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Comparison of the standards of air kerma of the NMi and the BIPM for ^{60}Co γ rays

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Abstract

The results of the two comparisons made previously between the standards of air kerma of the Nederlands Meetinstituut Van Swinden Laboratorium, Utrecht, The Netherlands and of the Bureau International des Poids et Mesures, Sèvres, France have been confirmed recently. The present result shows that the standards show agreement to within 0,3 % across the three comparisons made since 1972.

1. Introduction

A direct comparison between the Nederlands Meetinstituut Van Swinden Laboratorium (NMi) standard of air kerma and that of the Bureau International des Poids et Mesures (BIPM) was made in ^{60}Co gamma radiation at the BIPM in 1972 [1]. Subsequently in 1991 the standards were compared indirectly using an ionization chamber belonging to the NMi (Nuclear Enterprises Type NE2561 serial number 246) as a transfer instrument [2].

In 1994, the NMi standards were moved from Bilthoven to a new location in Utrecht where a new calibration facility was brought into use. Consequently, it seemed prudent to make a further comparison in view of the changes made at the NMi (a new ^{60}Co source, shorter source to detector distance and hence higher air kerma rate). For this latest comparison the same transfer chamber was used as in 1991.

2. Determination of air kerma

The standard for the determination of air kerma at the NMi is described in [1]. In 1972, the NMi had two air kerma standards, one graphite ionization chamber of cylindrical geometry and one of spherical geometry. The latter is the one in use today. The BIPM standard for the determination of air kerma is a pancake graphite ionization chamber described in [3].

The air kerma rate is determined from

$$\dot{K} = \frac{I}{m}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{a,c}} \bar{s}_{\mathrm{c,a}}\Pi k_i \quad , \qquad (1)$$

where

I/m is the mass ionization current measured by the standard,
W is the average energy spent by an electron of charge e to produce an ion pair in dry air,
$\bar{g}$ is the fraction of electron energy lost by bremsstrahlung,
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ is the ratio of the mean mass-energy absorption coefficients of air and graphite,
$\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean stopping powers of graphite and air,
Πk_i is the product of the correction factors to be applied to the standard.

The values of the physical constants and the correction factors entering in (1) are shown in Table 1 for both the NMi and the BIPM standards together with their associated uncertainties. In Table 1, the values for the NMi are given for the spherical standard [2].

The relative uncertainties of the direct comparison, the result of which is expressed as $R_{\dot{K}} = \dot{K}_{\mathrm{NMi}}/\dot{K}_{\mathrm{BIPM}}$, are also given in Table 1. As the physical constants are derived from the same basic data in both laboratories, the relative uncertainty in $R_{\dot{K}}$ is due only to the relative uncertainties in the correction factors, the volumes of the standards and the ionization currents measured.

3. Air kerma calibration factor

The air kerma calibration factor N_K for a transfer chamber measured at a given laboratory is given by

$$N_{K\,\mathrm{lab}} = \dot{K}_{\mathrm{lab}}/I_{\mathrm{lab}} \quad , \qquad (2)$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate and I_{lab} is the ionization current of the transfer chamber. The experimental method for calibrations at the NMi is described in Section 3.1 and that for the BIPM in [4]. The NMi transfer chamber is a graphite cavity chamber manufactured by Nuclear Enterprises (Type NE 2561 Serial N$^{\mathrm{o}}$246). Its main characteristics are listed in Table 2. This transfer chamber has been calibrated periodically at the NMi over thirteen years. The results are shown in Figure 1 together with the three calibrations carried out at the BIPM in 1991, 1993 and 1996. As is shown in the figure, the calibration factors of the two laboratories vary in a similar way with time. Although the calibration factor measured at the NMi appears to have changed by 0,6 % over 13 years, check source measurements made over the same period at the NMi do not show the same trend (Figure 2).

