Metrologia 2013, **50**, *Tech. Suppl.*, 06011

APMP/TCRI Key Comparison Report of Measurement of Air Kerma for ^{60}Co Gamma-Rays (APMP.RI(I)-K1)

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Abstract

The APMP.RI(I)-K1 key comparison of the measurement standards of air kerma for ^{60}Co gamma-rays was undertaken by the APMP/TCRI Dosimetry Working Group between 2004 and 2006, coordinated by the Korean Research Institute of Standards and Science (KRISS). In total, 10 institutes took part in the comparison, among which 7 were APMP member laboratories. Three Farmer-type commercial cavity chambers were used as transfer chambers and circulated among the participants. All the participants carried out their measurements according to the guidelines for the comparison established by the KRISS with the cooperation of the ARPANSA. For each transfer chamber, an NMI calibration coefficient was obtained and a ratio derived by dividing by the average result from the linking laboratories, ARPANSA and NMIJ. The APMP comparison reference value for each chamber was calculated as the mean of the NMI-determined calibration coefficients divided by the average result from the linking laboratories. The results showed that the maximum difference between the APMP linked ratio of a participating NMI and the APMP reference value was 1.76 %.

The measured ratios of the calibration coefficient $R_{\text{NMI, BIPM}}$ between the participating NMI and the BIPM via the link laboratories for the transfer chambers were obtained. The maximum expanded uncertainty of $R_{\text{NMI, BIPM}}$ for any participating laboratory was 2.0 %.

The degree of equivalence of each participating laboratory with respect to the key comparison reference value was also evaluated. The expanded uncertainty of the difference between the results ranged from 0.5 % to 1.2 %. The pair-wise degree of equivalence between each pair of laboratories was also obtained and the largest difference of the expanded uncertainty of the difference for any pair-wise degree of equivalence was within the expanded uncertainty of the measurement for the pair of laboratories.

1. Introduction

The Ionizing Radiation Technical Committee (TCRI) of the Asia Pacific Metrology Program (APMP) undertakes a program of dosimetry comparisons that is determined by its Dosimetry Working Group. The Dosimetry Working Group has several comparison projects that include the following five key comparisons:

- Measurement of air kerma for ^{60}Co gamma-rays (APMP.RI(I)-K1)
- Measurement of air kerma for low-energy x-rays (10 kV to 50 kV) (APMP.RI(I)-K2)
- Measurement of air kerma for medium-energy x-rays (100 kV to 250 kV)

(APMP.RI(I)-K3)

- Measurement of absorbed dose to water for ^{60}Co gamma-rays (APMP.RI(I)-K4)
- Measurement of air kerma for ^{137}Cs gamma-rays (APMP.RI(I)-K5)

This report presents the results of the regional comparison of standards for air kerma at ^{60}Co carried out in 2004-5 (APMP.RI(I)-K1).

2. Plans for the APMP RI(I)-K1 key comparison

In 2001, the Korea Research Institute of Standards and Science (KRISS) was invited by the TCRI chairperson to act as the coordinator of the APMP RI(I)-K1 key comparison project and take the responsibility for planning and organizing the comparison programs for the measurement of air kerma for ^{60}Co gamma-rays. Thus, in September 2002, the KRISS drafted a guideline for the comparison and delivered it with a questionnaire to each member laboratory to gauge their intentions with respect to this comparison. After several revisions of the draft, the final guideline [1] was made with the agreement of the participating members and the CCRI(I) by 16 August, 2004 and the comparison was initiated on 24 August, 2004 by sending the transfer chambers to the NMIJ, Japan. The participating laboratories were seven full members of the APMP, two associate members and one non-member of the APMP at the time of the comparison. Table 1 gives more information on the participating laboratories and the contact persons for this APMP.RI(I)-K1 key comparison.

2.1 Comparison methodology

The methods used in international comparisons for ionization radiation can be divided into two types: direct comparisons (DC) and indirect comparisons (IC). Direct comparisons mean that every participating laboratory brings its primary standard chamber to a certain laboratory to participate in a measurement comparison. That is, every participating laboratory performs the comparison in the same radiation fields using the same environmental conditions and irradiation facilities. Indirect comparisons mean that all the participating laboratories sequentially calibrate the same transfer chambers using similar radiation fields. Considering that only four participants are primary dosimetry laboratories and the rest are secondary dosimetry laboratories, it was not possible to have a direct comparison. It was decided that this APMP.RI(I)-K1 key comparison be an indirect comparison. A brief description of the comparison procedure [1] is as follows:

1) Transfer Chambers: Three Farmer-type chambers (two NE2571, one PTW30001).

2) The KRISS made the stability checks for the transfer chambers after each NMI finished its

measurements.

3) Each NMI performed the measurements based on its status (either primary or secondary standard laboratory).

4) Transfer chambers were passed to a participating NMI and returned to the KRISS after the measurements were completed; the chambers were calibrated by the ARPANSA and the NMIJ to obtain the ratio between each participating NMI and the BIPM, (NMI / BIPM).

The conditions of measurement for the transfer chambers were referenced to the calibration conditions for the determination of air kerma rates for ^{60}Co gamma-rays at the BIPM. The detailed measurement conditions are given in Table 2.

2.2 The transfer chambers used in the comparison

This comparison employed two NE2571 and one PTW30001 ionization chambers as transfer chambers. The NE2571 chambers were donated by the ARPANSA and the INER and one PTW30001 by the KRISS. These Farmer-type chambers are widely used in standards laboratories and hospitals as transfer instruments for calibrations in terms of either air kerma or absorbed dose to water. It was decided to circulate three transfer chambers with build-up caps because a smaller uncertainty for the air kerma could be assigned by repeating the same measurement with three instruments. Another reason was for redundancy in that if one chamber changed during transport or handling, the remaining two could still be used. With only two chambers, if one changes it may be difficult to have confidence in either result. The characteristics of the transfer chambers are given in Table 3.

2.3 Schedule of the comparison

After discussions with all the participating laboratories, this comparison was scheduled to begin in August 2004 and end in May 2006. Every laboratory was requested to finish its calibrations within three weeks. In order to verify the stability and functioning of the transfer chambers during the period of the comparison, every laboratory was required to send these three chambers back to the KRISS for stability tests in ^{90}Sr/^{90}Y as soon as it finished its calibrations [1]. It took about a month for the round trip of these three transfer chambers between the KRISS and each participating laboratory. The KRISS passed these chambers onto the next laboratory for calibration when the stability tests were complete.

