Activity measurements of the radionuclide ^{201}Tl for the LNE-LNHB, France, PTB, Germany and the NPL, UK in the ongoing comparison BIPM.RI(II)-K1.Tl-201

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Abstract

In 2005, the Laboratoire national de métrologie et essais-Laboratoire national Henri Becquerel (LNE-LNHB) and the Physikalisch-Technische Bundesanstalt (PTB) each submitted a sample of known activity of ^{201}Tl to the International Reference System (SIR). In 2006, the National Physical Laboratory (NPL) submitted their first sample. The range of values of the activity submitted was between 2 MBq and 63 MBq. These key comparison results have been included in the re-evaluated key comparison reference value and replaced the previous results for France and Germany in the matrix of degrees of equivalence in the key comparison database that now contains seven results, identifier BIPM.RI(II)-K1.Tl-201.

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 form or a different standard ampoule for radioactive gases. 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 reference 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 2007, the SIR has measured 905 ampoules to give 662 independent results for 63 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) that was set up under the CIPM Mutual Recognition Arrangement (CIPM MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Tl-201 key comparison that was first published in 2004 [3]. As the KCRV has been re-evaluated following the present submissions, all the details concerning previous measurements are also given in this report.

2. Participants

In addition to the present solutions, the LNE-LNHB, PTB, four other NMIs and another laboratory have submitted 16 ampoules for the comparison of ^{201}Tl activity measurements since 1979. The participants' 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 participation in the comparison BIPM.RI(II)-K1.Tl-201

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	1979-07-23 1982-12-16 1983-06-29 1998-06-29
–	PTB	Physikalisch-Technische Bundesanstalt	Germany	EUROMET	1981-05-27 2005-09-28
NIRH	–	National Institute of Radiation Hygiene	Denmark	EUROMET	1982-12-14
LMRI BNM-LNHB	LNE-LNHB	Laboratoire national de métrologie et essais-Laboratoire national Henri Becquerel	France	EUROMET	1983-06-09 2003-09-19 # 2005-09-14
NAC*	NMISA	National Metrology Institute of South Africa	South Africa	SADCMET	1991-10-29
–	ANSTO	Australian Nuclear Science and Technology Organisation	Australia	APMP	1994-06-02
OMH	MKEH	Magyar Kereskedelmi Engedéyezési Hivatal	Hungary	EUROMET	1997-11-07
–	NPL	National Physical Laboratory	UK	EUROMET	2006-11-09

* another laboratory in the country.
# pilot study

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 the laboratory, the activities submitted and the relative standard uncertainties (k = 1) are given in Table 2. The uncertainty budget is given in Appendix 1. The acronyms used for the measurement methods are given in Appendix 2.

The half-life given in Table 2 is the value (with its uncertainty) as used by the participant. The half-life now used by the BIPM is 3.0421 (17) d as published in *BIPM Monographie 5* [4].

Details regarding the solution submitted are shown in Table 3, including any impurities, when present, as identified by the laboratory. The BIPM has a standard method for evaluating the activity of impurities using a calibrated Ge(Li) spectrometer [5]. The CCRI(II) agreed in 1999 [6] that this method should be followed according to the protocol described in [7] when an NMI makes such a request or when there appear to be discrepancies. Impurity checks were carried out at the BIPM for the three latest submissions in view of the short half-life (see Table 3 for the LNE-LNHB).

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a database known as the "master-file". The activity measurements for ^{201}Tl arise from nineteen 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 and are used in the KCDB and all references in this report.

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].

All the results in Table 4 were updated according to the revised value of the ^{201}Tl half-life [4] although the change is negligible in all cases.

The correction factors for impurities are typically between 1.02 and 1.08 but reach 1.15 for the ANSTO, 1.23 for the NIST (1982) and 5.41 for the NIST (1979). They are dominated by the contribution of ^{202}Tl ($T_{1/2}$ = 12.65 (32) d [8]). All the impurity corrections were revised for the present report using the presently updated KCRV, 312.8 (1.3) MBq (see section 5) for the equivalent activity of ^{201}Tl and the results in Table 4 were updated accordingly. However the change in the results is negligible compared to the other sources of uncertainty.

