Quality of Radon Measurements

- Radon and Radon Progeny Chambers for Calibration -

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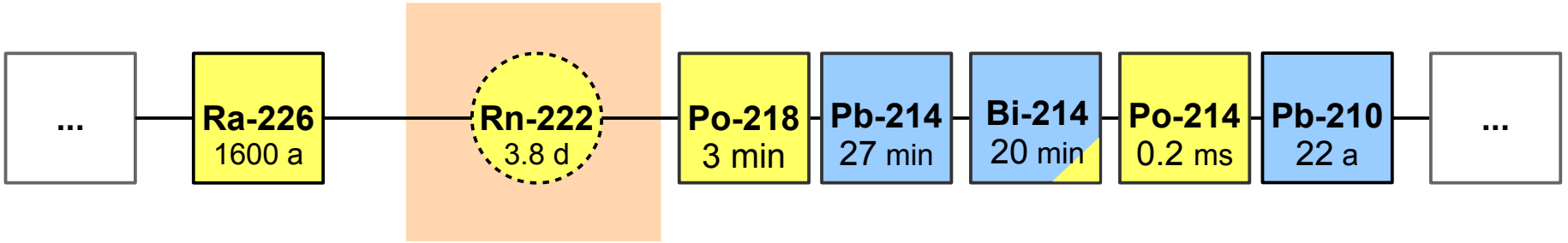
Calibration procedures - Rn-222 Dp

Summary

Radon measurands – Rn-222 gas



Rn-222 activity concentration

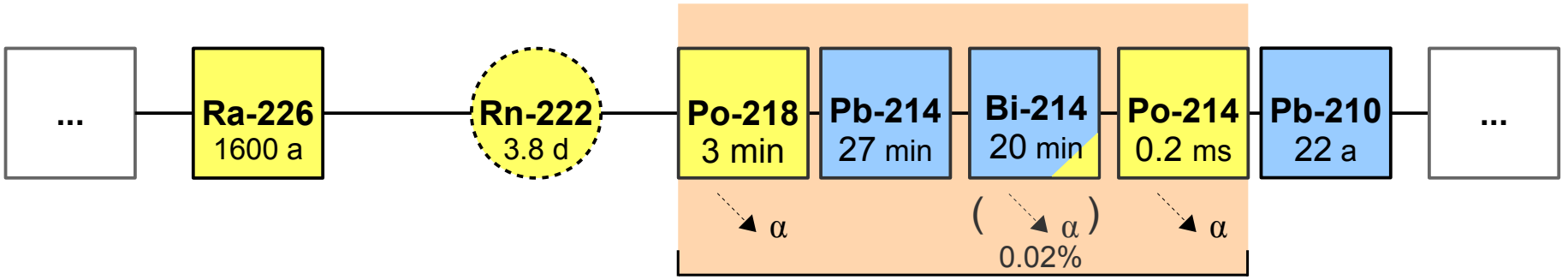
→ average amount of Rn-222 decays per second within a volume
→ measurement unit: [**Bq/m³**]

Rn-222 exposure

→ Rn-222 activity concentration multiplied by exposure time
→ measurement unit: [**Bq·h/m³**]

→ measuring instruments for this measurand: **“Exposimeters“**

Radon measurands – Rn-222 decay products



Potential Alpha-Energy

$$PAE_{Rn\text{-}222}\ [\mu J] \approx N_{Po\text{-}218} \cdot E_{\alpha,Po\text{-}218} + (N_{Po\text{-}218} + N_{Pb\text{-}214} + N_{Bi\text{-}214} + N_{Po\text{-}214}) \cdot E_{\alpha,Po\text{-}214}$$

with N_i: number of atoms of nuclide i; α-energies: $E_{\alpha,Po\text{-}218} = 0.962\ pJ$, $E_{\alpha,Po\text{-}214} = 1.232\ pJ$

Potential Alpha-Energy Concentration → PAE per volume

$$PAEC_{Rn\text{-}222}\ [\mu J/m^3] = 5.56\ nJ/Bq \cdot C_{Rn\text{-}222,eq}\ [Bq/m^3]$$

in case of radioactive equilibrium

with $C_{Rn,eq}$: Rn-222 activity concentration in equilibrium with short-lived decay products

Equilibrium Equivalent (activity) Concentration

→ *a radon activity concentration, in equilibrium with its short-lived decay products, which **would have the same PAEC** as the actual existing mixture of nuclides*

$$EEC_{Rn\text{-}222}\ [Bq/m^3] = 0.105 \cdot C_{Po\text{-}218} + 0.516 \cdot C_{Pb\text{-}214} + 0.379 \cdot C_{Bi\text{-}214} + 10^{-8} \cdot C_{Po\text{-}214}$$

with C_i: activity concentration of nuclide i

Examples of radon measuring devices

Exposimeters (integrating detectors)
measurand: exposure [Bq*h/m³]

- solid-state nuclear track detectors (SSNTD)
- electrets

Examples of radon measuring devices

Electronical measuring instruments, measurand: Rn-222 activity concentration [Bq/m³]

- **scintillation cells**

  e.g., flow-through scintillation cells
  with photo multiplier + analyzer
  and controlled flow

- **alpha spectrometry** (filtered air, Si detector)

- **ionisation chambers**

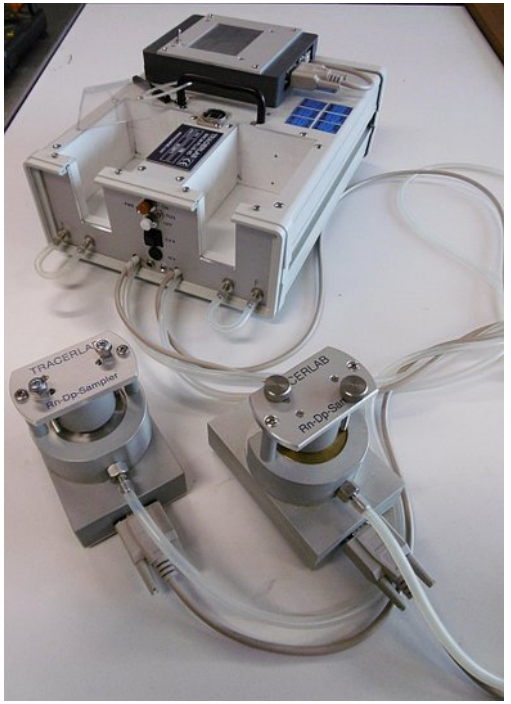
picture: Handbuch
Radona Expert+
Waltec GmbH

