)EC-γ coincidence 4P-PP-MX-NA-GR-CO	27.706(7) [7]	7 485	1998-05-01	0.05	0.13

Table 2 continued. Standardization methods of the participants for ^{51}Cr

NMI	Method used and acronym (see Appendix 2)	Half-life / d	Activity A_i / kBq	Reference date	Relative standard uncertainty × 100 by method of evaluation	
				YYYY-MM-DD	A	B
BFKH 1980	4π(e,x)-γ coincidence 4P-PP-MX-NA-GR-CO	27.70(4)	23 570	1980-06-01 12 h UT	0.03	0.61
1989		27.703(4)	89 410	1989-10-15 12 h UT	0.08	0.24
AECL 1980	4π(PC)-γ coincidence 4P-PC-MX-NA-GR-CO	–	39 683	1980-06-04 17 h UT	0.06	0.18
NPL 1980	4πβ-γ coincidence 4P-PC-BP-NA-GR-CO	–	15 533	1980-12-05 0 h UT	0.24	0.33
2004		27.7009 (20)	3 803	2004-05-25 12 h UT	0.10	0.66
JRC 1981	4π(e_A,x)-γ coincidence 4P-PC-MX-NA-GR-CO	–	10 414 10 339	1981-06-01	0.03	0.17
LNE-LNHB 1984	4πx-γ coincidence	27.706(7) [7]	3 373 3 375	1984-12-17	0.13	0.13
1994	4P-PP-XR-NA-GR-CO		13 813 13 675	1994-04-20 12 h UT	0.20	0.05
2006	4π(PC) β-γ 4P-PC-MX-GE-GR-AC	27.703(3) [8]	10 820	2006-07-01 12 h UT	0.10	0.15
NMIJ 1993	4π(e,x)-γ coincidence 4P-PC-MX-NA-GR-CO	–	5 938	1993-11-01 0 h UT	0.04	0.30
2004		27.702(3) [9]	7 896	2004-03-01 0 h UT	0.18	0.21
KRISS 2012	4P-PP-AE-NA-GR-CO	27.703(3) [8]	23 406	2011-10-11 15 h UT	0.09	0.45
POLATOM 2022	4π(LS)-γ coincidence and anticoincidence methods 4P-LS-MX-NA-GR-CO 4P-LS-MX-NA-GR-AC	27.704(4)	24 762[‡‡] 24 798	2022-06-01 12 h UT	0.89 0.85	0.02 0.04

* calibrated by 4πx-γ coincidence 4P-??-XR-??-GR-CO

**calibrated on 28 July 1981 using a ^{51}Cr solution whose activity was determined by the 4π(e+x)-γ anti-coincidence efficiency-extrapolation technique

† calibrated for ^{51}Cr in 1978 by 4π(PC) EC-γ coincidence (4P-PP-MX-NA-GR-CO) by the PTB

‡ calibrated in 1978 using an absolute measurement for the nuclide considered

‡‡ The weighted mean result reported by the POLATOM is 24 784(152) kBq.

Table 3. Details of the solution of ^{51}Cr submitted

NMI	Chemical composition	Solvent conc. / (mol dm^{-3})	Carrier conc. / (µg g^{-1})	Density /(g cm^{-3})	Relative activity of impurity†
NIST 1977	Cr in HCl	1	Cr : 13	–	^{192}Ir: 0.015 (3) %
1978			Cr : 7	1.015(2)	^{54}Mn: 6.1 × 10^{-5} % ^{58}Co: 7.9 × 10^{-4} % ^{59}Fe: 2.1 × 10^{-4} % ^{60}Co: 4.8 × 10^{-4} % ^{65}Zn: ^{137}Cs : traces
1981			Cr : 10	1.016(2)	^{65}Zn: 3 × 10^{-4} % ^{75}Se: 6.2 × 10^{-3} %
1999	$CrCl_2$ in HCl	1	$CrCl_2$: 1000	1.017(1)	–
CMI 1978	$Cr(NO_3)_3$ in HCl	0.08	$Cr(NO_3)_3$: 50	–	< 0.01 %
1982					< 0.1 %
IAEA 1978	$Cr(NO_3)_3$ in HCl	0.08	$Cr(NO_3)_3$: 50	–	< 0.01 %
ANSTO 1978	$CrCl_2$ in HCl	1	–	1	< 0.1 %
PTB 1979	$CrCl_2$ in HCl	0.1	$CrCl_2$: 50	1.000	< 0.01 %
1983	$CrCl_3$ in HCl	0.1	$CrCl_3$: 20	1.0005	< 0.1 %
1995			$CrCl_3$: 50	1.00	–
1998			$CrCl_3$: 40	0.9995	–
BFKH 1980	Cr in HCl	0.1	Cr: 25	–	^{124}Sb: 1.5(6) × 10^{-3} %
1989			Cr: 28	–	^{60}Co: 2(1) × 10^{-4} %
AECL 1980	$CrCl_3$ in HCl	0.3	$CrCl_3$: 30	1	< 0.1 %
NPL 1980	$CrCl_3$ in HCl	0.1	Cr: 30	1.001	–
2004	Na_2CrO_4 in H_2O	–	Na_2CrO_4 : 10	1	–
JRC 1981	$Na_2{}^{51}CrO_4$ in HCl (with NaCl: 450 µg/g)	0.002	–	1.00(1)	–

