Uncertainties and Traceability in radon measurements

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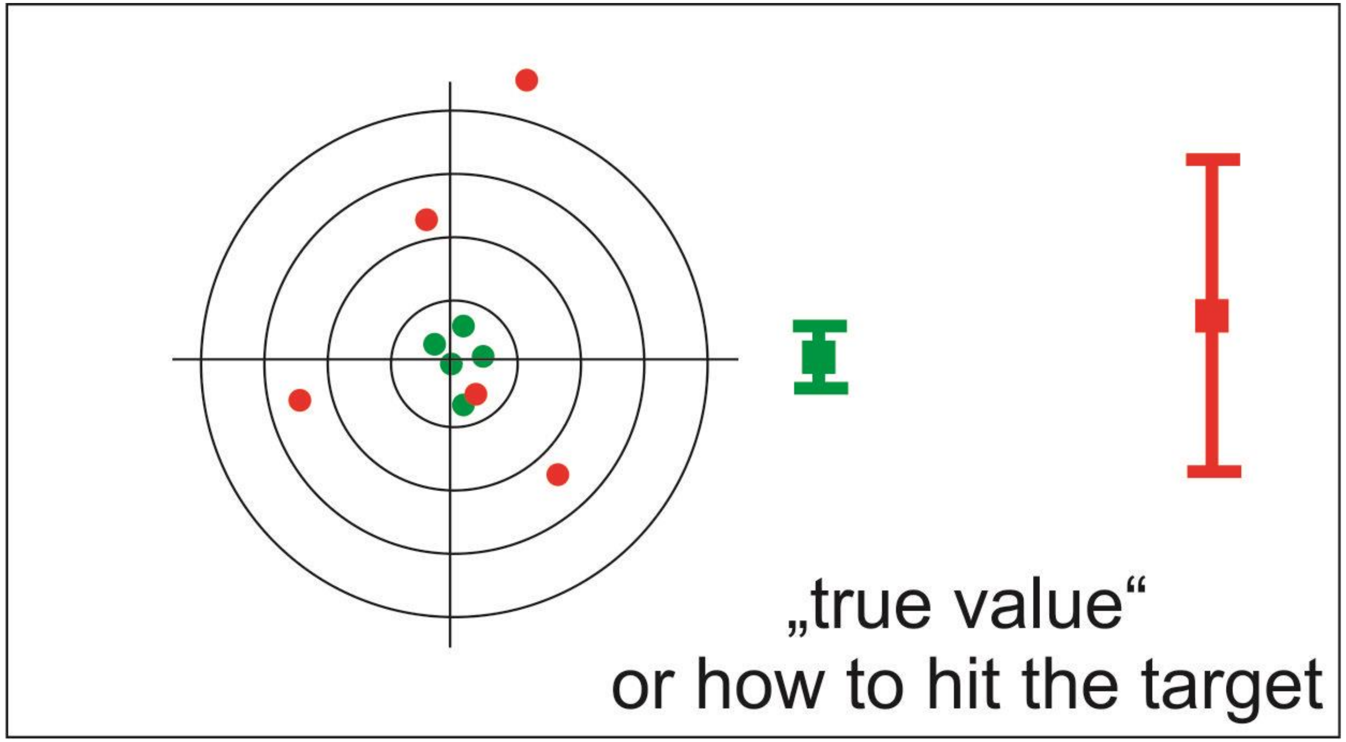
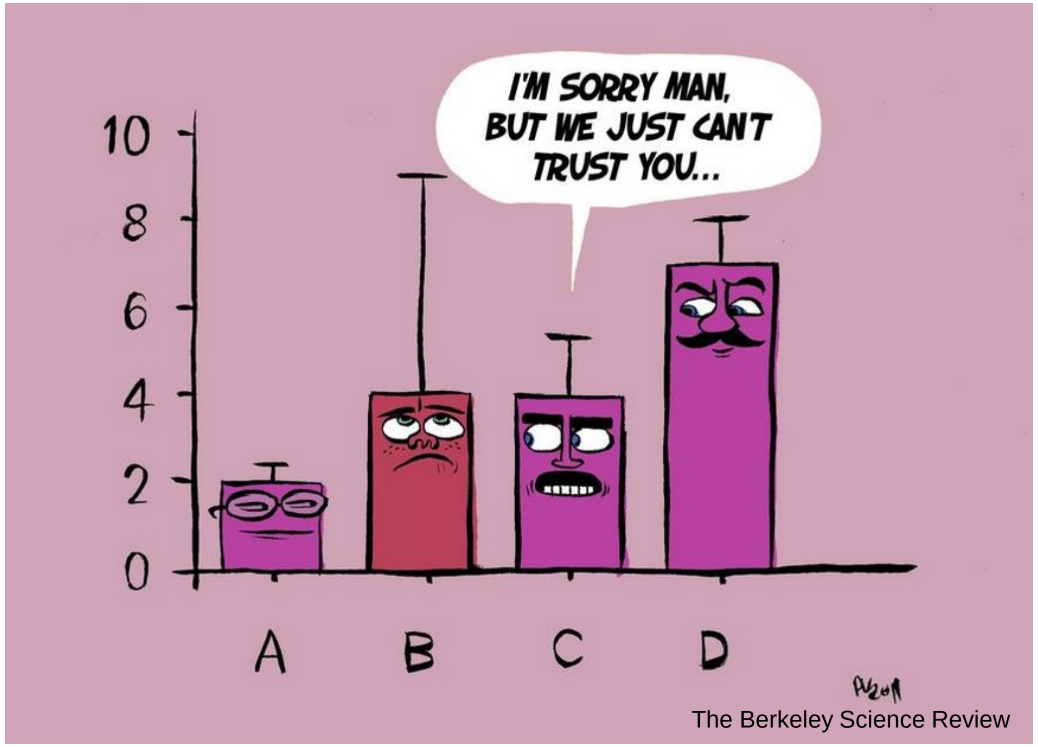
Uncertainties and Traceability in radon measurements