2.4 Calibration certificate

All participating laboratories were expected to submit their calibration certificates, in English, within a month of the calibrations. The content was to include at least the air kerma calibration coefficients (mGy/nC) of the ionization chambers, air kerma rate of the radiation field (mGy/s), calibration distance, field size at the calibration distance and the expanded uncertainty (k = 2) of the calibration coefficients. Furthermore, it was required that the relative humidity conditions at the time of calibration be stated on the certificate. If the humidity of a participating laboratory at the time of measurement was not within the range from 40 % to 70 %, a humidity correction would need to be applied [2].

2.5 Uncertainty estimation of the measurement

Each participating laboratory was required to estimate the percentage relative standard uncertainty of their air kerma standard as outlined in the ISO document 'Guide to the Expression of Uncertainty in Measurement', 2nd edition, 1995 [3]. As specified in this document, all the contributing uncertainties were to be classified as either type A or type B and their values tabulated. The Type A uncertainty is obtained by the statistical analysis of series of observations; the Type B uncertainty is obtained by means other than the statistical analysis of series of observations. In order to analyze the uncertainties and take correlation into account for the BIPM KCDB degrees of equivalence, the BIPM recommended that the participating laboratories submit their detailed uncertainty budgets to the pilot laboratory.

2.6 The final report of the comparison

When the comparison was completed, the KRISS combined all the measured calibration coefficients $N_{K(\mathrm{NMI})}$ from the participating laboratories to obtain the APMP reference value of the calibration coefficients ratios, whose expression is given as $\frac{\sum_{i=1}^{10} R_{Ki(\mathrm{NMI,\ Link})}}{10}$, where $R_{Ki(\mathrm{NMI,\ Link})} = N_{K(\mathrm{NMI}\ i)} / N_{K(\mathrm{Link})}$ are NMI ratios as given in the guideline [1]. This allowed the production of a plot of the distribution of the measured calibration coefficients and the production of a draft comparison report. The draft comparison report was sent to the participating laboratories for confirmation of results and any additional comments. When all participants had responded, the draft was further edited into a final report and submitted to the APMP/TCRI chairperson. This report was accepted and the degrees of equivalence were then calculated as presented in this report.

3. Linking of the regional comparison to the BIPM key comparison

Two participating laboratories, the ARPANSA and the NMIJ, had participated in comparisons previously with the BIPM for measurements of air kerma in ^{60}Co gamma-rays and were used as "link laboratories" to link the APMP.RI(I)-K1 comparison with the corresponding BIPM key comparison. According to the document published by the CCRI(I) [6], a ratio is evaluated that represents the link between the participating NMI and the BIPM and is given by

$$R_{K(\text{NMI, BIPM})} = R_{K(\text{NMI, LINK})} \times R_{K(\text{LINK, BIPM})} \ , \quad (1)$$

where

$R_{K(\text{NMI, LINK})} = N_{K(\text{NMI})} / N_{K(\text{LINK})}$ is the ratio of the measurement value from a participating NMI to the average for the two link laboratories

$R_{K(\text{LINK, BIPM})} = K_{\text{Link}} / K_{\text{BIPM}} = N_{K(\text{LINK})} / N_{K(\text{BIPM})}$ is the average key comparison result for the two link laboratories in the BIPM RI(I)-K1 key comparison

$R_{K(\text{NMI, BIPM})}$ is the derived ratio of the participating laboratory and the BIPM.

The link laboratories, the ARPANSA (Australia) and the NMIJ (Japan), participated in a comparison with the BIPM of ^{60}Co gamma-ray air kerma standards in 1997 [4] and 2004 [5], respectively. The key comparison results of the ARPANSA and the NMIJ for the ^{60}Co gamma-ray air kerma standards are given in Table 4. The ratio $N_{K(\text{LINK})} / N_{K(\text{BIPM})}$ was 0.9974 for ARPANSA and 1.0018 for NMIJ, differing by 0.44 %. The average value of these key comparison results was used as the linking ratio for this regional comparison. Using these key comparison results in equation (1), the measurement results for each participating laboratory could be linked to that of the BIPM. The results of the derived ratios of the participating laboratory and the BIPM for this comparison via the link laboratories are given in Table 7.

4. Results

The results of transfer chamber stability tests made at the KRISS are given in Table 5 and Figure 1, this stability being within the ± 0.23 % range. The final calibration results for the transfer chambers are given in Tables 6 and 7. Figure 2 which was produced using the data of Table 6 shows that the calibration coefficients of the transfer chambers from most participants are located within the range of the mean value ± 2 σ (where σ is the standard deviation of the distribution).

Figure 3 shows the evaluated ratio of the calibration coefficient $R_{K(\text{NMI, BIPM})}$ between the participating NMI and the BIPM for the transfer chambers. The ratio, $R_{K(\text{NMI, BIPM})}$, was obtained by multiplying the average value of $R_{K(\text{NMI, Link})} = N_{K\,(\text{NMI})} / N_{K(\text{Link})}$ for the two link laboratories by the average value of $R_{K(\text{Link,BIPM})} = N_{K\,(\text{Link})} / N_{K(\text{BIPM})}$ for the BIPM key comparison results of ARPANSA and NMIJ. According to Figure 3 and Table 7, the expanded uncertainties of $R_{\text{NMI, BIPM}}$ for all the participating NMIs were within 2.0 %.

5. Degrees of equivalence

According to the document published by the CCRI(I) [6], the comparison ratios between any participating NMI and the BIPM obtained through the link laboratories are given by the equation:

$$R_{K(\text{NMI, BIPM})} = R_{K\,(\text{NMI, LINK})} \times R_{K(\text{LINK, BIPM})} = N_{K\,(\text{NMI})} / N_{K(\text{BIPM})} \qquad (2)$$

and its uncertainty is given by

$$u^2(R_{K(\text{NMI, BIPM})}) = \left(u^2_{\text{NMI}} + u^2_{\text{BIPM}} - \sum_k f_k^2 \left(u^2_{\text{NMI}}(k) + u^2_{\text{BIPM}}(k) \right) \right) + u^2_{\text{stab}} + u^2_{\text{LINK}} \qquad (3)$$

where u_{NMI} is the total standard uncertainty reported by the participating NMI,

u_{BIPM} is the combined standard uncertainty of the BIPM air kerma determination,

u_{LINK} is the statistical uncertainty of $N_{K\,(\text{LINK})} / N_{K(\text{BIPM})}$,

u_{stab} is the statistical uncertainty of the transfer instrument stability measurements.

