

Report of the CCRI Comparison CCRI(II)-K2.Lu-177

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Abstract

An international key comparison of ^{177}Lu was performed in 2009, with identifier CCRI(II)-K2.Lu-177. A total of twelve laboratories performed assays for radioactivity content on aliquots of a common master solution of ^{177}Lu , leading to eleven results submitted for entry into the Key Comparison Database. A proposed Comparison Reference Value was calculated to be $3.288(5) \text{ MBq}\cdot\text{g}^{-1}$ using all eleven results. Preliminary degrees of equivalence were calculated for each reporting laboratory based on the Comparison Reference Value. The Key Comparison Reference Value and final degrees of equivalence will be calculated from the data contained herein and data from measurements made in the International Reference System (SIR) held at the International Bureau of Weights and Measures (BIPM).

1. Introduction

There has been increasing interest during the past 10 years in the use of ^{177}Lu for radionuclide-based radiotherapy for certain types of cancers. Accurate administrations of drugs using this radionuclide require accurate standards against which instrumentation used in the clinics and radiopharmacies can be calibrated. Several new ^{177}Lu -based radiotherapy drugs are being investigated worldwide, which will cause an even greater need for such standards.

Lutetium-177 decays with three primary β branches ($E_{\beta\text{max}} = 176 \text{ keV}$, 385 keV , and 498 keV) and has two reasonably strong γ -rays at 113 keV and 208 keV , making it suitable for analysis using a variety of techniques, including coincidence counting.

To date, the only previous comparison of ^{177}Lu that has been carried out was a bilateral comparison conducted between the NIST and the PTB in 2000. In this case, both laboratories were able to submit ampoules to the SIR and report activity values based on liquid scintillation counting using the CIEMAT/NIST efficiency tracing method. The results indicated a difference of about 1.4 % in the SIR equivalent activity (see report of the BIPM-RI(II)-K1.Lu-177 comparison [1]). The short half-life of the ^{177}Lu did not allow for follow-up studies to be performed.

Since 2000, several more NMIs have standardized this radionuclide. In order to establish a link between primary standards of β -emitters in the NMIs and the SIR, as well as to provide a means for laboratories to substantiate Calibration and Measurement Capability claims for β - γ emitting nuclides, a key comparison of ^{177}Lu was proposed in 2008. This proposal was initiated as an action item arising from a meeting of the Life Sciences Working Group (LSWG) of the International Committee on Radionuclide Metrology (ICRM), held in January 2007.

2. Organization of the comparison

The participating laboratories of the comparison are listed in Table 1. As noted in the table, the Instituto de Pesquisas Energéticas e Nucleares/ Comissão Nacional de Energia Nuclear (IPEN-CNEN) is not the designated radioactivity metrology institute for its country, but it submitted a value that was combined with data from the Laboratório Nacional de Metrologia das Radiações Ionizantes, Instituto de Radioproteção e Dosimetria (LNMRI-IRD) to arrive at a final submitted value from LNMRI-IRD (which is the designated institute for radioactivity in Brazil). Where appropriate, the final values from each institute are given separately, although only the combined value will appear in the Key Comparison Database (KCDB).

The agreed protocol called for the ^{177}Lu aliquots to be prepared and distributed by the National Institute of Standards and Technology (NIST) from a single master solution. A flame-sealed ampoule containing 5 mL of solution having nominally 3.7 MBq of activity in a carrier solution of $20\text{ }\mu\text{g Lu}^{+3}$ per gram of solution in $1\text{ mol}\cdot\text{L}^{-1}\text{ HCl}$ was sent to each participating laboratory on 17 April 2009. Most participants received the vials within five days of shipment, although two laboratories received their samples more than a week later due to internal bureaucratic delays.

According to the protocol, the participants were to report the activity concentration (in $\text{Bq}\cdot\text{g}^{-1}$) as of the reference time of 12:00 UTC 1 May 2009. Corrections for radioactive decay to the reference time were to be carried out using a half-life of 6.647(4) d [2].

3. Results and Discussion

3.1 Proposed Comparison Reference Value (CRV)

The results of each laboratory's measurements of the ^{177}Lu solution at the reference time are summarized in Table 2 and Fig. 1. The uncertainties in both Table 2 and Fig. 1 are combined standard uncertainties as reported by each of the participants. Uncertainty budgets for all submitted results are given in Tables 3 to 14.

