

# Comparison of calibration facilities for radon activity concentration



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A. Röttger and A. Honig, Physikalisch-Technische Bundesanstalt (PTB),  
V. Schmidt and H. Buchröder, Bundesamt für Strahlenschutz (BfS),  
A. Rox, Material Prüfungsamt Nordrhein-Westfalen (MPA),  
G. Butterweck and Ch. Schuler, Paul Scherrer Institut (PSI),  
F. J. Maringer, Austrian Research Centers Seibersdorf (ARCS), since 2004 at BEV (see below),  
N. Michielsen, Institut de Radioprotection et de Sûreté Nucléaire (IRSN),  
C. Howarth and J. C. H. Miles, National Radiation Protection Board (NRPB),  
A. Vargas and X. Ortega, Universitat Politècnica de Catalunya (INTE-UPC),  
I. Burian, Státní ústav jaderné chemické a biologické ochrany (SUJCHBO),  
T. Turtiainen, Radiation and Nuclear Safety Authority (STUK),  
P. Jachs and R. Edelmaier, Bundesamt für Eich- und Vermessungswesen (BEV),  
Nils Hagberg, Swedish Radiation Protection Authority (SSI)

### Abstract

Prior to 2002, no comparisons of radon activity concentration had been performed within the scope of the EUROMET. The comparison presented here fulfils the need to provide confidence in the capability of national metrology institutes and calibration laboratories to measure radon activity concentration in air. This has been achieved by the measurement of radon reference atmospheres using an electronic, radon measuring instrument as the transfer comparison device (CD). Each of the twelve institutes, from nine countries, calibrated the CD using standard calibration procedures according to their quality system, at three different activity concentrations: 1 kBq/m<sup>3</sup>, 3 kBq/m<sup>3</sup> and 10 kBq/m<sup>3</sup>. For each activity concentration, a comparison reference value and its uncertainty have been derived. From these the degrees of equivalence have been calculated and are presented graphically and in the form of matrices. All the results are consistent within the assigned uncertainties.

### 1. Introduction

International comparison exercises are used as an important tool to provide confidence in the capability of national metrology institutes and calibration laboratories. The quality systems of national institutes provide the basis for running comparisons, in our case, in the field of the radon activity concentration in air. Interchange of an electronic radon measuring instrument (comparison device) which demonstrated ruggedness during shipping in the past was considered a convenient means for a relative comparison of radon reference atmospheres.

Before 2002, for radon activity concentration, neither a key comparison nor any other form of comparison had been performed within the scope of Euromet. The comparison presented here is the first step towards fulfilling the requirements of the MRA (21st General Conference of the Metre Convention (CGPM) in Paris on October 14, 1999: the Mutual Recognition Arrangement (MRA): 'Arrangement of mutual recognition of equivalence of national standards and of calibration certificates issued by national metrology institutes') for calibration certificates for the radon activity concentration. The basic concept of the comparison therefore is not to achieve uncertainties as small as possible by using special calibration procedures, but to use standard calibration procedures according to the quality systems of each calibration institute for the comparison device named CD (Radon monitor, type AlphaGuard, SN 1145) in the following.

In total, 12 institutes from 9 countries calibrated the CD according to their quality system at three different activity concentrations: 1 kBq/m<sup>3</sup>, 3 kBq/m<sup>3</sup> and 10 kBq/m<sup>3</sup>. For abbreviations of the institutes see chapter 3.

## 1.1 Traceability of the involved quantities

The traceability chains in their length as well as in their origin are fundamental for the correct analysis of the comparison data. Table 1 shows the involved quantities used in realizing a reference atmosphere and thus calibrating the comparison device (CD).

Table 1: Quantities and units used in the data analysis of the comparison.

$A$	Bq	Activity of the radon gas standard
$V_r$	m <sup>3</sup>	Volume of the reference chamber
$V_t$	m <sup>3</sup>	Displaced volume by transfer standard
$V_c$	m <sup>3</sup>	Displaced volume by comparison device
$c_r$	Bq m <sup>-3</sup>	Activity concentration of the reference atmosphere
$c_t$	Bq m <sup>-3</sup>	Activity concentration measured by the transfer standard
$c_{t,bg}$	Bq m <sup>-3</sup>	Background activity concentration of the transfer standard, due to contamination
$c_c$	Bq m <sup>-3</sup>	Activity concentration measured by the comparison device
$c_{c,bg}$	Bq m <sup>-3</sup>	Background activity concentration of the comparison device, due to contamination
$k_t$		calibration factor of the transfer standard
$k_c$		calibration factor of the comparison device (CD)

The measurand (output quantity) is  $k_c$ . For all calculations:  $c_{c,bg} \ll c_c$ ,  $c_{t,bg} \ll c_t$  and  $V_c \ll V_r$ ,  $V_t \ll V_r$ .

### I. Traceability to a reference atmosphere:

$$c_r = \frac{A}{V_r - V_c}$$

## II. Traceability to a reference instrument (transfer standard):

$$k_t = \frac{c_r}{c_t - c_{t,bg}} = \frac{A}{V_r - V_t} (c_t - c_{t,bg})^{-1}$$

$$k_c = k_t \frac{c_t - c_{t,bg}}{c_c - c_{c,bg}}$$

### Traceability chain I. :

The IRSN and the PTB are the only one with calibrations directly to a reference atmosphere (PTB only in two of three calibration points of the comparison: 3 kBq m<sup>-3</sup> and 10 kBq m<sup>-3</sup>).

### Traceability chain I. and II. :

The input quantity A is either from PTB 6.11 (Inte-UPC, NRPB, PSI, PTB, SUJCHBO), or from LNHB (IRSN) or from NIST (SSI). The activity is used to calibrate the reference instrument. This reference instrument is used to calibrate the comparison device.

### Traceability chain II. :

The calibration factor  $k_t$  from PTB 6.12 is directly used for ARCS, BEV, BfS, MPA, PTB, STUK.

The length of each individual traceability chain is summarized in the absolute value of the uncertainty which can be reached. While the uncertainty increases with the length of the traceability chain, the correlation (if there is one) decreases. Figure 1 shows this effect for the participants of the comparison.

## 1.2 Traceability of the measurements

All participants in the comparison are operating a quality system. This includes the existence of a traceability chain to national or international calibration standards as well as the statement of complete results (value with assigned uncertainty).

The traceability of the radon activity concentration is established by using either a reference atmosphere (primary standard) or one or more reference instruments (secondary standard).

Calibration by a primary standard is based on the specification of the activity concentration by means of a radon gas activity standard and a noble gas-tight vessel of known volume. The system under test and the radon gas activity standard are enclosed in the vessel. The activity concentration chosen for the point of calibration is calculated and compared to the reading of the system under test for the calculation of the calibration factor.

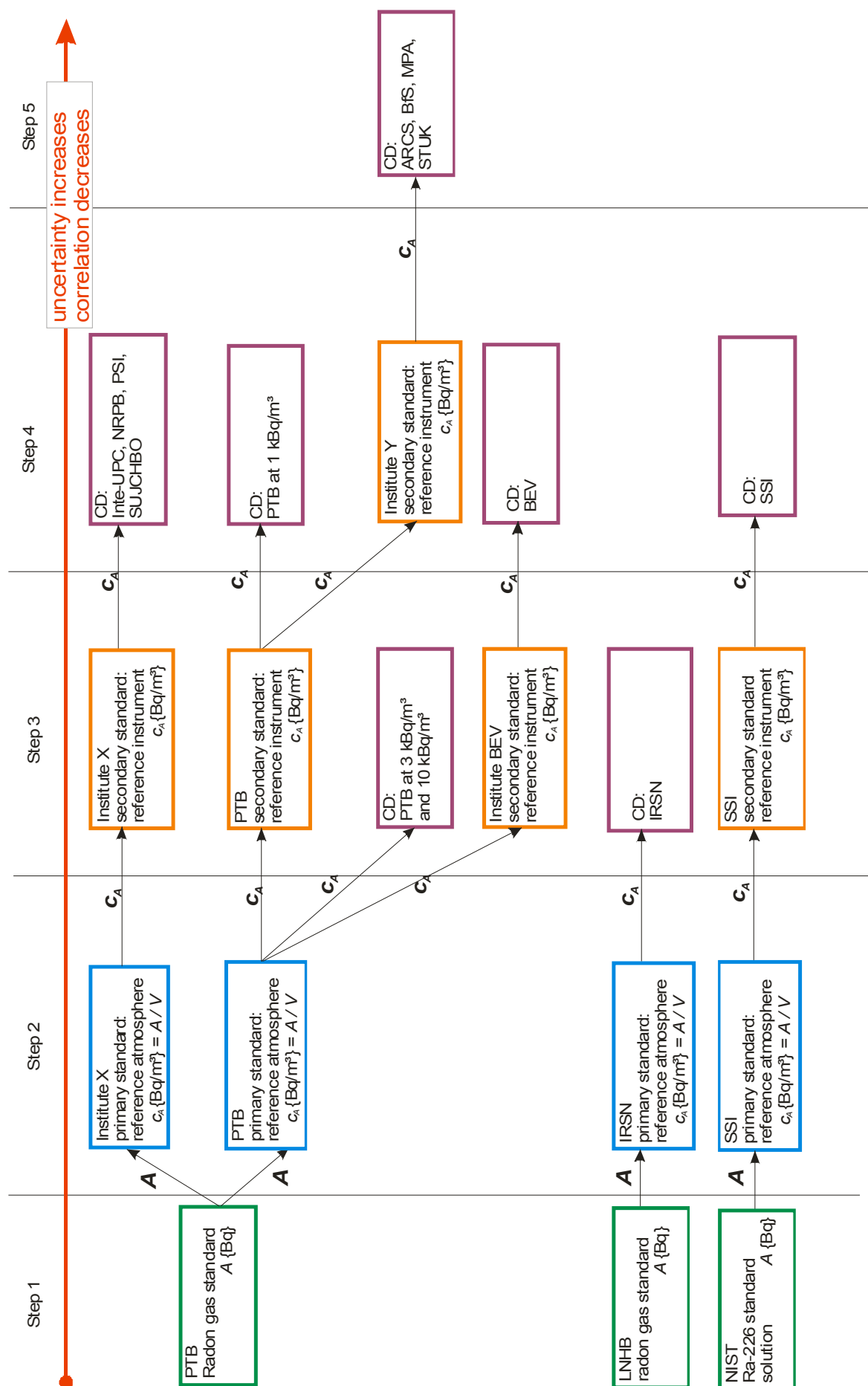


Figure 1: Traceability chains for the radon activity concentration of the participants down to the calibration of the comparison device CD.