Examples of radon PAEC measuring devices

Electronical measuring instruments – measurand, e.g., PAEC [µJ/m³]

- alpha spectrometry with filter

- with filter + wirescreen (unattached fraction f_p)



Calibration

Calibration (ISO/IEC Guide 99:2007)

Operation that, under ***specified conditions*** […] *establishes a relation between the* ***quantity values*** *with measurement* ***uncertainties*** *provided by measurement standards* [e.g., **reference measurement**]
and […] *uses this information to* ***establish a relation*** [e.g., calibration factor or curve] *for obtaining a measurement result from an indication* [e.g., of a **calibration object**].

e.g., an instrument for the measurand activity concentration showing indication value $\mathbf{C_M}$

$\mathbf{C_M \neq C_{Ref}}$

e.g., a measurement standard for activity concentration $\mathbf{C_{Ref}}$, tracable to national standards

→ **main goal**: find a relation k(C_{Ref}, C_M) **to correct indication** values and consider measurement **uncertainties**

→ **adjustment** of a calibration object is **not included**
(a new calibration is necessary if the object has been modified)

Calibration prerequisits – **Source**, Chamber, Measurement standard

flow-through sources

for example
made by CMI (CZ)

emanator:
dry Ra-226 (salt)

activity: 500 kBq

purged with air

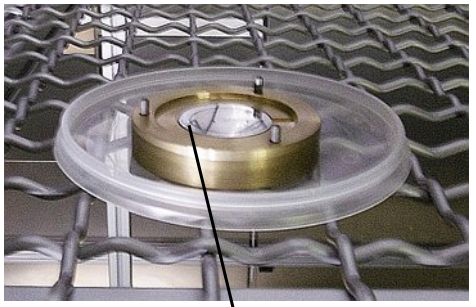
picture: www.eurostandard.cz/
Eurostandard-catalog-2011.pdf

gas standard

for example made by
LNHB (France)

certified Rn-222
activity with 50 kBq

other emanation sources



for example made by
PTB (Germany)

e.g., produced by
electro-deposition

Calibration prerequisits – Source, **Chamber**, Measurement standard

walk-in calibration chambers

- practical issues
  → one can go inside to fix problems / look after instruments
  → more/larger devices can be exposed
- bigger volume means less disturbance of
  → radon activity concentration, e.g., while inserting objects
  → surface influences for Rn-222 decay products
  PAEC measurements only possible in larger chambers
  (but not too large for homogeneity reasons)
- often adjustment of environmental parameters possible
- expensive, need space

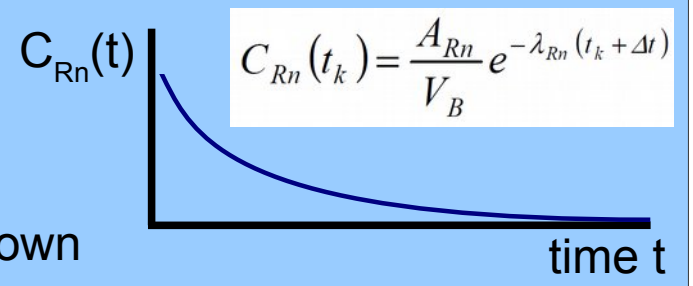
small calibration chambers (containers)

- smaller sources / less Rn-222 activity needed
- good for operation of many containers in parallel
  e.g., at different activity concentrations each
- good for long-term exposures without blocking a whole walk-in chamber

Calibration prerequisits – Source, **Chamber**, Measurement standard

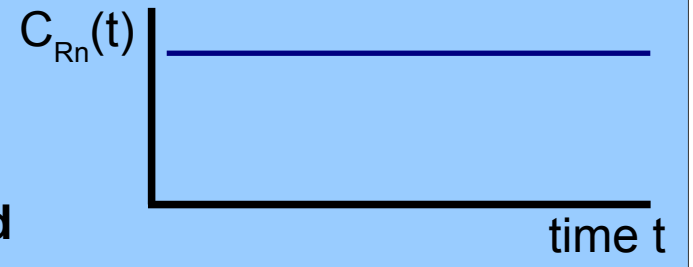
Modes of chamber operation

decay mode



- one activity injection, e.g., gas standard
- decay of activity concentration $C_{Rn}(t)$
- e-Function, Rn-222 decay constant λ_{Rn} is known
- reference activity concentration can be
  a) **measured** or
  b) **calculated** if chamber volume and the initial activity is known

constant mode



- decay of activity concentration $C_{Rn}(t)$
- redosing needed to compensate decay
- reference activity concentration is **measured**
- constant mode needed for long term exposures,
  e.g., **integrating detectors** and for **Rn decay product calibrations**

Calibration prerequisits – Source, Chamber, **Measurement standard**

e.g., activity standard
+ volume standard
= activity concentration

National (measurement) **standard**

*Measurement standard **recognized by national authority** to serve in a state […] as basis for assigning quantity values to other measurement standards […].*

Reference (measurement) **standard**

*Measurement standard **designated for the calibration** of other measurement standards […] in a given organization or at a given location.*

Working (measurement) **standard**

*Measurement standard that is **used routinely to calibrate** or verify measuring instruments or measuring systems.*

increasing uncertainty

definitions acc. to ISO/IEC Guide 99:2007

Calibration procedures – BfS radon calibration laboratory

- **ISO 17025** accredited since 1999 as calibration laboratory
- accredited measurands **Rn-222 activity concentration** and **PAEC** of short-lived Rn-222 decay products
- non-accredited: Rn-220 (thoron) activity concentration

- 2 walk-in chambers: **30 m³** and **11 m³**
  6 stainless steel containers: **0.4 m³** each
  1 vacuum chamber **0.17 m³**
- accredited ranges
  activity concentration **50** … **12 000 Bq/m³**
  PAEC **0.32** … **640 µJ/m³**
- mainly **flow-through Ra-226** sources (CMI, Pylon)
- control of **temperature**, **humidity**, **pressure**, **turbulence**, amount and size spectra of **aerosols**