Table 2. Standardization methods of the participants for ^{201}Tl

NMI	Method used and acronym (see Appendix 2)	Half-life / d	Activity A_i / kBq	Reference date YY-MM-DD	Relative standard uncertainty / 10^{-2} by method of evaluation	
					A	B
NIST	Pressurized IC 4P-IC-GR-00-00-00 calibrated in 1976 by 4π(e,x)-γ coinc. 4P-PC-MX-NA-GR-CO	3.047	48 360	79-06-21 20 h UT	0.02	0.49
		3.0465 (10)	13 118	82-12-15 12 h UT	0.01	0.48
		–	11 226	83-06-22 19 h UT	0.01	0.48
		3.045 (1)	68 500	98-06-29 12 h UT	0.03	0.38
PTB	4πPPC-γ (GeLi) coincidence 4P-PP-MX-GL-GR-CO	–	16 442[#] 16 418	81-05-28 0 h UT	0.11	0.56
	4πPPC(e,x)-γ coincidence 4P-PP-MX-NA-GR-CO	3.0424 (26)	62 800	05-09-22 0 h UT	0.07	0.74
NIRH	Pressurized IC* 4P-IC-GR-00-00-00	–	207 400[#] 198 400	82-12-13 12 h UT	1.4	1.4
LNE-LNHB	4πγ 4P-NA-GR-00-00-00	–	3 512[#] 3 449	83-06-10 12 h UT	0.04	0.54
	4πLSe$_c$-γ anti-coincidence 4P-LS-CE-GH-GR-AC	3.0409 (29) [9]	7 605[#] 8 134 7 714	03-09-16 12 h UT	0.37	0.20
	4πLSβ-γ anti-coincidence 4P-LS-MX-NA-GR-AC	[4]	2 193	05-09-13 12 h UT	0.30	0.12
NMISA	4πLS(e,x)-γ coincidence [10] 4P-LS-MX-NA-GR-CO	3.038 [11]	56 800	91-10-24 12 h UT	0.06	0.52
ANSTO	Pressurized IC** 4P-IC-GR-00-00-00	–	11 460	94-05-19 23 h 01 UT	0.04	3.02
MKEH	4πPPC-γ coinc. and anti-coinc. 4P-PP-MX-NA-GR-CO 4P-PP-MX-NA-GR-AC	3.043 (3) [12]	32 060	97-11-07 0 h UT	0.06	1.20
NPL	4πβ-γ coincidence 4P-PC-CE-NA-GR-CO	[4]	39 070	06-11-07 12 h UT	0.20	0.38

