

**BIPM comparison BIPM.RI(II)-K1.Ga-67 of  
activity measurements of the radionuclide  $^{67}\text{Ga}$**

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**Abstract**

Since 1978, seven national metrology institutes (NMIs) and one other laboratory have submitted twelve samples of known activity of  $^{67}\text{Ga}$  to the International Reference System (SIR) for activity comparison at the Bureau International des Poids et Mesures. The activities ranged from about 4 MBq to 600 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 for seven NMIs. 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.Ga-67.

**1. Introduction**

The SIR for activity measurements of  $\gamma$ -ray-emitting radionuclides was established in 1976. Each 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  $^{226}\text{Ra}$  using pressurized ionization chambers. Details of the SIR method, experimental set-up and the determination of the equivalent activity are all given in [1].

Since its inception, the SIR has measured over 835 ampoules to give 606 independent results for 62 different radionuclides. The SIR makes it possible for national laboratories to check the reliability of their activity measurements at any time. This is achieved by the determination of the equivalent activity of the radionuclide and by comparison of the result with the key comparison reference value determined from the results of primary realizations. These comparisons are described as BIPM ongoing comparisons and the results form the basis of the BIPM key comparison database (KCDB) of the Mutual Recognition Arrangement (MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Ga-67 key comparison.

## 2. Participants

Seven NMIs and one other laboratory have submitted twelve ampoules for the comparison of  $^{67}\text{Ga}$  activity measurements since 1978. One other laboratory participated but ultimately withdrew its result. The laboratory details are given in Table 1. In cases where the laboratory has changed its name since the original submission, both the earlier and the current acronyms are given, as it is the latter that are used in the KCDB.

**Table 1. Details of the participants in the BIPM.RI(II)-K1.Ga-67**

Original acronym	NMI	Full name	Country	Regional metrology organization	Date of measurement at the BIPM
NBS	NIST	National Institute of Standards and Technology	United States	SIM	1978-03-21 1998-04-27 1999-04-28
UVVVR	CMI-IIR	Český Metrologický Institut/Czech Metrological Institute, Inspectorate for Ionizing Radiation	Czech Republic	EUROMET	1981-04-24
LMRI	BNM-LNHB	Bureau national de métrologie-Laboratoire national Henri Becquerel	France	EUROMET	1981-11-10
–	NPL	National Physical Laboratory	United Kingdom	EUROMET	1982-04-30
NIRH	–	National Institute of Radiation Hygiene	Denmark	EUROMET	1983-05-05
NAC*	CSIR-NML	National Metrology Laboratory	South Africa	SADCMET	1986-10-28
–	OMH	Országos Mérésügyi Hivatal	Hungary	EUROMET	1995-11-30
–	NMIJ	National Metrology Institute of Japan	Japan	APMP	2001-11-26 2002-05-17

\* another 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 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. Full uncertainty budgets have been requested as part of the comparison protocol only since 1998. When submitted by the NMIs, the uncertainty budgets are given in Appendix 1 attached to this report. Consequently, uncertainty budgets are given for the NMIJ.

The half-life used by the BIPM is 78.26 (7) hours [3] which is in good agreement with the recently published evaluation of 78.22 (2) hours [4].

**Table 2. Standardization methods of the participants for  $^{67}\text{Ga}$**

NMI	Method used and acronym (see Appendix 3)	Half-life	Activity $A_i$ / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
NIST	Pressurized IC* 4P-IC-GR-00-00-00	–	565 200	78-03-15 19 h UT	0.01	1.49
		3.2614 (6) d	94 860	98-04-27 12 h UT	0.03	0.27
			53 990	99-04-28 12 h UT	0.01	0.30
CMI-IIR	$4\pi(e,x)\text{-}\gamma$ coincidence 4P-PP-MX-NA-GR-CO	78.26 h	22 750	81-04-08 12 h UT	0.05	0.87
BNM-LNHB <sup>†</sup>	$4\pi(e_A,x)\text{-}\gamma$ anti-coincidence 4P-PP-MX-NA-GR-AC	–	4 772 4 771	81-11-13 12 h UT	0.02	0.38
NPL	Pressurized IC** 4P-IC-GR-00-00-00	–	30 090	82-04-28 0 h UT	0.04	1.22
NIRH	Pressurized IC 4P-IC-GR-00-00-00	–	118 290	83-05-04 12 h UT	0.04	0.60
CSIR-NML	$4\pi(\text{LS})(e,x)\text{-}\gamma$ coincidence [5] 4P-LS-MX-NA-GR-CO	78.26 h	222 770	86-10-24 10 h UT	0.15	0.17
OMH	$4\pi(e_A,x)\text{-}\gamma$ anti-coincidence 4P-PP-MX-NA-GR-AC	3.26154 (54) d [6]	6 817	95-12-01 0 h UT	0.06	0.51