Table 1. Physical constants and correction factors entering in the determination of air kerma and their estimated relative uncertainties

	BIPM values	BIPM relative uncertainty[(1)]		NMi values[(2)]	NMi relative uncertainty[(1)]		$R_{\dot{K}}$ relative uncertainty[(1)]	
		$100\,s_i$	$100\,u_i$		$100\,s_i$	$100\,u_i$	$100\,s_i$	$100\,u_i$
Physical constants								
dry air density / kg·m^{-3} [(3)]	1,293 0	-	0,01	1,293 0	-	0,01	-	-
$(\mu_{en}/\rho)_{a,c}$	0,998 5	-	0,05	0,999 2	-	0,05	-	-
$\bar{s}_{c,a}$	1,001 0	-	0,30	1,000 7	-	0,20	-	-
W/e / (J·C^{-1})	33,97	-	0,15	33,97	-	0,15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0,003 2	-	0,02	0,003 2	-	0,02	-	-
Correction factors								
k_s recombination losses	1,001 6	0,01	0,01	1,003 0	-	0,03	0,01	0,03
k_h humidity	0,997 0	-	0,03	0,997 0	-	0,10	-	-
k_{st} stem scattering	1,000 0	0,01	-	0,999	-	0,05	0,01	0,05
k_{at} wall attenuation	1,040 2	0,01	0,04	1,026	-	0,20	0,01	0,20
k_{sc} wall scattering	0,971 6	0,01	0,07				0,01	0,07
k_{CEP} mean origin of electrons	0,992 2	-	0,01	0,995	-	0,20	-	0,20
k_{an} axial non-uniformity	0,996 4	-	0,07	1,000	-	0,15	-	0,17
k_{rn} radial non-uniformity	1,001 6	0,01	0,02	1,000	-	0,03	0,01	0,03
V volume / cm^3	6,811 6	0,01	0,03	4,845	-	0,10	0,01	0,10
I ionization current / pA		0,01	0,02		0,02	0,07	0,02	-
Relative standard uncertainty								
quadratic summation		0,02	0,36		0,02	0,44	0,03	0,36
combined uncertainty		0,36			0,44		0,36	

[(1)] Expressed as one standard deviation
s_i represents the relative standard uncertainty estimated by statistical methods, type A,
u_i represents the relative standard uncertainty estimated by other means, type B.

[(2)] Values for the spherical 5 cm^3 standard

[(3)] At 101 325 Pa and 273,15 K.

Table 2. Characteristics of the NMi transfer chamber

Chamber	NE 2561-246	Nominal value
Dimensions	Outer diameter / mm	8,4
	Inner diameter / mm	7,4
	Wall thickness / mm	0,5
	Cavity length / mm	9,2
Electrode	Diameter / mm	
Volume	Air cavity / mm^3	325
Wall	Materials	high purity extruded graphite
	Density / g·cm^{-3}	1,80
Build-up cap	Material	“Delrin” air-equivalent plastic
	Thickness / mg·cm^{-2}	600
Applied tension	Negative polarity / V	200

3.1 Measuring Conditions at the NMi and the BIPM

The measuring conditions at the two laboratories were very similar.

- *Position of the transfer chamber*. The axis of the transfer chamber was located in the reference plane, 1 m from the source. The field size at the reference plane is 10 cm x 10 cm, the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre of the square. The position of the chamber was verified without the build-up cap. Its serial number on the stem was placed so as to face the source. The uncertainty in positioning is 0,2 mm at the NMi and 0,04 mm at the BIPM.

- *Build-up cap.* The chamber was supplied with a build-up cap for use in ^{60}Co radiation and this was in place for all measurements of ionization current. The inscription on the build-up cap was placed to face the source.

- *Humidity, temperature and pressure*. During calibration, the relative humidity was in the range of 10 % to 30 % at the NMi and 40 % to 50 % at the BIPM. No correction for humidity was applied to the ionization current measured by the chamber. However, a difference of about 0,1 % in the ionization current could occur between these two ranges of humidity, as shown by Hofmeester and Somerwil (Figure 3) [5]. The air temperature was about 21 °C. During a series of measurements, the air temperature was stable to better than 0,1 °C at the NMi and 0,03 °C at the BIPM. The measured ionization current was normalized to 295,15 K and 101,325 kPa.

- *Collecting voltage*. A collecting voltage of 200 V (negative polarity), supplied at the individual laboratories, was applied to the chamber.