The value submitted for the LNMRI-IRD was originally calculated by that laboratory as being the median of six values: three coincidence measurements from LNMRI-IRD (using two different energy windows and two different extrapolation methods), two anticoincidence measurements from LNMRI-IRD (using two different energy windows), and one coincidence measurement from IPEN-CNEN. Following the advice of the Key Comparison Working Group (KCWG) of the CCRI(II), the Pilot Laboratory has combined the results from the same technique into a single value for each technique from each of the two institutions. This now gives three results as follows: two values from LNMRI-IRD (one each for coincidence and anticoincidence counting) and one for IPEN-CNEN. These are the values given in Table 2. The final submitted value for the KCDB, however, was not recalculated and remains the same as that submitted by LNMRI-IRD.

From a visual inspection of the data, no single data point appears to be an outlier. However, using the weighted mean of $3.286(3)\text{ MBq}\cdot\text{g}^{-1}$ for the entire data set ($n = 11$) as a starting point, a Birge ratio of 1.56 was calculated, indicating that the data set is most likely inconsistent. Applying a “normalized error test with a test value of four”¹ to the data set using an unweighted mean of $3.299(33)\text{ MBq}\cdot\text{g}^{-1}$ as the CRV indicated that only ANSTO could be considered to be out of norm with a score value

¹ Test selected by the KCWG of the CCRI(II) for the BIPM.RI(II)-K1 comparisons

of 4.18, while a “modified normalized error test with a test value of 2.5” indicated that only IFIN-HH is an outlier candidate with a score value of 2.58. These two laboratories were contacted and given an opportunity to review their submissions for possible errors before the results were announced and both responded that none were found.

The fact that a single test could not reveal that any one particular data point was an outlier prompted the use of a technique that uses all the data in the set to calculate the CRV. The method that was chosen was that of Vangel and Ruhkin [3,4]. In this approach, the measurement uncertainties reported by the laboratories are assumed to include an additional component of variance that is typically unrevealed, but that reflects inter-operator and inter-laboratory effects. In the Vangel-Ruhkin approach, the magnitude of the additional effect is quantified by maximum likelihood analysis. Using software developed by the NIST Statistical Engineering Division [5], a CRV of 3.288(5) MBq·g⁻¹ was calculated, where the quoted uncertainty corresponds to a standard ($k=1$) uncertainty interval.

A more detailed discussion of the results can be found in Zimmerman *et al.* [6].

3.2 Impurity analyses

Analyses for possible radionuclidic impurities were carried out by all the laboratories, with most of the results having been obtained using calibrated high-purity germanium photon detectors. The ratios of activities of the identified impurities to the ¹⁷⁷Lu activity at the reference time are given in Table 15.

3.3 Degrees of equivalence

The degree of equivalence of each laboratory i with respect to the reference value is given by a pair of terms both expressed in the same units: the difference, D_i , and U_i , its expanded uncertainty ($k=2$). These quantities are expressed as:

$$D_i = x_i - x_{ref} \quad (1)$$

where x_i and x_{ref} are each participant's result and the CRV, respectively. The uncertainty on D_i is given by [7]:

$$U_i = 2 \left(\sqrt{(1 - 2w_i)u_i^2 + u_{ref}^2} \right) \quad (2)$$

where u_{ref} is the standard uncertainty on the reference value given by

$$\left(\sum_i w_i^2 u_i^2 \right)^{0.5}$$

u_i is the combined standard uncertainty as reported by each laboratory, and w_i are the normalized weighting factors given by

$$w_i = \frac{1/(u_i^2 + u_b^2)}{\sum_{i=1}^n 1/(u_i^2 + u_b^2)} \quad (3)$$

The u_b term in (3) refers to the inter-laboratory component of variability, which was calculated to have a magnitude of 0.31 % relative to the consensus mean value.

The preliminary degrees of equivalence for participants in the comparison are presented graphically in Figure 2 and numerically in Table 17. Final degrees of equivalence, as well as the final Key Comparison Reference Value (KCRV) will be calculated using measurements made in the International Reference System (SIR).

From the data in Table 16, it can be seen that the values of D_i range from $-0.0235 \text{ MBq} \cdot \text{g}^{-1}$ to $0.0981 \text{ MBq} \cdot \text{g}^{-1}$, which on a percentage basis corresponds to -0.71% to 3.0% of the CRV. Most of the submitted values, however, fall within 0.6% of the CRV.

4. Conclusion

An international key comparison of ^{177}Lu has been carried out successfully. Although initial tests indicated that the data were not consistent, no single laboratory was identified as being an outlier, prompting the use of a method that allowed for all the data from the participating laboratories to be included in the calculation of the CRV. Using the calculated CRV, it is demonstrated that most respondents reported values within 0.6% of the CRV.