Realization of the measurand Rn-222 activity concentration

certified Rn-222 activity + **certified volume** = **Rn-222 activity concentration**

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Seite 2 zum Kalibrierschein vom 12.12.2016, Kalibrierzeichen: PTB-6.13-11/2016
Page 2 of calibration certificate of 12.12.2016, calibration mark: PTB-6.13-11/2016

Gegenstand: *Object*	Aktivitätsnormal *Activity standard*
Typ: *Type*	Edelstahlzylinder mit Rn-222 *High-grade steel cylinder containing Rn-222*
Kenn-Nummer: *Serial number*	2016-1537
Radionuklid: *Radionuclide*	Radon-222 *Radon-222*
Kalibrierverfahren: *Method of calibration*	Die Aktivität des Rn-222-Gases wurde durch Messung der Gammastrahlung der kurzlebigen, mit Rn-222 im radioaktiven Gleichgewicht stehenden Folgeprodukte mit einem kalibrierten NaI(Tl)-Detektor bestimmt. Die Kalibrierkonstante für diesen Detektor wurde mit Rn-222 Aktivitätsnormalen der PTB ermittelt, deren Aktivitätsbestimmungen mit einem Halbleiter-Alpha-Spektrometer mit bekanntem Raumwinkel erfolgten. *The activity of the Rn-222 gas was determined with a calibrated NaI(Tl) detector by measuring the gamma radiation emitted by the short-lived decay products, which were in radioactive equilibrium with Rn-222 at the time of measurement. The calibration constant of this detector was determined with Rn-222 standards. The activities of these standards were measured at the PTB with a semiconductor alpha spectrometer with defined solid angle.*
Aktivität: *Activity*	$A = (6{,}59 \pm 0{,}12)$ kBq
Bezugszeitpunkt: *Reference date*	21. September 2016, 00:00 Uhr MEZ *00:00 CET on 21 September 2016*

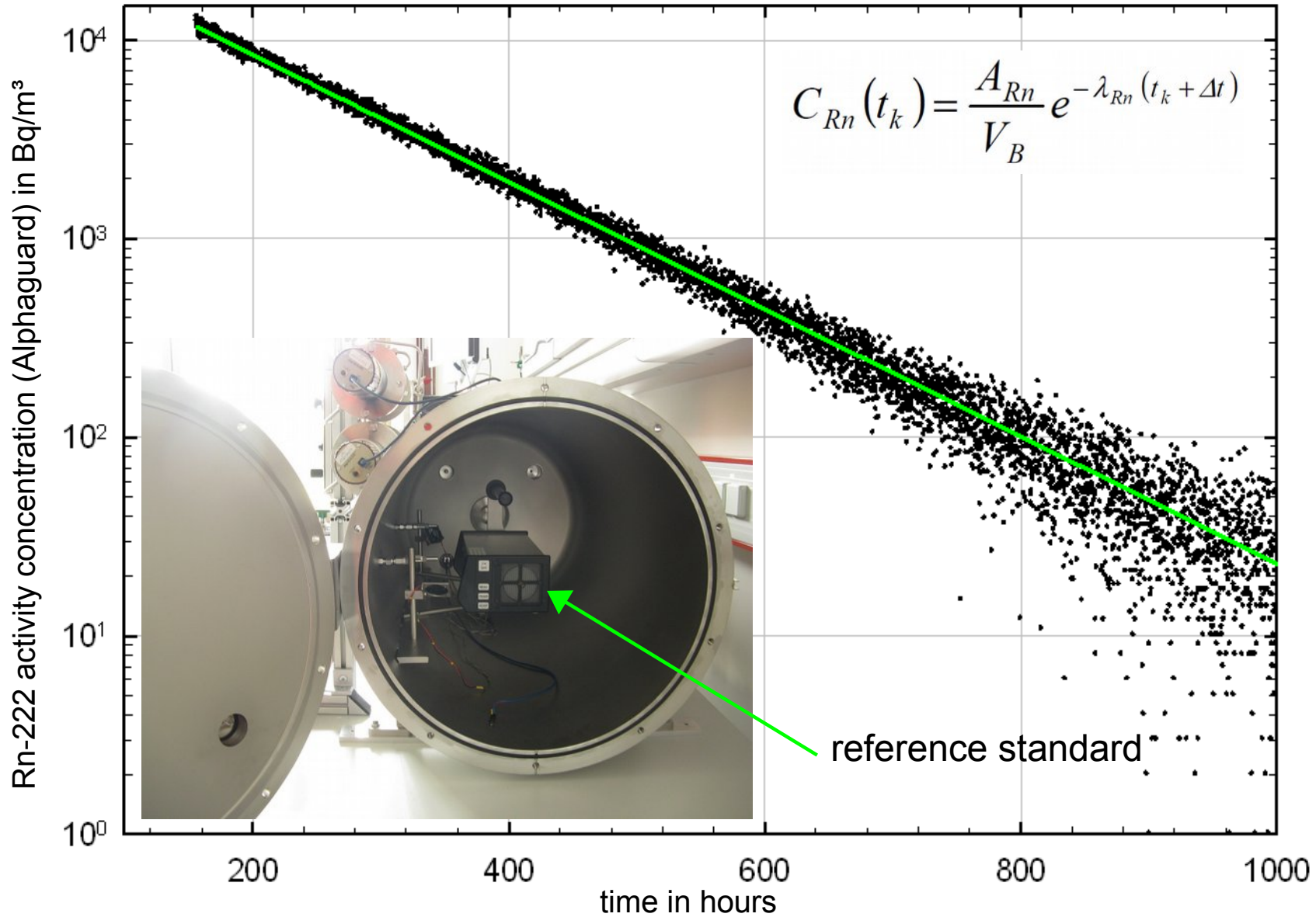
vacuum chamber
empty: **168.1** dm³
+ AG: **166.2** dm³

activity transfer
(by vacuum)

→

pressure and
temperature
controlled

Realization of the measurand Rn-222 activity concentration



Calibration procedures - Rn-222 activity concentration

reference standard

calibration of working standards

- scintillation cells and
- flow-through scintillation cells
- Alphaguards, Atmos