Table 3 continued. Details of the solution of ^{51}Cr submitted

NMI	Chemical composition	Solvent conc. / (mol dm^{-3})	Carrier: conc. /(µg g^{-1})	Density / (g cm^{-3})	Relative activity of impurity†
LNE-LNHB 1984	$CrCl_2$ in HCl	0.1	$CrCl_2$: 10	0.999	–
1994	$CrCl_3$ in HCl	0.1	$CrCl_3$: 100	1.00	^{124}Sb: 0.0024(4) %
2006	$CrCl_3 .6H_2O$ in HCl	0.1	$CrCl_3 .6H_2O$: 100	1.00	–
NMIJ 1993	$CrCl_2$ in HCl	0.1	$CrCl_2$: 50	1.00	–
2004*			$CrCl_2$: 100	1.002	–
KRISS 2012	^{51}Cr in HCl	1	–	1.0176	–
POLATOM 2022**	^{51}Cr in HCl	0.1	Na_2CrO_4 : 25	1.00	^{60}Co: 1.57(15) × 10^{-4} %

† the ratio of the activity of the impurity to the activity of ^{51}Cr at the reference date.
* same solution used in the 2004 APMP.RI(II).K2.Cr-51 comparison
** same solution used in the 2022 EURAMET.RI(II).K2.Cr-51 comparison

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a database known as the "master-file". The latest submissions have added two ampoules for the activity measurements of ^{51}Cr giving rise to 30 ampoules in total. The SIR equivalent activity, A_{ei}, for each ampoule received from each NM, i, including both previous and new results, is given in Table 4a. The relative standard uncertainty arising from each measurement in the SIR is also shown. This uncertainty is additional to that declared by the NMI 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].

The half-life used by the BIPM is 27.703(3) d from *Monographie BIPM*-5 Volume 1 [8], while in the EURAMET.RI(II)-K2 comparison the updated value of 27.704(4) d from the DDEP website (2014-06-15 update), has been selected.

Measurements repeated at the BIPM after periods of up to 2 months later produced comparison results in agreement within standard uncertainty for the POLATOM(2022).