- *Measurement of charge.* The charge Q collected by the chamber was measured using the BIPM or the NMi electrometer as appropriate.

- *Reproducibility of measurements*. The short-term relative standard deviation of the mean ionization current, measured with the transfer chamber, is estimated to be 0,02 % at the NMi and 0,01 % at the BIPM (2 series of 30 measurements).

3.2 Other Factors

- *Recombination.* No correction was applied for incomplete ion collection: the volume recombination is negligible for this type of chamber at an air kerma rate of the order of 5 mGy·s^{-1} and the initial recombination is the same in the two laboratories.

- *Leakage current.* The leakage current of the transfer chamber was negligible, being less than 0,01 % at both laboratories.

- *Stem scattering effect.* This has not been checked at the BIPM.

- *Radial non-uniformity of the beam*. No correction has been made to the results obtained at either laboratory for radial non-uniformity over the section of the transfer chamber. (In the BIPM beam, this effect is about 0,01 % for this type of chamber.)

4. Results of the comparison

The result of the indirect comparison, R'_K, is expressed in the form

$$R'_K = N_{K_{\mathrm{NMi}}} / N_{K_{\mathrm{BIPM}}} \quad , \qquad (3)$$

where N_K is the calibration factor of the transfer chamber determined at each laboratory. The chamber was calibrated at the BIPM in November 1996 and at the NMi in December 1996. The relevant $\dot{K}$, I and N_K values obtained are shown in Table 3 together with the result R'_K.

Contributions to the relative standard uncertainty in N_K are shown in Table 4 together with those related to the comparison result R'_K.

Table 3. Results of the air kerma comparison in ^{60}Co radiation using the NMi transfer chamber

Laboratory	$\dot{K}_{\mathrm{lab}}$ (1) / mGy·s^{-1}	I_{lab} (1) / pA	$N_{\dot{K}}$ / Gy·µC^{-1}	100 u_c	R'_K	100 u_c
NMi	6,611 7	70,311	94,03	0,44	1,003 1	0,37
BIPM	5,268 4	56,203	93,74	0,36		

(1) The half life of ^{60}Co is taken as (1 925,5 d, u = 0,5 d) [6]. The values are referenced to 1996-01-01, 0h UT.

Table 4. Estimated relative standard uncertainties in the calibration factor, N_K, of the transfer chamber and the comparison result, R'_K

	Uncertainty in $N_{K\mathrm{NMi}}$		Uncertainty in $N_{K\mathrm{BIPM}}$		Uncertainty in R'_K	
Relative standard uncertainty in the measurement of	100 s_i	100 u_i	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma rate	0,02	0,44	0,02	0,36	0,03	0,36
Ionization current of transfer chamber	0,02	-	0,01	-	0,02	-
Chamber position	-	0,04	0,01	0,02	0,01	0,04
Beam spectra difference	-	-	-	-	-	0,03
Humidity difference	-	-	-	-	-	0,03
Relative standard uncertainties						
quadratic summation	0,03	0,44	0,02	0,36	0,04	0,36
combined uncertainty	0,44		0,36		0,37	

5. Conclusion

Three air kerma comparisons between the BIPM and the NMi for ^{60}Co radiation have been made since 1972. All three results are shown in Table 5 and they are consistent to the 2 s level with the uncertainties (s = 0,07 %) associated with the positioning of the transfer chamber and the standards, the measurements of ionization current, the relative humidity and the differences between the beam spectra. This confirms the stability of the standards over a 24 year period.

Table 5. Air kerma comparisons between the NMi and the BIPM

Year	$N_{K\mathrm{NMi}}$	$N_{K\mathrm{BIPM}}$	$R_{\dot{K}}$	R'_K
1972 [1]	Direct comparison		1,001 5	-
1991 [2]	93,718	93,516	-	1,002 2
1996	94,035	93,739	-	1,003 1

Figure 4 shows the results of all air kerma comparisons made at the BIPM in ^{60}Co radiation. The standard deviation of the comparisons with the 15 national primary laboratories is 0,16 %. The values relating to recent comparisons are given in [7].