[#] more than one ampoule submitted

* result determined from the efficiency curve for the NIRH IG11 IC

** calibrated by interpolation from the standardization of other radionuclides at the ANSTO.

Table 3. Details of the solution of ^{201}Tl submitted

NMI	Chemical composition	Solvent conc. / (mol dm^{-3})	Carrier: conc. /(μg g^{-1})	Density /(g cm^{-3})	Relative activity of impurity[†]
NIST 1979	$TlNO_3$ in HNO_3	HNO_3: 1 mol dm^{-3}	$TlNO_3$: 48	1.029 (2)*	^{200}Tl : 0.008 (1) % ^{202}Tl : 0.21 (2) %
1982	TlCl in HCl	HCl: 0.1 mol dm^{-3}	TlCl: 117	1.002	^{202}Tl : 2.1 (2) %
1983	$TlNO_3$ in HNO_3	HNO_3: 1 mol dm^{-3}	$TlNO_3$: 10	1.031	^{200}Tl : 0.012 (2) % ^{202}Tl : 0.291 (44) %
1998	$TlNO_3$ in HNO_3	HNO_3: 1.15 mol dm^{-3}	$TlNO_3$: 150	1.035	^{200}Tl : 0.008 (1) % ^{202}Tl : 0.60 (1) % **
PTB 1981	Tl_2SO_4 in HNO_3	HNO_3: 0.1 mol dm^{-3}	Tl_2SO_4: 40	1.0	^{202}Tl : 0.41 (2) % ^{203}Pb : 0.056 (2) %
2005				1.002	^{200}Tl : 0.359 (10) % ^{202}Tl : 0.166 (5) %
NIRH	TlCl and NaCl in benzyl alcohol C_7H_8O	C_7H_8O: 0.08 mol dm^{-3} NaCl: 9000 μg g^{-1}	–	–	^{200}Tl : 0.050 (5) % ^{202}Tl : 0.16 (1) %
LNE-LNHB 1983	TlCl in HCl	HCl: 0.1 mol dm^{-3}	TlCl: 10	0.999	^{200}Tl : 0.152 (15) % ^{202}Tl : 0.29 (3) %
2003	Tl in HCl	HCl: 0.1 mol dm^{-3}	Tl : 30	1	^{200}Tl : 0.19 (2) % ^{202}Tl : 0.26 (3) % ^{200}Pb : 0.035 (4) % ^{203}Pb : 0.033 (4) %
2005	$TlCl_3{\cdot}4H_2O$ in HCl	HCl: 0.1 mol dm^{-3}	$TlCl_3{\cdot}4H_2O$: 24	1.000	^{200}Tl : 0.095 (10) % ^{202}Tl : 0.251 (8) % **
NMISA	$TlNO_3$ in HNO_3	HNO_3: 0.1 mol dm^{-3}	Tl^+ : 500	1.0020	^{200}Tl : 0.0437 (13) % ^{202}Tl : 0.0230 (12) %
ANSTO	TlCl	–	Tl	–	^{200}Tl : 0.22 (2) % ^{202}Tl : 0.17 (2) %
MKEH	TlCl in isotonic NaCl	water NaCl: 9000 μg g^{-1}	–	–	^{200}Tl : 0.009 (2) % ^{202}Tl : 0.76 (6) % #
NPL	NaCl in water	water NaCl: 700 μg g^{-1}	–	1.001	^{200}Tl : 0.133 (3) % ^{202}Tl : 0.206 (3) %

[†] the ratio of the activity of the impurity to the activity of ^{201}Tl at the reference date

* at 23.6 °C

** confirmed by γ-spectrometry measurements made at the BIPM

γ-spectrometry measurement at the BIPM gives 0.801 (12) % for ^{202}Tl (see [3] for discussion).

Measurements repeated at the BIPM after periods of up to about 8 days later produced comparison results in agreement within the SIR standard uncertainty for the PTB (2005) and the NPL, and within two SIR combined uncertainties for the LNE-LNHB (2005). For many other submissions, the results of the SIR measurements repeated at the BIPM show some trend although not significant in view of the uncertainty. This could motivate new measurements to be made of half-life and decay data for ^{200}Tl, ^{201}Tl and ^{202}Tl (see also section 4.1).

The latest PTB result agrees within two SIR combined uncertainties with the PTB 1981 result. Although the three results from LNE-LNHB (2 SIR submissions and one pilot study) do not agree within the uncertainties, it is important to note that their latest SIR measurement was made under improved conditions; the SIR measurement was closer to the reference date and there is a smaller SIR correction for impurities. For the latest LNE-LNHB result, a correction equal to 0.9920 (5) was applied to the extrapolated value applying the method presented by Chauvenet et al. in [13]. Such a correction factor is dependent on decay scheme parameters [13] as well as the experimental conditions. It may also have been applied by other NMIs, for example, the NPL. Indeed, a recommendation to apply such a correction, as presented by Funck [14], was made at the Activity Comparisons Workshop in 2004 [15].

In principle, the chemical composition of the solutions could have an influence on the SIR measurements due to the intense x-ray emission from ^{201}Tl. Indeed, using the efficiency curve of the SIR [14], the relative contribution of the x-rays to the ionization current is estimated to be 65 %. As a consequence, a supplementary contribution[1] of 9×10^{-4} was added to the SIR relative uncertainty when the density of the solution is 1.03 g cm^{-3} or more. Further study of this phenomenon is desirable.

One earlier submission was withdrawn and does not appear here. For all other NMIs, the most recent result is normally eligible for Appendix B of the MRA. However, the NIRH no longer undertakes the metrology of activity so this result is not included in the KCDB.

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, 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[2];
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).

[1] Based on an experimental study of the SIR carried out by Dr Rytz using ^{241}Am [15].
[2] Rule as modified at the CCRI(II) meeting in 2005.