Also, the summation in equation (3) contains the components $f_k\, u_{\text{NMI}}(k)$ and $f_k\, u_{\text{BIPM}}(k)$ from the correlation between the participating NMI and the BIPM with the correlation factor, f_k.

When using multiple transfer instruments in the comparison, the best estimate for $R_{K(\text{NMI, BIPM})}$ is the weighted mean given by the following equation [6],

$$R_{K\,(\mathrm{NMI,\,BIPM})} = \frac{\sum_n R_{K\,(\mathrm{NMI,\,BIPM}),\,\mathrm{n}} / u^2_{\mathrm{stab,n}}}{\sum_n 1/u^2_{\mathrm{stab,n}}} \tag{4}$$

and the combined standard uncertainty arising from the stability of the transfer chambers is given as

$$\frac{1}{u^2_{\mathrm{stab}}} = \sum_n \frac{1}{u^2_{\mathrm{stab,n}}} \tag{5}$$

The weighted mean value of the comparison ratio for each transfer chamber and thus the best estimate for the three chambers, and its uncertainty, were estimated according to equations (4) and (5), and the results are given in Table 9.

a) Degree of equivalence with respect to the key comparison reference value (KCRV)

The degree of equivalence for any NMI representing the consistency of the NMI with the KCRV has two components. One component is the value of the difference D_i between the NMI result and the KCRV and the other is its uncertainty. Following the decision of the CCRI to accept the BIPM air kerma determination as the reference value, the value of the difference can be expressed by [6]

$$D_i = R_{K\,(\mathrm{NMI}\,i,\mathrm{BIPM})} - 1 = R_i - 1 \;, \tag{6}$$

where the notation $R_i = R_{K\,(\mathrm{NMI}\,i,\mathrm{BIPM})}$ is adopted for laboratory *i*. The statistical uncertainty associated with the KCRV, u_{KCRV} is added to the comparison uncertainty $u\;(R_{K,\,\mathrm{NMI}\,i}) = u_i$ to give the relative combined uncertainty of the difference as

$$u_i(D_i) = \left[u_i^2 + u^2_{\mathrm{KCRV}}\right]^{1/2} \tag{7}$$

For the evaluation of the uncertainty, each laboratory submitted its uncertainty budget for u_{NMI} and these are summarized in Table 8. The uncertainty u_{BIPM} given by the BIPM is 0.17 %. For the linking uncertainty u_{LINK} in equation (3), the uncertainty of the linking measurements is evaluated for each linking laboratory and the mean value taken. The components of u_{LINK} are detailed in [6] and are essentially those associated with transfer chamber positioning and ionization current measurements for the linking laboratory in both the APMP and BIPM comparisons. The mean value for u_{LINK} has been taken as 0.2 %.

There are several correlated quantities to be taken into consideration in this comparison. Among the physical constants that enter into the determination of air kerma, the product of the graphite to air stopping power ratio and the energy to create an ion pair is important because all the NMIs with primary standards use the same value for this quantity. Therefore, this quantity is fully correlated (f_k = 1) and the contribution of the quantity to the uncertainty is 0.11 %. The quantities such as the air to graphite mass-energy absorption coefficient ratio and the loss of electron energy are also correlated. Unless the primary laboratory carried out the evaluation of these physical constants by itself, these values are taken from the CCRI agreed values and the uncertainties for these constants are 0.05 % and 0.02 %.

The correction factor for the humidity and the value of the dry air density are also fully correlated because every laboratory takes these values from the reference data (ICRU 31). The uncertainty for the humidity correction is 0.03 %, and 0.01 % for the air density.

The traceability of any participating secondary standard laboratory is also relevant. If a secondary standard laboratory taking part in this comparison is traceable to the BIPM, the uncertainty of the calibration coefficients obtained for the APMP comparison is fully correlated with the BIPM uncertainty u_{BIPM} of 0.17 %. Other quantities such as the wall correction factor, the uniformity correction factor and the chamber volume are assumed to be obtained by their experimental or theoretical evaluations and are not correlated.

In the comparison, three transfer chambers were sent to the participating laboratories with regular return for the stability check at the pilot laboratory. The weighted mean for $R_{K(\mathrm{NMI,\,BIPM})}$ varied from 0.9967 to 1.0146, as shown in Table 9, and u^2_{stab} is 0.06 %.

The relative combined uncertainty u_i of the degree of equivalence with respect to the KCRV was estimated by considering the above uncertainty components and the value ranged from 0.2 % to 0.6 %. The expanded uncertainty of the difference D_i for each participating laboratory, $U_i = 2\,u_i(D_i)$ was evaluated and the values for the degrees of equivalence for each laboratory are given in Figure 4 and Table 10.

b) Pair-wise degree of equivalence

For each pair of laboratories *i* and *j*, the pair-wise degree of equivalence is defined by the difference [6],

$$D_{ij} = R_i - R_j \tag{7}$$

and its uncertainty,

$$u_{i,j}^2 = \left(u_i^2 + u_j^2 - \sum_k f_k^2 \left(u_i^2(k) + u_j^2(k) \right) \right) + 2u_{\text{stab}}^2 \tag{8}$$

where u_i^2 and u_j^2 are the uncertainties of NMI *i* and *j* and $f_k u_i(k)$ and $f_k u_j(k)$ are correlated components between NMI *i* and *j*. The estimated relative combined uncertainty of the pair-wise difference between any pair of the participating NMIs ranged from 0.28 % to 0.64 %. The value of pair-wise difference, D_{ij}, and its expanded uncertainty, U_{ij}, are given in Table 10.

6. Conclusion

This comparison of the air kerma standards for ^{60}Co gamma-rays was the second dosimetry comparison that was conducted in the Asia-Pacific region. The participating laboratories consisted of seven APMP members, the IAEA, the NMISA (South Africa) and the PNRI (Philippines) who was not a member of APMP when the measurements were performed. Three Farmer-type ionization chambers (two NE2571 and one PTW30001) were used as transfer chambers for the comparison and each laboratory was required to provide calibration certificates and associated uncertainties for the chambers. The transfer chambers were sent back to the KRISS for the stability check after the measurement was made at each NMI during the comparison. The transfer chambers maintained their normal conditions during the comparison showing stabilities within ± 0.23 %.