References

[1] HOFMEESTER G.H. and SOMERWIL A., Absolute exposure measurements in the Netherlands in the 10 - 250 kV x-ray region and for ^{60}Co gamma rays, *Annalen van de Belgische Vereniging voor Stralingsbescherming*, 1976, **Vol 1**, N° 4, 317-326.

[2] VAN DIJK E and GRIMBERGEN T.W.M., Report of the indirect comparison of kerma standards of BIPM and NMi December 1991, *NMi Report*, 1993, Bilthoven, 10 pp.

[3] BOUTILLON M. and NIATEL M.T., A study of a graphite chamber for absolute exposure measurement of ^{60}Co gamma rays, *Metrologia*, 1973, **9**, 139-146.

[4] BOUTILLON M., Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM-96/1*, 1996, 19 pages.

[5] HOFMEESTER G.H. and SOMERWIL A., Interim report of the influence of humidity on ionization in air *CCEMRI(I)77-22*, 5 p, BIPM (Paris: Offilib).

[6] IAEA, X- and gamma-ray standards for detector calibration, *IAEA TECDOC-619*, 1991.

[7] QUINN T.J., Results of recent international comparisons of national measurement standards carried out by the BIPM, 1996, *Metrologia*, 1996, **33**, 271-287.

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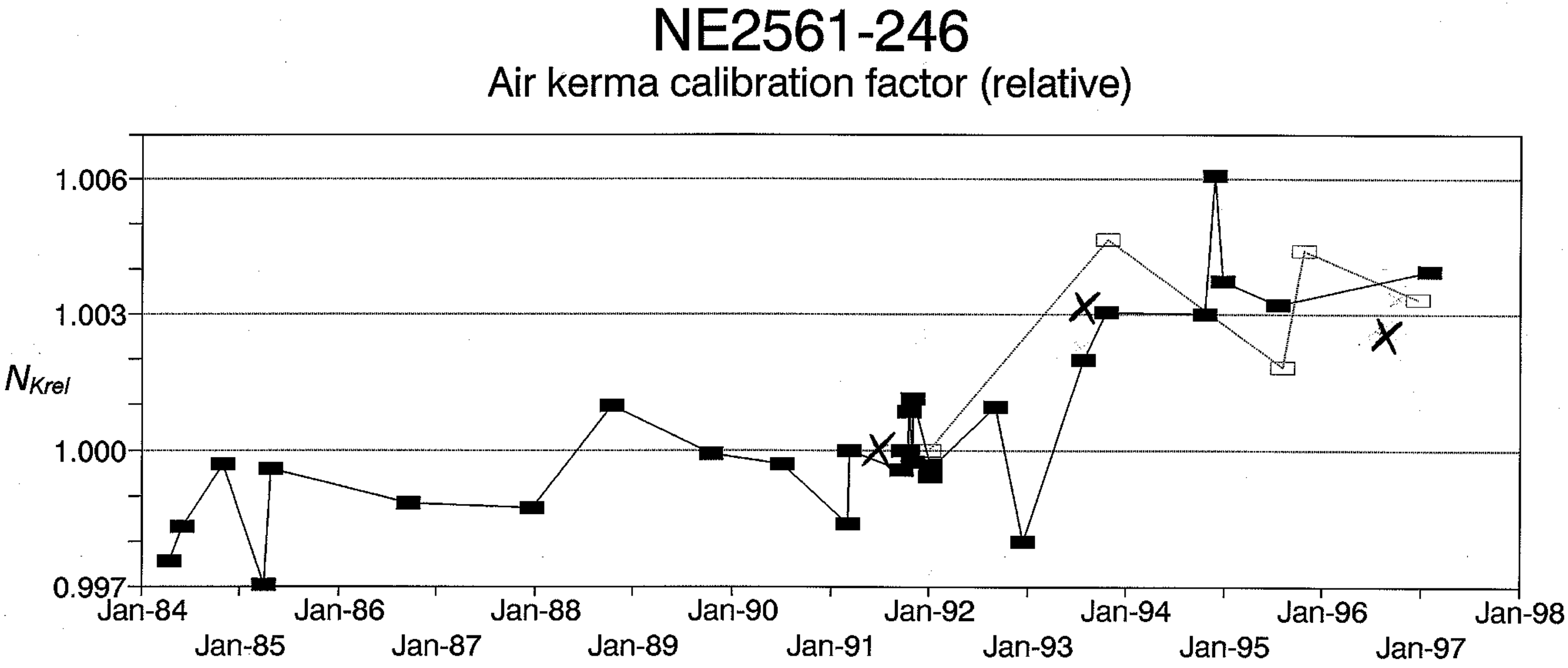
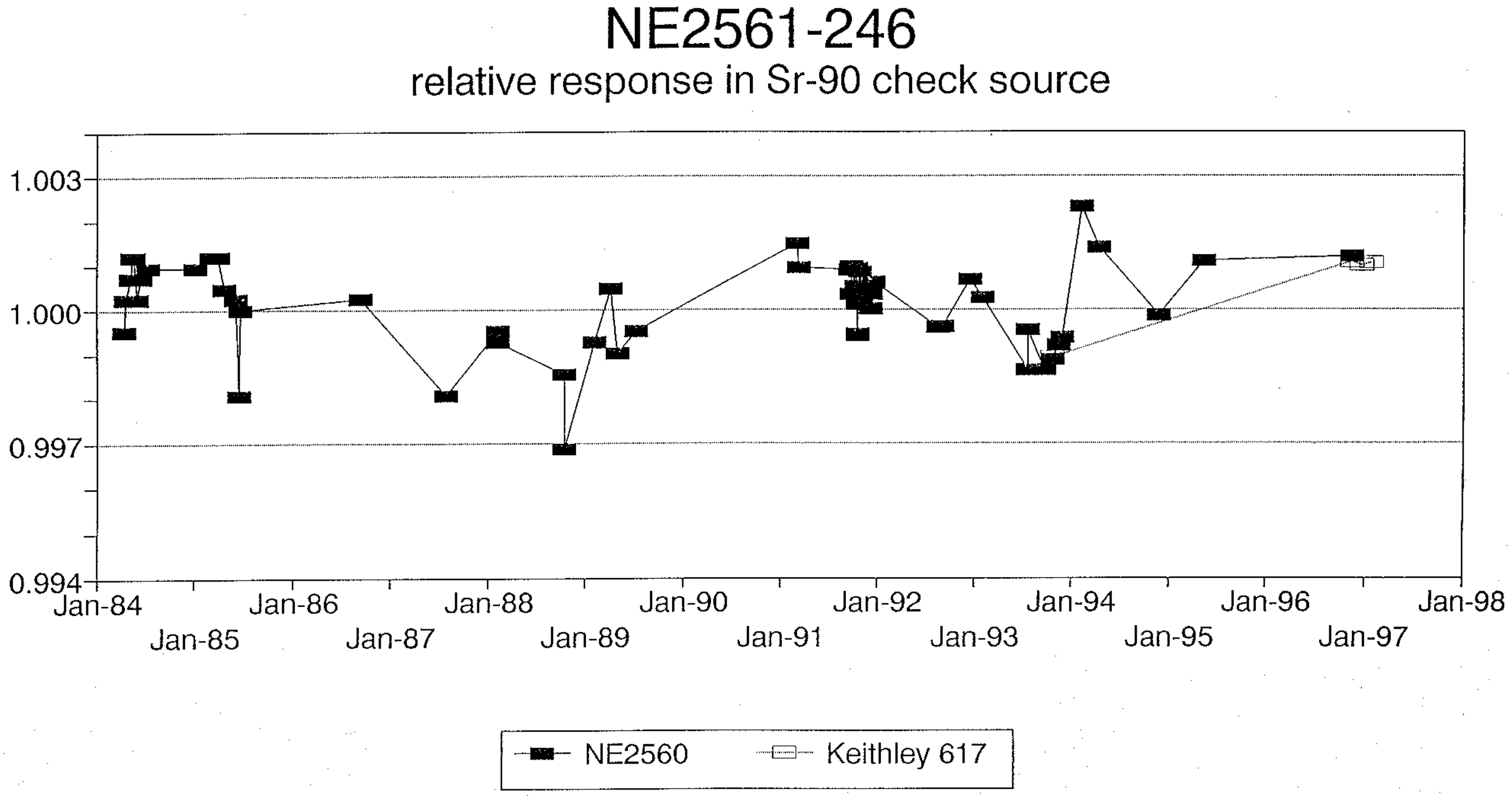
Figure 1