5. References

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5. eMetrology Software pre-release version (2009) National Institute of Standards and Technology Statistical Engineering Division, *private communication*.
6. Zimmerman *et al.* (2012) “Results of an international comparison for the activity measurement of ^{177}Lu ”, [*Appl. Radiat. Isot.*, **70**, 1825–1830](#).
7. Ratel, G. (2005) “Evaluation of the uncertainty of the degree of equivalence”, [*Metrologia*, **42**, 140-144](#).
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Table 1. Laboratories participating in CCRI(II) Key Comparison
CCRI(II)-K2.Lu-177 for ^{177}Lu .

Laboratory Name	Acronym	Country	Regional Metrology Organization
Australian Nuclear Science and Technology Organisation	ANSTO	Australia	Asia-Pacific Metrology Programme (APMP)
Laboratório Nacional de Metrologia das Radiações Ionizantes, Instituto de Radioproteção e Dosimetria	LNMRI-IRD	Brazil	Inter-American Metrology System (SIM)
Instituto de Pesquisas Energéticas e Nucleares/ Comissão Nacional de Energia Nuclear*	IPEN-CNEN	Brazil	SIM
European Commission-Joint Research Centre/Institute for Reference Materials and Measurements	IRMM	European Commission	European Collaboration in Measurement Standards (EURAMET)
Laboratoire national de métrologie et d'essais-Laboratoire national Henri Becquerel	LNE-LNHB	France	EURAMET
Physikalisch- Technische Bundesanstalt	PTB	Germany	EURAMET
Italian National Agency for New Technologies, Energy, and Environment – National Institute for Ionising Radiation Metrology	ENEA-INMRI	Italy	EURAMET
Institute of Atomic Energy POLATOM, Radioisotope Centre, Laboratory of Radioactivity Standards	POLATOM	Poland	EURAMET
National Institute of Research and Development for Physics and Engineering “Horia Hulubei”	IFIN-HH	Romania	EURAMET
National Metrology Institute of South Africa	NMISA	South Africa	Intra-Africa Metrology System (AFRIMETS)
National Physical Laboratory	NPL	United Kingdom	EURAMET
National Institute of Standards and Technology	NIST	United States of America	SIM

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Table 2. Specific activity, C_A , of ^{177}Lu solution at the reference time of 12:00 UTC 1 May 2009 as reported by the participating institutions.

The uncertainties, u_i , are the combined standard ($k = 1$) uncertainties as reported by each participant. In cases in which more than one value was submitted, the one to be entered into the KCDB is given in parenthesis. The acronyms used to describe the assay methods used conform to those used in the KCDB [8].

Institution	C_A (MBq·g ⁻¹)	u_i (MBq·g ⁻¹)	Method
ANSTO	3.2644	$7.8 \cdot 10^{-3}$	4P-PC-BP-NA-GR-CO
LNMRI-IRD	3.2183 [#] 3.2947 [#] (3.2764)	$7.3 \cdot 10^{-3}$ $1.83 \cdot 10^{-2}$ ($1.98 \cdot 10^{-2}$)	4P-PC-BP-NA-GR-AC 4P-PC-BP-NA-GR-CO Median of six values obtained from LNMRI/IRD and IPEN/CNEN
IPEN- CNEN*	3.277	$2.9 \cdot 10^{-2}$	4P-PC-BP-NA-GR-CO
IRMM	3.270 3.382 (3.320)	$1.5 \cdot 10^{-2}$ $3.0 \cdot 10^{-2}$ ($5.4 \cdot 10^{-2}$)	4P-LS-MX-00-00-CN 4P-PC-BP-NA-GR-CO Partially weighted mean of above results
LNE-LNHB	3.309 3.313 (3.311)	$9 \cdot 10^{-3}$ $9 \cdot 10^{-3}$ ($9 \cdot 10^{-3}$)	4P-LS-BP-NA-GR-AC 4P-LS-MX-00-00-TD Mean of above results
PTB	3.2802 3.2914 3.2708 (3.2812)	$6.6 \cdot 10^{-3}$ $1.02 \cdot 10^{-2}$ $1.18 \cdot 10^{-2}$ ($6.2 \cdot 10^{-3}$)	4P-PC-BP-NA-GR-CO 4P-LS-MX-00-00-TD 4P-LS-MX-00-00-CN Mean of above results