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

Table 4a. Results of SIR measurements of ^{51}Cr

NMI	Mass of solution m_i / g	Activity submitted A_i / kBq	N° of Ra source used	SIR A_e / MBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / MBq
NIST 1977	5.072 5	10 260	1	494.5	22×10^{-4}	6.8
1978	3.762 75	3 936	1	495.2	15×10^{-4}	3.2
1981	3.726 64	6 082	1	488.3	16×10^{-4}	1.8
1999	3.759 6(2)	24 449	2	489.4	10×10^{-4}	1.4
CMI 1978	3.703 82	3 570	1	485.8	17×10^{-4}	2.6
1982	3.643 67	7 233	1	488.7	12×10^{-4}	1.4
IAEA 1978	3.604 58	3 781	1	486.0	21×10^{-4}	2.7
ANSTO 1978	3.605 79	7 368	1	489.9	16×10^{-4}	1.0
PTB 1979	3.732 9(1)	15 428	2	488.1	9×10^{-4}	0.9
1983	3.596 8(1) 3.611 4(1)	13 984 14 041	1	488.7 488.3	13×10^{-4} 12×10^{-4}	2.3 2.2
1995	3.544 8 3.535 7	8 425 8 403	2	487.3 487.3	9×10^{-4} 10×10^{-4}	2.0
1998	3.656 28	7 485	1	487.6	12×10^{-4}	0.9
BFKH 1980	3.603 9	23 570	3	487.4	9×10^{-4}	3.0
1989	3.618 3	89 410	4	487.3	7×10^{-4}	1.3
AECL 1980	1.304 0	39 683	2	486.5	10×10^{-4}	1.1
NPL 1980	3.390 1	15 533	2	488.3	9×10^{-4}	2.0
2004	3.537 36	3 803	1	487.0	19×10^{-4}	3.4
JRC 1981	2.883 20(2) 2.862 52(2)	10 414 10 339	1	484.0 483.9	15×10^{-4} 14×10^{-4}	1.1 1.0
LNE-LNHB 1984	3.615 64 3.618 62	3 373 3 375	1	494.0 493.3	16×10^{-4} 17×10^{-4}	1.2
1994	3.543 6 3.508 2	13 813 13 675	2	488.4 488.3	10×10^{-4} 11×10^{-4}	1.1
2006	3.571 0(6)	10 820	1	489.2	14×10^{-4}	1.1
NMIJ 1993	3.654 09	5 938	1	484.7	13×10^{-4}	1.6
2004§	3.602 52	7 896	1	487.1	18×10^{-4}	1.6

Table 4a continued. Results of SIR measurements of ^{51}Cr

NMI	Mass of solution m_i / g	Activity submitted A_i / kBq	N° of Ra source used	SIR A_e / MBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / MBq
KRISS 2012	3.607	23 406	1	488.4	19×10^{-4}	2.4
POLATOM 2022[§§]	3.641 99(30)	24 784[#]	2	483.62	9.8×10^{-4}	3.00

[#] See footnote in Table 2

[§] result used to link the 2004 APMP.RI(II)-K2.Cr-51 comparison

[§§] result used to link the 2022 EURAMET.RI(II)-K2.Cr-51 comparison

A bilateral comparison, EURAMET.RI(II)-K2.Cr-51, was held in 2022 [6] and the laboratory from this comparison to be added to the matrix of degrees of equivalence is given in Table 1b together with the POLATOM participation that served to link the comparison to the BIPM.RI(II)-K1.Cr-51 comparison. The LNE-LNHB used the EURAMET.RI(II)-K2.Cr-51 comparison to update its degree of equivalence from earlier SIR participation.

The results $(A/m)_i$ of the EURAMET.RI(II)-K2.Cr-51 comparison have been linked to the BIPM.RI(II)-K1.Cr-51 comparison through the measurement in the SIR of one ampoule of the EURAMET.RI(II)-K2.Cr-51 solution standardized by the POLATOM. The linking factor L_j is defined to be

$$L_j = A_{e,j} \,/\, (A/m)_j = 71.068 \text{ g} \qquad (1)$$

where the activity (MBq), mass (g) and equivalent activity (MBq) are taken from the row indicated in Table 4a for the POLATOM (2022). The relative standard uncertainty of L_j is 9.8×10^{-4}, the uncertainty from the SIR measurement of the linking ampoule combined quadratically with the relative uncertainty of the mass solution in the ampoule, also given in Table 4a.

The linked result is evaluated as

$$A_{e,\text{LNE-LNHB}} = (A/m)_{\text{LNE-LNHB}}\, L_j \qquad (2)$$

where the primary activity concentrations measured by the LNE-LNHB in the EURAMET.RI(II)-K2.Cr-51 comparison is taken from the Final report [6] and are shown in Table 4b. The uncertainties for the EURAMET.RI(II)-K2.Cr-51 comparison results linked to the SIR are comprised of the original uncertainties combined quadratically with the uncertainty in the link.

Table 4b. Results of the 2022 EURAMET.RI(II)-K2.Cr-51 comparison of ^{51}Cr including POLATOM, the linking laboratory

NMI	Measurement method and acronym (see Appendix 2)	Activity* concentration measured $(A/m)_i$ / (MBq g^{-1})	Standard uncertainty u_i / (MBq·g^{-1})	Linked equivalent activity A_{ei} / MBq	Combined standard uncertainty u_{ci} / MBq
LNE-LNHB	4π(LS)-γ anti-coincidence 4P-LS-MX-NA-GR-AC 4π(NaI(Tl))γ counting 4P-NA-GR-00-00-00	6.845# 6.800	0.021# 0.056	486.5	1.6
POLATOM	4π(LS)-γ coincidence and anticoincidence methods 4P-LS-MX-NA-GR-CO 4P-LS-MX-NA-GR-AC	6.799## 6.809	0.060## 0.058	483.6	3.0

*referenced to 1 June 2022 12:00 UTC
result selected by the LNE-LNHB for use in the KCDB
same results as for the SIR comparison.