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 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 only made by the CCRI(II), normally during one of its biennial meetings.

Table 4. Results of SIR measurements of ^{201}Tl

NMI / SIR year	Mass of solution / g	Activity submitted / kBq	N° of Ra source used	SIR / kBq	Relative uncertainty from SIR	Combined uncertainty $u_{c,i}$ / kBq
NIST 1979	3.714 20	48 360	1	327 000	8.6×10^{-2} #	28 000
1982	3.740 46	13 118	3	311 400	2.2×10^{-2} ##	6 900
1983	3.691 6	11 226	1	313 400	1.3×10^{-2} ##	4 200
1998	3.745 77	68 500	4	317 900	16×10^{-4} *	1 300
PTB	3.706 4 (1)	16 442	3	308 080	19×10^{-4} ##	1 900
1981	3.701 1 (1)	16 418		308 280		1 900
2005	3.623 9 (9)	62 830	2	312 500	20×10^{-4} ##	2 400
NIRH	3.684 5	207 400	5	321 380	16×10^{-4} ##	6 400
	3.524 4	198 400		314 470[a]		6 200
LNE-LNHB	3.699 60	3 512	2	299 990	61×10^{-4} ##	2 400
1983	3.632 80	3 449		299 710	58×10^{-4}	2 400
2003	3.5619 (1)	7 605	1	318 660	47×10^{-4} ##	2 000
	3.8099 (1)	8 134		317 930		2 000
	3.6133 (1)	7 714		317 020[b]		2 000 [b]
2005	3.512 1 (9)	2 193	1	308 000	25×10^{-4} ##	1 300
NMISA	3.599 0**	56 800	3	312 500	12×10^{-4}	1 700
ANSTO	3.569	11 460	1	305 000	1.6×10^{-2} #	11 000
MKEH	3.605 8	32 060	3	314 400	56×10^{-4} ##	4 200
NPL	3.618 06	39 070	3	311 300	11×10^{-4}	1 400

[a] the mean of the A_e values shown for the same measurement date is used with an averaged uncertainty, as attributed to an individual entry [16]

[b] pilot study

* uncertainty increased from 13×10^{-4} to 16×10^{-4} due to solution density (see section 4)

** mass before dilution : 1.67887 g

due to a long delay between the measurement in the SIR and the reference date, combined with the uncertainty on the impurity as given by the laboratory. Revised uncertainty evaluation according to the present SIR procedure

reflecting the uncertainty on the impurity as given by the laboratory.

Consequently, the KCRV for ^{201}Tl has been identified as 312.8 (1.3) MBq using the results from the NMISA, MKEH, NIST (1998), LNE-LNHB (2005), PTB (2005) and the NPL. None of the earlier results has been used for the NIST even though the most recent result is furthest in time from the calibration of the ionization chamber. This is appropriate because of the large SIR uncertainty due to the delay between the SIR measurement and the reference date, or the large NIST uncertainty for the impurity in the earlier results.

The KCRV can be compared with the equivalent activity A_e^{model} evaluated using the SIR efficiency curve obtained by the least-squares minimization software SIRIC [14]. When using the decay data as recommended in *Monographie 5* [4], the A_e^{model} value is 306.8 (2.3) MBq, which is in agreement with the LNE-LNHB (2005) result. Nevertheless, it was noted in [17] that an agreement with many other SIR data is obtained when the measured ^{201}Tl x-ray emission probabilities cited in the Comments of [4] are used rather than the recommended calculated values. Indeed, the A_e^{model} value then becomes 312.6 (2.2) MBq, which is in very close agreement with the KCRV.

4.2 Degrees of equivalence

Every NMI that has submitted ampoules to the SIR is entitled to have one result included in the CIPM MRA KCDB as long as the NMI is a signatory or designated institute listed in the CIPM 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

$$D_i = A_{ei} - \text{KCRV} \qquad (1)$$

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

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

taking correlations into account as appropriate [18].

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

$$D_{ij} = D_i - D_j = A_{\mathrm{e}\,i} - A_{\mathrm{e}\,j} \qquad (3)$$

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

$$u_{D\,ij}{}^2 = u_i{}^2 + u_j{}^2 - 2u(A_{e,i}, A_{e,j}) \qquad (4)$$

where any obvious correlations between the NMIs (such as a traceable calibration) are subtracted using the covariance $u(A_{ei}, A_{ej})$, 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 the Key and Supplementary Comparisons section (Appendix B) of the CIPM MRA 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. The graphical 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.

