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Exposure to Radon

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- Thoron
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Radon

- **Radon (^{222}Rn)**
  - inert gas
  - naturally radioactive
  - Part of ^{238}U decay series
  - ^{226}Ra as its immediate parent
  - Half-life 3.8 days
  - Short-lived decay progeny: ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po
  - Main exposure pathway — Escape of ^{222}Rn to the air and subsequent inhalation
  - Secondary exposure pathway — Dissolution of ^{222}Rn in groundwater and subsequent ingestion (or inhalation on release from water into the air)

Decay chain of Rn-222

		Half-life
Radon gas	^{222}Rn	3.8 d
	↓	
Polonium	^{218}Po	3 min
	↓ α	
Lead	^{214}Pb	27 min
	↓	
Bismuth	^{214}Bi	20 min
	↓	
	^{214}Po	160 μs
	↓ α	
	^{210}Pb	22 y

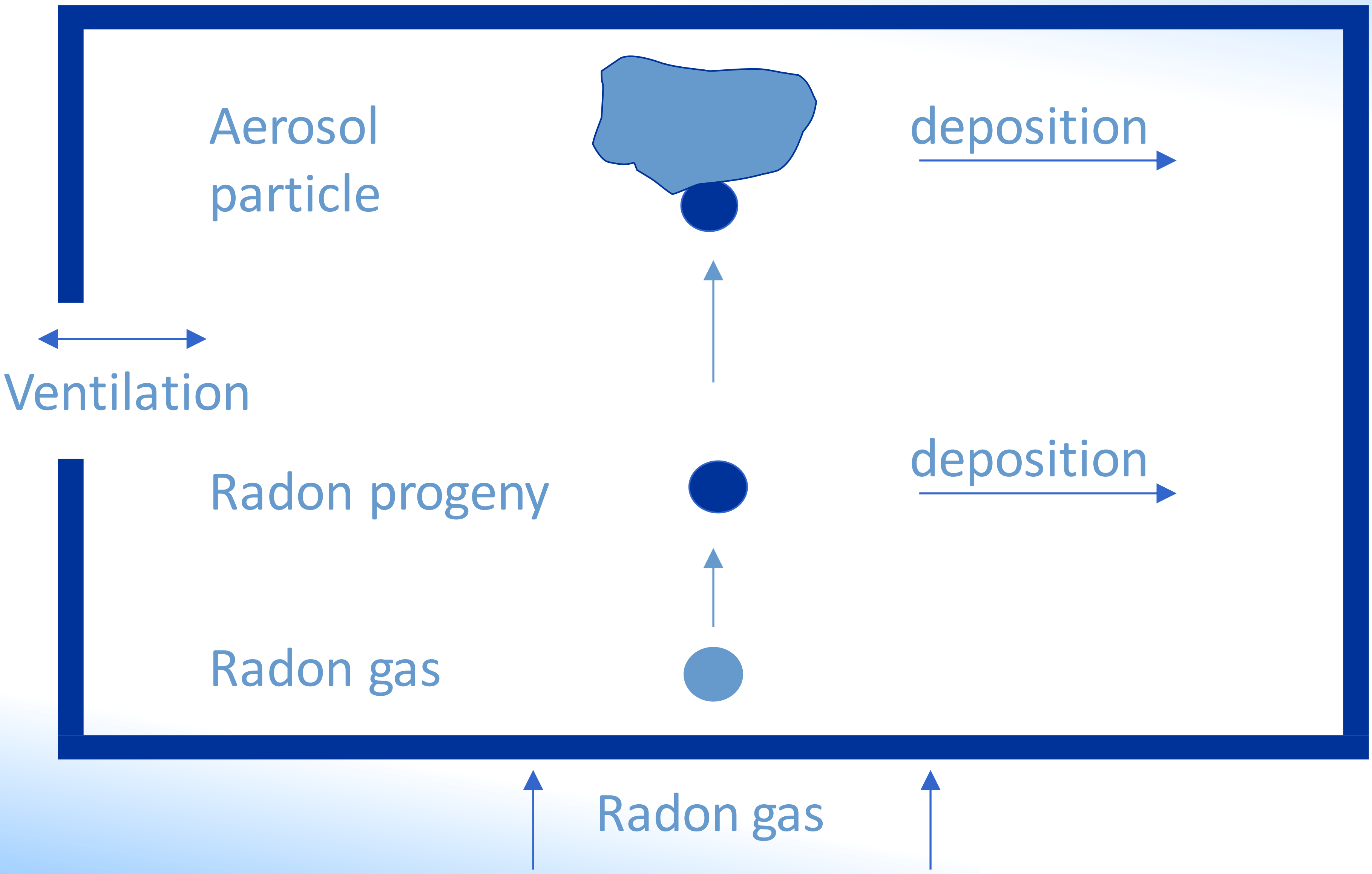
Thoron

- **^{220}Rn (thoron)**
  - Part of ^{232}Th decay series