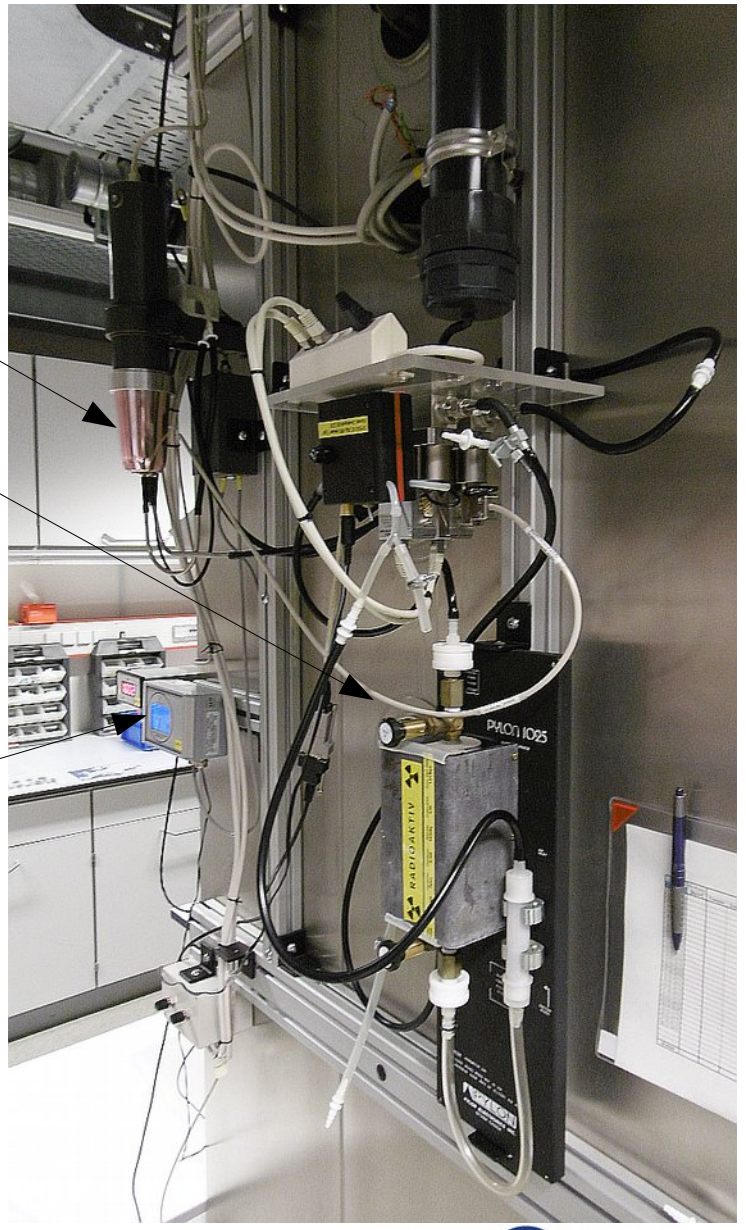
Calibration procedures - Rn-222 activity concentration

Example: BfS radon calibration chamber (11 m³)

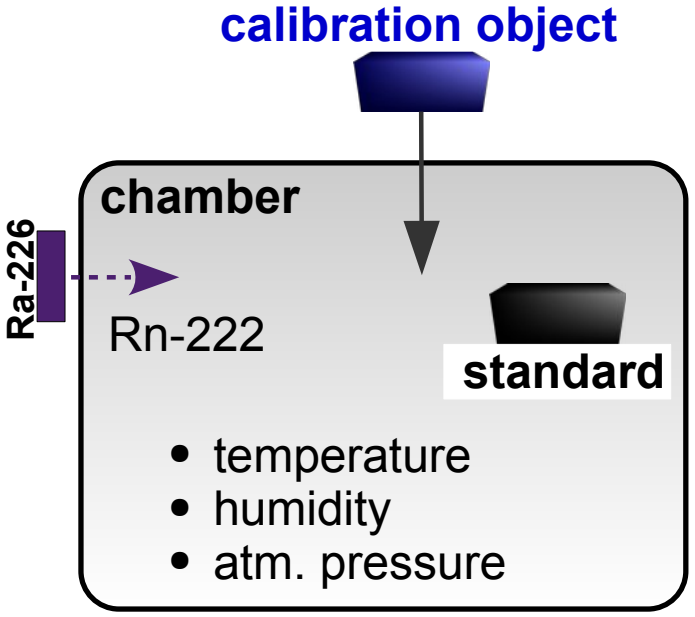
working standard: flow-through scintillation cell calibrated with reference standard

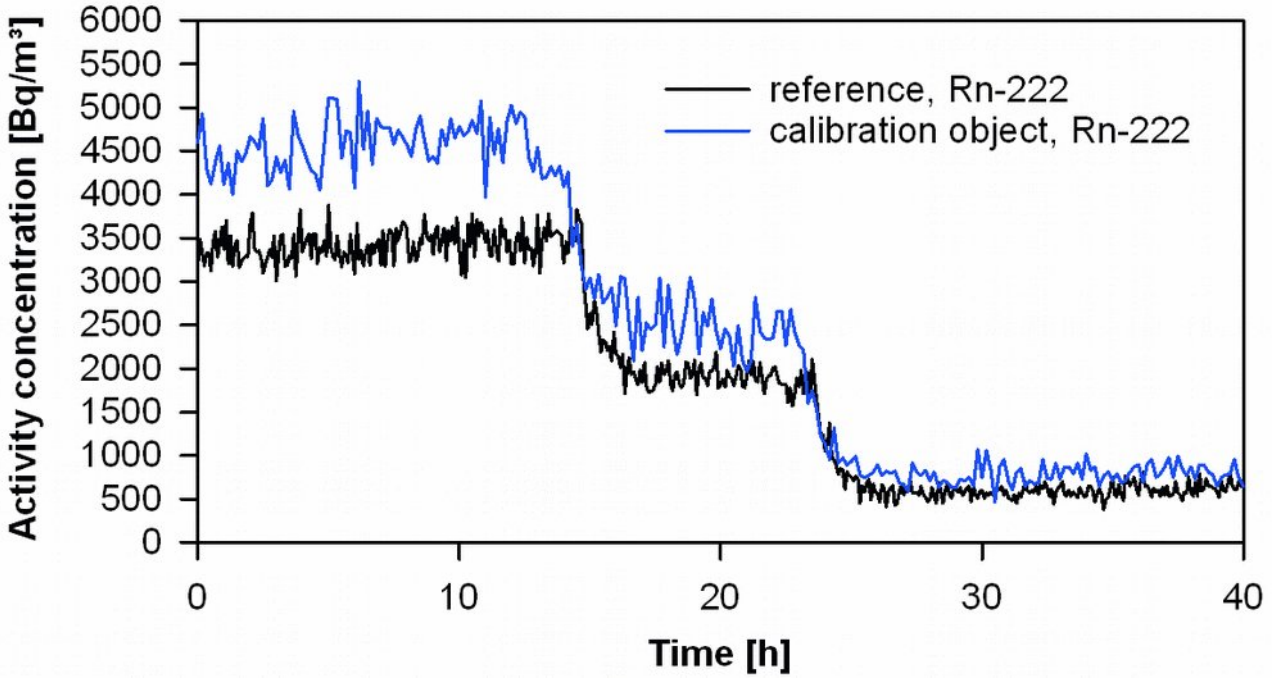
Pylon flow-through Ra-226 source with flow separation to adjust redosing