Institution	C_A (MBq·g ⁻¹)	u_i (MBq·g ⁻¹)	Method
ENEA-INMRI	3.316	$1.82 \cdot 10^{-2}$	4P-LS-MX-00-00-CN
	3.311	$1.25 \cdot 10^{-2}$	4P-NA-MX-00-00-HE
	(3.3135)	($2.21 \cdot 10^{-2}$)	Non-weighted mean of above results
POLATOM	3.279	$1.8 \cdot 10^{-2}$	4P-LS-BP-NA-GR-CO/AC
IFIN-HH	3.386	$4.4 \cdot 10^{-2}$	4P-LS-BP-NA-GR-CO
NMISA	3.293	$8.5 \cdot 10^{-3}$	4P-LS-BP-NA-GR-CO
NPL	3.295	$1.3 \cdot 10^{-2}$	4P-PC-BP-NA-GR-CO
	3.268	$1.3 \cdot 10^{-2}$	4P-LS-MX-00-00-CN
	3.294	$1.0 \cdot 10^{-2}$	4P-LS-BP-NA-GR-DC
	(3.286)	($1.0 \cdot 10^{-2}$)	Mean of above results
NIST	(3.286)	($1.1 \cdot 10^{-2}$)	4P-LS-BP -NA-GR-AC
	3.278	$7 \cdot 10^{-3}$	4P-LS-MX-00-00-CN

#Values obtained from multiple energy windows and extrapolation methods for the same technique have been averaged by the Pilot Laboratory to give a single value for each respective technique. See text for details.

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Table 3. Uncertainty budget ANSTO
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	5
Weighing	B	15
Background	A	1
Dead time	B	1
Resolving time	B	7×10^{-2}
Gandy effect	B	0
Pile-up	B	5
Extrapolation of efficiency curve	A	17
Half-life	B	0
Impurities	A	0.2
Adsorption	A	0.7
Combined standard uncertainty	24	

Table 4a. Uncertainty budget for LNMRI/IRD
(4π β - γ anticoincidence counting, 113 keV window).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	8
Weighing	B	5
Background	B	1
Dead time	B	1
Extrapolation of efficiency curve	A	13
Half-life	B	16
Combined standard uncertainty	23	

Table 4b. Uncertainty budget for LNMRI/IRD
(4π β - γ anticoincidence counting, 113 keV + 208 keV window).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	4
Weighing	B	5
Background	B	1
Dead time	B	1
Extrapolation of efficiency curve	A	8
Half-life	B	16
Combined standard uncertainty	19	

Table 4c. Uncertainty budget for LNMRI/IRD
(4π β - γ coincidence counting, 113 keV window, including linear and quadratic fits).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	24
Weighing	B	5
Background	B	36
Dead time	B	3.2
Resolving time	B	3
Gandy effect	B	34
Extrapolation of efficiency curve	A	23
Half-life	B	3
Combined standard uncertainty	55	

Table 4c. Uncertainty budget for LNMRI/IRD
(4π β - γ coincidence counting, 208 keV window).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	24
Weighing	B	5
Background	B	51
Dead time	B	0.1
Resolving time	B	1
Gandy effect	B	12
Extrapolation of efficiency curve	A	15
Half-life	B	13
Combined standard uncertainty	56	

Table 5. Uncertainty budget for IPEN-CNEN
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	14
Weighing	B	1
Background	B	3
Dead time	B	0.5
Resolving time	B	1
Extrapolation of efficiency curve ¹	A	123/56
Half-life	B	6
Impurities	B	15
Combined standard uncertainty¹	125/60	

¹ uncertainties for the results of coincidence measurements using two different gamma-ray windows, 112 keV and 208 keV, respectively.

Table 6a. Uncertainty budget for JRC-IRMM
(liquid scintillation counting with CIEMAT-NIST efficiency tracing).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	3
Weighing	A	20
Background	A	0.1
Dead time	A	10
Decay data	B	10
Tracer	B	35
Half-life	B	15
Impurities	A	1.5
Adsorption	A	1
Sample stability	A	10
Combined standard uncertainty		46

Table 6b. Uncertainty budget for JRC-IRMM
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Weighing	B	6
Dead time	B	5
Resolving time	B	included in dead time unc.
Gandy effect	B	included in dead time unc.
Pile-up	B	included in dead time unc.
Extrapolation of efficiency curve	B	90
Half-life	B	2
Impurities	B	4
Adsorption	B	negligible
Combined standard uncertainty		90

Table 7a. Uncertainty budget for LNE-LNHB
(liquid scintillation counting with Triple-to-Double Coincidence Ratio method).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	10
Weighing	B	11
Background	A	1
Quenching	B	8
Half-life	B	3
Impurities	B	1
Model	B	10
Efficiency	B	10
Dilution	B	16
Combined standard uncertainty	27	