  - ^{224}Ra as its immediate parent
  - Gaseous form
  - Short half-life ~56 seconds
  - Rapidly decays into thoron progeny
  - Progeny have a half-life of up to 10.66 hours
  - Exposures from progenies ^{212}Pb and ^{212}Bi
  - Inhalation exposure is the main concern particularly in thorium processing facilities
  - Only transported over short distances
  - In the absence of thoron gas the progeny concentrations decline slowly

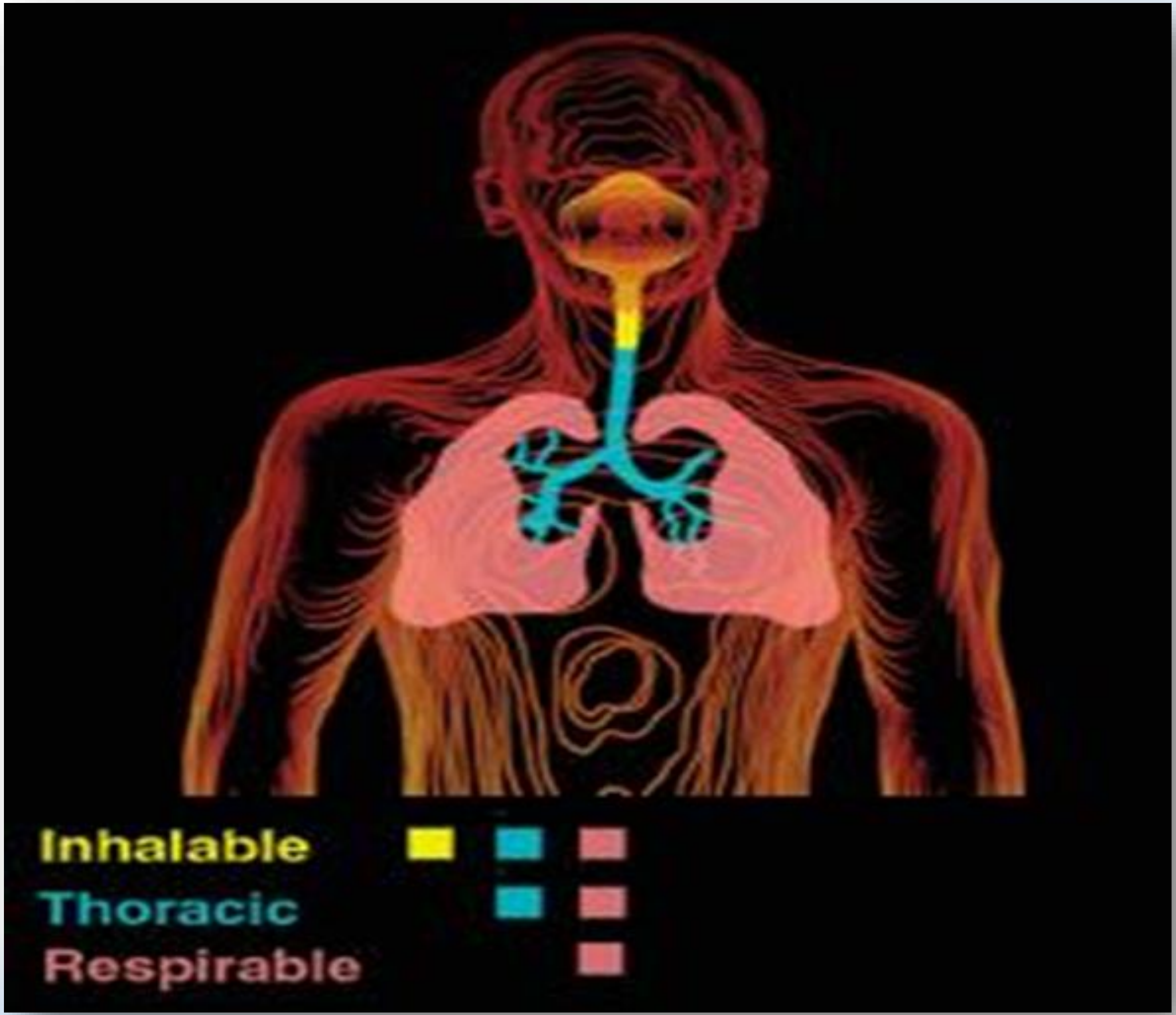
Exposure of the lung

- Contribution of ^{222}Rn itself to the lung dose is very small
  - Most of the inhaled gas is breathed out again
- Short-lived progeny are responsible for about 99% of the dose:
  - Atoms attach to condensation nuclei and dust particles in the air that is inhaled
  - Unattached progeny also inhaled
  - Deposited along the various airways in the bronchial tree
  - Most exposure comes from alpha particles
  - Contributions from beta and gamma emissions are small in comparison