- temperature
- rel. humidity
- atmospheric pressure



Calibration procedures - Rn-222 activity concentration



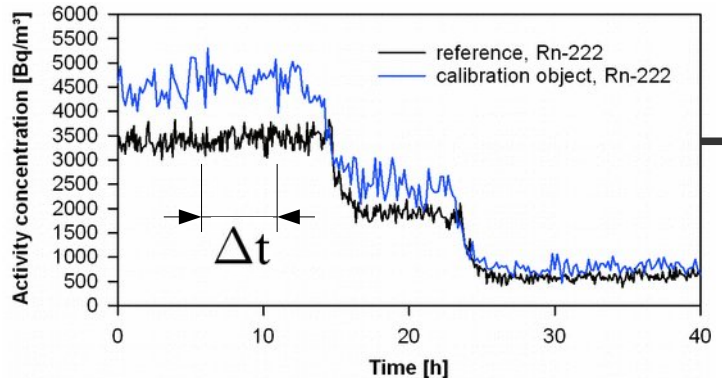


→ "*Operation [...] under **specified conditions ...**"*

→ **stable** concentration mode (continuous dosing)

Calibration procedures - Rn-222 activity concentration

Calculation of the calibration factor k_M



$$k_M = \frac{C_{Ref}}{C_M - C_0}$$

mean Rn-222 activity concentration within Δt

C_M: of the calibration object

C_{Ref}: of the working standard

C_0: blank indication of the calibration object

Δt depends on calibration object's sensitivity

Radon-222 activity concentration

C_0 = 4 Bq /m³

$U(C_0)$ = 5 Bq /m³

calibration results

Nr.*)	$C_M - C_0$	$U(C_M - C_0)$	C_{Ref}	$U(C_{Ref})$	k_M	$U(k_M)$	Δt	T	r.H.	p
	Bq/m³	Bq/m³	Bq/m³	Bq/m³			Stunden/ Hours	°C	%	hPa
1	320	22	272	27	**0,85**	0,11	54	25	49	1003
2	1622	98	1363	118	**0,84**	0,09	4	26	38	1001
3	4712	286	3489	243	**0,74**	0,08	4	25	43	1010

*)Nummer der Messung / *Number of measurement*

example table (not the same calibration as in the graph)

Calibration procedures - Rn-222 activity concentration

Accreditation certificate D-K-15063-01-00 (BfS)

measurand	measurement range	minimal reportable uncertainty U(k=2)
Rn-222 activity concentration	50 – <80 Bq/m³	17 %
	80 – <300 Bq/m³	12 %
	300 – <1000 Bq/m³	8 %
	1000 – <12000 Bq/m³	5 %
PAEC of short-lived Rn-222 decay products	0.32 – <6.4 µJ/m³	10 %
	6.4 – <64 µJ/m³	6 %
	64 – <640 µJ/m³	6 %

If uncertainty calculations show higher uncertainty values than these are reported.

calibration object
- st. error of the mean µ
- std. uncertainty of blank indication

$$u(\mu) = \frac{SD}{\sqrt{N}}$$

working standard
- std. error of the mean µ
- std. uncertainty of blank indication
- previous calibration hierarchy and drift

expanded uncertainty U = k * u with coverage probability >95%, k=2 for large number of values N (see also GUM JCGM 100:2008 Table G.2, e.g., k = 2.57 for N = 6)

Calibration procedures - Rn-222 activity concentration

Bundesamt für Strahlenschutz
Radon-Kalibrierlaboratorium
Köpenicker Allee 120 – 130
10318 Berlin

