Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the NRC, Canada and the BIPM in ^{60}Co gamma radiation

C. Kessler[1], D. Burns[1], B. Downton [2], M. McEwen[2] and E. Mainegra-Hing [2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
[2] National Research Council of Canada, Ottawa, Canada

Abstract

A new key comparison of the standards for air kerma of the National Research Council of Canada (NRC), Canada and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in October 2020. The comparison result, based on the calibration coefficients for three transfer chambers and expressed as a ratio of the NRC and the BIPM standards for air kerma, is 1.0022 with a combined standard uncertainty of 2.2 parts in 10^3. The result agrees within the uncertainties with the indirect comparison carried out in 2009. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison of the standards for air kerma of the National Research Council of Canada (NRC), Canada, and the Bureau International des Poids et Mesures (BIPM) was carried out in October 2020 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2009 (Kessler *et al.* 2010) published in the BIPM key comparison database (KCDB 2021) under the reference BIPM.RI(I)-K1. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories. The indirect comparison was made using three thimble-type ionization chambers as transfer instruments. The final results were supplied by the NRC in September 2021.

2. Details of the standards and the transfer chambers

The NRC ^{60}Co air-kerma standard is a graphite-walled cylindrical cavity ionization chamber (3C) constructed by W. H. Henry at the NRC in 1958 (Shortt and Ross 1986). The 3C dimensions were determined by the Length and Mechanical Standards Group of NRC. The BIPM primary standard is a graphite-walled parallel-plate cavity ionization chamber described in Boutillon *et al.* (1973), Burns *et al.* (2007) and Burns and Kessler (2018). The main characteristics of the primary standards are given in Table 1. Details of the transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM and the NRC standards

Dimensions		BIPM CH6.2	NRC
Cavity	Diameter / mm	45.01	15.84
	Thickness / mm	5.16	–
	Height / mm	–	16.13
	Measuring volume / cm^3	6.8855	2.7552
Electrode	Diameter / mm	41.03	6.704
	Thickness / mm	1.005	–
	Height / mm	–	12.002
Wall	Thickness / mm	2.90	3.83
	Material	Graphite	Graphite
	Density / g cm^{-3}	1.85	1.66
Voltage applied to outer electrode / V		± 80	± 300

Table 2. Characteristics of the NRC transfer chambers

Nominal values		NE 2571	FC65G	PTW 30013	
Chamber	Outer diameter / mm	7.0	7.0	7.0	
	Outer length / mm	24.5	23.5	23.6	
Electrode	Diameter / mm	1.0	1.0	1.1	
	Length / mm	20.6	20.5	21.0	
Cavity	Nominal volume / cm^3	0.7	0.65	0.6	
Wall	Thickness / mm	0.36	0.4	0.335	0.09
	Material	graphite	graphite	PMMA	graphite
	Density / g cm^{-3}	1.7	1.8	1.19	1.85
Voltage applied [(1)] / V		300	300	300	

(1) At the BIPM, positive polarity was applied to the outer electrode; at the NRC the outer electrode is held at ground potential and the polarizing voltage is applied to the collecting electrode to create an equivalent electric field within the air cavity.

3. Determination of the air kerma

For a cavity chamber with measuring volume *V*, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{a,c}} \bar{s}_{\mathrm{c,a}} \prod k_i \qquad (1)$$

where

ρ_{air} is the density of air under reference conditions,

I is the ionization current under the same conditions,

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 production in air,

$(\mu_{en}/\rho)_{a,c}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,

$\bar{s}_{c,a}$ is the ratio of the mean mass stopping powers of graphite and air,

$\prod k_i$ is the product of the correction factors to be applied to the standard.

Physical data and correction factors

The values used for the physical constants, the correction factors, the volume of the primary standards entering in equation (1), and the associated uncertainties are given in Table 3. For the BIPM standards, these values are given in Kessler and Burns (2018).