continued overleaf

**Table 2. Continued. Standardization methods of the participants for  $^{67}\text{Ga}$** 

NMI	Method used and acronym (see Appendix 3)	Half-life	Activity $A_i$ / kBq	Reference date YY-MM-DD	Relative standard uncertainty $\times 100$ by method of evaluation	
					A	B
NMIJ	Pressurized IC*** 4P-IC-GR-00-00-00	3.2612 d	21 852	01-11-30 12 h UT	0.06	0.41
			36 646	02-05-15 12 h UT	0.06	0.36

† two ampoules submitted

\* calibrated by  $4\pi(e_{A,X})-\gamma$  coincidence (4P-PP-MX-NA-GR-CO) for  $^{67}\text{Ga}$  in 1977

\*\* calibrated by  $4\pi(e_{A,X})-\gamma$  coincidence (4P-PC-MX-NA-GR-CO) for  $^{67}\text{Ga}$

\*\*\* calibrated by  $4\pi(e,X)-\gamma$  anti-coincidence (4P-PP-MX-NA-GR-AC) in August 2001 for  $^{67}\text{Ga}$ .

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 [7]. The CCRI(II) agreed in 1999 [8] that this method should be followed according to the protocol described in [9] when an NMI makes such a request or when there appear to be discrepancies.

The same primary standardization was used to calibrate the ionization chamber used for the NIST submissions of 1978, 1998 and 1999. However, the latter two samples have smaller uncertainties due to better source characterizations and so the 1998 value, being closer in time to the 1977 calibration than the 1999 result, has been used for the KCRV (see section 4.1).

In 2001, at the same time that the NMIJ submitted a solution of Ga-citric acid to the SIR, it also sent a solution of  $^{111}\text{In}$ . In parallel, the NMIJ undertook other overseas comparisons with the KRISS and the INER using the same two chemical solutions. Comparisons of the ionization current ratios of Ga/In in each of the institutes (BIPM, KRISS and INER) showed a higher value than at the NMIJ. An explanation for this effect could be the precipitation of citric acid induced by the low temperature during air transport. Consequently, in 2002, the NMIJ sent a solution of  $\text{GaCl}_3$  to the SIR that had been calibrated against the same absolute measurement of August 2001. In view of the uncertainty over the Ga-citric acid solution, the result of 2002 has been used in the KCRV rather than the result from 2001 although the two results are consistent within the uncertainties.

**Table 3. Details of the solution of  $^{67}\text{Ga}$  submitted**

NMI	Chemical composition	Solvent conc. / (mol dm <sup>-3</sup> )	Carrier: conc. / (μg g <sup>-1</sup> )	Density / (g cm <sup>-3</sup> )	Relative activity of impurity <sup>†</sup>
NIST	$^{67}\text{Ga}$ in HCl	2	–	1.032	–
	GaCl <sub>3</sub> in HCl	2.1	GaCl <sub>3</sub> : 1950	1.036 (2)	–
			GaCl <sub>3</sub> : 805	1.035	–
CMI-IIR	GaCl <sub>3</sub> in HCl	1	GaCl <sub>3</sub> : 50	–	< 0.1 %
BNM-LNHB	Ga citrate in HCl	0.1	NaCl: 180	1.006	$^{57}\text{Co}$ : $5.1 (1.0) \times 10^{-4}$ % $^{60}\text{Co}$ : $7.2 (1.5) \times 10^{-4}$ %
NPL	$^{67}\text{Ga}$ in HCl	0.1	–	1.0015	–
NIRH	Ga citrate in NaCl solution	–	–	–	–
CSIR-NML	Na citrate* in HCl	1.0	Ga: 100	1.0143	–
OMH	Ga citrate	–	NaCl: 8000	–	–
NMIJ	Ga citrate in HCl	0.1	Ga: 200 NaCl: 9000	1.02	–
	GaCl <sub>3</sub> in HCl	0.1	GaCl <sub>3</sub> : 100	1.002	–

<sup>†</sup> the ratio of the activity of the impurity to the activity of  $^{67}\text{Ga}$  at the reference date

\*sodium citrate: Na<sub>3</sub>C<sub>6</sub>O<sub>7</sub>H<sub>5</sub>.