The linked EURAMET result for the LNE-LNHB agrees within two combined standard uncertainties with their 2006 SIR result.

4.1 The Key Comparison Reference Value

In May 2013 the CCRI(II) decided to calculate the key comparison reference value (KCRV) using the power-moderated weighted mean [10] 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 [10], 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) only results for solutions standardized by primary techniques are accepted, with the exception of radioactive gas standards (for which results from transfer instrument measurements that are directly traceable to a primary measurement in the laboratory may be included);
b) each NMI or other laboratory has 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.

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

Consequently, the KCRV for ^{51}Cr has been calculated to be 488.05(41) MBq with the power α = 1.75 on the basis of the SIR results from the ANSTO, AECL, NIST(1981), CMI(1982), ASMW(1983), BKFH(1989), PTB(1998), NMIJ(2004), NPL(2004), LNE-LNHB(2006), and the last results of the KRISS and the POLATOM. This updated value can be compared with the previous KCRVs of 487.44(54) MBq published in 2003 [3], and 488.0(3) MBq published in 2009 [5], and has been approved by the CCRI(II).

4.2 Degrees of equivalence

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

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

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

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

$$D_i = A_{\mathrm{e}\,i} - \mathrm{KCRV} \tag{3}$$

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

$$U_i = 2u(D_i)\,. \tag{4}$$

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

$$u^2(D_i) = (1\text{-}2w_i)\, u_i^2 + u^2(\mathrm{KCRV})\,. \tag{5}$$

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

$$u^2(D_i) = u_i^2 + u^2(\text{KCRV}). \qquad (6)$$

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

$$D_{ij} = D_i - D_j = A_{\mathrm{e}\,i} - A_{\mathrm{e}\,j} \qquad (7)$$

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

$$u_{D\,ij}^{\;2} = u_i^{\;2} + u_j^{\;2} - 2u(A_{\mathrm{e}i}, A_{\mathrm{e}j}) \qquad (8)$$

where any obvious correlations between the NMIs (such as a traceable calibration, or correlations normally coming from the SIR or from the linking factor in the case of linked comparison) are subtracted using the covariance $u(A_{\mathrm{e}i}, A_{\mathrm{e}j})$ (see [11] for more detail). However, the CCRI decided in 2011 that these “pair-wise degrees of equivalence” no longer need to be published as long as the methodology is explained.

Table 5 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 1. 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.

Conclusion

The BIPM ongoing key comparison for ^{51}Cr, BIPM.RI(II)-K1.Cr-51 currently comprises four valid results. The key comparison reference value has been updated using the power-moderated weighted mean to include the KRISS and POLATOM latest results.

The result of the LNE-LNHB that took part in the EURAMET.RI(II)-K2.Cr-51 comparison in 2022 has been linked to the BIPM ongoing key comparison, superseding its earlier result from the BIPM.RI(II)-K1.Cr-51 comparison.

The SIR results together with the previously published APMP.RI(II)-K2.Cr-51 results, have been analysed with respect to the updated KCRV determined for this radionuclide.

Six degrees of equivalence in total have been approved by the CCRI(II) and are published in the BIPM key comparison database. Further results may be added when other NMIs contribute ^{51}Cr activity measurements to the ongoing K1 comparison or take part in other linked comparisons.

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Table 5. Table of degrees of equivalence and introductory text for ^{51}Cr

Key comparison BIPM.RI(II)-K1.Cr-51

MEASURAND : **Equivalent activity of ^{51}Cr**

Key comparison reference value: the SIR reference value x_R for this radionuclide is 488.05 MBq, with a standard uncertainty u_R of 0.41 MBq.
The value x_i is taken as the equivalent activity for laboratory *i*.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2), both expressed in MBq, and
$U_i = 2((1 - 2w_i)u_i^2 + u_R^2)^{1/2}$ when each laboratory has contributed to the calculation of x_R.