Table 3. Physical constants, correction factors and relative standard uncertainty components of the BIPM and NRC standards for the ^{60}Co radiation beam at the BIPM and at the NRC

		BIPM			NRC		
		values	uncertainty (1)		values	uncertainty(1)	
			100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
Physical Constants							
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.01	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9990	–	0.05
$s_{c,a}$	ratio of mass stopping powers	0.9928	–	0.08 (3)	33.72 (4)	–	0.08 (4)
W/e	mean energy per charge / J C^{-1}	33.97					
g_a	fraction of energy lost in radiative processes	0.0031	–	0.02	0.0030	–	0.03
Correction factors and uncertainty components							
k_g	re-absorption of radiative loss	0.9996	–	0.01	0.9998	–	0.03
k_s	recombination losses	1.0019	0.01	0.02	1.0016	0.03	0.03
k_h	humidity	0.9970	–	0.03	0.9970	–	0.05
k_{st}	stem scattering	1.0000	0.01	–	0.9952	<0.01	–
k_{wall}	wall attenuation and scattering	1.0011	–	– (5)	1.0229	–	0.03
k_{comp}	compound wall	–	–	–	1.0051	–	0.09
k_{an}	axial non-uniformity	1.0020	–	– (5)	1.0002	–	0.05
k_{rn}	radial non-uniformity	1.0015	–	0.02	–	–	–
Measurement of *I* / *V*							
V	chamber volume / cm^3	6.8855	–	0.08 (5)	2.7552	–	0.09
I	ionization current / pA	–	0.01	0.02		0.01	0.03
Relative standard uncertainty							
quadratic summation			0.02	0.13		0.03	0.19
combined uncertainty			**0.13**			**0.19**	

(1) Expressed as one standard deviation
u_{iA} represents the type A relative standard uncertainty estimated by statistical methods,
u_{iB} represents the type B relative standard uncertainty estimated by other means

(2) At 101.325 kPa and 273.15 K for the BIPM and the NRC standards

(3) Combined uncertainty for the product of $s_{c,a}$ and W/e adopted from January 2019 (Burns and Kessler 2018)

(4) Product $W/e\ s_{c,a}$ adopted from ICRU Report 90 recommendations (ICRU 2016)

(5) The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al.* 2007)

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Kessler and Burns (2018):

– the distance from source to reference plane is 1 m,
– the field size in air at the reference plane is 10 cm × 10 cm, defined by 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 reference conditions at the NRC are the same as those at the BIPM.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\text{BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\text{BIPM}}$ values refer to an evacuated path length between source and standard corrected to the reference date of 2020-01-01, 0 h UTC. The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air attenuation coefficient 0.0602 $cm^2\ g^{-1}$ for ^{60}Co. The half-life of ^{60}Co used for the decay correction was taken as 1925.21 days (u = 0.29 days) (Bé *et al.* 2006).

At the NRC, no air attenuation correction is applied and the $\dot{K}_{\text{NRC}}$ value is given at the reference date of 2020-01-01, 12:00 PM EST, using the half-life value of 1925.02 days (u = 0.47 days) (Rutledge *et al.* 1983).

Beam characteristics

The characteristics of the BIPM and NRC beams are given in Table 4.

Table 4. Characteristics of the ^{60}Co beams at the NRC and the BIPM

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
NRC GammaBeam X-200	26.5	20	20	19 %	10 cm × 10 cm
BIPM Theratron 1000	6.4	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

The comparison of the NRC and BIPM standards was made indirectly using the calibration coefficients for three transfer chambers given by

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

where $\dot{K}_{\text{lab}}$ is the air-kerma rate and I_{lab} is the ionization current of a transfer chamber measured at the NRC or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers NE 2571, serial number 3694, FC65G, serial number 1233 and PTW 30013, serial number 1527, belonging to the NRC, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the NRC before and after the measurements at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2018); the essential details for the determination of the calibration coefficients $N_{K,\mathrm{lab}}$ for the transfer chambers are reproduced here.