#### 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  $^{67}\text{Ga}$  arise from twelve 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  $^{226}\text{Ra}$ , all the SIR results are normalized to the radium source number 5 [1].

No impurity measurement was made at the BIPM. The impurity content for the BNM-LNHB solution was misunderstood as the order of ( $10^{-4}$ ) and the original registered

result was based on this assumption. However, a later SIR measurement of the same ampoule showed a significant discrepancy from the original result on the basis of the presumed impurities. The impurity contribution was then confirmed by the BNM-LNHB as being of the order of ( $10^{-4}$ ) % (see Table 3). The corrected equivalent activity value is lower than the originally registered result as the impurity correction is proportional to the activity of the impurity [9]. Using the correct impurity content, the two consecutive measurements in the SIR for this ampoule agree to better than  $3 \times 10^{-4}$  showing that the impurity correction is now appropriate.

Measurements repeated at the BIPM after 1 to 8 half-lives later (periods of up to one month) produced the same comparison results for the CMI-IIR, BNM-LNHB, NIRH, CSIR-NML, OMH, NIST (1998 and 1999) and for the NMIJ (2001 and 2002). These measurements confirm the validity of the half-life value used.

No recent submission has been identified as a pilot study so the most recent result of each NMI is normally eligible for Appendix B of the MRA. However, the NIRH is not a designated laboratory of Denmark and therefore their result is not included in the KCDB.

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

**Table 4. Results of SIR measurements of  $^{67}\text{Ga}$**

NMI	Mass of solution $m_i$ / g	Activity submitted $A_i$ / kBq	N° of Ra source used	SIR $A_e$ / kBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / kBq
NIST	3.689 38	565 200	5	115 600	$14 \times 10^{-4}$	1700
	3.746 00	94 860	5	116 090	$8 \times 10^{-4}$	330
	3.711 19	53 990	4	116 220	$8 \times 10^{-4}$	360
CMI-IIR	3.457 40	22 750	1	118 800	$36 \times 10^{-4}$	1100
BNM-LNHB †	3.612 5	4 772	3	114 626	$11 \times 10^{-4}$	453
	3.611 9	4 771		114 607		452
NPL	3.682 1	30 090	4	116 000	$10 \times 10^{-4}$	1400
NIRH	3.573 6	118 290	5	115 640	$8 \times 10^{-4}$	710
CSIR-NML	3.605 65	222 770	4	116 410	$11 \times 10^{-4}$	290
OMH	3.639 4	6 817	3	115 200	$10 \times 10^{-4}$	610
NMIJ	3.603 96	21 852	4	114 680	$8 \times 10^{-4}$	480
	3.607 28	36 646	4	115 190	$9 \times 10^{-4}$	430

† the mean of the two  $A_e$  values is used with an averaged uncertainty, as attributed to an individual entry [10].

#### 4.1 The key comparison reference value

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

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

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

Consequently, the KCRV for  $^{67}\text{Ga}$  has been identified as 116 040 (520) kBq using the results from the CMI-IIR, BNM-LNHB, NPL, CSIR-NML, OMH, NIST (1998) and the NMIJ (2002).

#### 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

$$D_{ij} = D_i - D_j = A_{ei} - A_{ej} \quad (3)$$

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  $^{67}\text{Ga}$ , BIPM.RI(II)-K1.Ga-67 currently comprises seven 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  $^{67}\text{Ga}$  activity measurements to this comparison.

## Acknowledgements

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**Table 5. Table of degrees of equivalence and introductory text for <sup>67</sup>Ga**  
**Key comparison BIPM.RI(II)-K1.Ga-67**

**MEASURAND :** Equivalent activity of <sup>67</sup>Ga

**Key comparison reference value:** the SIR reference value  $x_R$  for this radionuclide is 116.04 MBq, with a standard uncertainty of 0.52 MBq (see Section 4.1 of the Report), the value  $x_i$  is taken as the equivalent activity for laboratory  $i$ .