X BIPM values

Year	N_K	N_{Krel}
1991	93,516	1,0000
1993	93,804	1,0031
1996	93,739	1,0024

Figure 2


NE2561-246
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1.000
0.997
0.994
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
NE2560
Keithley 617

Figure 3 - from **HOFMEESTER G.H. and SOMERWIL A. (1977)**

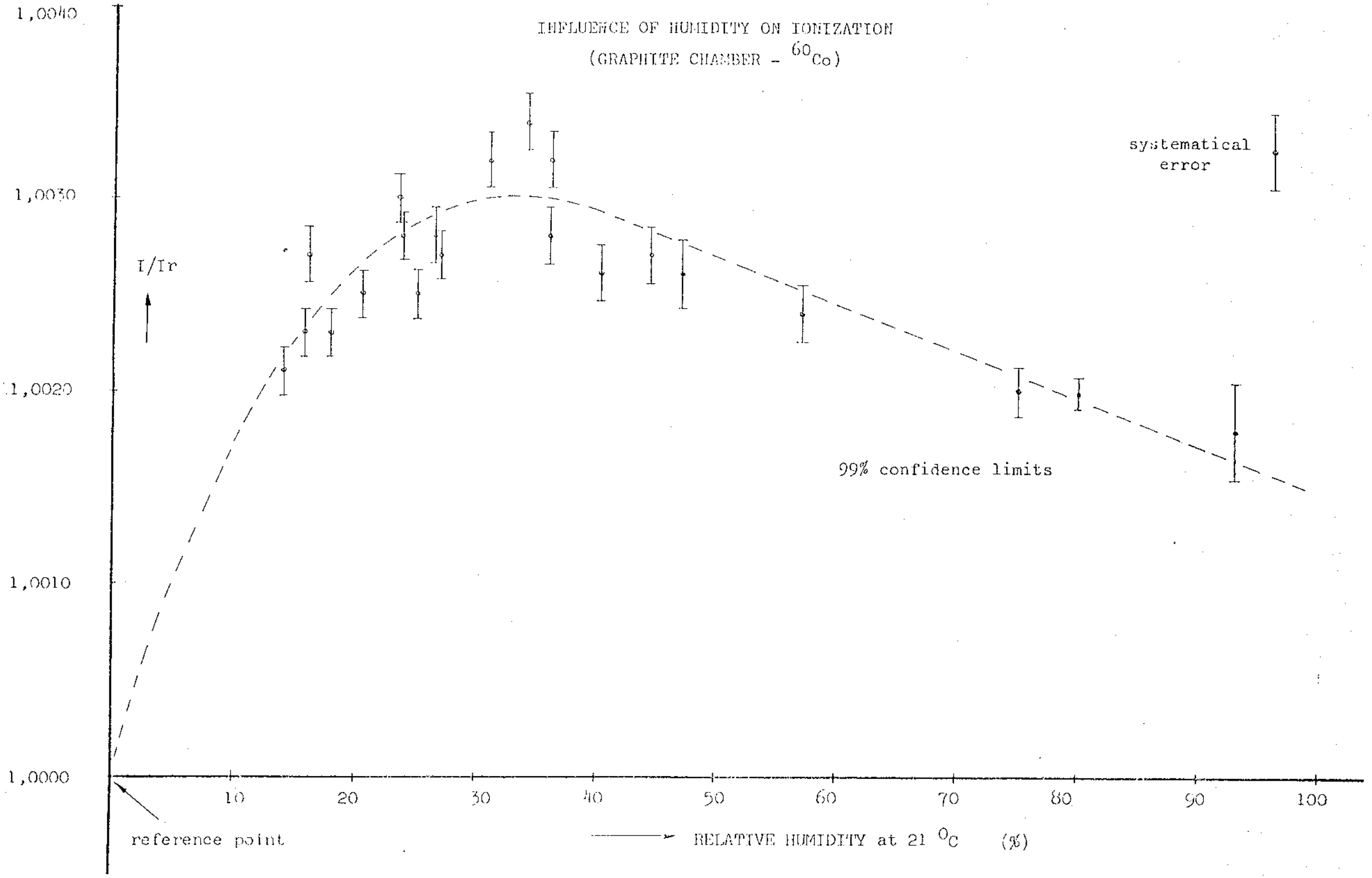
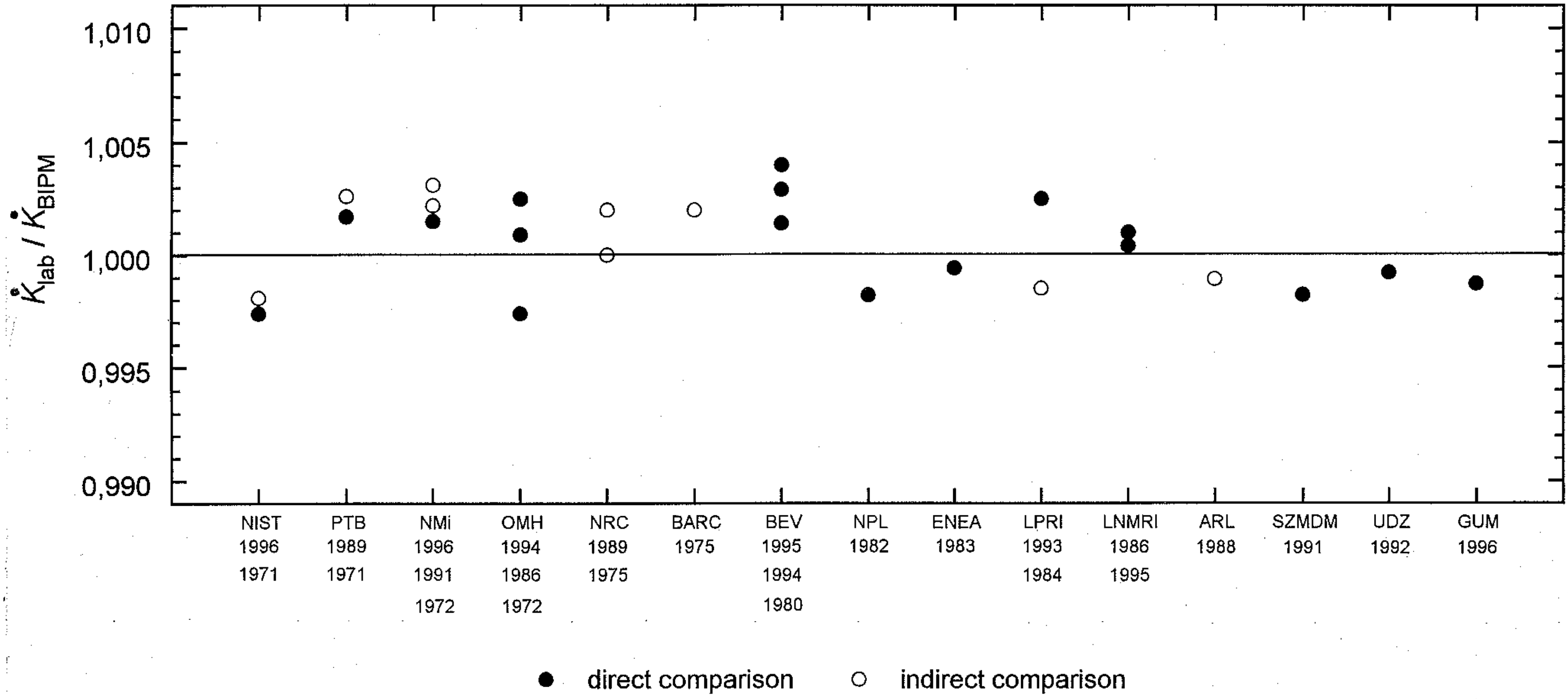


Figure 4

INTERNATIONAL COMPARISON OF AIR KERMA IN ^{60}Co γ RADIATION



All values for each laboratory with comparison dates