5. Conclusion

The latest SIR results for the PTB and the NPL in this ongoing comparison agree with the KCRV at the level of a standard uncertainty while the LNE-LNHB result is lower by 1.6 %.

The BIPM ongoing key comparison for ^{201}Tl, BIPM.RI(II)-K1.Tl-201 currently comprises seven results. These have been analysed with respect to the updated 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 is published in the CIPM MRA key comparison database.

Other results may be added as and when NMIs contribute ^{201}Tl activity measurements to this comparison or take part in linked comparisons.

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Table 5. Table of degrees of equivalence and introductory text for ^{201}Tl

Key comparison BIPM.RI(II)-K1.Tl-201

MEASURAND : Equivalent activity of ^{201}Tl

Key comparison reference value: the SIR reference value for this radionuclide is x_R = 312.8 MBq, with a standard uncertainty u_R = 1.3 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,
$U_i = 2((1-2/n)u_i^2 + (1/n^2)\Sigma u_i^2)^{1/2}$ 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.

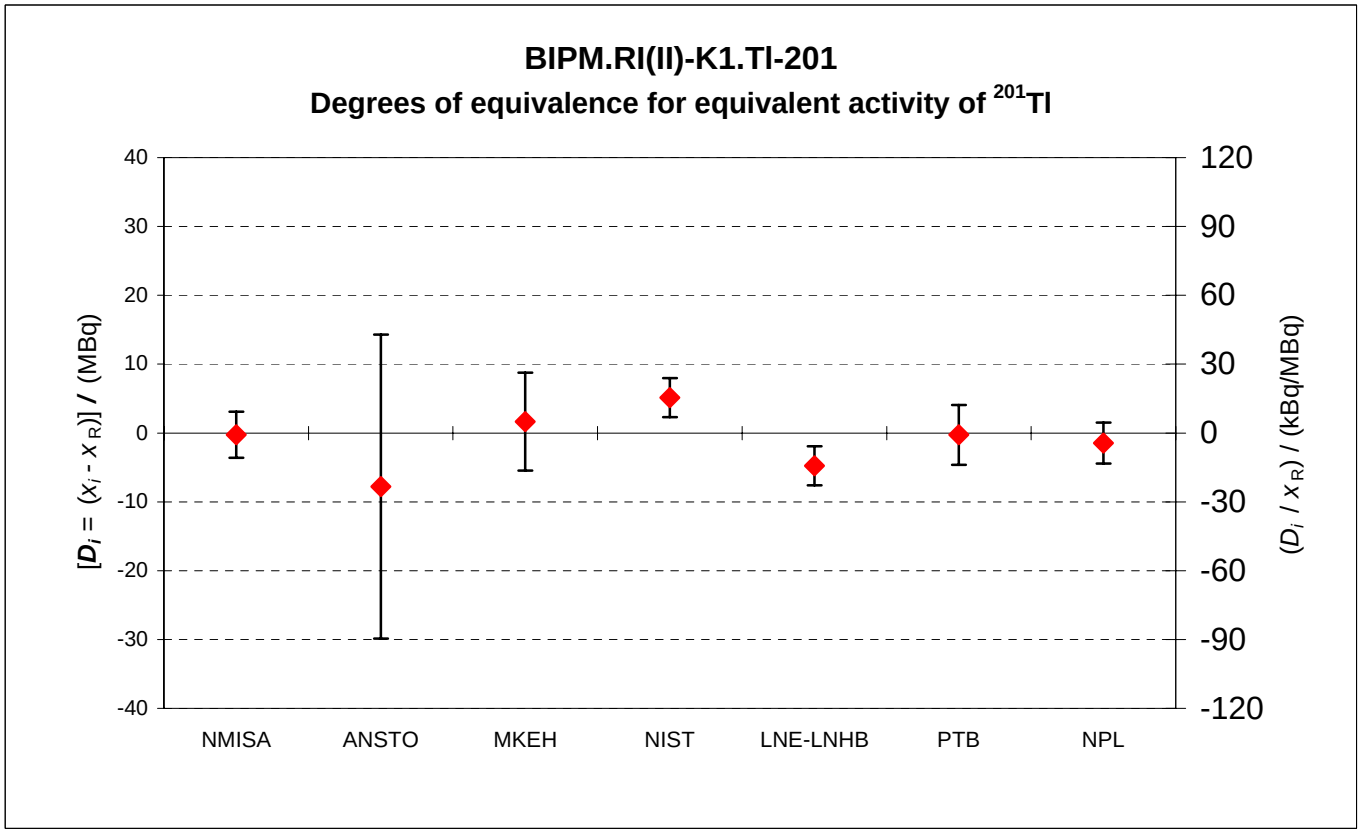
The approximation $U_{ij} \sim 2(u_i^2 + u_j^2)^{1/2}$ is used in the following table.