Motivation for dealing with uncertainty:

- compare results
- benchmark results
- accomplishment of decisions
- development of metrological infrastructure…





ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories

- ISO/IEC 17025 was first released in 1999
- Based on ISO Guide 25:1990;
  Originally published in 1978, labeled a guide originally; CASCO (CASCO - Committee on conformity assessment) was not given the authority to publish International Standards until late 1980's
- In 2005, ISO/IEC 17025 had minor revision to harmonize with ISO 9000:2000
- ISO/IEC 17025 was now 16 years old: Finally international majority for revision
- New in 2017

ISO/IEC 17025: Why is it so important?

The CIPM (International Committee for Weights and Measures) agreed on a “Mutual Recognition Arrangement” (MRA) with the following objectives:

- to establish the degree of equivalence of national measurement standards maintained by NMIs;
- to provide for the mutual recognition of calibration and measurement certificates issued by NMIs;
- and to provide governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce and regulatory affairs.

The process through which the CIPM MRA achieves these objectives involves:

- international comparisons of measurements, known as key comparisons;
- regional comparisons of measurements, known as regional key comparisons;
- other regional or bilateral comparisons of measurements known as supplementary comparisons;
- review of the technical competence of the participants based mainly on the results of comparisons;
- the implementation and review of quality systems and demonstrations of competence by NMIs.

http://www.bipm.org/en/cipm-mra/

ISO/IEC 17025: Why is it so important?

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- to provide for the ... ssued by NMIs;
- and to provide g... for wider agreements related to interna...

The participating institutes are required to operate an appropriate quality management system which is subject to an approval process run by the relevant regional metrology organization.

The accepted standards are ISO/IEC 17025 and ISO Guide 34 (for those institutes producing or assigning values to reference materials).

http://www.bipm.org/en/cipm-mra/approval-process.html

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- other regional or bilateral comparisons of measurements known as supplementary comparisons;
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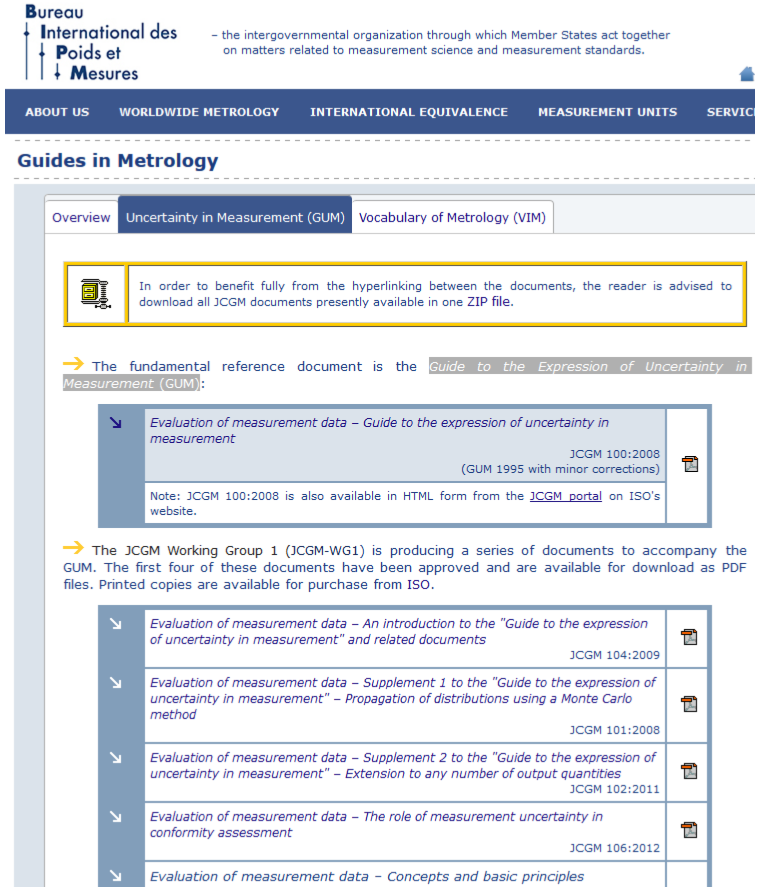
http://www.bipm.org/en/cipm-mra/

