RADON

30 different isotopes, only two reaching non negligible concentrations in the atmosphere:

- no chemical bond
- no surface attachment (adsorption, except char coal)
- can emanate from solids
- will diffuse easily through the most materials
- will fast disperse in air
- generates a chain of radioactive decay products, all of them are heavy metals

discovered in 1900 by F. Dorn

Inert, colourless, odourless, radioactive rare gas.
Radon Origin and Distribution

Variation of the Radon concentration in the environment

Indoor air: $10^6...10^7$ Bq/m$^3$

Outdoor air: $10^6...10^7$ Bq/m$^3$

- Exhalation from building materials
- Exhalation from water sources
- Ventilation
- Transfer from the basement
- Connection

Surface water: $10^3...10^4$ Bq/m$^3$

Ground water: $10^3...10^4$ Bq/m$^3$

Soil air: $10^3...10^4$ Bq/m$^3$

Emanation

Migration

Availability

Emanation
Airborne Radon Decay Products

Radon generates aerosols carrying radioactive decay products within in the air.
Dangerous Impact of Radon Daughters

No impact by Radon gas
Deposition of daughter products within the lung
Decay directly at the surface of the epithelium
Emitted Alpha radiation damages cell nucleus and cause genetic defects

Goal:
Assessment of the injurious impact of inhaled Radon daughter products!

Radon is risk factor No. 2 for lung cancer - after smoking!
Terms and Definitions

We know: some of the Radon daughters emitting dangerous Alpha radiation

Radon decay chain

PAE (Potential Alpha Energy)

PAEC (Potential Alpha Energy Concentration)

PAEE (Potential Alpha Energy Exposure)

Equivalent Dose

We want: a measure for the injurious impact to the human body
Radioactive Decay and Activity

\[ N(t) = N_0 e^{-\lambda t} \]

\[ \lambda = \ln 2 / T_{1/2} \]

\[ A = \frac{dN}{dt} = \lambda N = N \times \ln 2 / T_{1/2} \]

\[ N = A \times T_{1/2} / \ln 2 \]
The radioactive Alpha Decay

CHARACTERISTICS
Atoms with high mass number
Electrostatic forces > nuclide gravitation
Emitting a He kernel (2 protons, 2 neutrons)
Nuclide specific monoenergetic emission
Alpha energy range from 4 to 9 MeV
Ionisation of remaining atom

EXAMPLES:
Po-218 at 8.785 MeV
Am-241 at 5.485 MeV
U-238 at 4.197 MeV (77%) and 4.147 MeV (23%)
Radon (Rn-222) decay chain

Rn-222
\[ \alpha \ 5.40\text{MeV} \ 3.83\text{d} \]

Po-218
\[ \alpha \ 6.00\text{MeV} \ 3.05\text{min} \]

\[ \begin{align*}
Pb-214 & \xrightarrow{\beta} Bi-214 \\
      & \xrightarrow{\beta} Po-214 \\
      & \xrightarrow{\alpha} Pb-210 \\
\end{align*} \]

Biological Half Life Time much shorter \( \Rightarrow \) No Impact by Po-210

Po-210
\[ \beta \ 5\text{d} \ 5.30\text{MeV} \ 138\text{d} \]

Pb-206
\[ \alpha \ 7.69\text{MeV} \ 164\mu\text{s} \]
Potential Alpha Energy - PAE

\[ \sum E_\alpha \text{(any Radon daughter } \Rightarrow \text{ Pb-210)} \]
Potential Alpha Energy Concentration of any Progeny mixture in the air - PAEC

\[
\text{PAEC} = 75.38 \text{ MeV/Litre}
\]

\[
\sum (\text{PAE}) = \frac{\text{Bi-214, Po-214}}{\text{Po-218, Pb-214}} \frac{10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}}{\text{AIR VOLUME}}
\]
Potential Alpha Energy Exposure - PAEE

The amount of inhaled and deposited Radon progeny depends generally on:

- Potential Alpha Energy Concentration in the breathing air
- Time Interval during which a person is exposed to this PAEC

This connection is described by the term of PAEE:

\[
\text{PAEE} = \text{PAEC} \times \text{TIME}
\]

PAEE takes not in account individual deposition process in the lung (breathing rates and particle size distribution) and also not the biological impact to the human body!
Dose Coefficient and Equivalent Dose

To include the individual factors, the Dose Coefficient $D$ was defined. $D$ is the correlation factor between offered PAEE and biological impact specified by the Dose $H$

$$H = PAEE \times D$$

Because of the individuality of Dose Coefficient the most limits are stated as Exposures and not as Dose
Radon Gas and Progeny