Formation of radon progeny aerosol



Respiratory tract



Application of the Standards to ^{222}Rn in workplaces

- Workplaces where exposure to other U, Th series radionuclides already needs to be controlled as a planned exposure situation:
  - Exposure to ^{222}Rn is subject to the requirements for planned exposure situations, regardless of the radon concentration
  - Regulatory control must be considered
  - Any necessary control measures for ^{222}Rn must be included in the RPP

Application of the Standards to ^{222}Rn in workplaces

- Workplaces where exposure to other U, Th series radionuclides does not need to be controlled:
  - *Above-ground workplaces:*
    - High ^{222}Rn levels can usually be reduced to well below the reference level by remedial action:
    - Regulatory control as a planned exposure situation is therefore unlikely to be needed
  - *Underground workplaces*
    - ^{222}Rn may be more difficult to control by remedial action:
      - High ^{222}Rn ingress via rock surfaces or water, limitations on ventilation
    - Regulatory control as a planned exposure situation is necessary if the ^{222}Rn concentration remains above the reference level

Special quantities for concentration and exposure

- Short-lived ^{222}Rn progeny are unlikely to be in equilibrium with the parent
- Therefore, for radiation protection purposes, special quantities are needed for ^{222}Rn progeny:
  - Concentration in air
  - The resulting exposure
- These special quantities are derived from a quantity known as the ‘potential alpha energy’

Potential alpha energy

The potential alpha energy ε_p of a single atom of a short-lived ^{222}Rn progeny radionuclide is the total alpha energy emitted by that atom during its progressive radioactive decay down to, but not including, the relatively long-lived radionuclide ^{210}Pb

Potential alpha energy concentration

Potential alpha energy concentration (PAEC) in air:

For any mixture of short-lived ^{222}Rn progeny in air, the contribution of each radionuclide to the PAEC is its potential alpha energy per unit activity (ε_p/λ) given in the previous.

Table multiplied by its activity concentration, *c*. The total PAEC is then the sum of these individual contributions

$$PAEC = \sum_i c_i \left(\varepsilon_{p,i} / \lambda_i \right)$$

Equilibrium factor

- In practice, the progeny will rarely be in equilibrium
- The PAEC will therefore be some fraction of 5.56×10^{-9} J/m^3.
- This fraction is called the equilibrium factor (*F*)
- For a ^{222}Rn concentration of 1 Bq/m^3, the PAEC of any given non-equilibrium mixture will be:

$$PAEC\left(\mathrm{J}/m^3\right) = 5.56 \times 10^{-9} \times F$$

Equilibrium factor

The equilibrium factor can vary from:

- **Zero** (radon gas diffusing out of the grain surface of the mineral)

  to

- **1** (radon gas after three hours in stagnant air)

An equilibrium factor of 0.4 is usually taken as a default value

The older the air the higher the progeny concentrations

Equilibrium factor, F

F is a measure of the degree of dis-equilibrium between radon gas and its progeny

F=1

Nuclide	Bq m^{-3}
^{222}Rn gas	1.0
^{218}Po	1.0
^{214}Pb	1.0
^{214}Bi	1.0

F=0.4

Nuclide	Bq m^{-3}
^{222}Rn gas	1.0
^{218}Po	0.7
^{214}Pb	0.4
^{214}Bi	0.3

The value of *F* depends on the ventilation rate :

Indoors : F $\approx$ 0.4 Natural ventilation

Mines :F $\approx$ 0.2 Forced ventilation

Potential alpha energy concentration Exposure

- Multiply PAEC (J/m^3) by occupancy (h) to give exposure in units of $J \cdot h \cdot m^{-3}$
- The PAEC will vary with time, so the exposure has to be calculated as an integral over time (which in practice is the average concentration):
- Exposure usually determined over 1 year
- A default annual occupancy time of 2000 h may be assumed for workplaces (often conservative)