Table 7b. Uncertainty budget for LNE-LNHB
(4π β - γ anticoincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	B	10
Weighing	B	5
Background	A	5
Live-time	B	1
Extrapolation of efficiency curve	A	15
Half-life	B	5
Impurities	B	5
LS accidental coincidences	B	5
Dilution	B	16
Combined standard uncertainty	26	

Table 8a. Uncertainty budget for PTB
(liquid scintillation counting with Triple-to-Double Coincidence Ratio method).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	6
Weighing	B	7
Background	A	3
Dead time	B	3
Decay data	B	20
Half-life	B	4
Impurities	B	5
Adsorption	B	5
Measuring time	B	1
Dilution	B	10
Ionization quench, kB value	B	16
Combined standard uncertainty	30	

Table 8b. Uncertainty budget for PTB
(liquid scintillation counting with CIEMAT-NIST efficiency tracing).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	5
Weighing	B	7
Background	A	3
Dead time	B	10
Decay data	B	30
Quenching	B	3
Tracer	B	4
Half-life	B	6
Impurities	B	5
Adsorption	B	5
Measuring time	B	1
Dilution	B	10
Combined standard uncertainty	35	

Table 8c. Uncertainty budget for PTB
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	5.9
Weighing	B	15
Background	A	4.9
Dead time	B	<1
Resolving time	B	1
Gandy effect	B	2.3
Extrapolation of efficiency curve	B	1.1
Half-life	B	6.2
Impurities	B	10
Measuring time	B	<1
Combined standard uncertainty	21	

Table 9a. Uncertainty budget for ENEA-INMRI
(liquid scintillation counting with CIEMAT-NIST efficiency tracing).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	31
Weighing	A	5
Background	A	0.4
Dead time	B	10
Decay data	B	5
Quenching	A	30
Tracer	B	3
Half-life	B	15
Impurities	A/B	7
Adsorption	B	2
Counting time	B	1
PMT asymmetry	B	10
Ionization quench	B	20
Scintillator stability	A	10
TSIE determination	A	4
Mass determination	B	10
Combined standard uncertainty	55	

Table 9b. Uncertainty budget for ENEA-INMRI
(gamma-ray counting with high-efficiency NaI detector).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	15
Weighing	A	5
Background	A	1
Dead time	B	1.5
Decay data	B	15
Input parameters and statistical models	B	20
Half-life	B	20
Impurities	A/B	5
Adsorption	B	2
Counting time	B	1
Statistics of Monte Carlo simulation	A	1
Low level threshold setting	B	2
Crystal dimensions	B	1
Mass determination	B	10
Other	B	0.6
Combined standard uncertainty	38	

Table 10. Uncertainty budget for POLATOM
(4π β - γ coincidence/anticoincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	14
Weighing	B	12
Background	B	1
Dead time	B	1
Resolving time	B	3
Extrapolation of efficiency curve	B	50
Half-life	B	3
Impurities	B	1
Adsorption	B	4
Combined standard uncertainty	54	

Table 11. Uncertainty budget for IFIN-HH
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	126
Weighing	B	10
Background	B	8
Dead time	B	25
Resolving time	B	1
Impurities	B	20
Combined standard uncertainty	130	

Table 12. Uncertainty budget for NMISA
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	5
Weighing	B	5
Background	B	6
Dead time	B	4
Resolving time	B	5
Extrapolation of efficiency curve	B	20
Half-life	B	8
Impurities	B	1
Adsorption	B	1
Counting time	B	0.1
Afterpulsing	B	7
Combined standard uncertainty	25	

Table 13a. Uncertainty budget for NPL
(4π β - γ coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics		17
Weighing		5
Background		0.1
Dead time		1
Resolving time		0.1
Gandy effect		0.1
Pile-up		0.1
Extrapolation of efficiency curve		34
Half-life		9
Impurities		3
Adsorption		0.4
Dilution factor		2.1
Combined standard uncertainty		40

Table 13b. Uncertainty budget for NPL
(4π β - γ digital coincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	7
Weighing	B	5
Background	B	0.2
Dead time (beta)	B	1
Dead time (gamma)	B	0.1
Resolving time (beta)	B	3
Resolving time (gamma)	B	0.3
Gandy effect	B	0.1
Pile-up (beta)	B	1.5
Pile-up (gamma)	B	0.1
Extrapolation of efficiency curve	B	20
Half-life (Lu-177)	B	7.5
Half-life (Lu-177m)	B	0.1
Impurities	B	5
Adsorption	B	0.4
Choice of gamma gates	B	5
Combined standard uncertainty		24