After calibration, the former system under test can now be used as a secondary standard. A calibration by a secondary standard is based on a comparison of the system under test to a reference instrument, which was calibrated in or traceable to a reference atmosphere in the past. The radon activity concentration chosen for the point of calibration is established, and both systems are exposed to it. The reading of the reference instrument and the system under test are observed simultaneously for the calculation of the calibration factor. The transfer of the quantity activity concentration (created by a radon gas activity standard and a noble gas-tight vessel of known volume) can also be performed by the use of Lucas cells instead of enclosing a system under test in the vessel.

An overview of some traceability chains for the radon activity and the radon activity concentration in Europe is shown in figure 2. Detailed information about each participant in alphabetical order of the institutes is given in table 2.

Table 2: Traceability and quality assurance of the participants of the radon comparison exercise 2002-2004. The quantity  $c$  represents the radon activity concentration,  $A$  the radon gas activity and  $V$  the volume.

Institute	Traceability		Quality assurance principle
	to a reference atmosphere $c=A \cdot V^{-1}$	to a reference instrument $k_t$	
ARCS Vienna Austria		ATMOS12 DXP, SN.182, calibration certificate from PTB	ISO / IEC 17025, accreditation of the Austrian governmental certification authority
BEV Vienna Austria		AlphaGuard SN.1338, calibration certificate from PTB	ISO / IEC 17025, self-declaration option
BfS Berlin Germany		AlphaGuard SN.812, calibration certificate from PTB	ISO / IEC 17025, accreditation by Deutscher Kalibrierdienst (DKD)
INTE-UPC Barcelona Spain	A: radon gas activity standard with calibration certificate from PTB V: glass container, V traceable to mass, calibration certificate from Mettler-Toledo		ISO / IEC 17025 is followed according to the policy of the institute
IRSN Saclay France	A: radon gas activity standard with calibration certificate from BNM-LNHB V: stainless steel container measured with a measuring tape traceable to BNM		Management quality assurance of the department (IRSN/DSU/ SERAC)

MPA Dortmund Germany		ATMOS12 DXP SN.10468.01, calibration certificate from PTB	ISO / IEC 17025, DIN EN 45001, accreditation of Deutsches Akkreditierungs- system Prüfwesen GmbH
NRPB Chilton United Kingdom	A: radon gas activity standard with calibration certificate from PTB V: calibration tank measured with a tape with a calibration certificate from Birmingham City Council	ATMOS12 SN. ATM 185	ISO / IEC 17025 self-declaration option
PSI Villigen Switzerland	A: radon gas activity standard with calibration certificate from PTB V: stainless steel container with calibration from PTB		ISO / IEC 17025, accreditation by Bundesamt für Metrologie und Akkreditierung (METAS)
PTB Braunschweig Germany	A: radon gas activity standard with calibration certificate from PTB V: stainless steel container with calibration certificate from PTB	AlphaGuard SN.934 and SN.1031, calibration certificate from PTB	ISO / IEC 17025 self-declaration option
SSI Stockholm Sweden	A: Ra-226 solution with calibration certificate from NIST V: (internal lab. determination)		ISO / IEC 17025
STUK Helsinki Finland		AlphaGuard SN. 1136, calibration certificate from PTB	Accredited by: Finas Test laboratory code: T167 Standard: SFS- EN ISO/IEC 17025
SUJCHBO Mlín Czech Republic	A: radon gas activity standard from PTB V: without certificate	Lucas cells calibrated by NRPB and EPA	EN ISO / IEC 17025, accreditation by Czech Accreditation Institute



Figure 2: Traceability chains for the radon activity and the radon activity concentration of the participants. The arrows show the established transfer of the quantity, by sending from the institute at the starting point either a gas standard or a reference instrument to the institute at the ending point. Exception is SSI using a Ra-226 standard solution traceable to NIST as activity standard.

## 2. Data analysis

The number of participating institutes is  $N = 12$ , by numbers  $i = 1 \dots N$ . The input quantities to the evaluation are the institutes' measurements, denoted by  $x_i = k_{c,i}$  and the standard uncertainties associated with these values, denoted by  $u(x_i)$ .

In a first step, arithmetic mean and standard deviation are calculated. In a second step weighted mean and its assigned uncertainty is obtained. Finally the comparison reference value (CRV) and the coverage interval for 95 % is determined. The coverage interval so obtained is central with respect to probability, i.e. 2.5 % of the distribution of possible values lies to the left of the interval and 2.5 % to the right. It is not generally the shortest interval, unless the distribution is symmetric [1-4].

The comparison reference value (CRV)  $Y$  is calculated using  $X$ , the design matrix  $A$  and the covariance matrix  $U_X$ , where  $u(x_i, x_k) = u(x_i) u(x_k) r(x_i, x_k)$  with the correlation coefficient  $r(x_i, x_k)$ .

$$Y = (A^T U_X^{-1} A)^{-1} (A^T U_X^{-1} X) \quad , \quad (1)$$

$$A = \begin{pmatrix} 1 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 1 \end{pmatrix} \quad , \quad U_X = \begin{bmatrix} u^2(x_1) & u(x_1, x_2) & \cdots & \cdots & u(x_1, x_{12}) \\ u(x_2, x_1) & u^2(x_2) & \vdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ u(x_{12}, x_1) & \cdots & \cdots & \cdots & u^2(x_{12}) \end{bmatrix}$$

The fact of correlated results  $x_i$  is expressed in this formula by the non-diagonal elements of the matrix  $U_X$ . If all results would be uncorrelated, the matrix had only diagonal elements and the weighted mean value would be identical to the result obtained by equation (1).

The degree of equivalence is calculated with regard to the CRV  $Y$

$$d_j = x_j - Y$$

$$U(d_j) = 2 u(d_j) \quad , \quad u^2(d_j) = u^2(x_j) + u^2(Y) \quad ,$$

as well as to each participant:

$$d_{j,k} = x_j - x_k$$

$$U(d_{j,k}) = 2 u(d_{j,k}) \quad , \quad u^2(d_{j,k}) = u^2(x_j) + u^2(x_k) \quad .$$

The results for the three calibration points are given in paragraph 2.1 to 2.3.

## 2.1 Calibration point at 1 kBq m<sup>-3</sup>

The collected results for the calibration factor of the comparison device are given as vector  $X$  with standard uncertainties as vector  $U(X)$ :

$$X = \begin{bmatrix} X_{PTB} \\ X_{BfS} \\ X_{STUK} \\ X_{BEV} \\ X_{ARCS} \\ X_{Inte-UPC} \\ X_{IRSN} \\ X_{SUJCHBO} \\ X_{PSI} \\ X_{SSI} \\ X_{NRPB} \\ X_{MPA} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} = \begin{bmatrix} 1.006 \\ 1.035 \\ 1.021 \\ 1.028 \\ 1.027 \\ 0.999 \\ 0.987 \\ 0.994 \\ 0.986 \\ 1.039 \\ 0.933 \\ 0.995 \end{bmatrix}, \quad U(X) = \begin{bmatrix} u(x_{PTB}) \\ u(x_{BfS}) \\ u(x_{STUK}) \\ u(x_{BEV}) \\ u(x_{ARCS}) \\ u(x_{Inte-UPC}) \\ u(x_{IRSN}) \\ u(x_{SUJCHBO}) \\ u(x_{PSI}) \\ u(x_{SSI}) \\ u(x_{NRPB}) \\ u(x_{MPA}) \end{bmatrix} = \begin{bmatrix} u(x_1) \\ u(x_2) \\ u(x_3) \\ u(x_4) \\ u(x_5) \\ u(x_6) \\ u(x_7) \\ u(x_8) \\ u(x_9) \\ u(x_{10}) \\ u(x_{11}) \\ u(x_{12}) \end{bmatrix} = \begin{bmatrix} 0.019 \\ 0.049 \\ 0.051 \\ 0.046 \\ 0.045 \\ 0.025 \\ 0.022 \\ 0.056 \\ 0.017 \\ 0.026 \\ 0.034 \\ 0.045 \end{bmatrix}$$

The covariance matrix for the collected results for the calibration point at 1 kBq m<sup>-3</sup>

$$U_x = \begin{bmatrix} 3.46 & 0.181 & 0.043 & 0.243 & 0.312 & 1.79 & 0 & 0.908 & 0.346 & 0 & 1.47 & 0.397 \\ 0.181 & 23.7 & 4 \cdot 10^{-5} & 2 \cdot 10^{-4} & 3 \cdot 10^{-4} & 0.002 & 0 & 9 \cdot 10^{-4} & 3 \cdot 10^{-4} & 0 & 2 \cdot 10^{-4} & 4 \cdot 10^{-5} \\ 0.043 & 4 \cdot 10^{-5} & 26.0 & 6 \cdot 10^{-5} & 7 \cdot 10^{-5} & 4 \cdot 10^{-4} & 0 & 2 \cdot 10^{-4} & 8 \cdot 10^{-5} & 0 & 4 \cdot 10^{-5} & 9 \cdot 10^{-5} \\ 0.243 & 2 \cdot 10^{-4} & 6 \cdot 10^{-5} & 21.1 & 4 \cdot 10^{-4} & 0.002 & 0 & 0.001 & 5 \cdot 10^{-4} & 0 & 2 \cdot 10^{-4} & 5 \cdot 10^{-4} \\ 0.312 & 3 \cdot 10^{-4} & 7 \cdot 10^{-5} & 4 \cdot 10^{-4} & 21.1 & 0.003 & 0 & 0.002 & 6 \cdot 10^{-4} & 0 & 3 \cdot 10^{-4} & 7 \cdot 10^{-4} \\ 1.79 & 0.002 & 4 \cdot 10^{-4} & 0.002 & 0.003 & 5.95 & 0 & 0.009 & 0.003 & 0 & 0.002 & 0.004 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4.84 & 0 & 0 & 0 & 0 & 0 \\ 0.908 & 9 \cdot 10^{-4} & 2 \cdot 10^{-4} & 0.001 & 0.002 & 0.009 & 0 & 31.2 & 0.002 & 0 & 8 \cdot 10^{-4} & 0.002 \\ 0.346 & 3 \cdot 10^{-4} & 8 \cdot 10^{-5} & 5 \cdot 10^{-4} & 6 \cdot 10^{-4} & 0.003 & 0 & 0.002 & 2.66 & 0 & 3 \cdot 10^{-4} & 7 \cdot 10^{-4} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 6.76 & 0 & 0 \\ 1.47 & 2 \cdot 10^{-4} & 4 \cdot 10^{-5} & 2 \cdot 10^{-4} & 3 \cdot 10^{-4} & 0.002 & 0 & 8 \cdot 10^{-4} & 3 \cdot 10^{-4} & 0 & 11.6 & 4 \cdot 10^{-4} \\ 0.397 & 4 \cdot 10^{-5} & 9 \cdot 10^{-5} & 5 \cdot 10^{-4} & 7 \cdot 10^{-4} & 0.004 & 0 & 0.002 & 7 \cdot 10^{-4} & 0 & 4 \cdot 10^{-4} & 19.9 \end{bmatrix} \times 10^{-4}$$

is:

The results  $x_i$  and  $u(x_i)$  for 1 kBq m<sup>-3</sup> reported by each participant are given in figures 3 and 4.

arithmetic mean:	1.004	standard deviation:	0.028
weighted mean:	0.998	combined standard uncertainty:	0.011
CRV:	0.999	coverage interval at 95%:	0.057

Degree of equivalence for 1 kBq m<sup>-3</sup> :

	Degree of equivalence to the CRV	Expanded uncertainty of the degree of equivalence to the CRV
PTB	7.0E-03	8.9E-02
BfS	3.6E-02	1.3E-01
STUK	2.2E-02	1.3E-01
BEV	2.9E-02	1.2E-01
ARCS	2.8E-02	1.2E-01
Inte-UPC	0.0	9.5E-02
IRSN	-1.2E-02	9.2E-02
SUJCHBO	-5.0E-03	1.4E-01
PSI	-1.3E-02	8.8E-02
SSI	4.0E-02	9.6E-02
NRPB	-6.6E-02	1.1E-01
MPA	-4.0E-03	1.2E-01

Degree of equivalence  $d_{j,k}$  from institute  $j$  to institute  $k$ . The expanded uncertainty at 95 % is given by  $U(d_{j,k})$ . The values for  $d_{j,k} = -d_{k,j}$  with  $U(d_{j,k}) = U(d_{k,j})$  are omitted.

	PTB		BfS		STUK		BEV	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
BfS	-2.9E-02	1.1E-01						
STUK	-1.5E-02	1.1E-01	1.4E-02	1.4E-01				
BEV	-2.2E-02	1.0E-01	7.0E-03	1.3E-01	-7.0E-03	1.4E-01		
ARCS	-2.1E-02	9.8E-02	8.0E-03	1.3E-01	-6.0E-03	1.4E-01	1.0E-03	1.3E-01
Inte-UPC	7.0E-03	6.3E-02	3.6E-02	1.1E-01	2.2E-02	1.1E-01	2.9E-02	1.0E-01
IRSN	1.9E-02	5.8E-02	4.8E-02	1.1E-01	3.4E-02	1.1E-01	4.1E-02	1.0E-01
SUJCHBO	1.2E-02	1.2E-01	4.1E-02	1.5E-01	2.7E-02	1.5E-01	3.4E-02	1.4E-01
PSI	2.0E-02	5.1E-02	4.9E-02	1.0E-01	3.5E-02	1.1E-01	4.2E-02	9.8E-02
SSI	-3.3E-02	6.4E-02	-4.0E-03	1.1E-01	-1.8E-02	1.1E-01	-1.1E-02	1.1E-01
NRPB	7.3E-02	7.8E-02	1.0E-01	1.2E-01	8.8E-02	1.2E-01	9.5E-02	1.1E-01
MPA	1.1E-02	9.8E-02	4.0E-02	1.3E-01	2.6E-02	1.4E-01	3.2E-02	1.3E-01

	ARCS		Inte-UPC		IRSN		SUJCHBO	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
Inte-UPC	2.8E-02	1.0E-01						
IRSN	4.0E-02	1.0E-01	1.2E-02	6.7E-02				
SUJCHBO	3.3E-02	1.4E-01	5.0E-03	1.2E-01	-7.0E-03	1.2E-01		
PSI	4.1E-02	9.6E-02	1.3E-02	6.0E-02	1.0E-03	5.6E-02	8.0E-03	1.2E-01
SSI	-1.2E-02	1.0E-01	-4.0E-02	7.2E-02	-5.2E-02	6.8E-02	-4.5E-02	1.2E-01
NRPB	9.4E-02	1.1E-01	6.6E-02	8.4E-02	5.4E-02	8.1E-02	6.1E-02	1.3E-01
MPA	3.2E-02	1.3E-01	4.0E-03	1.0E-01	-8.0E-03	1.0E-01	-1.0E-03	1.4E-01

	PSI		SSI		NRPB	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
SSI	-5.3E-02	6.2E-02				
NRPB	5.3E-02	7.6E-02	1.1E-01	8.6E-02		
MPA	-9.0E-03	9.6E-02	4.4E-02	1.0E-01	-6.2E-02	1.1E-01

## 2.2 Calibration point at 3 kBq m<sup>-3</sup>

The collected results for the calibration factor of the comparison device are given as vector  $X$  with standard uncertainties as vector  $U(X)$ :

$$X = \begin{bmatrix} X_{PTB} \\ X_{BfS} \\ X_{STUK} \\ X_{BEV} \\ X_{ARCS} \\ X_{Inte-UPC} \\ X_{IRSN} \\ X_{SUJCHBO} \\ X_{PSI} \\ X_{SSI} \\ X_{NRPB} \\ X_{MPA} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} = \begin{bmatrix} 0.987 \\ 1.023 \\ 1.022 \\ 1.053 \\ 1.022 \\ 0.987 \\ 0.982 \\ 1.014 \\ 1.023 \\ 1.000 \\ 0.940 \\ 0.996 \end{bmatrix}, \quad U(X) = \begin{bmatrix} u(x_{PTB}) \\ u(x_{BfS}) \\ u(x_{STUK}) \\ u(x_{BEV}) \\ u(x_{ARCS}) \\ u(x_{Inte-UPC}) \\ u(x_{IRSN}) \\ u(x_{SUJCHBO}) \\ u(x_{PSI}) \\ u(x_{SSI}) \\ u(x_{NRPB}) \\ u(x_{MPA}) \end{bmatrix} = \begin{bmatrix} u(x_1) \\ u(x_2) \\ u(x_3) \\ u(x_4) \\ u(x_5) \\ u(x_6) \\ u(x_7) \\ u(x_8) \\ u(x_9) \\ u(x_{10}) \\ u(x_{11}) \\ u(x_{12}) \end{bmatrix} = \begin{bmatrix} 0.014 \\ 0.047 \\ 0.048 \\ 0.040 \\ 0.043 \\ 0.023 \\ 0.022 \\ 0.026 \\ 0.015 \\ 0.025 \\ 0.031 \\ 0.043 \end{bmatrix}$$

The covariance matrix for the collected results for the calibration point at 3 kBq m<sup>-3</sup> is:

$$U_x = \begin{bmatrix} 1.77 & 2.11 & 0.164 & 0.655 & 2.30 & 1.67 & 0 & 1.60 & 1.34 & 0 & 0.670 & 1.03 \\ 2.11 & 21.8 & 0.003 & 0.010 & 0.036 & 0.027 & 0 & 0.025 & 0.021 & 0 & 0.011 & 0.016 \\ 0.164 & 0.003 & 23.0 & 8 \cdot 10^{-4} & 0.003 & 0.002 & 0 & 0.002 & 0.002 & 0 & 8 \cdot 10^{-4} & 0.001 \\ 0.655 & 0.010 & 8 \cdot 10^{-4} & 16.1 & 0.011 & 0.008 & 0 & 0.008 & 0.007 & 0 & 0.003 & 0.005 \\ 2.30 & 0.036 & 0.003 & 0.011 & 18.6 & 0.029 & 0 & 0.027 & 0.023 & 0 & 0.012 & 0.018 \\ 1.67 & 0.027 & 0.002 & 0.008 & 0.029 & 5.06 & 0 & 0.020 & 0.017 & 0 & 0.008 & 0.013 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4.84 & 0 & 0 & 0 & 0 & 0 \\ 1.60 & 0.025 & 0.002 & 0.008 & 0.027 & 0.020 & 0 & 6.60 & 0.017 & 0 & 0.008 & 0.012 \\ 1.34 & 0.021 & 0.002 & 0.007 & 0.023 & 0.017 & 0 & 0.017 & 2.25 & 0 & 0.007 & 0.010 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 6.25 & 0 & 0 \\ 0.670 & 0.011 & 8 \cdot 10^{-4} & 0.003 & 0.012 & 0.008 & 0 & 0.008 & 0.007 & 0 & 9.61 & 0.005 \\ 1.03 & 0.016 & 0.001 & 0.005 & 0.018 & 0.013 & 0 & 0.012 & 0.010 & 0 & 0.005 & 18.1 \end{bmatrix} \times 10^{-4}$$

The results  $x_i$  and  $u(x_i)$  for 3 kBq m<sup>-3</sup> reported by each participant are given in figures 5 and 6.

arithmetic mean:	1.004	standard deviation:	0.028
weighted mean:	1.000	combined standard uncertainty:	0.009
CRV:	0.979	coverage interval at 95%:	0.075

Degree of equivalence for  $3 \text{ kBq m}^{-3}$  :

	Degree of equivalence to the CRV	Expanded uncertainty of the degree of equivalence to the CRV
PTB	8.0E-03	1.1E-01
BfS	4.4E-02	1.4E-01
STUK	4.3E-02	1.4E-01
BEV	7.4E-02	1.3E-01
ARCS	4.3E-02	1.4E-01
Inte-UPC	8.0E-03	1.1E-01
IRSN	3.0E-03	1.1E-01
SUJCHBO	3.5E-02	1.2E-01
PSI	4.4E-02	1.1E-01
SSI	2.1E-02	1.2E-01
NRPB	-3.9E-02	1.2E-01
MPA	1.7E-02	1.4E-01

Degree of equivalence  $d_{j,k}$  from institute  $j$  to institute  $k$ . The expanded uncertainty at 95 % is given by  $U(d_{j,k})$ . The values for  $d_{j,k} = -d_{k,j}$  with  $U(d_{j,k}) = U(d_{k,j})$  are omitted.