Two participating laboratories (ARPANSA and NMIJ) had made comparisons with the BIPM for the ^{60}Co gamma-ray air kerma standards and acted as link laboratories. The measurement results of the participating laboratories could be linked to the BIPM and compared to the key comparison reference value of the BIPM through the link laboratories.

The calibration coefficients of the transfer chambers were measured by each participating laboratory and the distribution of the measurement results from most laboratories were located within the range of the mean value ± 2 σ (standard deviation). The maximum difference between the comparison ratios $R_{K(\text{NMI, LINK})}$ of each NMI and the APMP reference value for the transfer chambers (as given in Table 6) is 1.76 %.

The link ratios $R_{K(\text{NMI, BIPM})}$ between the participating NMI and the BIPM for the transfer chambers were obtained and the expanded uncertainties of $R_{K(\text{NMI, BIPM})}$ for the participating laboratory showed a variation from 0.74 % to about 1.9 %.

The degree of equivalence of each laboratory with respect to the KCRV was calculated. The differences D_i are generally smaller than the expanded uncertainty U_i for each laboratory with the exception of the result from the PNRI which might indicate a problem with the measurement in that laboratory. The pair-wise degree of equivalence between any pair of laboratories was also obtained and the largest uncertainty of the pair-wise difference was 1.3 %. Each participating laboratory in the comparison with the exception of the PNRI demonstrated its measurement capability of ^{60}Co air kerma and achieved consistency with the BIPM within the expanded uncertainties. The long-term measurement stability of the transfer chambers, conducted by the KRISS, was always less than 0.5 % and so has no significant effect on the uncertainties of pair-wise differences. Although each laboratory could put more effort into improving their measurement capability for their ^{60}Co air kerma, each has not only verified its own measurement capabilities but this comparison has also strengthened the technical cooperation and exchange of ideas between all the participating laboratories.

7. Table of abbreviations and full names of organizations

Abbreviation	Full name
APMP	Asia Pacific Metrology Program
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
BARC	Bhabha Atomic Research Centre, India
BIPM	Bureau International des Poids et Mesures
CMC	Calibration and Measurement Capabilities
IAEA	International Atomic Energy Agency
INER	Institute of Nuclear Energy Research, Taiwan
KCDB	Key Comparison Database
KCRV	Key Comparison Reference Value

KRISS	Korea Research Institute of Standards and Science
Nuclear Malaysia	Malaysian Nuclear Agency
NE	Nuclear Enterprise Co. Ltd.
NMIJ	National Metrology Institute of Japan
NMISA	National Metrology Institute of South Africa
NIM	National Institute of Metrology, China
MRA	Mutual Recognition Arrangement
PNRI	Philippine Nuclear Research Institute
PTW	Physikalisch-Technische Werkstätten Ltd.
TCRI	Technical Committee on Ionizing Radiation (APMP)

8. Acknowledgement

The authors wish to record their sincere thanks Dr Carl Ross, National Research Council, Canada, for reviewing the report and having helpful discussions with one of the authors, and for his comments.

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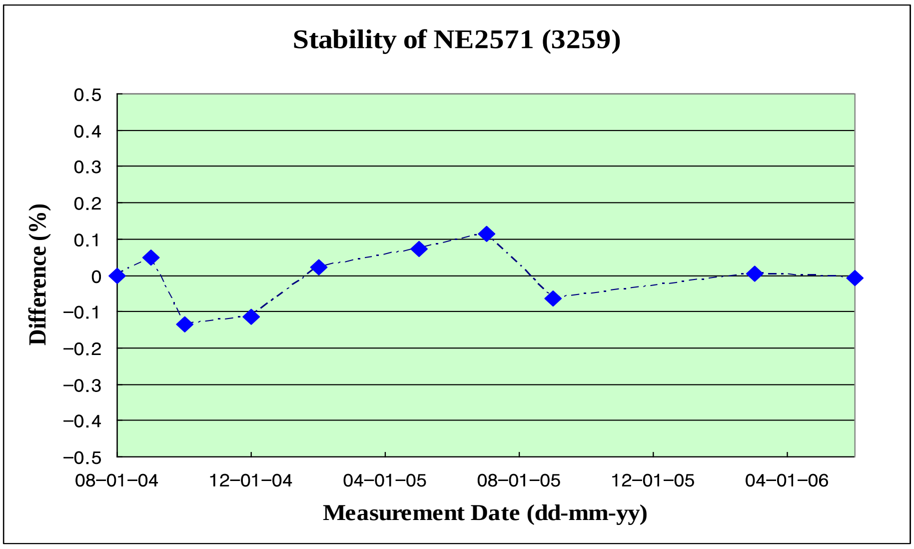
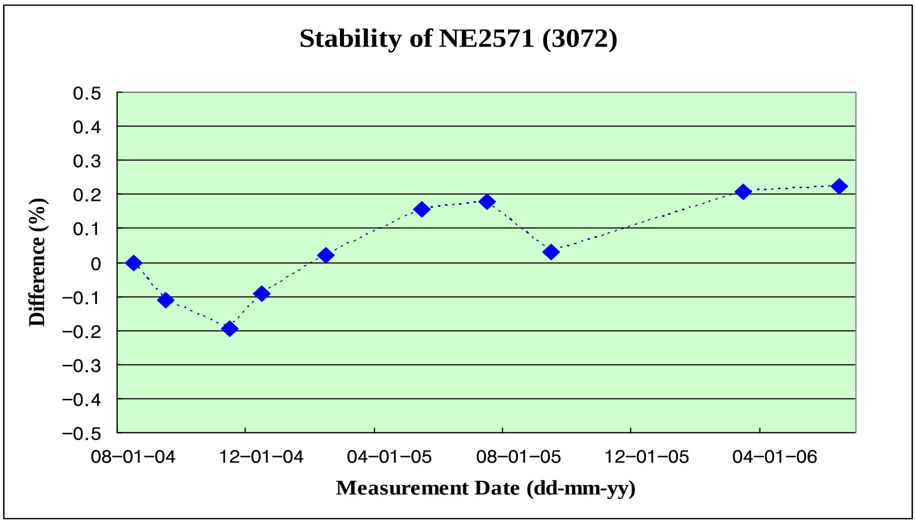
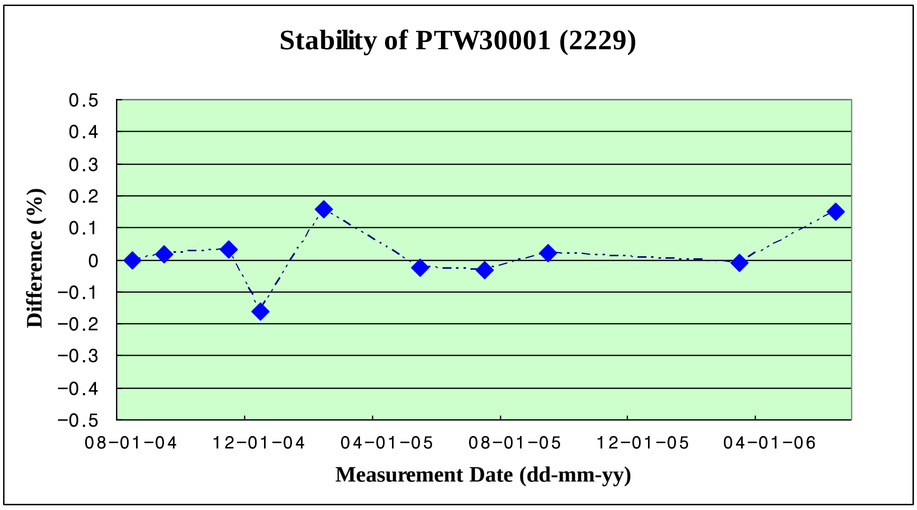
Figure 1. Stability of each transfer chamber