Bundesamt für Strahlenschutz

akkreditiert durch die / *accredited by the*

Deutsche Akkreditierungsstelle GmbH

DAkkS Deutsche Akkreditierungsstelle D-K-15063-01-00

als Kalibrierlaboratorium im / *as calibration laboratory in the*

Deutschen Kalibrierdienst DKD

1000
D-K-15063-01-00
2018-05

Kalibrierschein
Calibration certificate

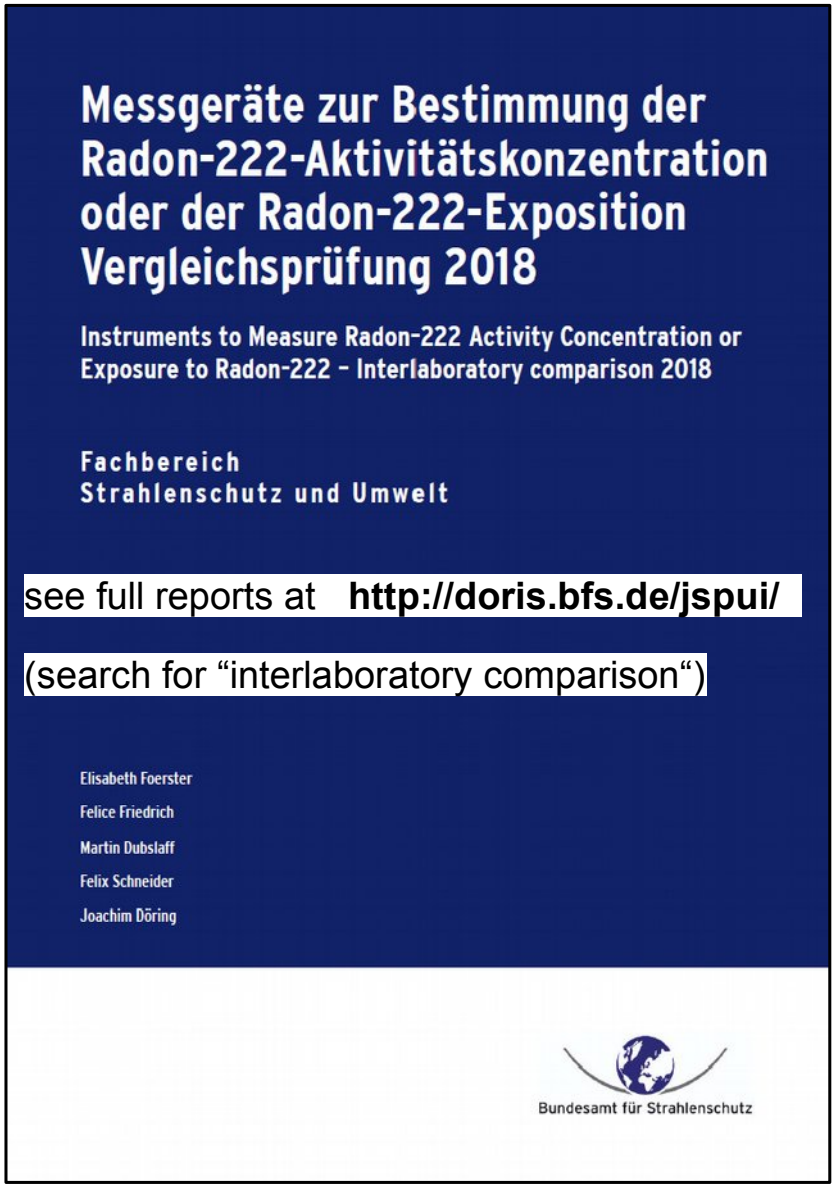
Kalibrierzeichen
Calibration mark

Gegenstand *Object*	**Radonmessgerät / *Radon measuring instrument***
Hersteller *Manufacturer*	**Super example company GmbH/Ltd.**
Typ *Type*	**VeryBestRadonDevice 2000**
Fabrikat/Serien-Nr. *Serial number*	**12345**

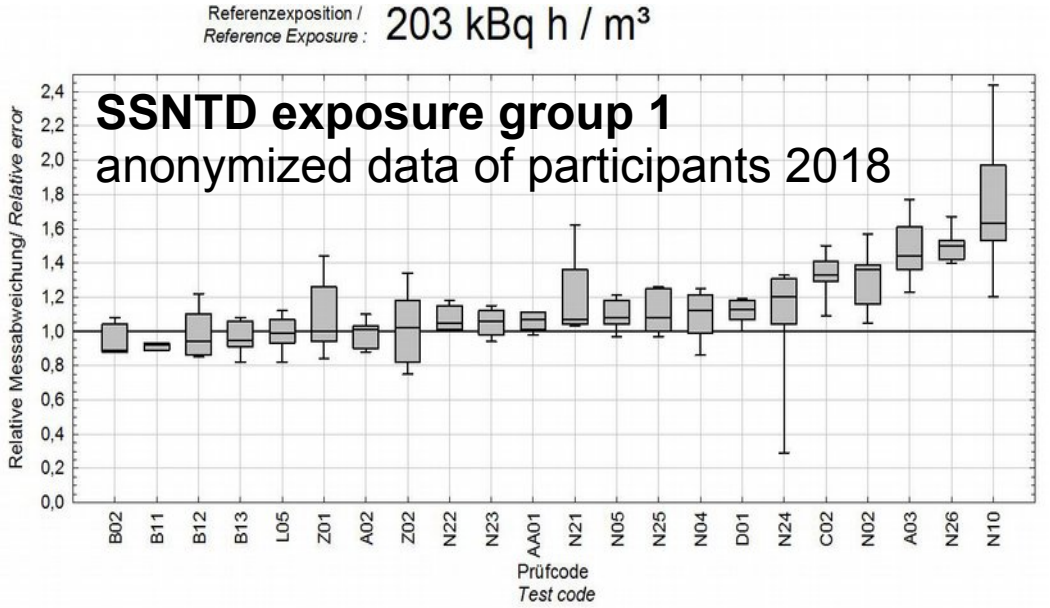
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).

Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur ge-

Interlaboratory comparisons and proficiency testing



- 35 SSNTD or 24 electrets per participant
- 4 exposure groups for SSNTD (3 for electrets)
- at least 2 exposure values close together
- results anonymized