Lab *j* ⇨

Lab *i* ⇩	D_i / MBq	U_i / MBq	NMISA		ANSTO		MKEH		NIST		LNE-LNHB		PTB		NPL	
			D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq	D_{ij} / MBq	U_{ij} / MBq
NMISA	-0.3	3.3			7.5	22.3	-1.9	9.1	-5.4	4.3	4.5	4.3	0.0	5.9	1.2	4.4
ANSTO	-7.8	22.1	-7.5	22.3			-9.4	23.5	-12.9	22.2	-3.0	22.2	-7.5	22.5	-6.3	22.2
MKEH	1.6	7.1	1.9	9.1	9.4	23.5			-3.5	8.8	6.4	8.8	1.9	9.7	3.1	8.9
NIST	5.1	2.8	5.4	4.3	12.9	22.2	3.5	8.8			9.9	3.7	5.4	5.5	6.6	3.8
LNE-LNHB	-4.8	2.8	-4.5	4.3	3.0	22.2	-6.4	8.8	-9.9	3.7			-4.5	5.5	-3.3	3.8
PTB	-0.3	4.3	0.0	5.9	7.5	22.5	-1.9	9.7	-5.4	5.5	4.5	5.5			1.2	5.6
NPL	-1.5	3.0	-1.2	4.4	6.3	22.2	-3.1	8.9	-6.6	3.8	3.3	3.8	-1.2	5.6		

Figure 1. Graph of degrees of equivalence with the KCRV for ^{201}Tl

(as it appears in Appendix B of the MRA)



N.B. The right-hand axis is approximate only

Appendix 1. Uncertainty budgets for the activity of ^{201}Tl submitted to the SIR

Uncertainty budget for the LNE-LNHB measurement (2005)

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	**A**	**B**
counting statistics*	10	–
weighing	–	5
dead time	–	< 1
counting time	–	< 1
accidental coincidences	–	2
extrapolation of efficiency curve	28	–
half-life	–	8
decay scheme parameters	–	5
radionuclide impurities	–	5
Quadratic summation	**30**	**12**
Relative combined standard uncertainty, u_c	**32**	

*including background

Uncertainty budget for the PTB measurement (2005)

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	**A**	**B**
counting statistics	7	–
weighing	–	22
dead time	–	< 2
resolving time	–	< 2
Gandy effect	–	< 1
adsorption	–	< 1
extrapolation	–	13
half life	–	10
background	–	< 2
impurities	–	69
Quadratic summation	**7**	**74**
Relative combined standard uncertainty, u_c	**75**	

Uncertainty budget for the NPL measurement (2006)

Relative standard uncertainties	$u_i \times 10^4$ evaluated by method	
Contributions due to	**A**	**B**
counting statistics	20	–
weighing	–	7
dead time	–	3
counting time	–	1
pile-up	–	5
extrapolation of efficiency curve	–	25
adsorption	–	0.1
correction for L/K emission ratios when L (Auger and x-rays) not detected	–	9
half life	–	7
background	–	1
impurities	–	24
Quadratic summation	**20**	**38**
Relative combined standard uncertainty, u_c	**43**	

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
		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
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
photons + electrons	PE	selective sampling	SS
alpha - particle	AP	high efficiency	HE
mixture of various radiations	MX	digital coincidence counting	DC

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