	PTB		BfS		STUK		BEV	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
BfS	-3.6E-02	9.8E-02						
STUK	-3.5E-02	1.0E-01	1.0E-03	1.3E-01				
BEV	-6.6E-02	8.5E-02	-3.0E-02	1.2E-01	-3.1E-02	1.2E-01		
ARCS	-3.5E-02	9.0E-02	1.0E-03	1.3E-01	0.0E+00	1.3E-01	3.1E-02	1.2E-01
Inte-UPC	0.0	5.4E-02	3.6E-02	1.0E-01	3.5E-02	1.1E-01	6.6E-02	9.2E-02
IRSN	5.0E-03	5.2E-02	4.1E-02	1.0E-01	4.0E-02	1.1E-01	7.1E-02	9.1E-02
SUJCHBO	-2.7E-02	5.9E-02	9.0E-03	1.1E-01	8.0E-03	1.1E-01	3.9E-02	9.5E-02
PSI	-3.6E-02	4.1E-02	0.0	9.9E-02	-1.0E-03	1.0E-01	3.0E-02	8.5E-02
SSI	-1.3E-02	5.7E-02	2.3E-02	1.1E-01	2.2E-02	1.1E-01	5.3E-02	9.4E-02
NRPB	4.7E-02	6.8E-02	8.3E-02	1.1E-01	8.2E-02	1.1E-01	1.1E-01	1.0E-01
MPA	-9.0E-03	9.0E-02	2.7E-02	1.3E-01	2.6E-02	1.3E-01	2.6E-02	1.2E-01

	ARCS		Inte-UPC		IRSN		SUJCHBO	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
Inte-UPC	3.5E-02	9.8E-02						
IRSN	4.0E-02	9.7E-02	5.0E-03	6.4E-02				
SUJCHBO	8.0E-03	1.0E-01	-2.7E-02	6.9E-02	-3.2E-02	6.8E-02		
PSI	-1.0E-03	9.1E-02	-3.6E-02	5.5E-02	-4.1E-02	5.3E-02	-9.0E-03	6.0E-02
SSI	2.2E-02	9.9E-02	-1.3E-02	6.8E-02	-1.8E-02	6.7E-02	1.4E-02	7.2E-02
NRPB	8.2E-02	1.1E-01	4.7E-02	7.7E-02	4.2E-02	7.6E-02	7.4E-02	8.1E-02
MPA	2.6E-02	1.2E-01	-9.0E-03	9.8E-02	-1.4E-02	9.7E-02	1.8E-02	1.0E-01

	PSI		SSI		NRPB	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
SSI	2.3E-02	5.8E-02				
NRPB	8.3E-02	6.9E-02	6.0E-02	8.0E-02		
MPA	2.7E-02	9.1E-02	4.0E-03	9.9E-02	-5.6E-02	1.1E-01

## 2.3 Calibration point at 10 kBq m<sup>-3</sup>

The collected results for the calibration factor of the comparison device are given as vector  $X$  with standard uncertainties as vector  $U(X)$ :

$$X = \begin{bmatrix} X_{PTB} \\ X_{BfS} \\ X_{STUK} \\ X_{BEV} \\ X_{ARCS} \\ X_{Inte-UPC} \\ X_{IRSN} \\ X_{SUJCHBO} \\ X_{PSI} \\ X_{SSI} \\ X_{NRPB} \\ X_{MPA} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} = \begin{bmatrix} 0.996 \\ 1.012 \\ 1.057 \\ 1.046 \\ 1.049 \\ 0.993 \\ 0.974 \\ 1.014 \\ 1.041 \\ 0.944 \\ 0.956 \\ 0.997 \end{bmatrix}, \quad U(X) = \begin{bmatrix} u(x_{PTB}) \\ u(x_{BfS}) \\ u(x_{STUK}) \\ u(x_{BEV}) \\ u(x_{ARCS}) \\ u(x_{Inte-UPC}) \\ u(x_{IRSN}) \\ u(x_{SUJCHBO}) \\ u(x_{PSI}) \\ u(x_{SSI}) \\ u(x_{NRPB}) \\ u(x_{MPA}) \end{bmatrix} = \begin{bmatrix} u(x_1) \\ u(x_2) \\ u(x_3) \\ u(x_4) \\ u(x_5) \\ u(x_6) \\ u(x_7) \\ u(x_8) \\ u(x_9) \\ u(x_{10}) \\ u(x_{11}) \\ u(x_{12}) \end{bmatrix} = \begin{bmatrix} 0.013 \\ 0.042 \\ 0.058 \\ 0.034 \\ 0.044 \\ 0.024 \\ 0.021 \\ 0.033 \\ 0.015 \\ 0.033 \\ 0.033 \\ 0.042 \end{bmatrix}$$

The covariance matrix for the collected results for the calibration point at 10 kBq m<sup>-3</sup> is:

$$U_x = \begin{bmatrix} 1.51 & 1.72 & 0.609 & 0.752 & 2.09 & 1.58 & 0 & 2.18 & 1.22 & 0 & 0.565 & 0.846 \\ 1.72 & 17.2 & 0.009 & 0.011 & 0.029 & 0.022 & 0 & 0.030 & 0.017 & 0 & 0.008 & 0.012 \\ 0.609 & 0.009 & 33.1 & 0.004 & 0.010 & 0.008 & 0 & 0.011 & 0.061 & 0 & 0.003 & 0.004 \\ 0.752 & 0.011 & 0.004 & 11.6 & 0.013 & 0.010 & 0 & 0.013 & 0.008 & 0 & 0.003 & 0.005 \\ 2.09 & 0.029 & 0.010 & 0.013 & 19.0 & 0.027 & 0 & 0.037 & 0.021 & 0 & 0.010 & 0.014 \\ 1.58 & 0.022 & 0.008 & 0.010 & 0.027 & 5.71 & 0 & 0.028 & 0.016 & 0 & 0.007 & 0.011 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4.41 & 0 & 0 & 0 & 0 & 0 \\ 2.18 & 0.030 & 0.011 & 0.013 & 0.037 & 0.028 & 0 & 10.8 & 0.022 & 0 & 0.010 & 0.015 \\ 1.22 & 0.017 & 0.061 & 0.008 & 0.021 & 0.016 & 0 & 0.022 & 2.25 & 0 & 0.006 & 0.008 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10.9 & 0 & 0 \\ 0.565 & 0.008 & 0.003 & 0.003 & 0.010 & 0.007 & 0 & 0.010 & 0.006 & 0 & 10.9 & 0.004 \\ 0.846 & 0.012 & 0.004 & 0.005 & 0.014 & 0.011 & 0 & 0.015 & 0.008 & 0 & 0.004 & 17.1 \end{bmatrix} \times 10^{-4}$$

The results  $x_i$  and  $u(x_i)$  for 10 kBq m<sup>-3</sup> reported by each participant are given in figures 7 and 8.

arithmetic mean:	1.007	standard deviation:	0.035
weighted mean:	1.011	combined standard uncertainty:	0.009
CRV:	0.987	coverage interval at 95%:	0.081

Figure 3 - 8: Reported results for the three activity concentrations, see pages 15 – 20.

Degree of equivalence for  $10 \text{ kBq m}^{-3}$  :