Table 13c. Uncertainty budget for NPL
(liquid scintillation counting with CIEMAT-NIST efficiency tracing).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Counting statistics	A	2.3
Weighing	B	1.4
Background	A	0.1
Dead time	B	8.7
Decay data	B	<1
Tracer	B	17.9
Interpolation of efficiency curve	B	3.3
Decay	B	19.7
Impurities	B	24.2
Adsorption	B	3
Dilution	B	2.1
CIEMAT-NIST model	B	5.4
Variation between LS cocktails	B	5.3
Variation between counters	B	3.2
Scintillation volume effects	B	1
Combined standard uncertainty	38	

Table 14a. Uncertainty budget for NIST
(4π β - γ anticoincidence counting).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Measurement variability	A	7
Weighing	B	5
Background	B	5
Live-time	B	10
Extrapolation of efficiency curve	B	31
Half-life (Lu-177)	B	1.2
Half-life (Lu-177m)	B	1.8×10^{-2}
Impurities	B	0.12
Combined standard uncertainty	34	

Table 14b. Uncertainty budget for NIST
(liquid scintillation counting with CIEMAT-NIST efficiency tracing).

Uncertainty component, u_i	Evaluation Method (A/B)	Relative uncertainty on C_A $u_i \times 10^4$
Single source repeatability	A	3.1
Measurement reproducibility	A	11
LS spectrometer dependence	A	10
Background	A	0.4
Lu-177 half-life	B	2.4
H-3 half-life	B	0.4
Lu-177m half-life	B	8×10^{-4}
H-3 standard	B	1.1
Impurity correction	B	0.04
Quench parameters	B	5.9
Fit of relationship between H-3 and Lu-177 efficiencies	B	0.06
Lu-177 decay energies	B	0.7
H-3 decay energies	B	2
Lu-177 branching ratios	B	0.03
Source mass	B	5
Dilution factor	B	2
Live time	B	5
Cocktail stability	B	10
Combined standard uncertainty	21	

Table 15. Relative activity of identified radionuclidic impurities in analysed ^{177}Lu solution.

Laboratory	Impurities identified	Activities of impurities relative to ^{177}Lu at reference time	Method of analysis
ANSTO	$^{177\text{m}}\text{Lu}$	0.000 30(3)	Gamma-ray spectrometry using HPGe detector
LNMRI-IRD	$^{177\text{m}}\text{Lu}$	0.000 353(8)	Gamma-ray spectrometry using HPGe detector
IPEN-CNEN*	$^{177\text{m}}\text{Lu}$	0.000 30(2)	Gamma-ray spectrometry using HPGe detector
IRMM	$^{177\text{m}}\text{Lu}$	0.000 4(1)	Gamma-ray spectrometry using HPGe detector
LNE-LNHB	$^{177\text{m}}\text{Lu}$	0.000 34(7)	Gamma-ray spectrometry using HPGe detector
PTB	$^{177\text{m}}\text{Lu}$	0.000 309(15)	Gamma-ray spectrometry using HPGe detector
ENEA-INMRI	$^{177\text{m}}\text{Lu}$	0.000 330(15)	Gamma-ray spectrometry using HPGe detector
		0.000 310(56)	Gamma-ray spectrometry using NaI detector
POLATOM	$^{177\text{m}}\text{Lu}$	0.000 33	Gamma-ray spectrometry using HPGe detector
IFIN-HH	$^{177\text{m}}\text{Lu}$	0.000 4	Gamma-ray spectrometry using HPGe detector
NMISA	$^{177\text{m}}\text{Lu}$	0.000 31	Ionization chamber with fits to chamber response and half-lives
NPL	$^{177\text{m}}\text{Lu}$	0.000 33(3)	Gamma-ray spectrometry using HPGe detector
NIST	$^{177\text{m}}\text{Lu}$	0.000 336(27)	Gamma-ray spectrometry using HPGe detector

Table 16. Preliminary degrees of equivalence.

Difference D_i , and associated uncertainty, U_i , for all comparison participants. See text for explanation of terms. Final degrees of equivalence will be calculated with respect to measurements made in the International Reference System (SIR).