ISO/IEC 17025 is fundamental for the quality assurance, it is supported by the Guide to the Expression of Uncertainty in Measurement (GUM) and the International Vocabulary of Metrology (VIM)



Bureau International des Poids et Mesures – the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

ABOUT US | WORLDWIDE METROLOGY | INTERNATIONAL EQUIVALENCE | MEASUREMENT UNITS | SERVIC

Guides in Metrology

Overview | Uncertainty in Measurement (GUM) | Vocabulary of Metrology (VIM)

In order to benefit fully from the hyperlinking between the documents, the reader is advised to download all JCGM documents presently available in one ZIP file.

The fundamental reference document is the Guide to the Expression of Uncertainty in Measurement (GUM):

Evaluation of measurement data – Guide to the expression of uncertainty in measurement
JCGM 100:2008
(GUM 1995 with minor corrections)

Note: JCGM 100:2008 is also available in HTML form from the JCGM portal on ISO's website.

The JCGM Working Group 1 (JCGM-WG1) is producing a series of documents to accompany the GUM. The first four of these documents have been approved and are available for download as PDF files. Printed copies are available for purchase from ISO.

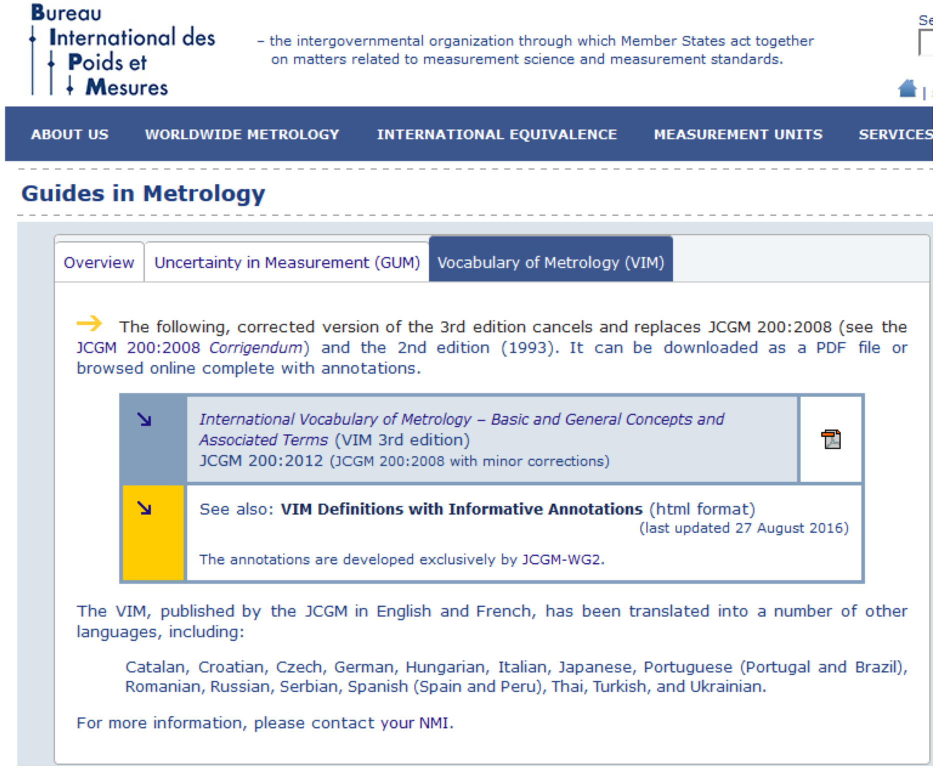
Evaluation of measurement data – An introduction to the "Guide to the expression of uncertainty in measurement" and related documents
JCGM 104:2009

Evaluation of measurement data – Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method
JCGM 101:2008

Evaluation of measurement data – Supplement 2 to the "Guide to the expression of uncertainty in measurement" – Extension to any number of output quantities
JCGM 102:2011

Evaluation of measurement data – The role of measurement uncertainty in conformity assessment
JCGM 106:2012

Evaluation of measurement data – Concepts and basic principles



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ABOUT US | WORLDWIDE METROLOGY | INTERNATIONAL EQUIVALENCE | MEASUREMENT UNITS | SERVICES

Guides in Metrology

Overview | Uncertainty in Measurement (GUM) | Vocabulary of Metrology (VIM)

The following, corrected version of the 3rd edition cancels and replaces JCGM 200:2008 (see the JCGM 200:2008 *Corrigendum*) and the 2nd edition (1993). It can be downloaded as a PDF file or browsed online complete with annotations.

International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM 3rd edition)
JCGM 200:2012 (JCGM 200:2008 with minor corrections)

See also: **VIM Definitions with Informative Annotations** (html format)
(last updated 27 August 2016)

The annotations are developed exclusively by JCGM-WG2.