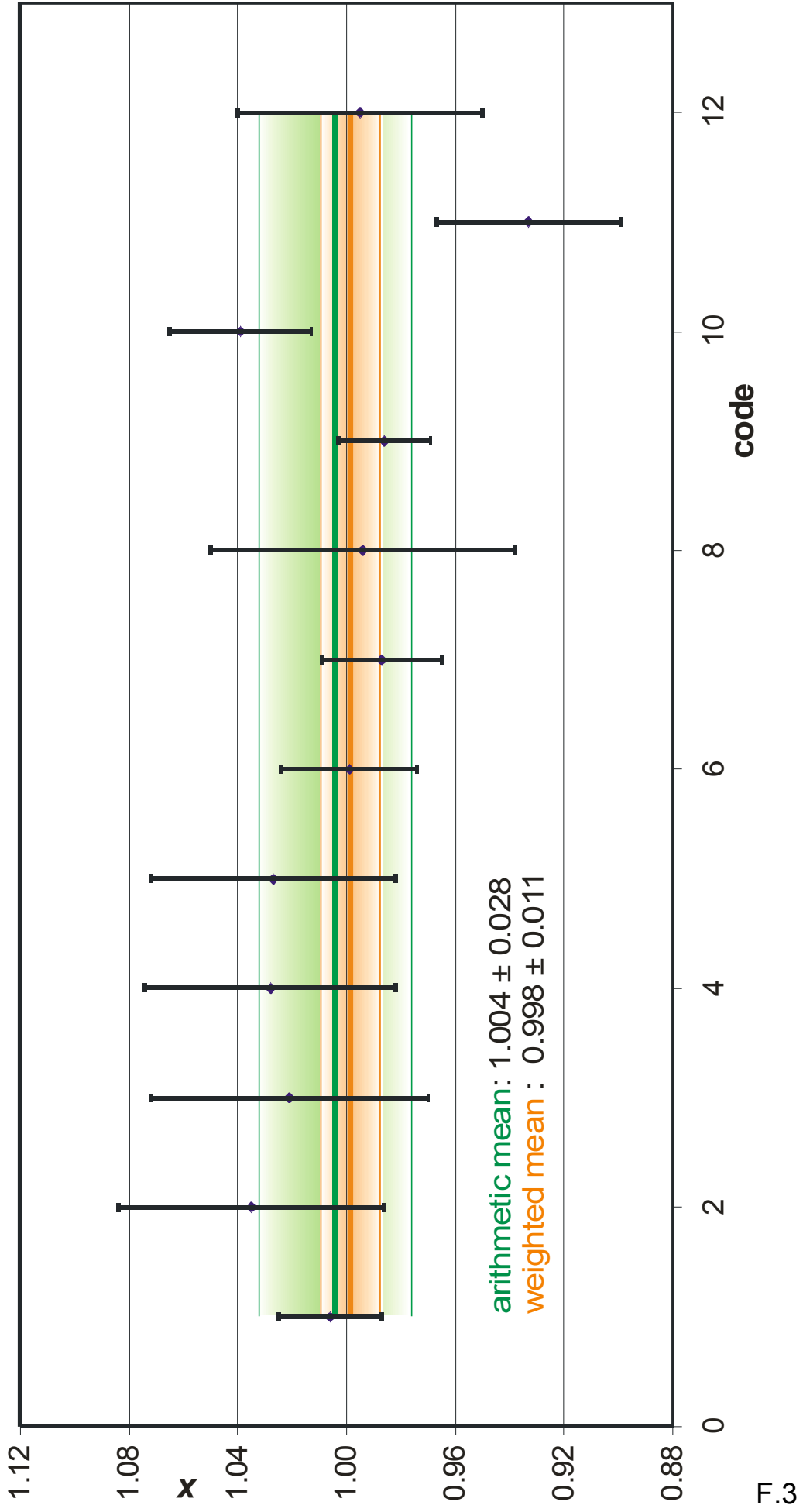
	Degree of equivalence to the CRV	Expanded uncertainty of the degree of equivalence to the CRV
PTB	9.0E-03	1.2E-01
BfS	2.5E-02	1.4E-01
STUK	7.0E-02	1.6E-01
BEV	5.9E-02	1.3E-01
ARCS	6.2E-02	1.4E-01
Inte-UPC	6.0E-03	1.2E-01
IRSN	-1.3E-02	1.2E-01
SUJCHBO	2.7E-02	1.3E-01
PSI	5.4E-02	1.2E-01
SSI	-4.3E-02	1.3E-01
NRPB	-3.1E-02	1.3E-01
MPA	1.0E-02	1.4E-01

Degree of equivalence  $d_{j,k}$  from institute  $j$  to institute  $k$ . The expanded uncertainty at 95 % is given by  $U(d_{j,k})$ . The values for  $d_{j,k} = -d_{k,j}$  with  $U(d_{j,k}) = U(d_{k,j})$  are omitted.

	PTB		BfS		STUK		BEV	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
BfS	-1.6E-02	8.8E-02						
STUK	-6.1E-02	1.2E-01	-4.5E-02	1.4E-01				
BEV	-5.0E-02	7.3E-02	-3.4E-02	1.1E-01	1.1E-02	1.3E-01		
ARCS	-5.3E-02	9.2E-02	-3.7E-02	1.2E-01	8.0E-03	1.5E-01	-3.0E-03	1.1E-01
Inte-UPC	3.0E-03	5.5E-02	1.9E-02	9.7E-02	6.4E-02	1.3E-01	5.3E-02	8.3E-02
IRSN	2.2E-02	4.9E-02	3.8E-02	9.4E-02	8.3E-02	1.2E-01	7.2E-02	8.0E-02
SUJCHBO	-1.8E-02	7.1E-02	-2.0E-03	1.1E-01	4.3E-02	1.3E-01	3.2E-02	9.5E-02
PSI	-4.5E-02	4.0E-02	-2.9E-02	8.9E-02	1.6E-02	1.2E-01	5.0E-03	7.4E-02
SSI	5.2E-02	7.1E-02	6.8E-02	1.1E-01	1.1E-01	1.3E-01	1.0E-01	9.5E-02
NRPB	4.0E-02	7.1E-02	5.6E-02	1.1E-01	1.0E-01	1.3E-01	9.0E-02	9.5E-02
MPA	-1.0E-03	8.8E-02	1.5E-02	1.2E-01	6.0E-02	1.4E-01	5.2E-02	1.1E-01

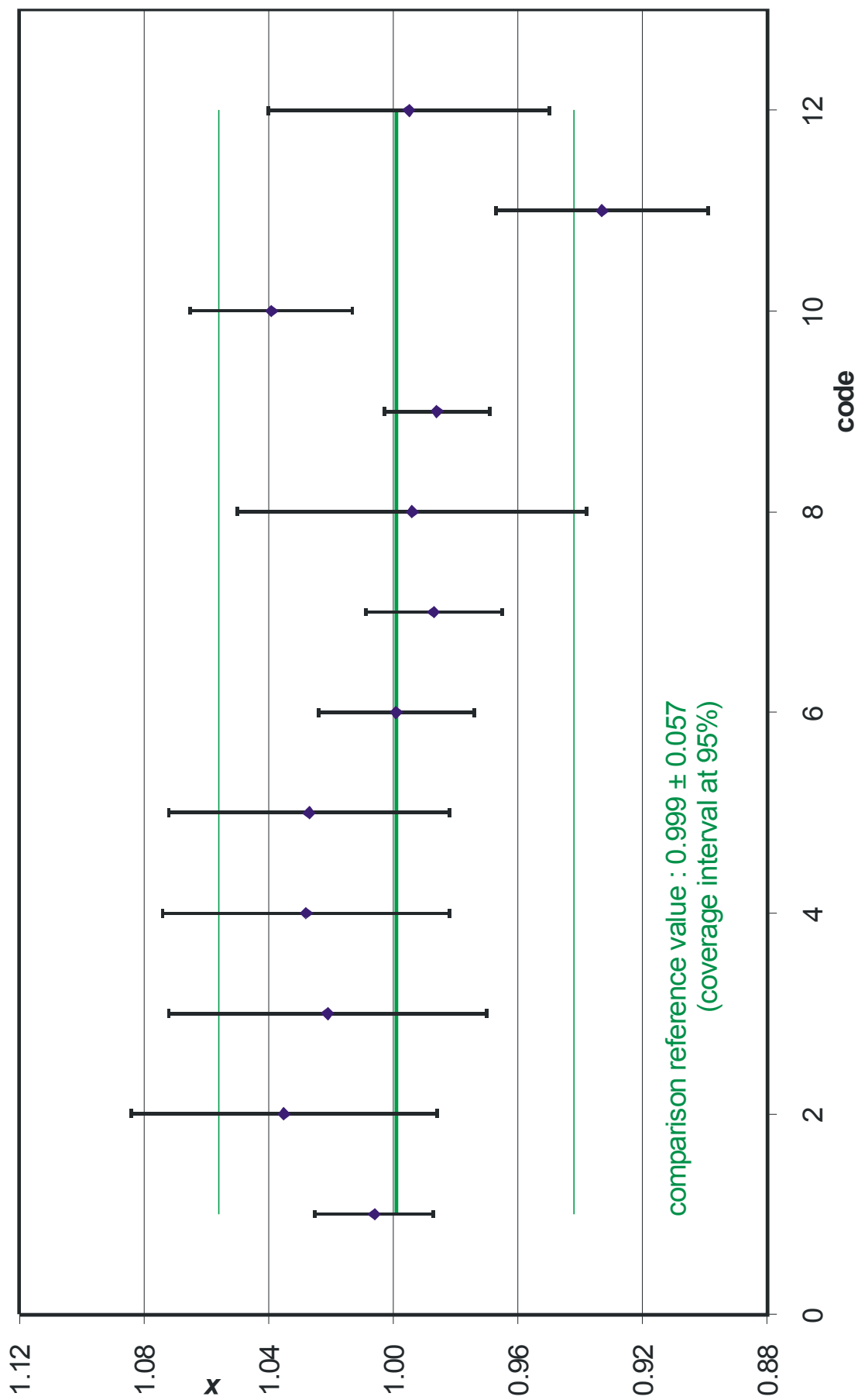
	ARCS		Inte-UPC		IRSN		SUJCHBO	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
Inte-UPC	5.6E-02	1.0E-01						
IRSN	7.5E-02	9.8E-02	1.9E-02	6.4E-02				
SUJCHBO	3.5E-02	1.1E-01	-2.1E-02	8.2E-02	-4.0E-02	7.8E-02		
PSI	8.0E-03	9.3E-02	-4.8E-02	5.7E-02	-6.7E-02	5.2E-02	-2.7E-02	7.2E-02
SSI	1.1E-01	1.1E-01	4.9E-02	8.2E-02	3.0E-02	7.8E-02	7.0E-02	9.3E-02
NRPB	9.3E-02	1.1E-01	3.7E-02	8.2E-02	1.8E-02	7.8E-02	5.8E-02	9.3E-02
MPA	5.2E-02	1.2E-01	-4.0E-03	9.7E-02	-2.3E-02	9.4E-02	1.7E-02	1.1E-01

	PSI		SSI		NRPB	
	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
SSI	9.7E-02	7.2E-02				
NRPB	8.5E-02	7.2E-02	-1.2E-02	9.3E-02		
MPA	4.4E-02	8.9E-02	-5.3E-02	1.1E-01	-4.1E-02	1.1E-01