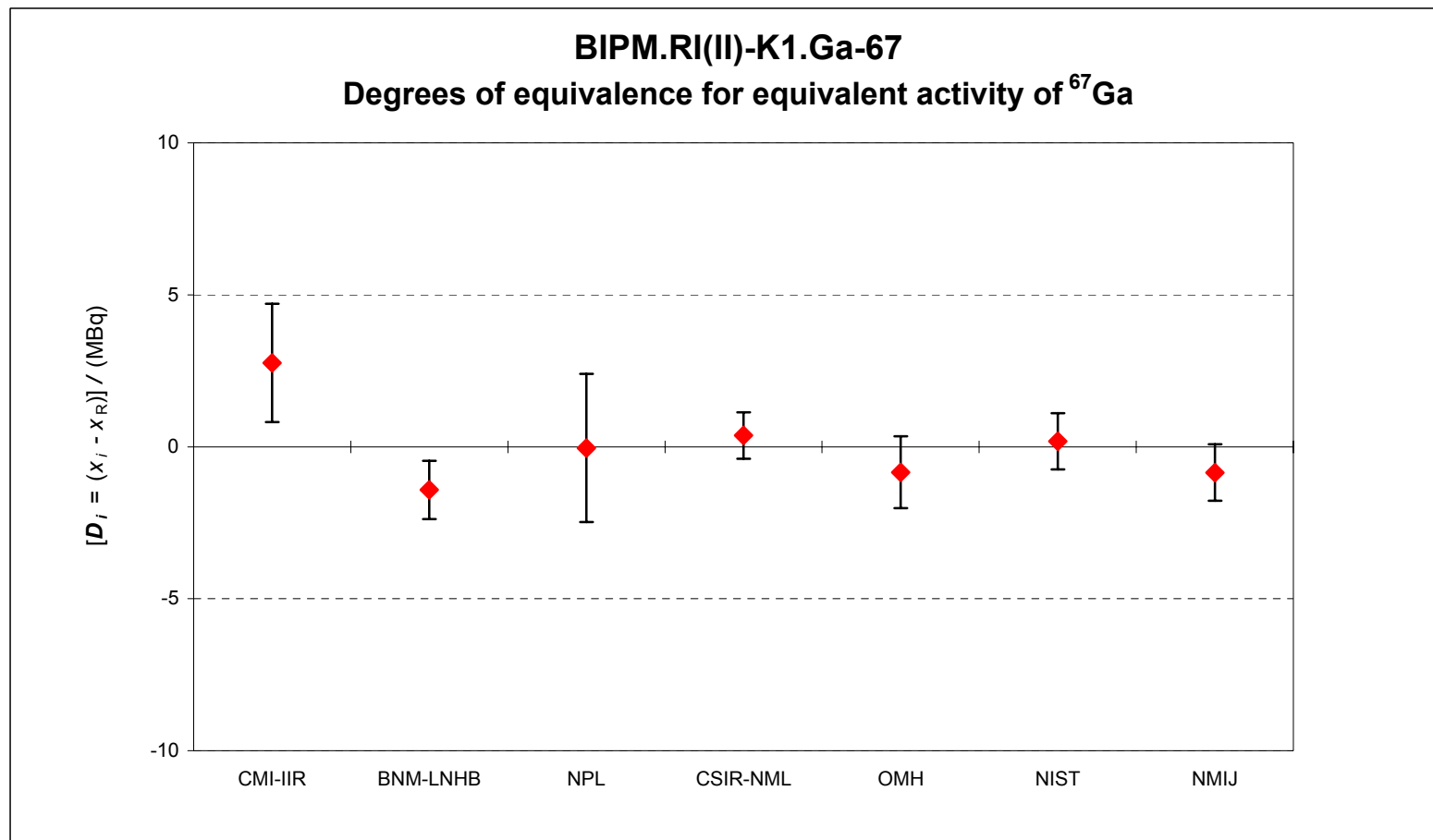
The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms:  $D_i = (x_i - x_R)$  and  $U_i$ , its expanded uncertainty ( $k = 2$ ), both expressed in MBq, and  $U_i = 2((1 - 2/n)u_i^2 + (1/n^2)\Sigma u_i^2)^{1/2}$  when each laboratory has contributed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

The degree of equivalence between two laboratories is given by a pair of numbers:  $D_{ij} = D_i - D_j = (x_i - x_j)$  and  $U_{ij}$ , its expanded uncertainty ( $k = 2$ ), both expressed in MBq. The approximation  $U_{ij}^2 \sim 2^2(u_i^2 + u_j^2)$  is used in the following table.