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

At the BIPM, a collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the transfer chambers at least 40 min before any measurements were made; at the NRC the outer electrode is held at ground potential and the polarizing voltage is applied to the collecting electrode to create an equivalent electric field within the air cavity

Charge and leakage measurements

The charge Q collected by the transfer chambers was measured at the BIPM using a Keithley electrometer, model 642. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements (~13 Gy). Leakage current was measured before and after each series of measurements. The leakage correction, relative to the ionization current, was less than 1 part in 10^4. At the NRC, the ionization current I is measured using a Keithley electrometer, model 35617. A pre-irradiation of at least 15 min (~20 Gy) was made for each chamber before any measurements. Leakage current was measured for each chamber. The relative leakage correction for each chamber was less than 3 parts in 10^5.

Radial non-uniformity correction

The correction for the radial non-uniformity of the beam for the transfer chambers is less than 3 parts in 10^4 at the BIPM and a similar correction is appropriate for the NRC beam. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 6.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible for continuous beams for these chamber types at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; a relative uncertainty component of 2 parts in 10^4 is included in Table 6.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.06 °C at the BIPM. At the NRC, the air temperature is also measured for each current measurement and was stable to better than 0.1 ºC. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories.

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the NRC, relative humidity is controlled and was in the range from 34 % to 47 %; no correction for humidity is applied to the ionization current measured

5. Results of the comparison

The transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 2 parts in 10^4.

The result of the comparison, R_K , is expressed in the form

$$R_K = N_{K,\mathrm{NRC}} / N_{K,\mathrm{BIPM}} \tag{3}$$

in which the average value of measurements made at the NRC before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM.

Table 5 lists the relevant values of N_K at the stated reference conditions (293.15 K and 101.325 kPa) and the final results of the indirect comparison. The uncertainties associated with the calibration of the transfer chambers are presented in Table 6.

The values $N_{K,\mathrm{NRC}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose rms value is taken as a representation of the stability of the transfer instruments. The short-term stability is estimated to be 5 parts in 10^4. Table 6 includes a component of 4 parts in 10^4 for the difference in the comparison result between the three transfer chambers.

Table 5. Results of the indirect comparison

Transfer chamber	$N_{K,\mathrm{NRC}}$/ Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2571-3694	41.12	41.10	41.11	41.03	1.0019	0.0022
FC65G-1233	44.00	43.97	43.98	43.91	1.0017	0.0022
PTW 30013-1527	49.24	49.19	49.22	49.08	1.0029	0.0022
				Mean value	1.0022	0.0022

Table 6. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		NRC	
Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Air-kerma rate	0.02	0.13	0.03	0.19
Ionization current for the transfer chambers	0.01	0.02	0.01	0.03
Distance	0.01	–	–	0.02
Reproducibility	0.02	–	0.02	–
Correction factors (P,T)			0.05	0.10 (1)
$N_{K,\mathrm{lab}}$	0.03	0.13	0.06	0.21
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (2)	0.07		0.20	
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
Stability of the chambers	0.05		–	
Different chambers	0.04		–	
$R_{K,\mathrm{NRC}}$	u_c = 0.0022			

(1) Takes account of known spatial variations in the measured air temperature

(2) The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

Some uncertainties in $\dot{K}_{air}$ that appear in both the BIPM and the NRC determinations (namely air density, W/e, μ_{en}/ρ, $\bar{g}$, s_{ca} and k_h) cancel when evaluating the uncertainty of the ratio R_K of the NRC and BIPM calibration coefficients.

The mean ratio of the air-kerma calibration coefficients of the transfer chambers determined by the NRC and the BIPM taken from Table 5 is 1.0022 with a combined standard uncertainty, u_c, of 0.0022.

6. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here K_{BIPM}, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each NMI *i* having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{BIPM,i}) / K_{BIPM,i} = x_i - 1$ and its expanded uncertainty $U_i = 2\, u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 7 gives the values for D_i and U_i for each NMI, *i*, taken from the KCDB of the CIPM MRA (1999) and this report. These data are presented graphically in Figure 1.

When required, the degree of equivalence between two laboratories *i* and *j* can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\, u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j. Following the advice of the CCRI(I) in 2011, results for D_{ij} and U_{ij} are no longer published in the KCDB.