(a)



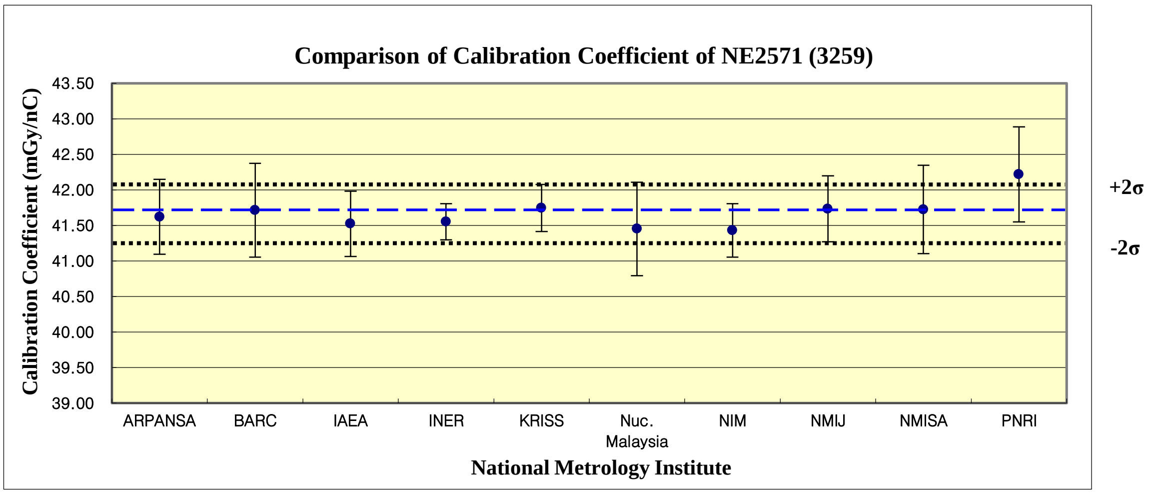
(b)



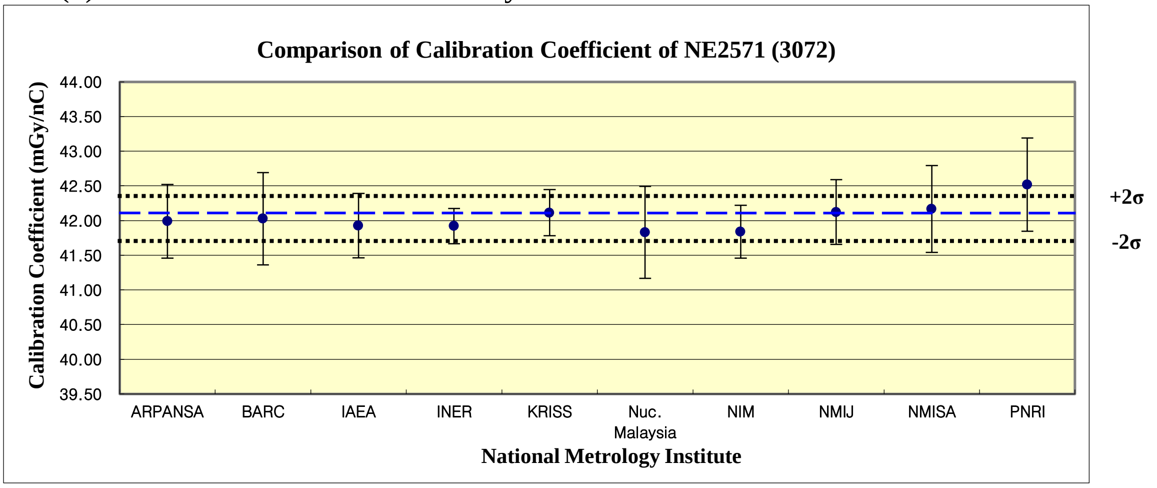
(c)

Figure 2. The average values of the calibration coefficients and their distributions