The VIM, published by the JCGM in English and French, has been translated into a number of other languages, including:

Catalan, Croatian, Czech, German, Hungarian, Italian, Japanese, Portuguese (Portugal and Brazil), Romanian, Russian, Serbian, Spanish (Spain and Peru), Thai, Turkish, and Ukrainian.

For more information, please contact your NMI.

Free download of GUM and VIM!

http://www.bipm.org/en/publications/guides/#gum

After we all agree that **uncertainty is of fundamental importance**, how can we proceed?

- Need for **concepts and basic principles**
- Need for **procedures**: Stages of uncertainty evaluation!
  - ✓ The formulation stage
  - ✓ The calculation stage

Example (formulation stage):

$$C_i = k_k\ (C_m - C_{bg})$$

Output quantity: C_i

Input quantities: k_k, C_m, C_{bg}

		Probability distribution
C_i	activity concentration	
C_m	measured activity concentration (indication value)	normal
C_{bg}	background reading	rectangular
k_k	calibration factor	normal

1. Concepts and basic principles

- The purpose of measurement is to provide information about a quantity of interest: a **measurand.**

- No measurement is exact. When a quantity is measured, the outcome depends on the measuring system, the measurement procedure and other effects. The result is an **indication value.**

- The dispersion of the indication values would relate to how well the measurement is made. Their average would provide an **estimate of the true quantity value** that generally would be more reliable than an individual indication value.

- The measuring system may provide indication values that are not dispersed about the true quantity value, but about some value offset from it. The difference between the offset value and the true quantity value is sometimes called the **systematic error value**.

- There are **two types of measurement error quantity, systematic and random**.

  A systematic error (an estimate of which is known as a measurement bias) is associated with the fact that a measured quantity value contains an offset. A **random error** is associated with the fact that when a measurement is repeated it will generally provide a measured quantity value that is different from the previous value. It is random in that the next measured quantity value cannot be predicted exactly from previous such values.

There are **two types of measurement error quantity, systematic and random**.

Note: The purpose of the Type A and Type B classification is to indicate the **two different ways of evaluating uncertainty components and is for convenience of discussion** only; the classification is not meant to indicate that there is any difference in the nature of the components resulting from the two types of evaluation. Both types of evaluation are based on probability distributions, and the uncertainty components resulting from either type are quantified by variances or standard deviations.

- Type A evaluation is calculated from series of repeated observations (example: frequent reading of a device)

- Type B evaluation is means using available knowledge (example: calibration factor of a device)

In other words:

- **Type A standard uncertainty is obtained from a probability density function derived from an observed frequency distribution**, while a

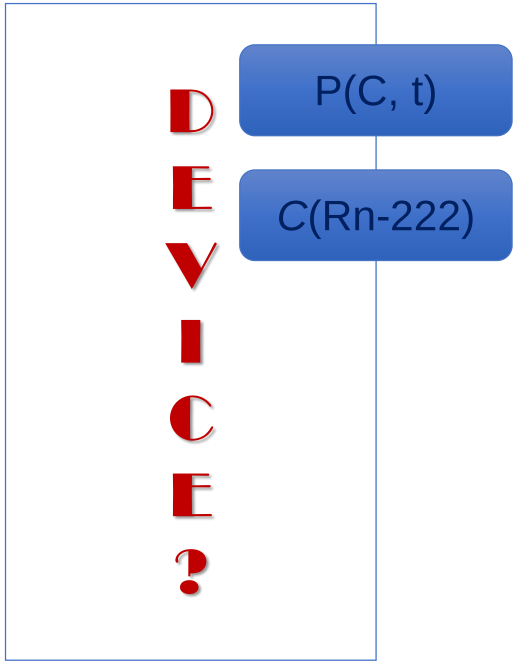
- **Type B standard uncertainty is obtained from an assumed probability density function** based on the degree of belief that an event will occur.

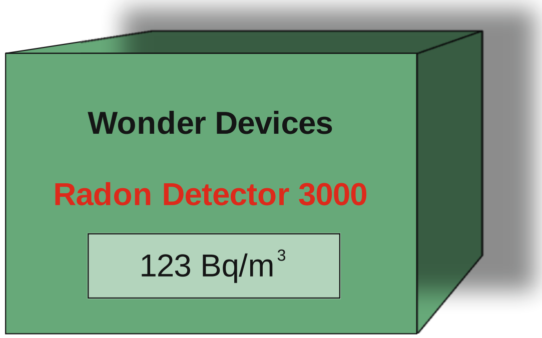
All input quantities and the measurand are a sample from a probability distribution.

Doing measurements is obtaining random numbers from a distribution.

General aspects: How to choose a measuring device? Appropriate to the task!

- What is the measurand? *P(C,t)*, *C*(Rn-222), *C*(Rn-220), *F*, …
- What range of measurement is required? Do I have a traceable calibration in that range?
- Which range of uncertainty has to be achieved **at** the required range of measurement?