Radon Activity Concentration → „Plate Out“ → Equilibrium Factor F → EEC (Equilibrium Equivalent [Radon] Concentration) → PAEC → Equivalent Dose
Radioactive Equilibrium

Assumption: No „Plate Out“ ⇒ Radioactive Equilibrium of Radon and Progeny

is given:
if the generated number is equal to the decayed number of atoms of any nuclide within the decay chain (all nuclides have the same activity A)
takes place:
after about 4...5 Half Life Times $T_{1/2}$ of the nuclide with the longest HLT

because of: $N = A*T_{1/2}/\ln 2$

particle number $N$ of nuclides with longer live must growing compared with the shorter living ⇒ Different particle numbers

For an atmosphere where Radon Progeny are in equilibrium with the Radon the PAEC can be derived, because the number of atoms $N$ of each nuclide can be calculated
Equilibrium Factor F and EEC

Radioactive Equilibrium never is given for Radon and its Progeny in the air because of the “Plate Out” effect.

Need for a relation between Equilibrium and non-equilibrium state:

\[ C(\text{Radon}) \times F = EEC \]

for the real Radon concentration \( C(\text{Radon}) \) of any non-equilibrium atmosphere with a given PAEC.

A factor F can be found to calculate a virtual Radon concentration (EEC) of an assumed atmosphere in equilibrium covering the same PAEC.

F characterises an atmosphere regarding the ratio Radon/Progeny.

Range of F is 0...1

Typical values for F are:
- Rooms with normal ventilation: 0.3 ... 0.6
- Large rooms with dusty or smoky air: 0.8
- Small volumes, moved air: 0.1
- Outdoor air: 0.7
Equilibrium Equivalent (Radon) Concentration - EEC

\[
\begin{align*}
\text{PAEC} & \quad \iff \quad \text{PAEC} \\
\text{of any mixture of Radon daughters} & \quad \iff \quad \text{of a virtual mixture of Radon daughters in radioactive equilibrium} \\
\frac{N_{\text{Po-218}}}{N_{\text{Pb-214}}} & \quad \neq \quad \frac{1}{6.53} \\
\frac{N_{\text{Po-218}}}{N_{\text{Pb-214}}} & \quad = \quad \frac{1}{6.53} \\
\text{EEC of this mixture} & \quad = \quad C_{\text{Po-218}} = C_{\text{Pb-214}} = C_{\text{Bi-214}} \\
\end{align*}
\]

\text{EXAMPLE}

\[
\begin{align*}
\text{PAEC} & = 105.5 \text{ MeV/L} \\
2x & \quad \text{Po-218} \quad 1x \\
8x & \quad \text{Pb-214} \quad 8.79x \\
5x & \quad \text{Bi-214} \quad 6.53x \\
\text{PAEC} & = 105.5 \text{ MeV/L} \\
\end{align*}
\]
Dose Calculation by Radon or Progeny?

Progeny measurement

\[ H = EEC \times t \times D \]

Radon measurement

\[ H = C_{Rn} \times t \times F \times D \]

Variable!
Physical Units - SI and US

<table>
<thead>
<tr>
<th>Physical Unit</th>
<th>SI Unit</th>
<th>US Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>Bq (Bequerel)</td>
<td>Ci</td>
</tr>
<tr>
<td>Activity Concentration (C, EEC)</td>
<td>Bq/m³</td>
<td>pCi/L</td>
</tr>
<tr>
<td>PAEC</td>
<td>J/m³ or MeV/m³</td>
<td>WL</td>
</tr>
<tr>
<td>Exposure</td>
<td>Jh/m³</td>
<td>WLM</td>
</tr>
<tr>
<td>Dose</td>
<td>Sv (Sievert)</td>
<td>rem (mrem)</td>
</tr>
<tr>
<td>Dose Coefficient</td>
<td>Sv/(Jh/m³)</td>
<td>rem/WLM</td>
</tr>
</tbody>
</table>

Unit conversion:
- 1 Bq = 27 pCi
- 1 Bq/m³ = 0.027 pCi/L
- 1 J/m³ = 6.24*10^{12} MeV/m³ = 4.8*10^4 WL
- 1 Jh/m³ = 282.35*10^{-6} WLM
- 1 Sv = 100 rem

Using EEC:
- 1 Bq/m³(EEC) = 5.4*10^{-9} J/m³ = 270.27*10^{-6} WL
# International Limits for Radon Exposure (Examples)