Calibration factor at 1 kBq/m<sup>3</sup>

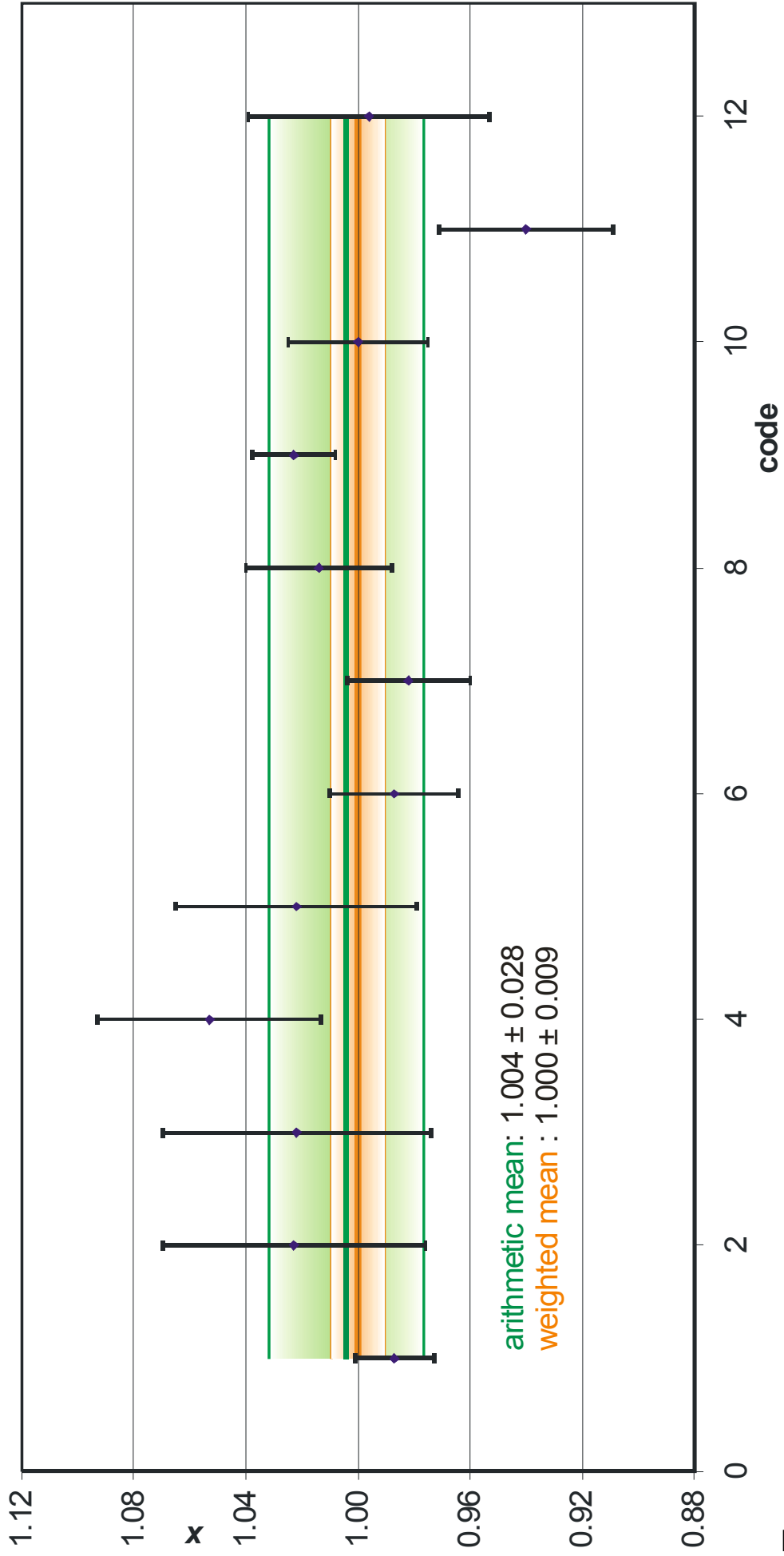
F.3

Calibration factor at 1 kBq/m<sup>3</sup>

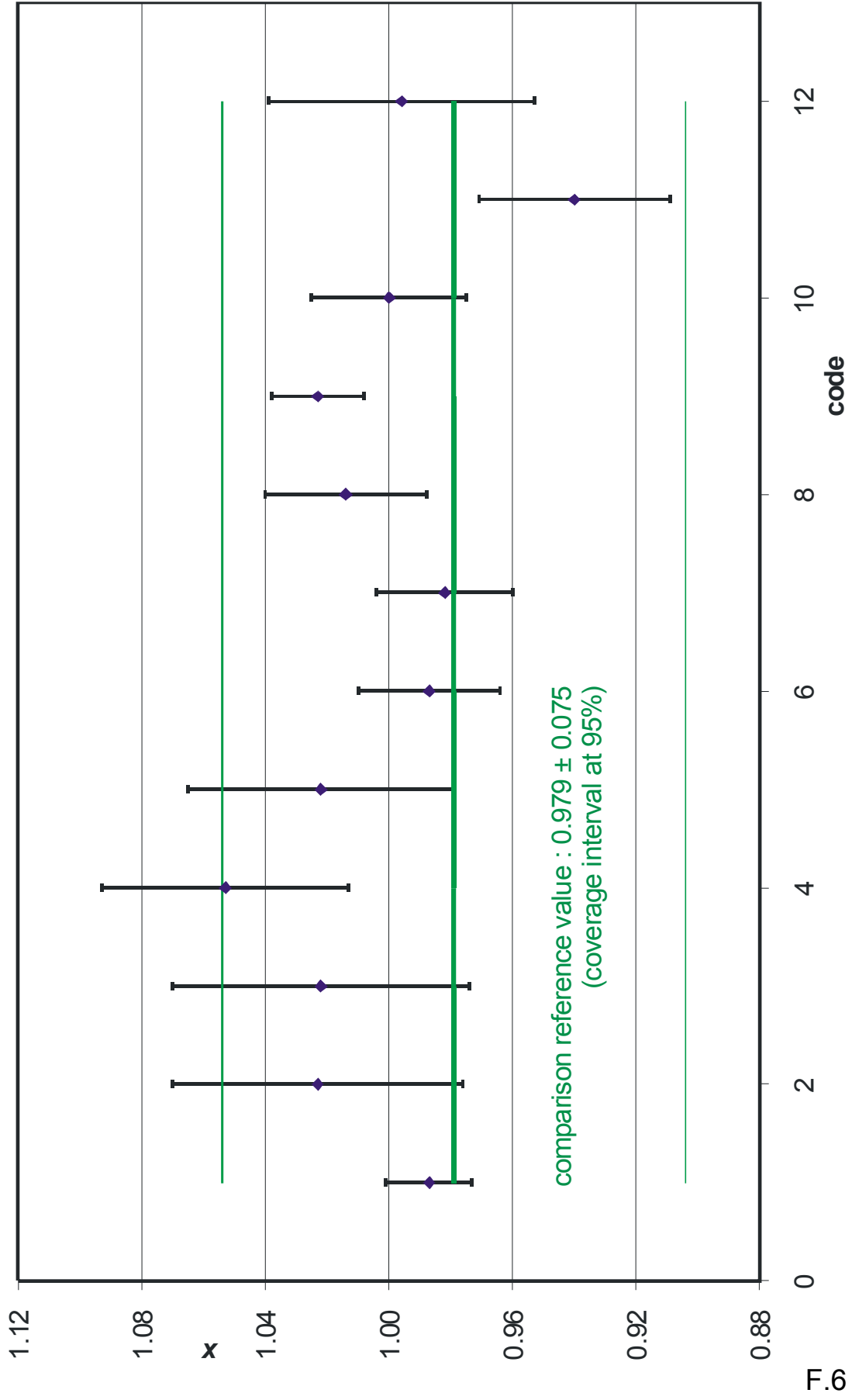


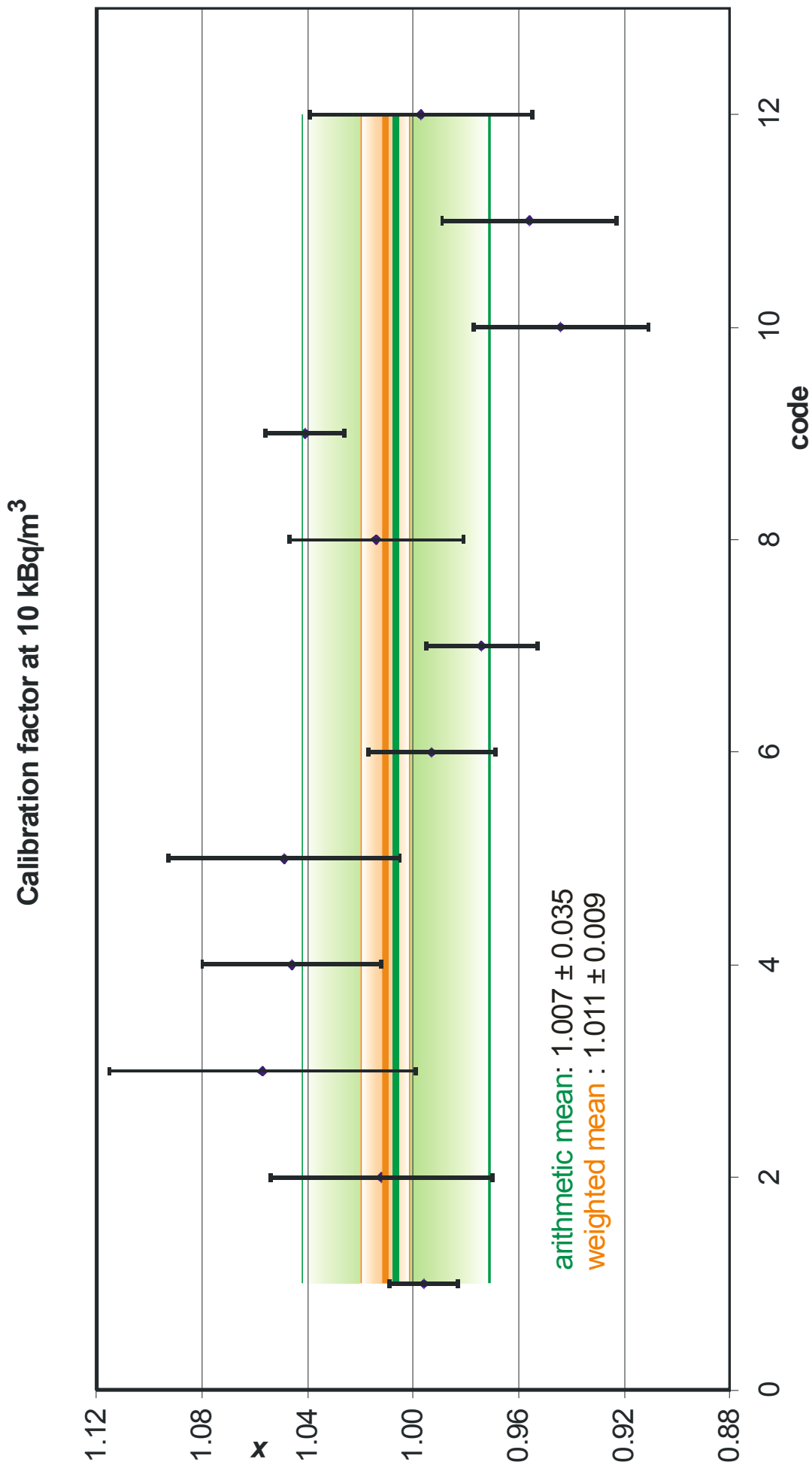
F.4

# Calibration factor at 3 kBq/m<sup>3</sup>

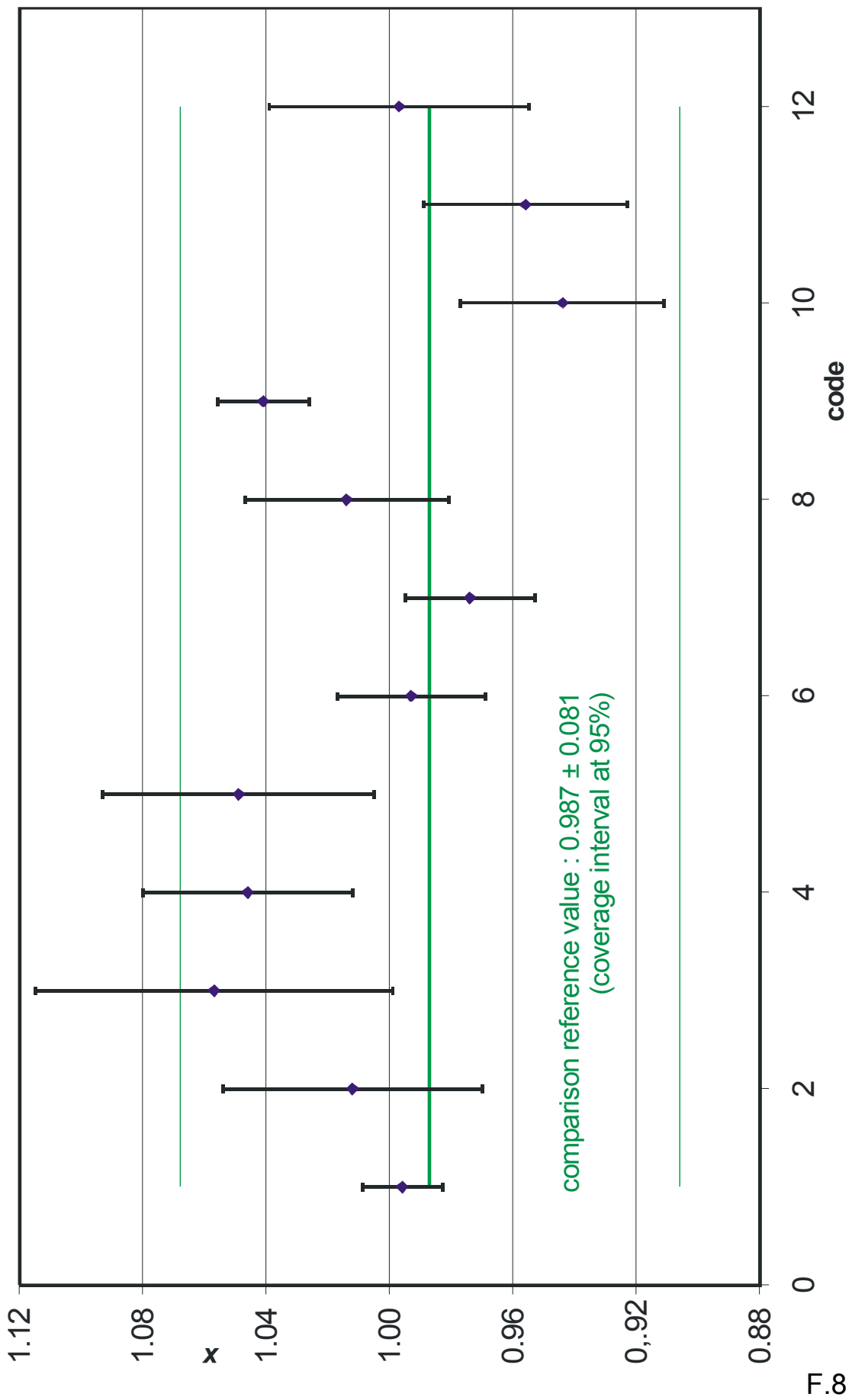


# Calibration factor at 3 kBq/m<sup>3</sup>





Calibration factor at 10 kBq/m<sup>3</sup>



## 2.5 History of the comparison device

The CD was always returned to the PTB after the calibration process was finished at an institute, and before being sent to the next one. During this stop-over, the CD's basic functions were tested, the background (due to build-up of  $^{210}\text{Po}$  activity in the ionization chamber) was measured and the completeness of the equipment (including the collection of raw data files) was checked.

The progress of the comparison was documented by comparison newsletters via e-mail.

The complete history of the CD exposure to natural or artificial atmospheres (activity concentration, temperature, pressure, humidity) is documented by its data files as well as in the accompanying lab book. This offers