(a) NE2571-3259: 41.68±0.40 mGy/nC



(b) NE2571-3072: 42.06±0.36 mGy/nC



(c) PTW 30001-2229: 49.74±0.58 mGy/nC

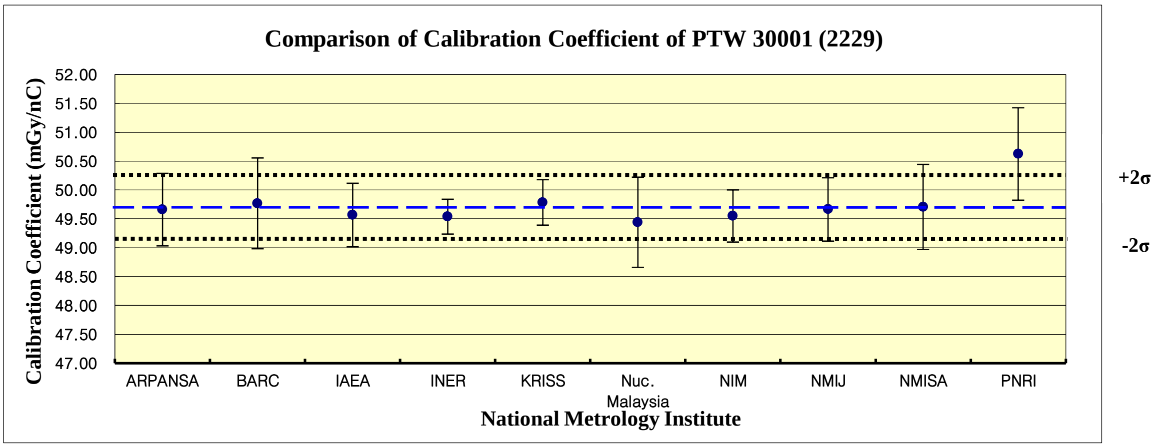


Figure 3. $R_{K(\mathrm{NMI,\,BIPM})}$ **of each NMI to the BIPM via the link laboratories for the three transfer chambers** (■: NE2571-3259, ▲: NE2571-3072 and ◆: PTW 30001-2229).

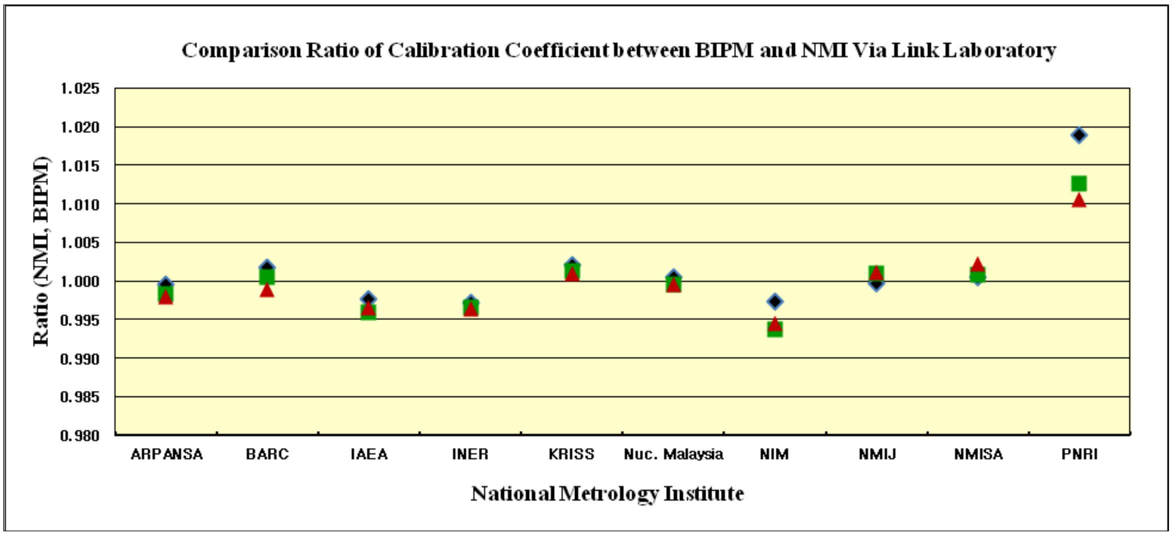


Figure 4. Degree of equivalence for the participating laboratories. The red points in the graph represent the degrees of equivalence and uncertainties for the linking laboratories reported in the KCDB.

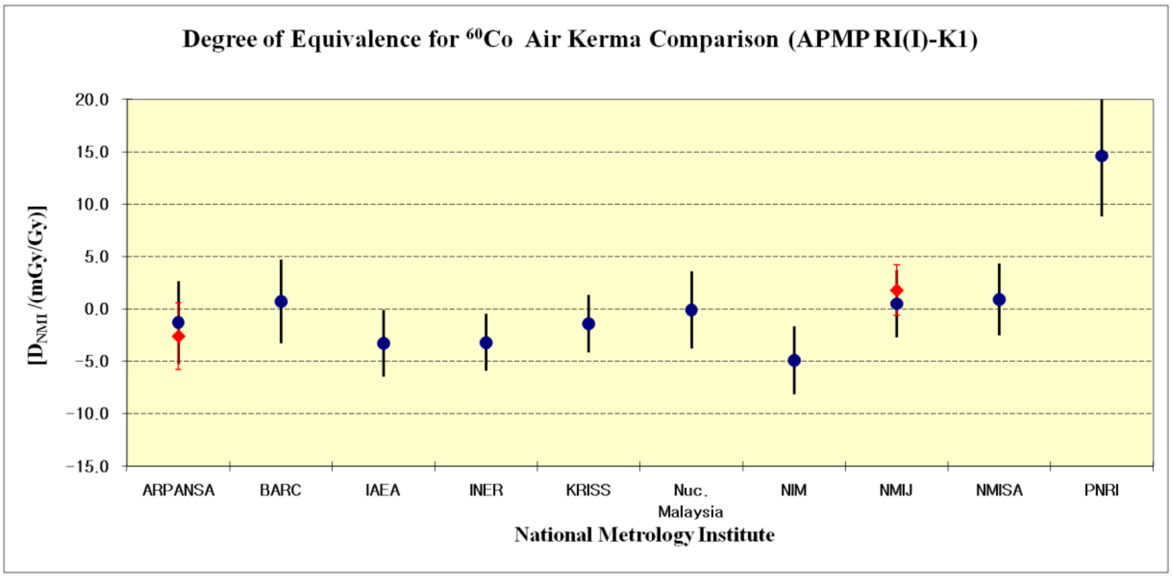


Table 1. **Participating laboratories and their contact persons for APMP.RI(I)-K1 key comparison**

The traceability of the primary or secondary in each case is indicated.

