

**BIPM comparison BIPM.RI(II)-K1.F-18 of
activity measurements of the radionuclide ^{18}F**

G. Ratel and C. Michotte
BIPM

Abstract

Since 2001, three national metrology institutes have submitted three samples of known activity of ^{18}F to the International Reference System (SIR) for activity comparison at the Bureau International des Poids et Mesures. The activities ranged from about 1 MBq to 8 MBq. The degrees of equivalence between each equivalent activity measured in the SIR and the key comparison reference value (KCRV) have been calculated and the results are given in the form of a matrix. A graphical presentation is also given. The results of this comparison have been approved by Section II of the Consultative Committee for Ionizing Radiation (CCRI(II)), comparison identifier BIPM.RI(II)-K1.F-18.

1. Introduction

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

Since its inception, the SIR has measured over 840 ampoules to give 611 independent results for 62 different radionuclides. The SIR makes it possible for national laboratories to check the reliability of their activity measurements at any time. This is achieved by the determination of the equivalent activity of the radionuclide and by comparison of the result with the key comparison reference value determined from the results of primary realizations. These comparisons are described as BIPM ongoing comparisons and the results form the basis of the BIPM key comparison database (KCDB) of the Mutual Recognition Arrangement (MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.F-18 key comparison.

2. Participants

Three NMIs have submitted three ampoules for the comparison of ^{18}F activity measurements since 2001. The laboratory details are given in Table 1.

Table 1. Details of the participants in the BIPM.RI(II)-K1.F-18

NMI	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
IRA	Institut de Radiophysique Appliquée	Switzerland	EUROMET	2001-09-21 13 h 10 UT
BNM-LNHB	Bureau national de métrologie-Laboratoire national Henri Becquerel	France	EUROMET	2002-04-10 12 h 06 UT
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	EUROMET	2002-11-12 11 h 48 UT

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 for each laboratory, the activities submitted and the relative standard uncertainties ($k = 1$) are given in Table 2. The list of acronyms used to summarize the methods is given in Appendix 3. The uncertainty budgets for each participant are given in Appendix 1.

The half-life used by the BIPM is 1.8290 (5) hours [3]. Such a short half-life requires a correction for the decay during the SIR measurement.

Details regarding the solution submitted are shown in Table 3, including any impurities, when present, as identified by the laboratories. When given, the standard uncertainties on the evaluations are shown. Recently the BIPM has developed a standard method for evaluating the activity of impurities using a calibrated Ge(Li) spectrometer [4]. The CCRI(II) agreed in 1999 [5] that this method should be followed according to the protocol described in [6] when an NMI makes such a request or when there appear to be discrepancies.

Table 2. Standardization methods of the participants for ^{18}F

NMI	Method used and acronym (see Appendix 3)	Half-life / h	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
IRA	pressurised ionization chamber* / 4P-IC-GR-00-00-00	1.8290 (5)	1109	01-09-21 14 h 00 UT	0.06	0.37
BNM-LNHB	liquid scintillation using TDCR / 4P-LS- 00-TD-00-00	1.8290 (5)	6793	02-04-10 12 h 00 UT	0.98	0.21
BEV	pressurised ionization chamber [#] / 4P-IC-GR-00-00-00	1.8295	7722	02-11-12 05 h 00 UT	0.03	1.01

* calibrated by $4\pi\gamma(\text{NaI})$ counting and liquid scintillation in 1997 / 4P-NA-GR-00-00-00 and 4P-LS-00-00-00-00

[#] secondary standard, calibrated by the NPL

Table 3. Details of the solution of ^{18}F submitted

NMI	Chemical composition	Solvent conc. / (mol dm ⁻³)	Carrier: conc. / ($\mu\text{g g}^{-1}$)	Density / (g cm ⁻³)	Relative activity of impurity [†]
IRA	F in HCl	0.1	NaCl:50	0.999 (9)	⁵² Mn: .0123 (2) % ⁵⁵ Co: .0082 (2) % ⁵⁶ Co: .0028 (1) % ⁵⁸ Co: .0049 (1) %
BNM-LNHB	F in HCl	0.1	NaCl:56	0.97 (1)	–
BEV	F in water	–	NaCl:9400	[‡]	–

[†] the ratio of the activity of the impurity to the activity of ^{18}F at the reference date

[‡] density estimated from [7] : 1.005

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a database known as the "mother-file". The activity measurements for ^{18}F arise from three ampoules and the SIR equivalent activity for each ampoule, A_{ei} , is given in Table 4 for each NMI, i . The dates of measurement in the SIR are given in Table 1.