Lab  $j$   $\longrightarrow$

Lab $i$ $\downarrow$	$D_i$ $U_i$		CMI-IIR		BNM-LNHB		NPL		CSIR-NML		OMH		NIST		NMIJ	
	/ MBq		$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$	$D_{ij}$	$U_{ij}$
CMI-IIR	2.8	1.9			4.2	2.4	2.8	3.6	2.4	2.3	3.6	2.5	2.6	2.3	3.6	2.4
BNM-LNHB	-1.4	1.0	-4.2	2.4			-1.4	2.9	-1.8	1.1	-0.6	1.5	-1.6	1.2	-0.6	1.2
NPL	0.0	2.4	-2.8	3.6	1.4	2.9			-0.4	2.9	0.8	3.1	-0.2	2.9	0.8	2.9
CSIR-NML	0.4	0.8	-2.4	2.3	1.8	1.1	0.4	2.9			1.2	1.4	0.2	0.9	1.2	1.0
OMH	-0.8	1.2	-3.6	2.5	0.6	1.5	-0.8	3.1	-1.2	1.4			-1.0	1.4	0.0	1.5
NIST	0.2	0.9	-2.6	2.3	1.6	1.2	0.2	2.9	-0.2	0.9	1.0	1.4			1.0	1.1
NMIJ	-0.9	0.9	-3.6	2.4	0.6	1.2	-0.8	2.9	-1.2	1.0	0.0	1.5	-1.0	1.1		

**Figure 1.** Graph of degrees of equivalence with the KCRV for  $^{67}\text{Ga}$   
(as it appears in Appendix B of the MRA)



**Appendix 1. Uncertainty budgets for the activity of <sup>67</sup>Ga submitted to the SIR**

The NMIJ submitted an uncertainty budget in 2001 as follows:

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
<b>Contributions due to</b>		
stability of electrometer	6	-
calibration factor	-	35
weighing	-	5
background	2	-
timing	-	5
half-life	-	1
radionuclide impurities	-	5
chemical composition	-	20
<b>Quadratic summation</b>	<b>6</b>	<b>41</b>
<b>Relative combined standard uncertainty, <math>u_c</math></b>	<b>42</b>	

The NMIJ submitted an uncertainty budget in 2002 as follows:

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
	A	B
<b>Contributions due to</b>		
stability of electrometer	6	-
calibration factor	-	35
weighing	-	5
background	2	-
timing	-	5
half-life	-	2
radionuclide impurities	-	5
<b>Quadratic summation</b>	<b>6</b>	<b>36</b>
<b>Relative combined standard uncertainty, <math>u_c</math></b>	<b>37</b>	

## 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

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

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

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

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

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

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

Then the total combined uncertainty becomes

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

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

or, after recombination

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

similar to (A-11).

## Appendix 3. Acronyms used to identify different measurement methods

Each acronym has six components, geometry-detector (1)-radiation (1)-detector (2)-radiation (2)-mode. When a component is unknown, ?? is used and when it is not applicable 00 is used.

<b>Geometry</b>	<b>acronym</b>	<b>Detector</b>	<b>acronym</b>
4 $\pi$	4P	proportional counter	PC
defined solid angle	SA	press. prop counter	PP
2 $\pi$	2P	liquid scintillation counting	LS
undefined solid angle	UA	Nal(Tl)	NA
		Ge(HP)	GH
		Ge-Li	GL
		Si-Li	SL
		CsI	CS
		ionization chamber	IC
		grid ionization chamber	GC
		bolometer	BO
		calorimeter	CA
		PIPS detector	PS
<b>Radiation</b>	<b>acronym</b>	<b>Mode</b>	<b>acronym</b>
positron	PO	efficiency tracing	ET
beta particle	BP	internal gas counting	IG
Auger electron	AE	CIEMAT/NIST	CN
conversion electron	CE	sum counting	SC
bremstrahlung	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	SS

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