Linking APMP.RI(II)-K2.Cr-51 to BIPM.RI(II)-K1.Cr-51

The value x_i is the equivalent activity for laboratory *i* participant in APMP.RI(II)-K2.Cr-51 having been normalized using the value of the NMIJ as the linking laboratory.

The degree of equivalence of laboratory *i* participant in APMP.RI(II)-K2.Cr-51 with respect to the key comparison 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.
The approximation $U_i = 2(u_i^2 + u_R^2)^{1/2}$ is used in the following table as none of these D_i contributed to the KCRV.

Linking EURAMET.RI(II)-K2.Cr-51 to BIPM.RI(II)-K1.Cr-51

The value x_i is the equivalent activity for laboratory *i* participant in EURAMET.RI(II)-K2.Cr-51 having been normalized using the value of the POLATOM as the linking laboratory.

The degree of equivalence of laboratory *i* participant in EURAMET.RI(II)-K2.Cr-51 with respect to the key comparison 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.
The approximation $U_i = 2(u_i^2 + u_\mathrm{R}^2)^{1/2}$ is used in the following table as none of these D_i contributed to the KCRV.

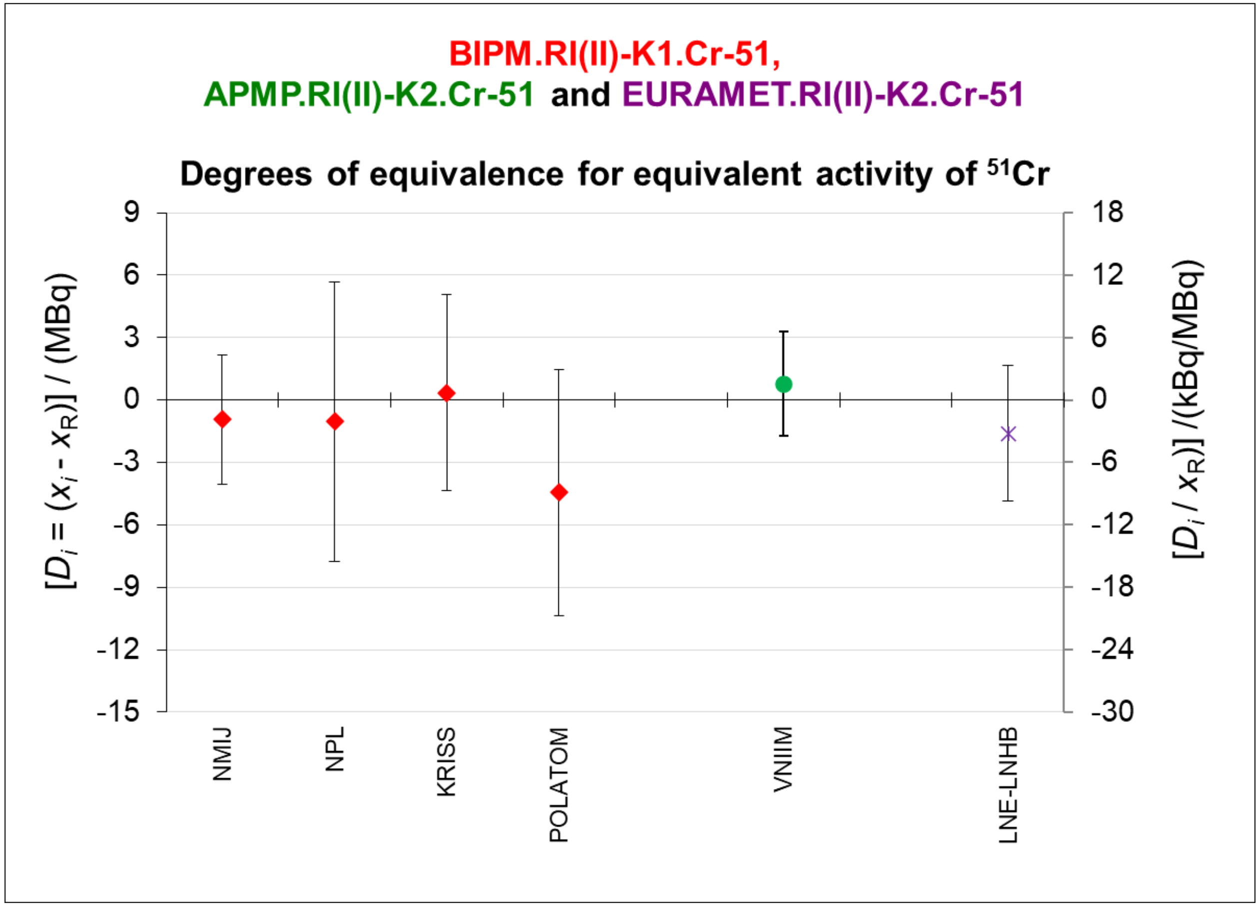
These statements make it possible to extend the BIPM.RI(II)-K1.Cr-51 matrices of equivalence to the participants in APMP.RI(II)-K2.Cr-51 and EURAMET.RI(II)-K2.Cr-51.