Participating Laboratories	Contact Persons	Standard Traceability
ARPANSA, Australia	Duncan Butler	ARPANSA
BARC, India	A. K. Mahant	BIPM
IAEA	Ahmed Meghzifene	BIPM
INER, Taiwan	Jeng-Hung Lee	INER
KRISS, Korea	Kook Jin Chun	BIPM
Nuclear Malaysia, Malaysia	Taiman Bin Kadni	IAEA
NIM, China	Yanli Zhang	NIM
NMIJ, Japan	Tadahiro Kurosawa	NMIJ
NMISA, South Africa	Zakithi LM Msimang	BIPM
PNRI, Philippine	Estrella S. Caseria	IAEA

Table 2. **Conditions of measurement for the determination of the air kerma calibration coefficient**

1. Beam Condition	At SDD = 1 m with a size of 10 cm × 10 cm in rectangular beam or φ = 10 cm in circular beam.
2. Chamber Calibration	The chambers were calibrated with the build-up cap in place.
3. Charge measurement	Charge collected by the transfer chamber was measured using the NMI's electrometer.
4. Measurement Unit	Measurement results were expressed in mGy/nC.
5. Experimental Conditions	
a) Chamber Positioning	Axis of the chamber was in the reference plane at 1 m from source. Chamber was oriented with the straight line inscribed on the stem facing the source.
b) Collecting Voltage	A collecting voltage of 250 V (negative polarity) was applied to the outer shell of the chamber.
c) Ambient Conditions	Air temperature was required to be stable to better than 0.05 ℃. Measured current was normalized to T = 20 ℃ and p = 101.325 kPa. Relative humidity was maintained between 40 % and 70 %.
d) Reproducibility of Measurement	A set of at least ten measurements were taken for each chamber.

Table 3. Main physical characteristics of transfer chambers

Physical Characteristics	NE2571 (S/N 3259, 3072)	PTW 30001 (S/N 2229)
Geometry	Cylindrical	Cylindrical
Inner Diameter / cm	0.63	0.688
Wall Material	Graphite	PMMA + Graphite
Wall Thickness / (g cm^{-2})	0.045	0.045
Nominal Volume / cm^3	0.69	0.60
Polarizing d.c. Voltage /V	-250	-250

Table 4. NMI/BIPM ratios of air kerma calibration coefficients for ^{60}Co gamma-rays for the link NMIs.

NMI	Year of Comparison	$R_K = N_{K\,(\mathrm{LINK})} / N_{K\,(\mathrm{BIPM})}$	Relative Standard Uncertainty $u_c(R_K)$
ARPANSA	1997	0.9974	0.0032
NMIJ	2004	1.0018	0.0024

Table 5. Stability of chambers used in the comparison as measured using a $^{90}Sr/^{90}Y$ check source at the KRISS.

Values expressed as percentage differences from the mean value for each chamber

	Date of Stability Check (dd-mm-yy)	PTW30001-2229 (%)	Date of Stability Check (dd-mm-yy)	NE2571-3259 (%)	Date of Stability Check (dd-mm-yy)	NE2571-3072 (%)
	10-Sep-04	0.02	10-Sep-04	0.05	08-Sep-04	-0.11
	02-Nov-04	0.03	29-Oct-04	-0.13	03-Nov-04	-0.20
	08-Dec-04	-0.16	06-Dec-04	-0.12	04-Dec-04	-0.09
	24-Feb-05	0.16	19-Feb-05	0.02	21-Feb-05	0.02
	21-May-05	-0.02	24-May-05	0.07	25-May-05	0.16
	26-Jul-05	-0.03	22-Jul-05	0.12	25-Jul-05	0.18
	09-Sep-05	0.02	07-Sep-05	-0.06	08-Sep-05	0.03
	21-Mar-06	-0.10	20-Mar-06	0.03	17-Mar-06	0.21
	26-Jun-06	0.15	21-Jun-06	-0.09	20-Jun-06	0.22
Standard uncertainty of chamber stability		0.29		0.25		0.46
Standard uncertainty of comparison stability, u_{stab}	0.06					

Table 6. The measured calibration coefficients $N_{K\,(\mathrm{NMI})}$ of three transfer chambers and the APMP reference values for the APMP.RI(I)-K1 key comparison.

Participants	Calibration coefficients / (Gy/nC)			Combined Standard Uncertainty (%)
	NE2571(3259)	NE2571(3072)	PTW30001(2229)	
ARPANSA	41.62	41.99	49.66	0.53
BARC	41.71	42.03	49.77	0.54
IAEA	41.52	41.93	49.57	0.40
INER	41.55	41.92	49.54	0.19
KRISS	41.62	41.99	49.64	0.29
Nuc. Malaysia	41.67	42.06	49.71	0.51
NIM	41.43	41.84	49.55	0.37
NMIJ	41.73	42.12	49.66	0.35
NMISA	41.72	42.17	49.71	0.46
PNRI	42.22	42.52	50.62	0.91
Average value of linked NMIs: $N_{K(\mathrm{Link})}^{\mathrm{ave}}$	41.675	42.055	49.660	0.32
Average value of NMIs: $N_{K\,(\mathrm{NMI})}^{\mathrm{ave}}$	41.679	42.057	49.743	
APMP reference value $\frac{1}{10}\sum_{i=1}^{10} R_{Ki(\mathrm{NMI,\ Link})}$	1.00010	1.00005	1.00167	

Table 7. The comparison link ratios $R_{K(\mathrm{NMI,\,BIPM})}$ between any participating NMI and the BIPM through the link laboratories (ARPANSA and NMIJ), and the corresponding uncertainties.

Participants	Calibration coefficient ratios			Combined Standard Uncertainty
	NE2571(3259)	NE2571(3072)	PTW 30001(2229)	
ARPANSA	0.9983	0.9981	0.9996	0.62
BARC	1.0004	0.9990	1.0018	0.63
IAEA	0.9959	0.9966	0.9978	0.51
INER	0.9966	0.9964	0.9972	0.37
KRISS	0.9983	0.9981	0.9992	0.43
Nuc. Malaysia	0.9995	0.9997	1.0006	0.60
NIM	0.9937	0.9945	0.9974	0.49
NMIJ	1.0009	1.0011	0.9996	0.47
NMISA	1.0007	1.0023	1.0006	0.56
PNRI	1.0127	1.0107	1.0189	0.96

Table 8. Uncertainty budgets of the participating laboratories

NMI	**ARPANSA**		**BARC**		**IAEA**		**INER**		**KRISS**	
Source of Uncertainty	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
NMI Air kerma rate										
Air Kerma Determination		0.49		0.390		0.23	0.067	0.146		0.17
Long term Stability of Standard		0.10				0.20			0.07	
Positioning of Standard	0.07		0.100	0.010		0.04	0.05			
Source Decay		0.03								
Temperature and Pressure	0.04		0.020	0.200	0.04	0.06		0.0133	0.03	0.02
Current Measurement	0.03	0.07	0.020	0.020	0.04	0.14	0.04	0.0186	0.02	0.12
Calibration of Transfer Chamber										
Positioning of Transfer Chamber	0.07		0.100	0.010	0.04	0.06	0.05			0.12
Temperature, Pressure, Humidity	0.05		0.200	0.200	0.04	0.14		0.0167	0.04	0.02
Current Measurement of Transfer Chamber	0.07	0.07	0.020	0.020		0.10	0.06	0.0186	0.02	0.12
Quadratic Summation	0.14	0.51	0.247	0.483	0.08	0.39	0.121	0.150	0.09	0.27
Combined Standard Uncertainty	**0.53**		**0.54**		**0.40**		**0.19**		**0.29**	