The relative standard uncertainties arising from the measurements in the SIR are also shown. This uncertainty is additional to that declared by the NMI for the activity

measurement shown in Table 2. Although activities submitted are compared with a given source of ^{226}Ra , all the SIR results are normalized to the radium source number 5 [1].

Measurements repeated at the BIPM for up to one half-life produced the same comparison results for the IRA and the BNM-LNHB. The impurity correction for the SIR measurement of the IRA ampoule was lower than 10^{-3} . The BEV ampoule was measured after two half-lives and also produced the same comparison result and this confirmed that there was no impurity present.

As no submission has been identified as a pilot study, the result of each NMI is eligible for Appendix B of the MRA.

A regional comparison for this radionuclide is running currently and will be linked to the SIR comparison through the measurements of these three laboratories once the EUROMET.RI(II)-K2.F-18 comparison is complete.

Table 4. Results of SIR measurements of ^{18}F

NMI	Mass of solution m_i / g	Activity submitted A_i / kBq	N° of Ra source used	SIR A_e / kBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i} / \text{kBq}$
IRA	3.6812 (1)	1109	3	15 312	7.3×10^{-4}	57
BNM-LNHB	3.4995 (5)	6793	4	15 169	5.4×10^{-4}	152
BEV	3.6237	7722	2	15 390	11.8×10^{-4}	156

4.1 The key comparison reference value

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

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

The reduced data set used for the evaluation of the KCRVs is known as the KCRV file and is the reduced data set from the SIR mother-file. Although the KCRV may be modified when other NMIs participate, on the advice of the Key Comparison Working Group of the CCRI(II), such modifications are only made by the CCRI(II), normally during one of its biennial meetings.

Consequently, the KCRV for ^{18}F has been identified as 15 241 (71) kBq using the results from the IRA and the BNM-LNHB.

4.2 Degrees of equivalence

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

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

4.2.1 *Comparison of a given NMI with the KCRV*

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

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

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

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

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

4.2.2 *Comparison of any two NMIs with each other*

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

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

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

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

and any obvious correlations in the standard uncertainties for a given component, $u_{\text{corr},k}$, between the NMIs (such as a traceable calibration) are subtracted using an appropriate correlation coefficient, f_k , as are normally those correlations coming from the SIR.

The uncertainties of the differences between the values assigned by individual NMIs and the key comparison reference value (KCRV) are not necessarily the same uncertainties that enter into the calculation of the uncertainties in the degrees of equivalence between a pair of participants. Consequently, the uncertainties in the table of degrees of equivalence cannot be generated from the column in the table that gives

the uncertainty of each participant with respect to the KCRV. However, the effects of correlations have been treated in a simplified way as the degree of confidence in the uncertainties themselves does not warrant a more rigorous approach.

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

Conclusion

The BIPM ongoing key comparison for ^{18}F , BIPM.RI(II)-K1.F-18 currently comprises three results. These have been analysed with respect to the KCRV determined for this radionuclide, and with respect to each other. The matrix of degrees of equivalence has been approved by the CCRI(II) and will be published in the BIPM key comparison database. Other results may be added as and when other NMIs contribute ^{18}F activity measurements to this comparison.

Acknowledgements

The authors would like to thank the NMIs for their participation in this comparison, Mr Christian Colas of the BIPM for his dedicated work in maintaining the SIR since its inception and for the thousands of measurements he has made over the years, and Dr P.J. Allisy-Roberts of the BIPM for editorial assistance.