Technical Data:
Wonder Devices Radon Detector 3000

Measuring from 1 Bq/m^3 to 100.000 Bq/m^3
Only 10 minutes measuring time!
Calibrated and ready to use!

?

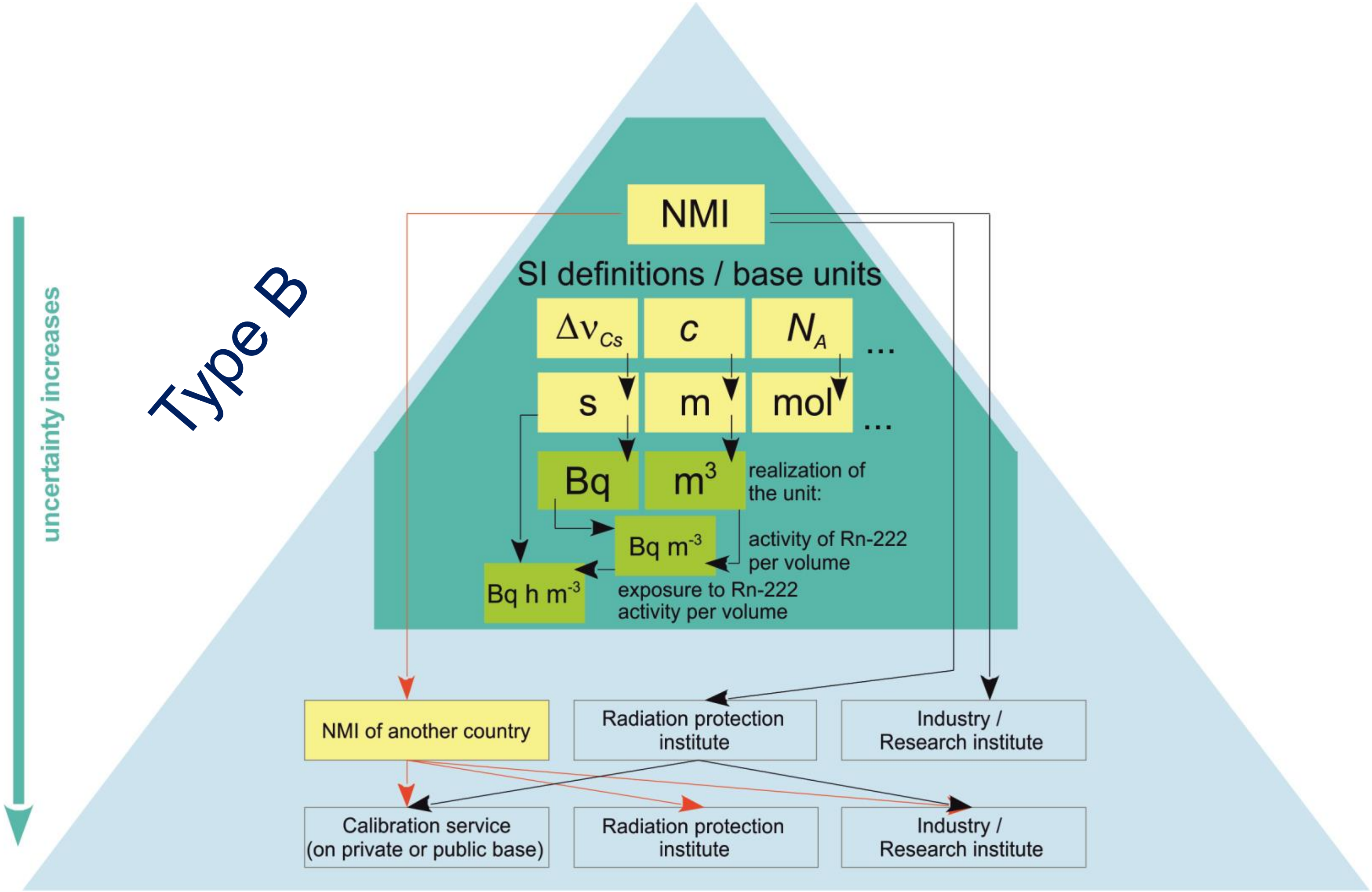
We assume an active volume of 0.25 liter:
1000 Bq/m^3 => 0.25 Bq/l
number of counts after 1 hour:
n = 900 with u(n)=30: u(n)/n=0.03

100 Bq/m^3 = 0.025 Bq/l
number of counts after 1 hour:
n = 90 with u(n)=10: u(n)/n=0.11

Type A

Always include statistical uncertainty in your uncertainty budget.

Type B standard uncertainty: Typical example is the uncertainty from the traceability chain!