the possibility of correlating the total exposure of the CD to its background reading and of observing the amount of automatic background correction performed twice a year. The complete exposure history is given in Fig. 9

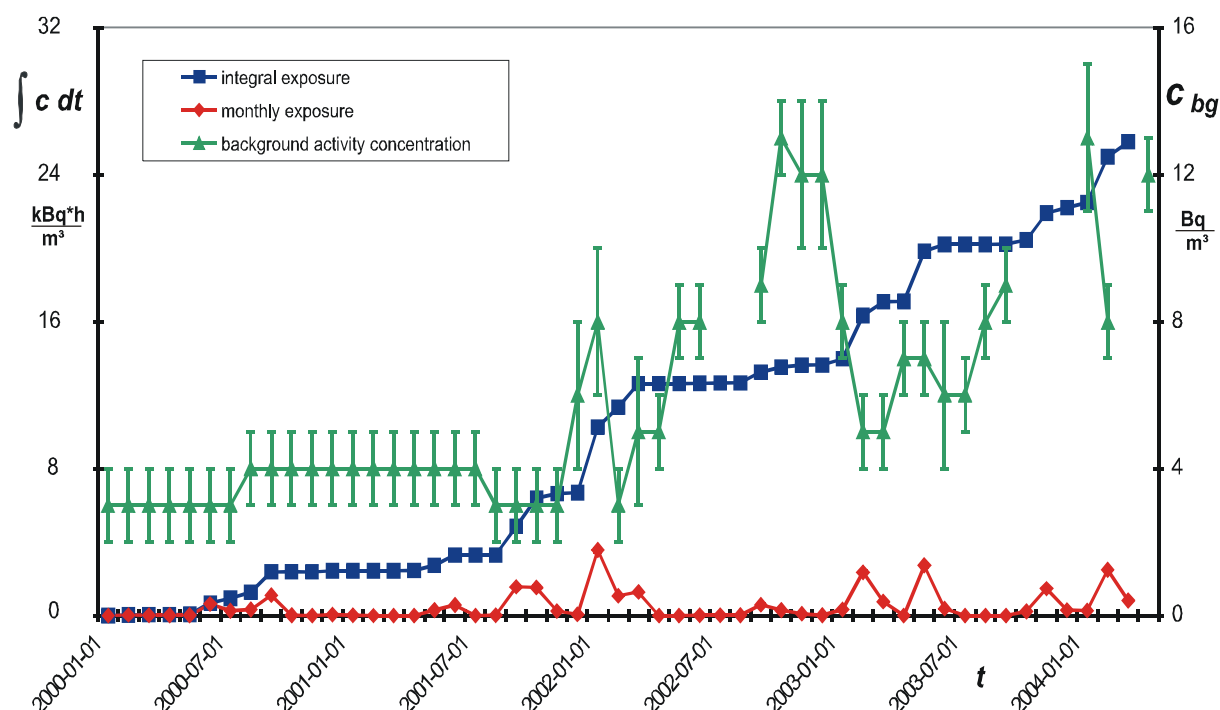


Figure 9: Background reading of the CD in comparison to the monthly integral (from 0 to 1 month) and overall integral activity concentration. The automatic background correction for this instrument is observable by the decrease of the background activity concentration twice a year.

## 2.6 Influence Parameters

The following parameters were considered to be potential influence parameters of the calibration:

1. Time (drift of response of the CD during the comparison)
2. Linearity of the response at different activity concentrations
3. Environmental parameters (temperature, humidity, pressure)

A drift in the response of the instrument would be observable by comparing the collected results of all participants in all three calibration points, since the calibrations

were performed in series. As Fig. 10 shows, this is not the case in the scope of the assigned uncertainties.