NMI	**Nuclear Malaysia**		**NIM**		**NMIJ**		**NMISA**		**PNRI**	
Source of Uncertainty	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
NMI Air kerma rate										
Air Kerma Determination		0.480	0.09	0.26	0.05	0.325		0.200		0.300
Long term Stability of Standard		0.100	0.18					0.250		
Positioning of Standard		0.060	0.06			0.04				0.400
Source Decay				0.02						
Temperature and Pressure		0.064		0.015		0.03		0.171		0.700
Current Measurement	0.020	0.040	0.08	0.04	0.01	0.01	0.02			0.200
Calibration of Transfer Chamber										
Positioning of Transfer Chamber		0.060	0.06			0.05		0.231		
Temperature, Pressure, Humidity		0.064		0.03		0.08		0.171		0.075
Current Measurement of Transfer Chamber	0.020	0.040	0.1	0.05	0.03	0.01	0.01		0.047	0.200
Quadratic Summation	0.028	0.509	0.253	0.271	0.06	0.34	0.022	0.463	0.047	0.909
Combined Standard Uncertainty	**0.51**		**0.37**		**0.35**		**0.46**		**0.91**	

Table 9. Values of the link ratio $R_{K(\mathrm{NMI,BIPM})}$ for individual transfer chambers and the mean ratios unweighted and weighted by the stability of the chambers (u_{stab}).

NMI	$R_{K(\mathrm{NMI,\ BIPM})}$ (PTW30001-2229)	$R_{K(\mathrm{NMI,\ BIPM})}$ (NE2571-3259)	$R_{K(\mathrm{NMI,\ BIPM})}$ (NE2571-3072)	Mean $R_{K(\mathrm{NMI,\ BIPM})}$ (Un-weighted)	Best Estimate for $R_{K(\mathrm{NMI,\ BIPM})}$ (Weighted Mean)	Standard Uncertainty of $R_{K(\mathrm{NMI,\ BIPM})}$ (Weighted Mean)
ARPANSA	0.9996	0.9983	0.9981	0.9986	0.9987	0.39 %
BARC	1.0018	1.0004	0.9990	1.0004	1.0007	0.38 %
IAEA	0.9978	0.9959	0.9966	0.9968	0.9967	0.32 %
INER	0.9972	0.9966	0.9964	0.9967	0.9968	0.27 %
KRISS	0.9992	0.9983	0.9981	0.9985	0.9986	0.28 %
Nuc. Malaysia	1.0006	0.9995	0.9997	0.9999	0.9999	0.37 %
NIM	0.9974	0.9937	0.9945	0.9952	0.9951	0.33 %
NMIJ	0.9996	1.0009	1.0011	1.0006	1.0005	0.32 %
NMISA	1.0006	1.0007	1.0023	1.0012	1.0009	0.35 %
PNRI	1.0189	1.0127	1.0107	1.0141	1.0146	0.57 %

Table 10. Degree of equivalence of the participating NMIs with respect to KCRV and pair-wise degree of equivalence for each pair of NMIs.

NMI *j* ⇨

NMI *i* ⇩

	BIPM		ARPANSA		BARC		IAEA		INER		KRISS	
	Di /(mGy/Gy)	*Ui*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*
ARPANSA	-2.6	6.4			3.3	9.5	-0.7	8.6	-0.6	7.8	1.2	7.9
BARC	0.7	7.6	-3.3	9.5			-4.0	8.4	-3.9	7.6	-2.1	7.7
IAEA	-3.3	6.4	0.7	8.6	4.0	8.4			0.1	6.4	1.9	6.5
INER	-3.2	5.4	0.6	7.8	3.9	7.6	-0.1	6.4			1.8	5.6
KRISS	-1.4	5.5	-1.2	7.9	2.1	7.7	-1.9	6.5	-1.8	5.6		
Nuc. Malaysia	-0.1	7.4	-2.5	9.3	0.8	9.1	-3.2	8.1	-3.1	7.3	-1.3	7.4
NIM	-4.9	6.6	2.3	8.7	5.6	8.5	1.6	7.3	1.7	6.6	3.5	6.7
NMIJ	1.8	4.8	-4.4	8.6	-1.1	8.4	-5.1	7.2	-5.0	6.4	-3.2	6.5
NMISA	0.9	6.9	-3.5	9.0	-0.2	8.8	-4.2	7.7	-4.1	6.9	-2.3	7.0
PNRI	14.6	11.4	-17.2	12.7	-13.9	12.6	-17.9	12.1	-17.8	11.6	-16.0	11.4

	Nuclear Malaysia		NIM		NMIJ		NMISA		PNRI	
NMI	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*	*Dij* /(mGy/Gy)	*Uij*
ARPANSA	2.5	9.3	-2.3	8.7	4.4	8.6	3.5	9.0	17.2	12.7
BARC	-0.8	9.1	-5.6	8.5	1.1	8.4	0.2	8.8	13.9	12.6
IAEA	3.2	8.1	-1.6	7.3	5.1	7.2	4.2	7.7	17.9	12.1
INER	3.1	7.3	-1.7	6.6	5.0	6.4	4.1	6.9	17.8	11.6
KRISS	1.3	7.4	-3.5	6.7	3.2	6.5	2.3	7.0	16.0	11.4
Nuc. Malaysia			-4.8	8.2	1.9	8.1	1.0	8.5	14.7	12.6
NIM	4.8	8.2			6.7	7.4	5.8	7.8	19.5	12.2
NMIJ	-1.9	8.1	-6.7	7.4			-0.9	7.7	12.8	12.1
NMISA	-1.0	8.5	-5.8	7.8	0.9	7.7			13.7	12.2
PNRI	-14.7	12.6	-19.5	12.2	-12.8	12.1	-13.7	12.2		