General aspects: How to choose a measuring device? Appropriate to your task:

C(Rn-222) $C_i = k_k\,(C_m - C_{bg})$

P(C, t) $P_{Rn} = k_v\,k_s\,C_i\,t$

P_{Rn}: exposure 17 %
C_i: activity concentration

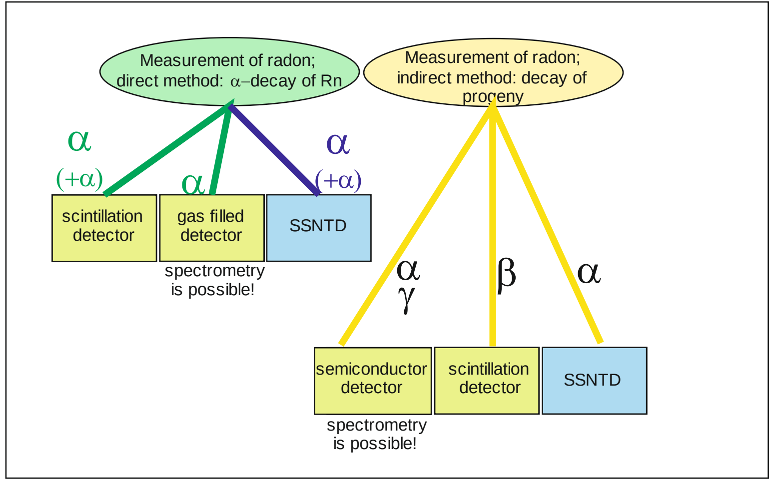
C_m: measured activity concentration (indication value)
C_{bg}: background reading
k_k: calibration factor 39 %
k_v: correction factor for daily variation
k_s: correction factor for seasonal variation
t: exposure time

Determination of the activity concentration (short term) results to large uncertainty in long term exposure estimation!

quantity	value	uncertainty (k=1)	distribution
C_i	71 Bq/m³	12 Bq/m³	
k_k	0.95	0.05	normal
C_m	100 Bq/m³	11 Bq/m³	normal
C_{bg}	25 Bq/m³	3 Bq/m³	rectangular

Uncertainties and Traceability in radon measurements

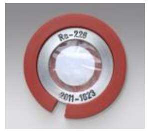
Field measurement of Rn-222



Determination of C or $\frac{\int C \cdot dt}{t}$

Traceable calibration


$C = \frac{A}{V}$

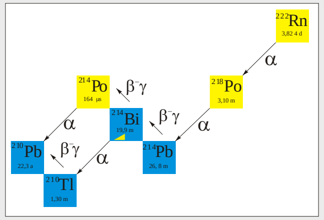


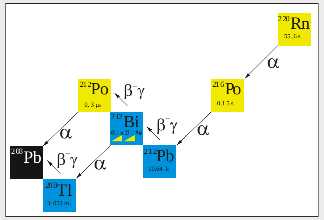

Calculation and Modelling

$C_{eq} = C \cdot F$ with $F \approx 0.4$ (assumed)

$c_p = C_{eq} \cdot k_u$

Rn-222: k_u=5.57(10) · 10^{-6} mJ/Bq





Rn-220: k_u=7.565 (8) · 10^{-5} mJ/Bq

$P_{RnF} = C_p \cdot t$ with t = 2000 h or t = 8760 h

$H = P_{RnF} \cdot k_{ICRP}$ with k_{ICRP} = ?

$1.43 \frac{\text{mSv m}^3}{\text{mJ h}}$ $3.0 \frac{\text{mSv} \cdot \text{m}^3}{\text{mJ} \cdot \text{h}}$ $6.0 \frac{\text{mSv m}^3}{\text{mJ h}}$

Effective dose for the non-SI unit 1 WLM with ICRP-65 conversion

Quantity	Value	Standard uncertainty	Contribution to uncertainty	Index
C	7400 Bq/m³	10.0 Bq/m³	6.8·10⁻³ mSv	0.0 %
t	170 h	11.5 h	0.34 mSv	21.8 %
F	0.5	0.0577	0.58 mSv	63.1 %
C_{eq}	3700 Bq/m³	427 Bq/m³		
C_p	20.60·10⁻³ mJ/m³	2.38·10⁻³ mJ/m³		
k_u	5.568·10⁻⁶ mJ/Bq	1·10⁻⁹ mJ/Bq	900·10⁻⁶ mSv	0.0 %
P_{RnF}	3.502 mJ h/m³	0.469 mJ h/m³		
$k_{ICRP-65}$	1.43 mSv ·m³/(mJ·h)	0.08 mSv ·m³/(mJ·h)	0.28 mSv	15.1 %
H	5.01 mSv	0.73 mSv		

POTENTIAL ALPHA ENERGY CONCENTRATION
1 Working Level (WL) = 1.3 x 10^5 MeV.L^{-1}
= 2.08 x 10^{-5} J.m^{-3}
1 WL corresponds to radon progeny concentration in equilibrium with 100 pCi.L^{-1} radon (3700 Bq.m^{-3})

All quantities k=1.