Laboratory	D_i (MBq·g ⁻¹)	U_i (MBq·g ⁻¹)
ANSTO	-0.024	0.017
LNMRI-IRD	-0.012	0.038
IRMM	0.032	0.106
LNE-LNHB	0.023	0.018
PTB	-0.007	0.014
ENEA-INMRI	0.026	0.043
POLATOM	-0.009	0.035
IFIN-HH	0.098	0.086
NMISA	0.005	0.018
NPL	8×10^{-5}	0.020
NIST	-0.002	0.022

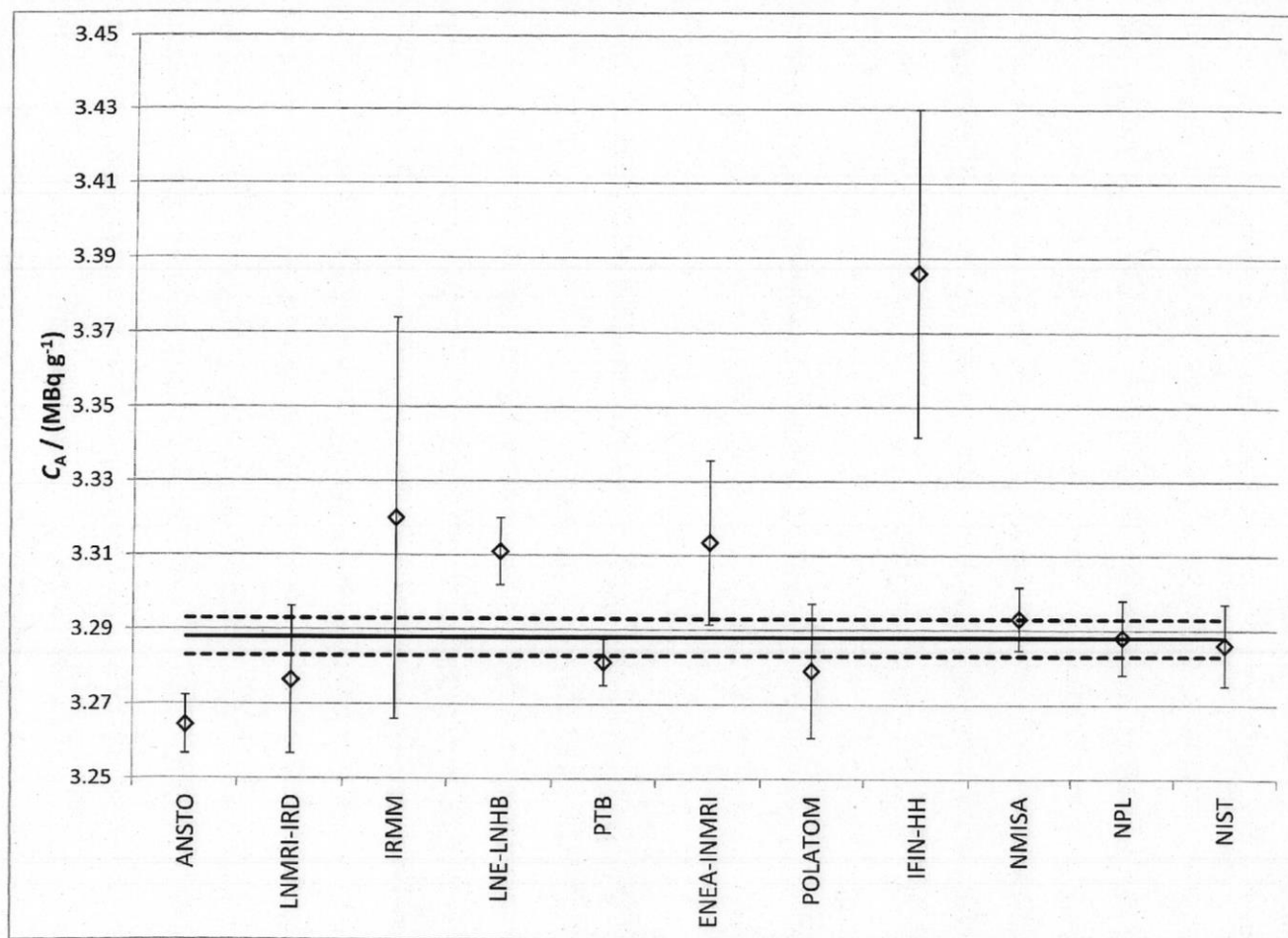


Figure 1. Radioactivity concentration of the ^{177}Lu comparison solution as reported by the participants. The uncertainty bars correspond to the combined standard uncertainty on each respondent's value. The solid line represents the proposed Comparison Reference Value (CRV) of $3.288 \text{ MBq} \cdot \text{g}^{-1}$ and the dashed lines represent the combined standard uncertainty on the CRV.