<table>
<thead>
<tr>
<th></th>
<th>Dwellings</th>
<th>Workplaces</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EU</strong></td>
<td>200 Bq/m³ (buildings under construction)</td>
<td>6*10^6 Bq/m³ (WLM)</td>
</tr>
<tr>
<td></td>
<td>400 Bq/m³ (existing buildings)</td>
<td></td>
</tr>
<tr>
<td><strong>P.R. China</strong></td>
<td>200 Bq/m³</td>
<td></td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td>4 pCi/L = 150 Bq/m³ (EPA)</td>
<td>4 WLM (DOE, EPA)</td>
</tr>
<tr>
<td><strong>ICRP</strong></td>
<td>200...600 Bq/m³ (1993)</td>
<td>4 WLM (1994)</td>
</tr>
</tbody>
</table>
Radon & Progeny Instrumentation

Radon Gas

Passive Methods
No power supply
integral exposure measurement
Analysis after exposure using special equipment

Track Etch  Electret

Silicon detector with HV- Attachment and Alpha Spectroscopy

Active Instruments
Electrical power required
Storing the time distribution of Radon concentration
Direct data reading

Ionisation Chamber  Szintillation Chamber (Lucas Cell)

First sample then analyse  Continuos analysis

Progeny

Pump/Filter Assembly
Alpha spectroscopy - The most sophisticated way to measure Radon!

- High Radon sensitivity
- Radon can fully corrected against Thoron interference
- Simultaneous Thoron measurement possible
- Fast response to dynamic concentration changes
- No long term contamination by Po-210
- No background correction necessary, low detection limits
- 100% linearity by count mode over the whole range
- Transparent measurements and source level quality insurance by available alpha spectrum and count sums
- No EMI and vibration interference
Detection of Alpha Rays

Strong interaction with matter (mass, charge)
continuos energy lost over the track
100% energy absorption even in thin layers (80...100µm Silicon)

Semiconductor Detector:

Low band gap → low ionisation energy
Electrons shifted from valence into conduction band by electrostatic interaction with the Alpha particle
Number of generated electron/hole pairs ~ particle energy
Electrons/holes drifting to the electrodes by electrical field
Alpha Spectroscopy

\[ E = mV^{1/2} \]

COUNTER ARRAY RELATED TO A SEQUENCE OF CONSECUTIVE ENERGY INTERVALS

FREQUENCY DISTRIBUTION OF ALPHA PARTICLES VS. ENERGY

ALPHA SPECTRUM

Counts

\[ \Delta E \]

Counter\# ~ Energy

0 1 254 255
Ideal and real Spectrum

PEAK:
Shape within the spectrum generated by a mono-energetic Alpha emission

PEAK AREA:
Number of counts within a peak (number of counts generated by this emission)

SPECTR. RESOLUTION
Increases with decreasing peak width (peak separation)
Counting Statistics

Nuclear (Activity) Measurement → Counting Experiment

Number of counts detected within fixed time interval is a Poisson distributed random variable with $\bar{X} = N_0$; $\sigma = \sqrt{N_0}$

$N$: 68% within $N_0 \pm 1\sigma$, 95% within $N_0 \pm 2\sigma$; 99.7% within $N_0 \pm 3\sigma$
Error of a single Measurement

The probability that the single measurement is placed within the $1\sigma$ band of the mean value is 68% ⇒ The probability that the real mean value is covered by the $1\sigma$ error of the single measurement is also 68%!

For each measurement statistical error and confidence interval have to be stated!

Generally, nuclear instrumentation uses 1-Sigma confidence interval if not stated explicitly otherwise.
Radon within the natural decay chains

- **U-238** → **Ra-226** → **Rn-222**
- **Th-232** → **Ra-224** → **Rn-220**

**Rn-222** (short living Radon daughters (Progeny))
- **Po-218** (12 min)
- **Po-214** (180 min)
- **Po-210**
- **Pb-210**

**Po-216** (1 sec)
- **Bi-212**
- **Po-212** (36%, 40 hrs)
- **Pb-208** (64%, Beta)

**Nuclide of origin**
Radon chamber operation

Filter prevents progeny inlet from ambient air
Radon/Thoron decay generates positive charged Po-218/Po-216 ions
Ions are collected on detector by electrical field forces
Alpha particle emitted by the decay of Po-218/Po-216 and their daughters are detected with high probability
Equilibrium state between collection and decay process after about four half life times of each nuclide
Progeny activity on detector surface is proportional to the Radon/Thoron air concentration
Radon calculation based either on Po-218 only (Fast Mode) or on sum of Po-218 and Po-214 (Slow Mode)