Lab i BIPM.RI(II)-K1.Cr-51	D_i / MBq	U_i / MBq
NMIJ	-0.9	3.1
NPL	-1.0	6.7
KRISS	0.4	4.7
POLATOM	-4.4	5.9

Lab i APMP.RI(II)-K2.Cr-51	D_i / MBq	U_i / MBq
VNIIM	0.8	2.5

EURAMET.RI(II)-K2.Cr-51	D_i / MBq	U_i / MBq
LNE-LNHB	-1.6	3.2

Figure 1. Graph of degrees of equivalence with the KCRV for ^{51}Cr



N.B. The right-hand axis shows approximate values only

Appendix 1. Uncertainty budgets for the activity of ^{51}Cr submitted to the SIR

KRISS, 2012

Relative standard uncertainties	**Comments**	**Relative sensitivity factor**	$u_{\mathrm{rel},i} \times 10^4$ evaluated by method	
Contributions due to			**A**	**B**
counting statistics	Standard deviation of the mean	0.20	9	–
weighing	One dilution and two weighings	0.35	–	16
dead time	Re-analysis after varying	0.11	–	5
background	Background set	0.76	–	35
Counting time	For 10 ms / 100 s	0.02	–	1
Decay correction	For 30 d decay correction	0.02	-	1
extrapolation of efficiency curve	From extrapolation results	0.48	-	22
Pile-up, adsorption, impurities	neglected		-	7
Quadratic summation			**9**	**45**
Relative combined standard uncertainty, u_c			**46**	

POLATOM, 2022

Measurement method	4π(LS)-γ coincidence		
ACRONYM	4P-LS-MX-NA-GR-CO		**Comments:**
Uncertainty budget			
Uncertainty component	**Relative uncertainty / 10^{-2}**	**Evaluation type (A or B)**	**Comment**
Counting statistics	0.76	A	Counting statisctics and background in %
Background			
Weighing	0.05	A	in %
Dilution			
Dead time	0.001	B	in %
Resolving time	0.023	B	in %
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.06	A	in %
Decay data			
Extra-/Inter-polation of efficiency curve	0.45	A	in %
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.887**		

POLATOM, 2022

Measurement method	4π(LS)-γ anticoincidence		
ACRONYM	4P-LS-MX-NA-GR-AC	**Comments:**	

Uncertainty budget

Uncertainty component	**Relative uncertainty / 10^{-2}**	**Evaluation type (A or B)**	**Comment**
Counting statistics	0.7	A	Counting statisctics and background in %
Background			
Weighing	0.05	A	in %
Dilution			
Dead time	0.001	B	in %
Resolving time	0.023	B	in %
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.06	A	in %
Decay data			
Extra-/Inter-polation of efficiency curve	0.47	A	
Quenching, kB value			
Tracer			
Reproducibility			
Anticoincidence window	0.031	B	in %
Combined standard uncertainty	**0.848**		

Appendix 2. 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(Tl)	CS
		ionization chamber	IC
		grid ionization chamber	GC
		Cerenkov detector	CD
		calorimeter	CA
		solid plastic scintillator	SP
		PIPS detector	PS
		$CeBr_3$	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	anti-coincidence	AC
gamma rays	GR	coincidence counting with efficiency tracing	CT
X - rays	XR	anti-coincidence counting with efficiency tracing	AT
photons (x + γ)	PH	triple-to-double coincidence ratio counting	TD
alpha - particle	AP	selective sampling	SS
mixture of various radiation	MX	high efficiency	HE

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(Ge(HP))-anticoincidence counting	4P-PP-MX-GH-GR-AC
4π CsI-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