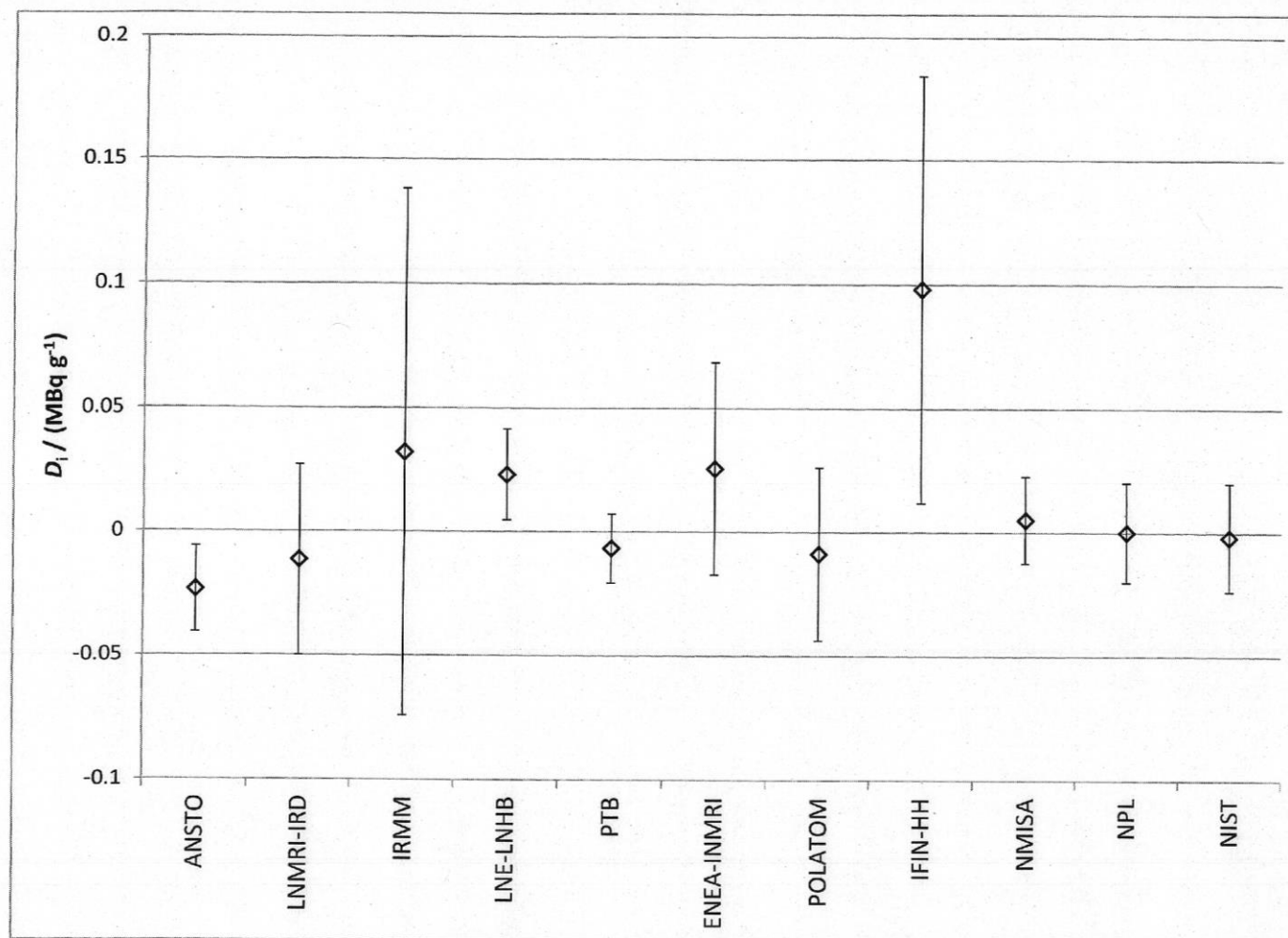


Figure 2. Preliminary degrees of equivalence for participants in the CCRI Key Comparison CCRI(II)-K2-Lu-177. The value of D_i is computed as $x_i - x_{ref}$, where x_i is the laboratory reported result and x_{ref} is the proposed Comparison Reference Value of $3.288 \text{ MBq} \cdot \text{g}^{-1}$. The uncertainty bars correspond to the expanded uncertainty, U_i , on D_i as calculated by (2).