Note that the data presented in Table 7, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

7. Conclusion

The previous comparison of the air-kerma standards for ^{60}Co gamma radiation of the NRC and the BIPM was made indirectly in 2009. The comparison result was 1.0032 (28). As both laboratories adopted the same changes recommended by the ICRU 90 in the determination of air kerma, the comparison result of 2009 should be unchanged.

For the present comparison, made indirectly using transfer instruments, the NRC standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0022 (22), in agreement within the uncertainties with the previous comparison result. The NRC standard agrees within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K1 ongoing key comparison for air-kerma standards in ^{60}Co gamma-ray beam.

Table 7. Degrees of equivalence

For each laboratory i, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K1

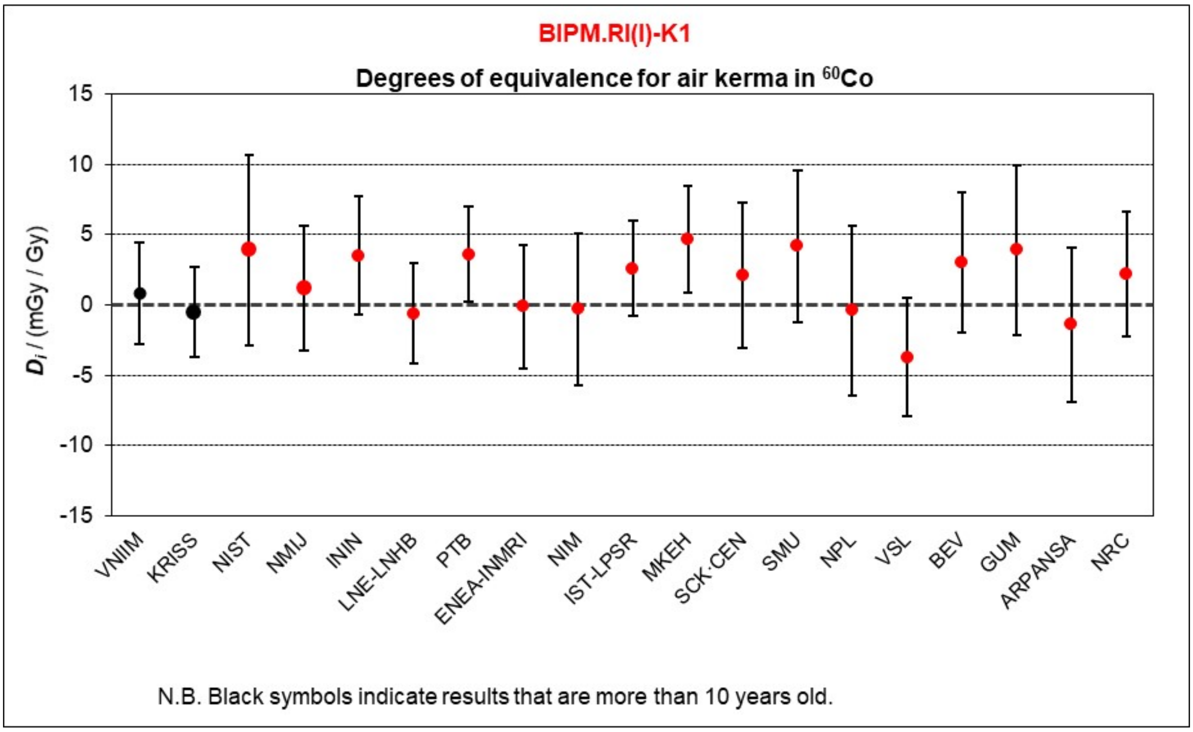
Lab *i*	D_i / (mGy/Gy)	U_i
VNIIM	0.8	3.6
KRISS	-0.5	3.2
NIST	3.9	6.8
NMIJ	1.2	4.4
ININ	3.5	4.2
LNE-LNHB	-0.6	3.6
PTB	3.6	3.4
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
IST-LPSR	2.6	3.4
MKEH	4.7	3.8
SCK·CEN	2.1	5.2
SMU	4.2	5.4
NPL	-0.4	6.0
VSL	-3.7	4.2
BEV	3.0	5.0
GUM	3.9	6.0
ARPANSA	-1.4	5.5
NRC	2.2	4.4