References

- [1] Ratel G. The international reference system for activity measurements of γ -emitting radionuclides (SIR), *BIPM Monograph XX*, 2003, (in preparation).
- [2] MRA: *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 14 October 1999, 45 pp. Available from the BIPM website: <http://www.bipm.org/pdf/mra.pdf>.
- [3] BNM-CEA/DTA/DAMRI/LPRI, *Nucléide*, Nuclear and Atomic Decay Data Version : 1-98 19/12/98 CD ROM, BNM-LNHB, Gif-sur-Yvette.
- [4] Michotte C., Efficiency calibration of the Ge(Li) detector of the BIPM for SIR-type ampoules, *Rapport BIPM-1999/03*, 15 pp.
- [5] CCRI *Rapport de la 16^e session* (June 1999), CCRI(II) 81-82. (Paris: Off. Lib.)

- [6] Michotte C., Protocol on the use of the calibrated spectrometer of the BIPM for the measurement of impurities in ampoules submitted to the SIR, *CCRI(II)/01-01*, 2001, 2p.
- [7] Weast R.C. and Selby S.M., *Handbook of Chemistry and Physics*, 47th edition, 1966, The Chemical Rubber Co.

Table 5. Table of degrees of equivalence and introductory text for ^{18}F

Key comparison BIPM.RI(II)-K1.F-18

MEASURAND : Equivalent activity of ^{18}F

Key comparison reference value: the SIR reference value for this radionuclide is $x_R = 15.24$ MBq, with a standard uncertainty $u_R = 0.07$ MBq.
 x_R is computed as the mean of the results obtained by primary methods.

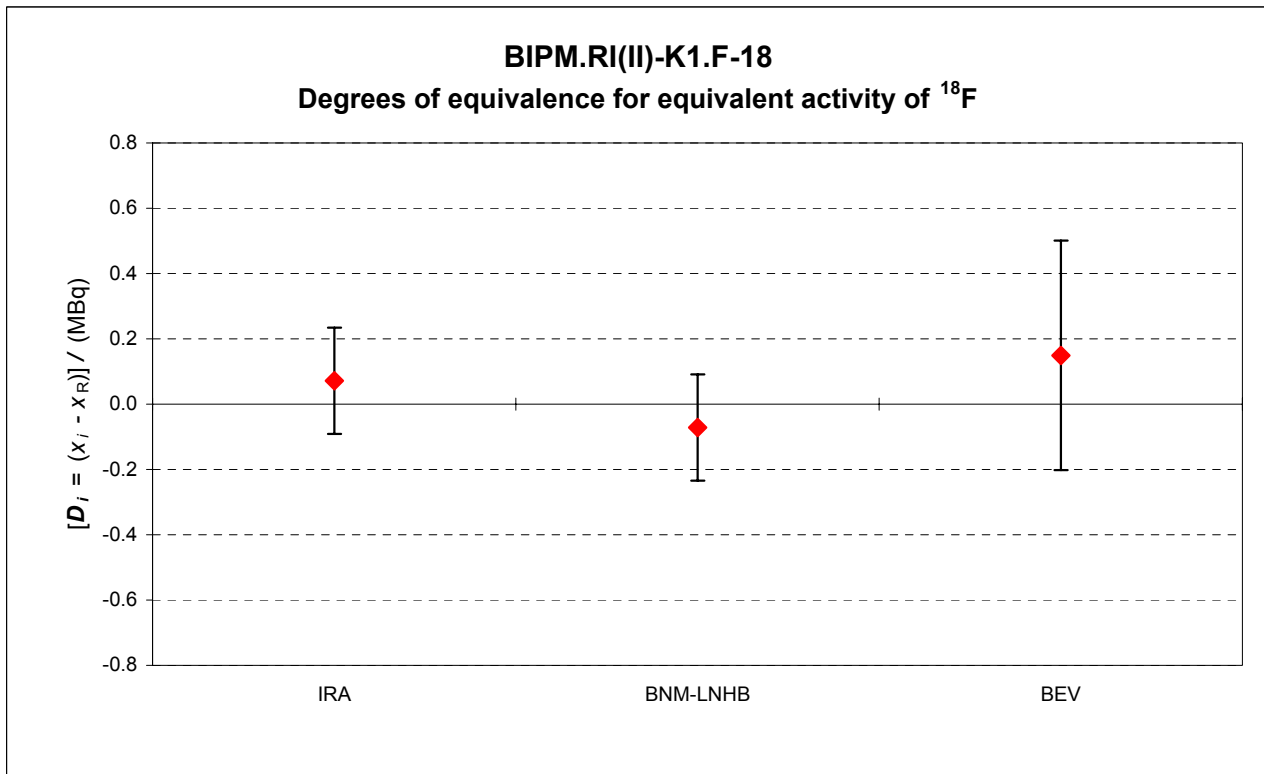
The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms: $D_i = (x_i - x_R)$ and U_i , its expanded uncertainty ($k = 2$), both expressed in MBq, with n the number of laboratories, $U_i = 2((1-2/n)u_i^2 + (1/n^2)\sum u_i^2)^{1/2}$ when each laboratory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