- **Fast Mode:** short response time
- **Slow Mode:** increased response time but doubled count statistics

Thoron calculation based on Po-216 only because of the slow response of Bi-212/Po-212
Nuclide separation by $\alpha$ spectroscopy

Acquisition of the alpha spectrum by a MCA connected to the detector

Definition of four ROI (region of interest) assigned to the several nuclides

Determination of ROI areas by addition of all counted events within a ROI

Count sum calculation for each nuclide taking into account the left peak slope (tailing) and the Bi-212 overlay in ROI1

**Tailing:**

Because tailings are detector constants a known percentage of the ROI area of the interfering peak will be subtracted from the affected ROI

**Bi-212:**

The Bi-212 count sum will be calculated by the unaffected Po-212 count sum within ROI4 and can subtracted from the peak area of ROI1 (ratio Po-212:Bi-212 is always 1:1.78).
Progeny Sampling Head Operation

Collection of Radon progeny on a filter

Equilibrium between collection and decay after about 3 hours

Filter activity of Alpha emitters Po-218 and Po-214 proportional PAEC (collected Pb-214 and Bi-214 results in increased Po-214 activity)
Special Features of Progeny Sampling

Po-218 as a fast tracer

Po-218 - after 12 min in equilibrium - indicates dangerous PAEC levels immediately

Filter analysis after switch off the pump ...

... ensures 100% accuracy by including all collected aerosols into the exposure calculation

LLRD analysis using filter spectrum
Radon Measurements

**Radon in buildings**
(Risk assessment)

Passive methods, active Radon and Progeny monitors

**Radon at Workplaces**
(Dosimetry)

Passive methods, active Radon and Progeny monitors

**Air Quality Monitoring**

Active Radon and Progeny monitors

**Investigation of building ground**

Active Radon Monitors

**Special applications**
(Geological survey, tracer applications)

Active Radon Monitors
Radon in Buildings

Problem:

The Radon concentration is affected by external factors like ventilation, weather or pressure conditions. Variations by a factor of 100 are possible!

„First Check“ (general survey) measurements

to proof whether increased Radon exposure is expected or not

Snapshot sample at one selected (experience based) place. One hour to one day sample time.

Radon Risk Assessment

to determine the real annual exposure including the external factors

to find out possibilities to decrease Radon levels

to optimise remedial action if necessary

Long period measurements at several locations accordant the habit of the owner
Example of a Radon affected Building
Instrument Requirements

- No disturbance of the people who living in the building
- Reliable data without need for device access during measurement
- Meaningful results with respect to remedial actions
- Easy data access and handling to create protocols
  - No noise emission (no or switched pump)
  - Mains power independence
  - Time distributed concentration available
  - Protection against unintended manipulation
  - Quality assurance features
  - Small and lightweight (may sent by mail)
  - Low price (simultaneous measurements)
Radon affected Workplaces

Mines, Shafts, Tunnels, Caves/Show Caves, Radon Spas, Waterworks

Dosimetry Concepts

Personal Dosimetry
For people who working temporary at several places with undefined conditions
Unknown Radon Concentrations
Unknown Equilibrium Factor
Heavy short time exposure

Localised Dosimetry (tied to a certain place)
For people who working continuos at defined places
Low Concentrations variations
Well known Equilibrium Factor
No hazardous Radon Levels

Radon Measurements
Radon or Progeny Measurements

SARAD® GmbH
ENVIRONMENTAL INSTRUMENTS
www.sarad.de
Workplace with changing conditions

- Aerosol Generator ON (Candle, Cigarettes)
- Air Cleaner ON
- Air Cleaner OFF
Assessment of Building Ground

Diffusion from foundation soil into the building is the most common source of increased indoor Radon concentrations. The Investigation helps to reduce costs - arrangements regarding Radon protection can made from begin.

A Grid of 1 to 2 m deep holes have to be drilled in the soil. After sealing the holes at the surface the Radon potential will be measured.

Requires a fast and easy to handle Monitor to carry out several measurements in a short time. An internal pump to take the samples is recommended.

Thoron is mostly available in soils. Don’t use instruments without Alpha spectroscopy.
Who needs to measure Radon/Progeny

- Government

   Regulations to protect the population

   Authorities

   Companies under authority observation

   Assurances

   Constructors, Sellers/Resellers of Buildings

   Buyers and Users