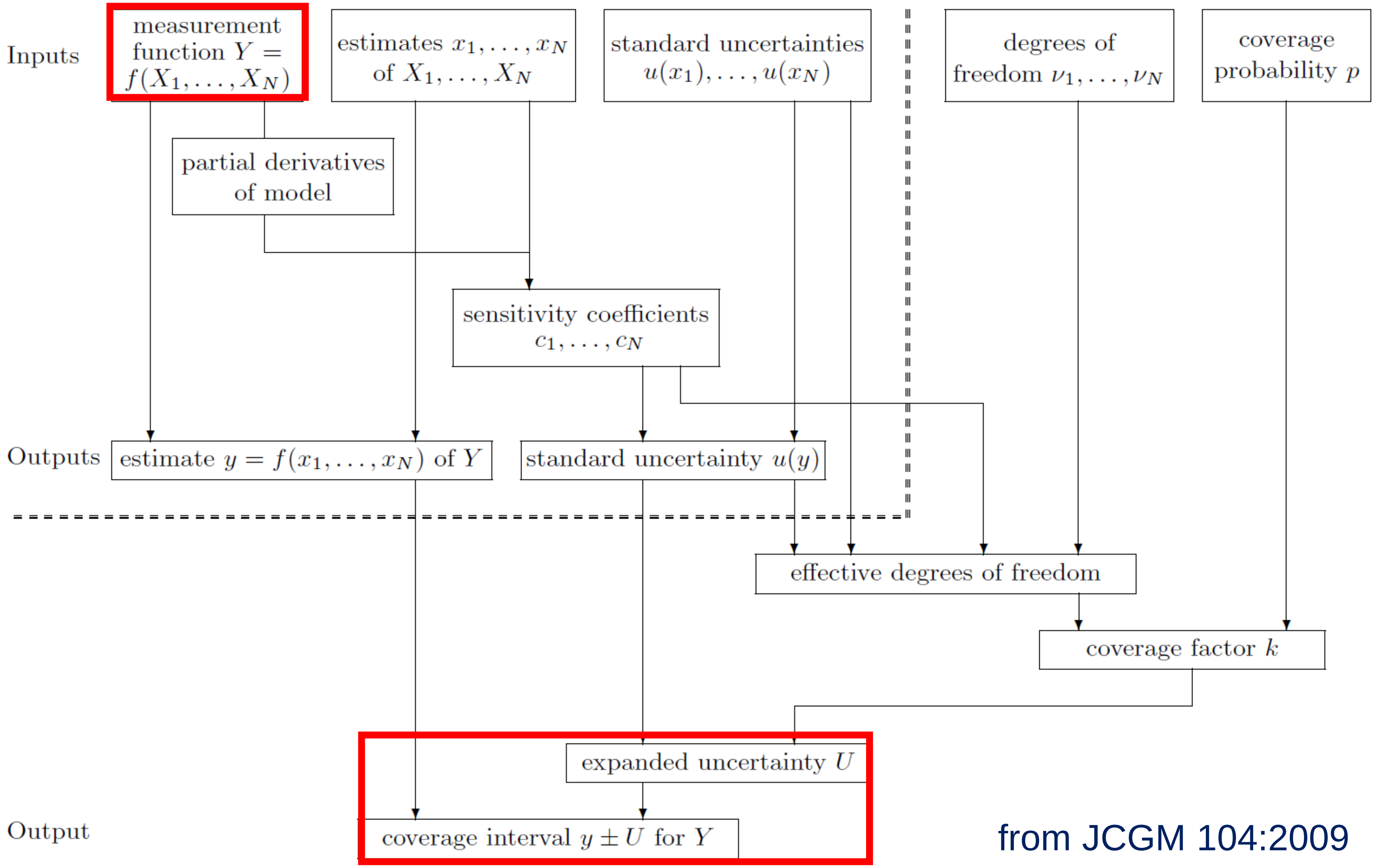
Effective dose for 2000 h at 300 Bq/m³ with different conversions

Quantity	Value	Standard uncertainty	Contribution to uncertainty	Index
C	300 Bq/m³	50 Bq/m³	0.32 mSv	53.6 %
t	2000 h	11.5 h	0.011 mSv	0.0 %
F	0.4	0.0577	0.28 mSv	40.2 %
C_{eq}	120 Bq/m³	26.5 Bq/m³		
C_p	$668 \cdot 10^{-6}$ mJ/m³	$147 \cdot 10^{-6}$ mJ/m³		
k_u	$5.5682 \cdot 10^{-6}$ mJ/JBq	$1 \cdot 10^{-9}$ mJ/JBq	$340 \cdot 10^{-6}$ mSv	0.0 %
P_{RnF}	1.34 mJ h/m³	0.30 mJ h/m³		
$k_{ICRP\text{-}65}$	1.43 mSv · m³/(mJ ·h)	0.081 mSv ·m³/(mJ ·h)	0.11 mSv	6.2 %
H	1.911 mSv	0.435 mSv		
$k_{ICRP\text{-}137}$	3 mSv · m³/(mJ ·h)	0.5 mSv ·m³/(mJ ·h)	0.39 mSv	[illegible].0 %
H	4.0 mSv	1.0 mSv		