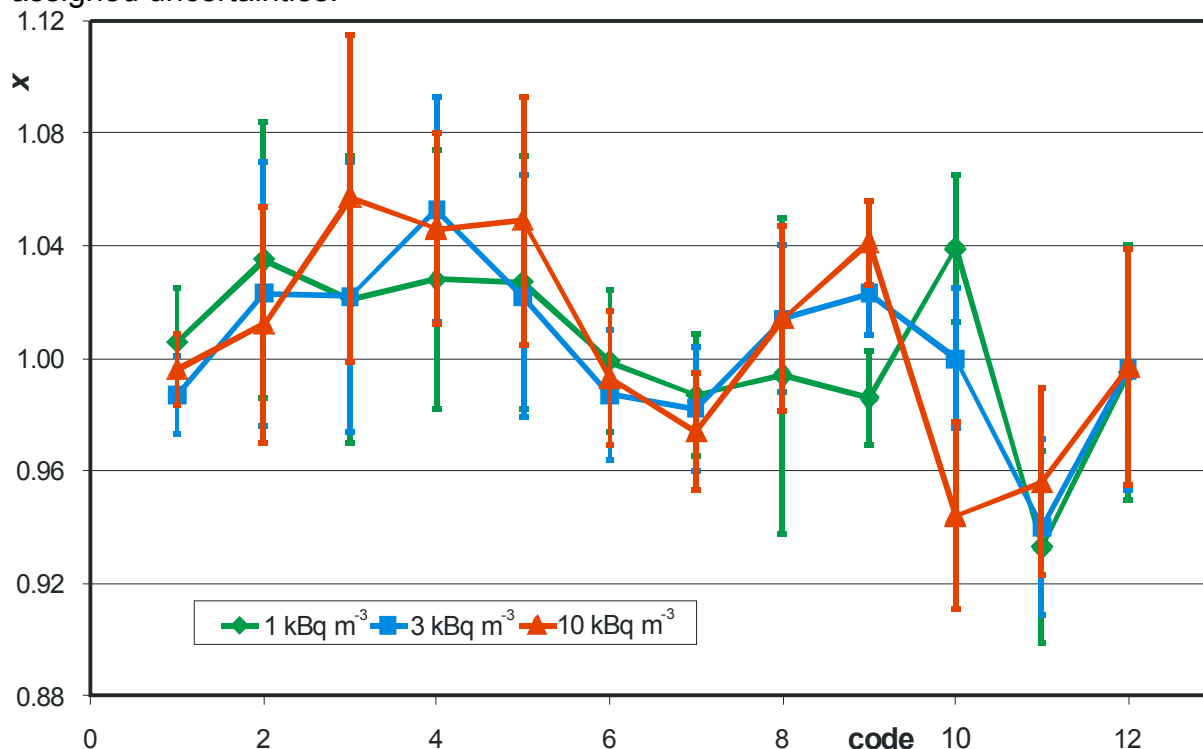
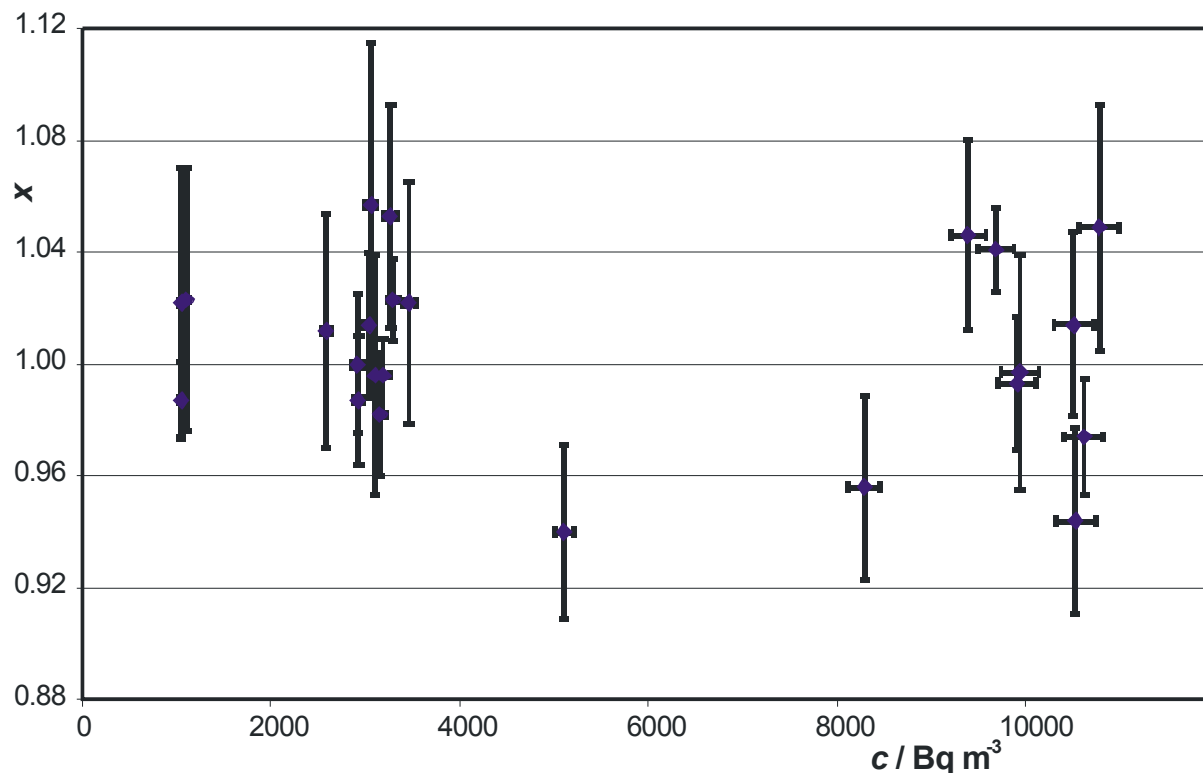


Figure 10: The results of the comparison in total. All measurements of a single participant (given by the code) are achieved during a relative short time (i.e. one month). The comparison stated in 2002 with participant with code 1 and ended with participant with code 12 in 2004.

A non-linear response of the CD would be observable by looking at the results (calibration factor) as a function of the activity concentration, see Figure 11.



There is no non-linearity response of the CD detected in the range of the activity concentration of the comparison and its assigned uncertainties.

The calibrations were performed over a quite wide range of environmental parameters. Table 3 summarizes ranges for the environmental parameter.

Table 3: Range of the environmental parameters during the calibrations of the comparison.

<b>quantity</b>	<b>lowest value</b>	<b>highest value</b>
temperature	15 °C	28 °C
air pressure	930 hPa	1025 hPa
relative humidity	29 %	60 %

There is no correlation between the change of environmental parameters and the results of the calibration detected in the scope of the assigned uncertainty for the CD.

## 2.7 Timetable of the comparison

April 2002	Planning of the comparison at the Radon Metrology Meeting in Vienna. Euromet Project proposed.
December 2002	Euromet Project 657 agreed, listed as BIPM supplementary comparison.
November 2002 – April 2004	Period of measurement
June 2004	Presentation of the results during the Radon Metrology Meeting in Braunschweig, distribution of Draft A.
December 2004	Draft B in preparation.

## 2.8 Summary

The Euromet project 657 was performed successfully according to the guidelines for Euromet projects and BIPM supplementary comparisons. The results of all participants are consistent in the scope of the assigned uncertainties.

In some cases the comparison initiated a detailed discussion of results, procedure of data analysis and calculation of uncertainties. This discussion will continue to achieve a better understanding of the respective measuring capabilities. The achievement of an even better agreement will therefore be possible.

The performance of a new comparison with different and / or increased number of participants is encouraged by the participants.

### 3 List of participants

A. Röttger: [annette.roettger@ptb.de](mailto:annette.roettger@ptb.de),  
A. Honig: [anja.honig@ptb.de](mailto:anja.honig@ptb.de),  
Physikalisch-Technische Bundesanstalt (PTB),  
Bundesallee 100,  
D-38116 Braunschweig,  
Germany

G. Butterweck: [gernot.butterweck@psi.ch](mailto:gernot.butterweck@psi.ch),  
Ch. Schuler: [christoph.schuler@psi.ch](mailto:christoph.schuler@psi.ch),  
Paul Scherrer Institut (PSI),  
CH-5232 Villigen PSI,  
Switzerland

V. Schmidt: [vschmidt@bfs.de](mailto:vschmidt@bfs.de),  
H. Buchröder: [hbuchroeder@bfs.de](mailto:hbuchroeder@bfs.de),  
Bundesamt für Strahlenschutz (BfS),  
Köpenicker Allee 120-130,  
D-10318 Berlin,  
Germany

A. Rox: [rox@mpanrw.de](mailto:rox@mpanrw.de),  
Materialprüfungsamt Nordrhein-Westfalen (MPA),  
Marsbruchstraße 186,  
D-44287 Dortmund,  
Germany

J. C. H. Miles: [jon.miles@nrpb.org](mailto:jon.miles@nrpb.org),  
C. Howarth: [chris.howarth](mailto:chris.howarth)  
National Radiological Protection Board (NRPB),  
Chilton, Didcot, Oxfordshire, OX11 0RQ,  
United Kingdom

I. Burian: [burian@sujchbo.cz](mailto:burian@sujchbo.cz),  
Státní ústav jaderné (SUJCHBO),  
chemické a biologické ochrany Příbram - Kamenná,  
26231 Milín,  
Czech Republic

N. Michielsen: [nathalie.michielsen@irsn.fr](mailto:nathalie.michielsen@irsn.fr),  
Institut de Radioprotection et de Sûreté Nucléaire (IRSN),  
CEA Saclay, Bât. 389, BP 68,  
91192 Gif-sur-Yvette Cedex,  
France

F. J. Maringer: [maringer.F@arsenal.ac.at](mailto:maringer.F@arsenal.ac.at),  
since 2004: [fj.maringer@metrologie.at](mailto:fj.maringer@metrologie.at) (due to change to BEV)  
ARC Seibersdorf Research GmbH (ARCS),  
Faradaygasse 3, Arsenal Obj. 214,  
A-1030 Vienna,  
Austria

A. Vargas: [arturo.vargas@upc.es](mailto:arturo.vargas@upc.es),  
Universitat Politècnica de Catalunya (INTE-UPC),  
Institut de Tècniques Enegetiques,  
Avda. Diagonal 647,  
E-08028 Barcelona,  
Spain

T. Turtiainen: [tuukka.turtiainen@stuk.fi](mailto:tuukka.turtiainen@stuk.fi)  
STUK - Radiation and Nuclear Safety Authority  
PO Box 14  
FIN-00881 HELSINKI  
FINLAND

P. Jachs: [p.jachs@metrologie.at](mailto:p.jachs@metrologie.at)  
Ionisierende Strahlung und Radioaktivität  
BEV - Bundesamt für Eich- und Vermessungswesen  
Arltgasse 35  
A-1160 Wien  
Austria

Nils Hagberg: [nils.hagberg@ssi.se](mailto:nils.hagberg@ssi.se)  
Swedish Radiation Protection Authority  
SE-17116 Stockholm  
Sweden

#### 4. Literature

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[4] K. Sommer: Praxisgerechtes Bestimmen der Messunsicherheit nach GUM, Technisches Messen 71, 2004.