Interlaboratory comparisons and proficiency testing

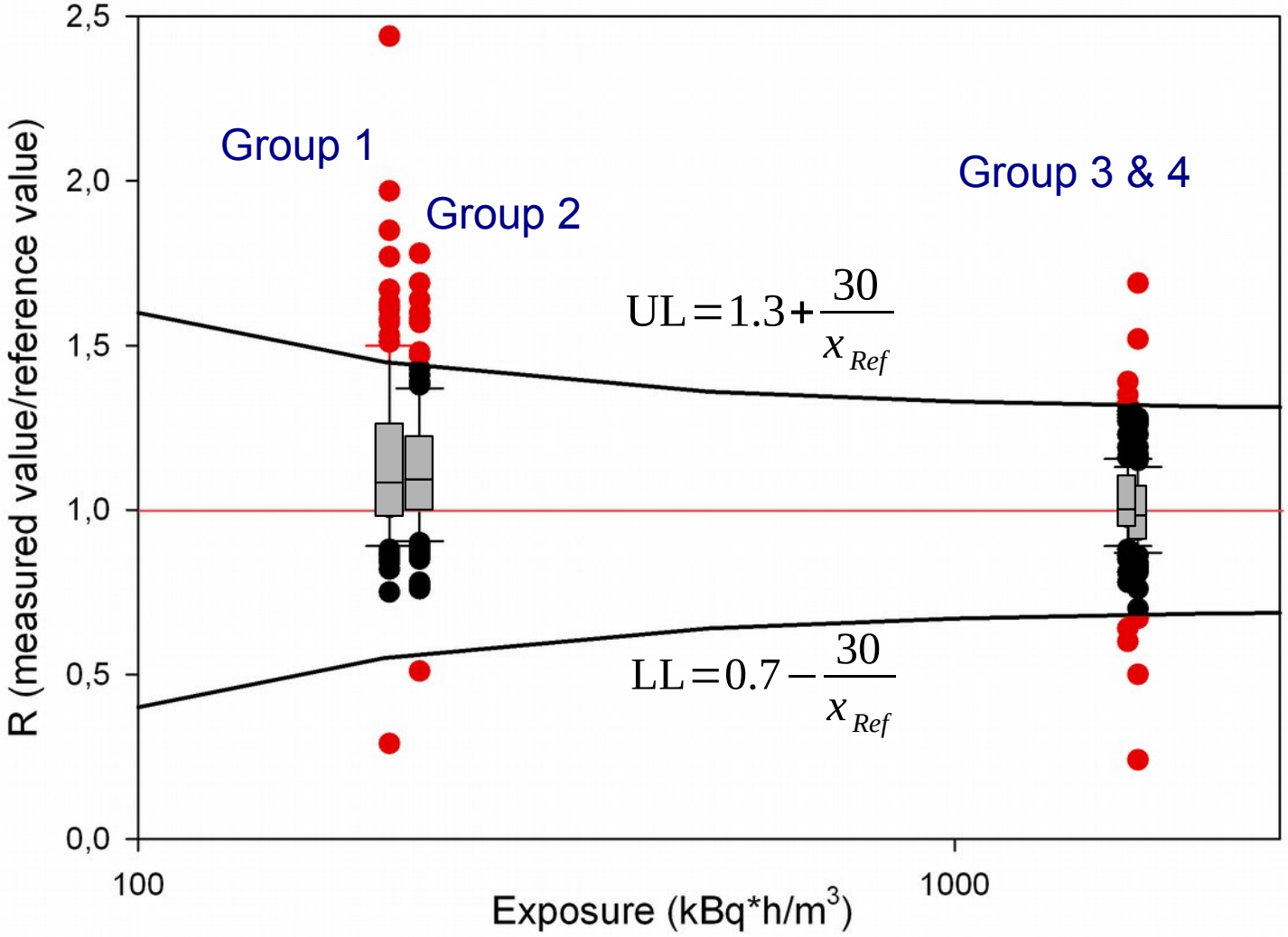
Additional **proficiency testing** since 2019 due to new Radiation Protection Ordinance with relative upper (UL) and lower (LL) **performance limits** shown in the trumpet curve:

Test with data from BfS Interlaboratory Comparison 2018

Boxplots and outliers of all 4 exposure groups

Group 1: **203** kBq*h/m³
Group 2: **221** kBq*h/m³
Group 3: **1629** kBq*h/m³
Group 4: **1676** kBq*h/m³

- outliers of proficiency testing



Interlaboratory comparisons and proficiency testing

Outliers to pass the test

number of detectors	accepted number of outliers
8 - 17	0
18 - 27	1
28 - 37	2
38 - 47	3

derived from:
Beck T. R., Foerster E., et al., *The measurement accuracy of passive radon instruments*, Rad. Prot. Dosim. (2014), Vol. 158, No. 1, S. 59-67

To pass the test is one requirement for institutions that want to provide exposimeters for radon measurements in Germany acc. to the new Radiation Protection Ordinance.

Interlaboratory comparisons

Blank indication interlaboratory comparison 2017 of BfS and ENEA

- Deliverable D1.6.7 of MetroERM, JRP EMRP-ENV57
- Project coordinator S. Neumaier (PTB) as independent referee
- AlphaGuard from ENEA sent to BfS, reports sent directly to PTB only
- Measurement of several days during radon-free gas purging

MetroERM radiological early warning

Results (all uncertainties with k=1)

ENEA-INMRI / Italy, Francesco Cardellini: (**2.5** ± 0.5) **Bq/m³**

BfS Radon calibration laboratory / Germany: (**2.9** ± 0.6) **Bq/m³**

Also for measurements < 300 Bq/m³ (EU BSS) blank indication gets more important!

Interlaboratory Comparison of Rn measurement devices

- work in progress: MetroRadon WP 5.2.4.
- BfS sent device to different metrological institutions
- calibration at 400 Bq/m³, 1 kBq/m³ and 6 kBq/m³

Metro RADON

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

→ see also presentation by Hannah Wiedner, BEV

Calibration procedures - Rn-222 decay products (PAEC)

Example: **BfS PAEC chamber (30 m³)** and calibration procedure

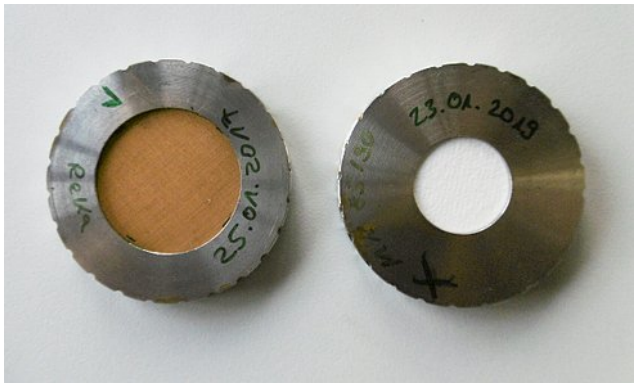
aerosols by
NaCl atomizer

aerosol counting
and spectra with
CPC & SMPS

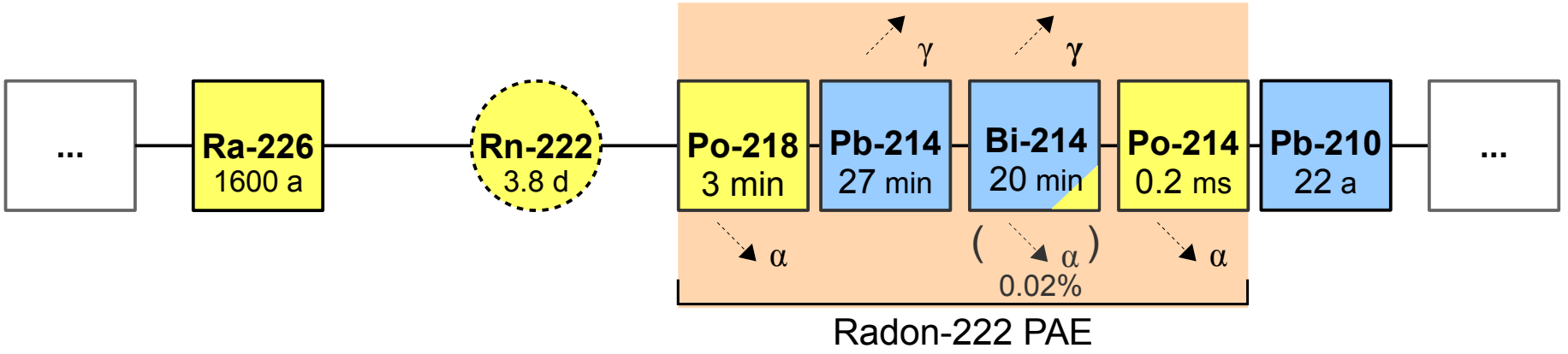
Calibration procedures - Rn-222 decay products (PAEC)