The degree of equivalence between two laboratories is given by a pair of terms: $D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij} , its expanded uncertainty ($k = 2$), both expressed in MBq.

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

		Lab j \longrightarrow						
		IRA		BNM-LNHB		BEV		
Lab i \downarrow	D_i U_i		D_{ij} U_{ij}		D_{ij} U_{ij}		D_{ij} U_{ij}	
	/ MBq		/ MBq		/ MBq		/ MBq	
IRA	0.07	0.16			0.14	0.32	-0.08	0.33
BNM-LNHB	-0.07	0.16	-0.14	0.32			-0.22	0.44
BEV	0.15	0.35	0.08	0.33	0.22	0.44		

Figure 1. Graph of degrees of equivalence with the KCRV for ^{18}F
(as it appears in Appendix B of the MRA)



Appendix 1. Uncertainty budgets for the activity of ^{18}F submitted to the SIRUncertainty budgets for the IRA:Evaluation for the $4\pi\gamma(\text{NaI})$ method

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	A	B
counting statistics	6	–
weighing	–	5
background	–	2
threshold	–	5
timing	–	2
decay scheme	–	10
efficiency	–	20
Quadratic summation	6	23.6
Relative combined standard uncertainty, u_c	24.4	

Evaluation for the liquid scintillation method

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	A	B
counting statistics	15	–
weighing, dilution	–	4
influence of the ^{14}C standard	–	20
effect of radionuclide impurities	–	10
emission probability	–	20
timing	–	60
Quadratic summation	15	67.2
Relative combined standard uncertainty, u_c	68.9	

Evaluation for the reference ionization chamber IG11

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	A	B
counting statistics including decay correction	6	–
combined uncertainty (mean) of the two primary methods above	–	36.8
Quadratic summation	6	36.8
Relative combined standard uncertainty, u_c	37.2	

Uncertainty budget for the BNM-LNHB:

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
counting statistics, $\nu = 4^\dagger$	98	–
weighing	–	5
timing	–	20
half-life	–	3
Quadratic summation	98	21
Relative combined standard uncertainty, u_c	100	

† number of degrees of freedom

Uncertainty budget for the BEV:

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
Contributions due to		
counting statistics	2.7	–
weighing, dilution	–	5
background	–	0.6
half-life	–	5.3
radionuclide impurities	–	–
calibration factor	–	100
ionization chamber	–	10
current measurement	–	10
Quadratic summation	2.7	101.3
Relative combined standard uncertainty, u_c	101.3	

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Then the total combined uncertainty becomes

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

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

or, after recombination

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

similar to (A-11).

Appendix 3. Acronyms used in the SIR database to identify different measurement methods

Geometry	acronym	Detector	acronym
4π	4P	proportional counter	PC
defined solid angle	SA	press. prop counter	PP
2π	2P	liquid scintillation counting	LS
		NaI(Tl)	NA
		Ge(HP)	GH
		Ge-Li	GL
		Si-Li	SL
		CsI	CS
		ionisation chamber	IC
		bolometer	BO
		calorimeter	CA
		PIPS detector	PS

Radiation	acronym	Mode	acronym
positron	PO	efficiency tracing	ET
beta particle	BP	internal gas counting	IG
Auger electron	AE	CIEMAT/NIST	CN
conversion electron	CE	sum counting	SC
bremsstrahlung	BS	coincidence	CO
gamma ray	GR	anti-coincidence	AC
X - rays	XR	coincidence counting with efficiency tracing	CT
alpha - particle	AP	anti-coincidence counting with efficiency tracing	AT
mixture of various radiation e.g. X and gamma	MX	triple-to-double coincidence ratio counting	TD
		selective sampling	SA

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