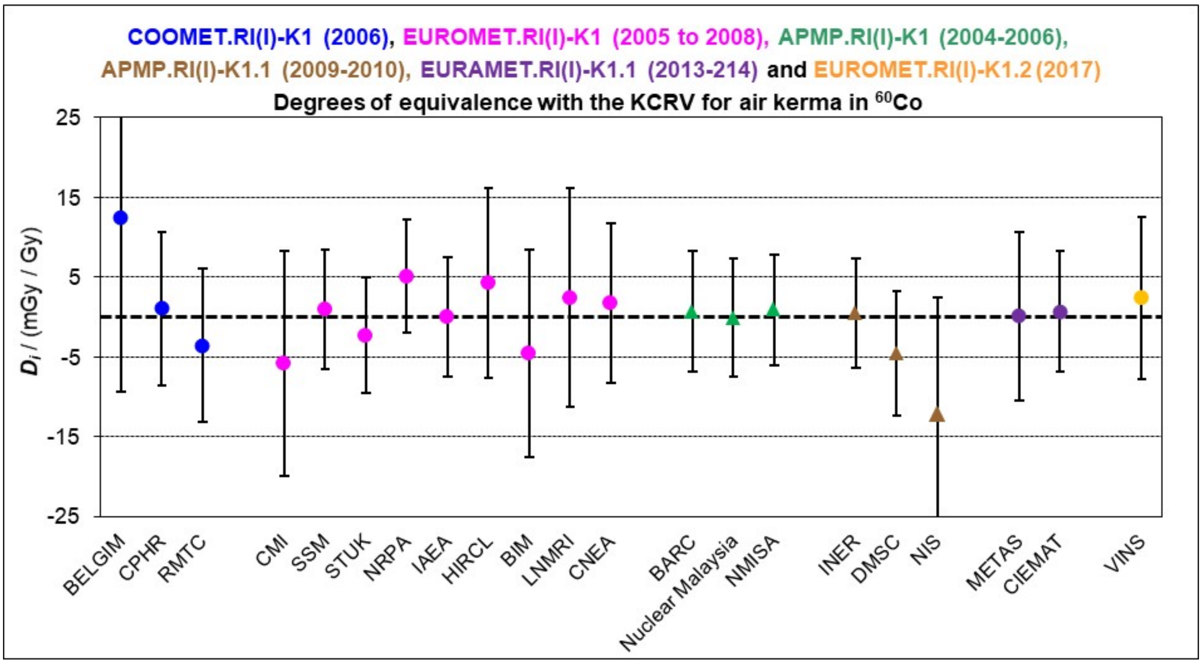
EURAMET.RI(I)-K1 (2005 to 2008) – COOMET.RI(I)-K1 (2006)
APMP.RI(I)-K1 (2004 to 2006) – APMP.RI(I)-K1.1 (2009 to 2012) –
EURAMET.RI(I)-K1.1 (2013-2015) – EURAMET.RI(I)-K1.2 (2017)

Lab *i*	D_i / (mGy/Gy)	U_i
CMI	-5.8	14.1
SSM	1.0	7.5
STUK	-2.3	7.3
NRPA	5.1	7.1
IAEA	0.0	7.5
HIRCL	4.2	11.9
BIM	-4.5	13.0
LNMRI	2.4	13.7
CNEA	1.8	10.0
BELGIM	12.5	21.8
CPHR	1.1	9.6
RMTC	-3.6	9.6

Lab *i*	D_i / (mGy/Gy)	U_i
BARC	0.7	7.6
Nuclear Malaysia	-0.1	7.4
NMISA	0.9	6.9
INER	0.5	6.9
DMSC	-4.5	7.8
NIS	-12.1	14.6
METAS	0.1	10.5
CIEMAT	0.7	7.6
VINS	2.4	10.2

Figure 1. **Graph of degrees of equivalence with the KCRV**





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