sampling rod with **glass fiber filter** + **wire screen** on top

→ collection of decay products (attached and unattached)



Calibration procedures - Rn-222 decay products (PAEC)



- determined **filter efficiency** (>99.9%)
- wire screen is used to determine unattached fraction only
- **alpha spectrometry**
  → calibrated via combined or sequential α and γ measurement
  (α from Po-214 and γ from Bi-214)

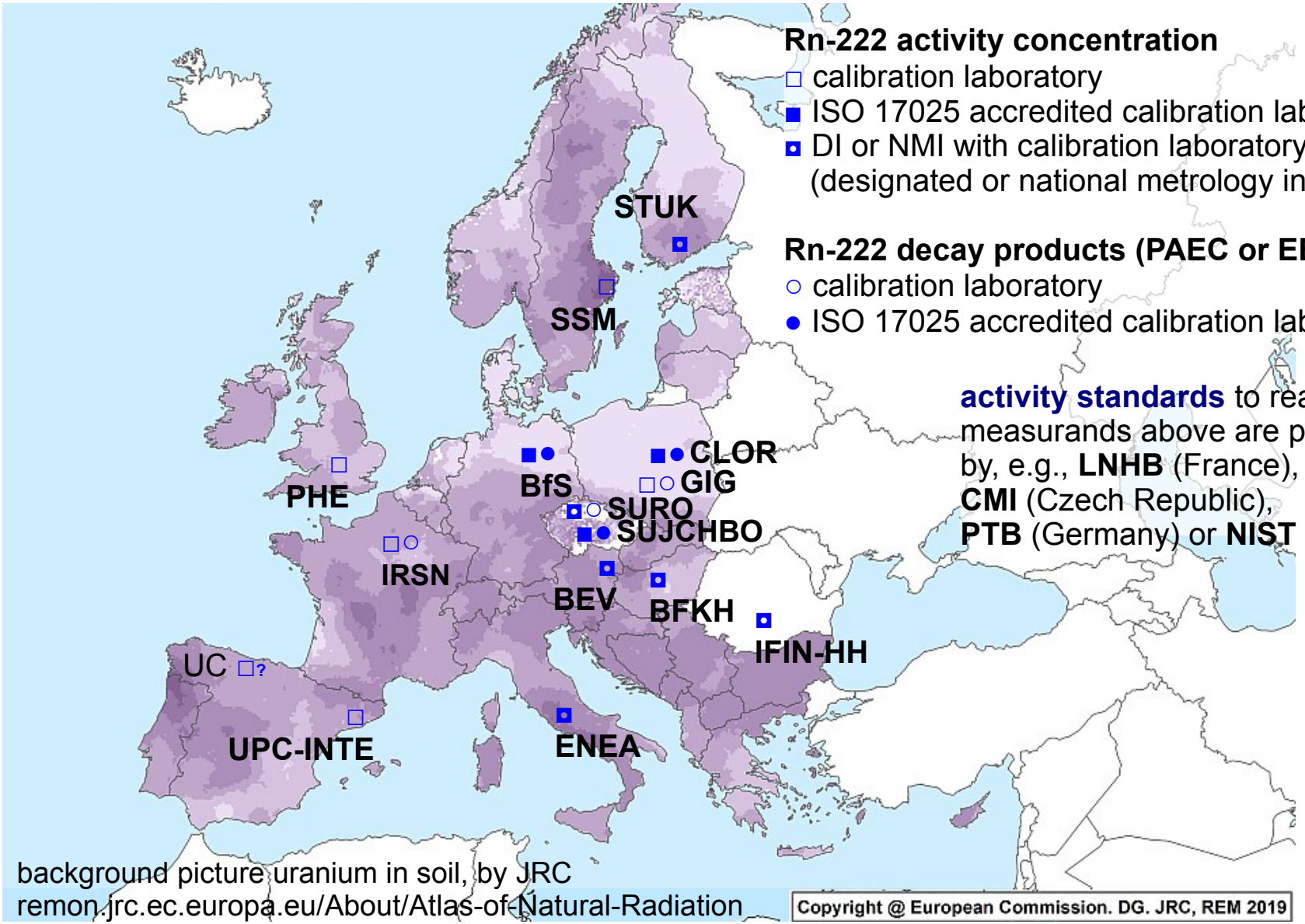
  → Po-214 and Bi-214 are always in equilibrium

  traceability:

  Ra-226 plane source (Dp in equilibrium) with PTB certified activity and **calibrated volume flow rate**

Radon chambers in Europe that offer calibration services

(as far as known to the author)



Rn-222 activity concentration

- □ calibration laboratory
- ■ ISO 17025 accredited calibration laboratory
- ◘ DI or NMI with calibration laboratory (designated or national metrology institute)

Rn-222 decay products (PAEC or EEC)

- ○ calibration laboratory
- ● ISO 17025 accredited calibration laboratory

activity standards to realize the measurands above are provided by, e.g., **LNHB** (France), **CMI** (Czech Republic), **PTB** (Germany) or **NIST** (USA)

background picture uranium in soil, by JRC
remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation

Summary

- **measurands** Rn-222 activity concentration and PAEC
- examples of radon **measuring instruments**
- **sources,** characteristics of **chambers** and measurement **standards**
- calibration **procedures** with examples of the BfS radon calibration laboratory
- interlaboratory **comparisons** and overview over radon calibration services

Acknowledgements to ...

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… and **YOU** for your attention.

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