For 8700 h in a year:
(17.4± 4.2) mSv

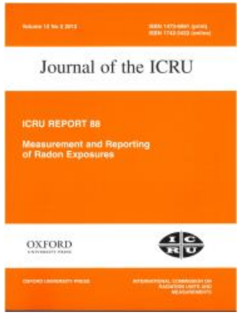
Determination of uncertainties according to GUM

Measurement uncertainty evaluation using the GUM uncertainty framework, where the top-left part of the figure (bounded by broken lines) relates to **obtaining an estimate y** of the **output quantity Y** and the **associated standard uncertainty u(y),** and the remainder relates to the determination of a **coverage interval for Y.**



from JCGM 104:2009

Measurement and Reporting of Radon Exposures



ICRU Report 88

“The objective of this report is, therefore, to provide conceptual and practical guidance for radon measurements in air and in water. The recommendations include **guidance for the choice of strategies** for **radon and radon progeny measurements and surveys** and for **interpreting and reporting measurement results**, appropriate for the goal of the measurements. The report also addresses methods to **determine and reduce uncertainties** associated with these measurements and resulting dosimetric estimates.
It describes the **state-of-the-art of radon measurement techniques** which is expected to be of relevance in view of the **reduced reference levels in dwellings and in the workplace** as well as for epidemiological studies. The recommendations in this report are aimed at authorities planning radon surveys, at experts performing measurements and at scientists involved in epidemiological studies on lung cancer risk due to radon inhalation.“

A simple example for the calibration of nuclear track detectors:

The calibration conditions are well known in terms of the exposure period, $\Delta t = (t_2 - t_1)$ and radon activity concentration C_{Rn-222}. This calibration is performed in a radon reference chamber, starting at time t_1 and ending at t_2.
The exposure is determined with a secondary standard. The exposure is given by

$$P = C_{Rn-222} \cdot (t_2 - t_1) \quad \text{with} \quad C_{Rn-222} = k_r \cdot (C_i - C_{bg})$$

Quantity	Value	Standard uncertainty	Index
C_{Rn-222}	30.7 kBq/m³	0.5 kBq/m³	
k_r	1.031	0.014	89.7 %
C_i	29.8 kBq/m³	0.13 Bq/m³	9.9 %
C_{bg}	59 Bq/m³	3 Bq/m³	0.0 %
t_2	49.00 h	0.04 h	0.2 %
t_1	0.0 h	0.04 h	0.2 %
P	1500 kBq h/m³	22 kBq h/m³	

During this **exposure a number of *m* nuclear track detectors** are exposed. The **track density that is obtained will have a variation**, which can be used to assign an uncertainty to the track density $u(\bar{n})$ itself.

$$u(\bar{n}) = f \cdot \sqrt{\frac{1}{\sum \frac{1}{u^2(n_i)}}}$$

A. Röttger et al.
In: Applied radiation and isotopes 2016, 109, p.330-334.

Uncertainties and Traceability in radon measurements

$$\kappa = \frac{P}{(\bar{n} - \bar{n}_{bg})}$$

If a group of *m* nuclear detectors is exposed to different radon levels, a linearization can be performed and if the **linear model passes the consistency check**, the calibration coefficient, κ can be calculated.

Quantity	Value	Standard uncertainty	Index
P	1500 kBq ·h/m³	22 kBq ·h/m³	3.2 %
$\bar{n}$	2030 cm⁻²	160 cm⁻²	96.5 %
$\bar{n}_{bg}$	69 cm⁻²	6 cm⁻²	0.3 %
κ	0.77 kBq ·h/m³ · cm²	0.06 kBq ·h/m³ · cm²	

Calibration of nuclear track detectors is finished. Field measurement starts…

$$P = (\bar{n} - \bar{n}_{bg}) \cdot \kappa$$

$$\bar{C} = \frac{(\bar{n} - \bar{n}_{bg}) \cdot \kappa}{\Delta t} = \frac{P}{\Delta t}$$

Quantity	Value	Standard uncertainty	Index
κ	0.77 kBq ·h/m³ · cm²	0.06 kBq ·h/m³ · cm²	56.8 %
$\bar{n}$	3290 cm⁻²	220 cm⁻²	43.2 %
$\bar{n}_{bg}$	50 cm⁻²	5 cm⁻²	0.0 %
P	2500 kBq ·h/m³	260 kBq ·h/m³	
Δt	2000 h	14 h	0.4 %
$\bar{C}$	1.25 kBq /m³	0.13 kBq /m³	

$P = (2.5 \pm 0.6) \cdot 10^3$ kBq · h/m³
(with a coverage factor k = 2)

References:

- Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008 (GUM)
- Supplement 1 to GUM, Propagation of distributions using a Monte Carlo method, JCGM 101:2008
- Determination of characteristic limits for measurements of ionizing radiation, ISO 11929:2010
- Radiation detection instrumentation – Determination of uncertainty in measurement, IEC TR 62461:2015
- ICRU REPORT 88, Measurement and Reporting of Radon Exposures

Thanks to Janwillem van Dijk for ideas from his presentations from EURADOS Training Course Florence, Italy, 24-28 April 2017

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