Equilibrium equivalent concentration

- Equilibrium equivalent concentration (EEC) is an alternative to using PAEC
- EEC is the concentration of ^{222}Rn in equilibrium with its progeny that would give the same PAEC as the actual non-equilibrium mixture
- The EEC is related to the PAEC by a constant factor:

$$PAEC\left(\text{in J/m}^3\right) = 5.56\times10^{-9}\times EEC\left(\text{in Bq/m}^3\right)$$

Historical unit of exposure (for awareness)

- Exposure is sometimes expressed in historical units of 'working level month' (WLM)

$$1\ \text{WLM} = 0.00354\ \text{J}\cdot\text{h}\cdot\text{m}^{-3}$$

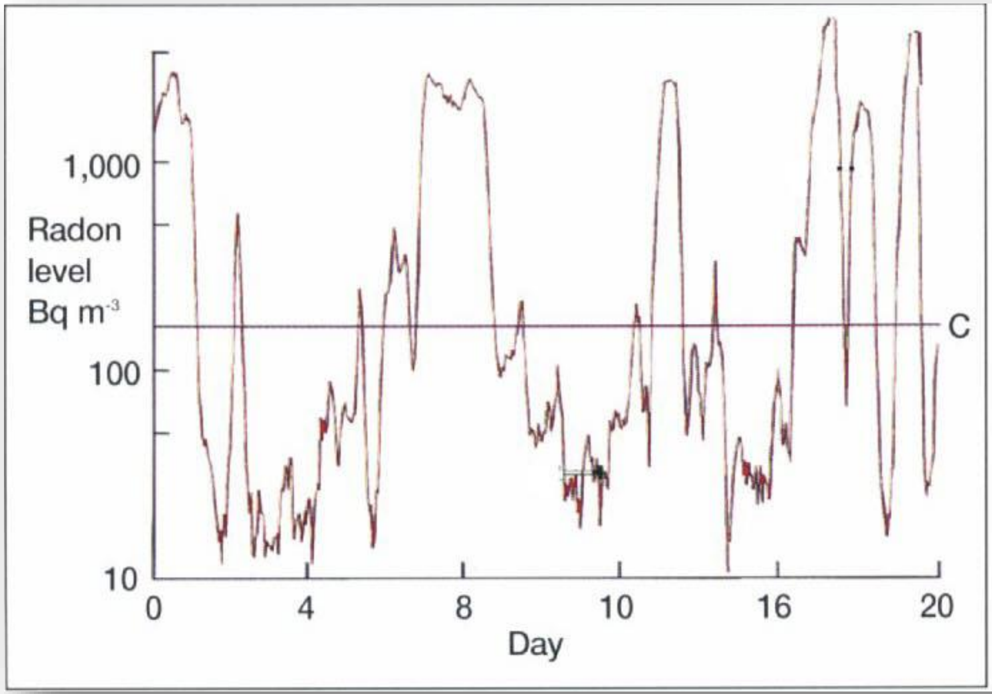
- Commonly used in uranium mines
- The use of this unit is discouraged

^{222}Rn gas concentration as a surrogate for ^{222}Rn progeny concentration

- Measurement of ^{222}Rn gas concentration is simpler
  e.g. measurements in buildings over extended periods
- Passive radon track-etch devices are small, simple, robust, inexpensive
- An equilibrium factor has to be assumed
- An assumed value of 0.4 is usually adequate for buildings, but can be significantly different in underground mines
- Usual approach in buildings
- It is also acceptable in many underground workplaces

Measurement

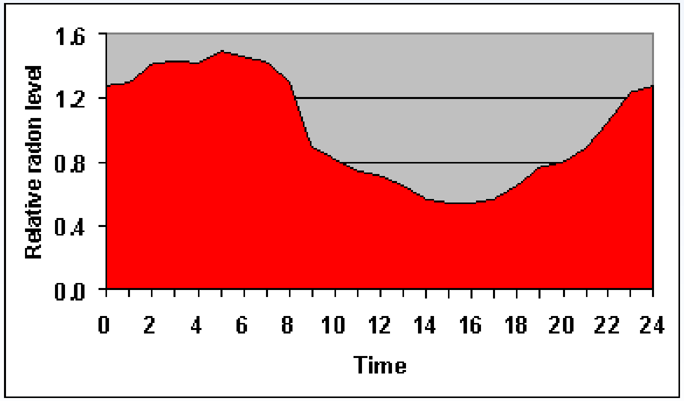
- A wide variety of measurement methods are available
- Either the gas or the progeny can be measured
- Rapid temporal variations can occur
- Integrated (long term measurements) are preferred due to the variability in the gas and progeny concentrations
- Equipment calibration is important



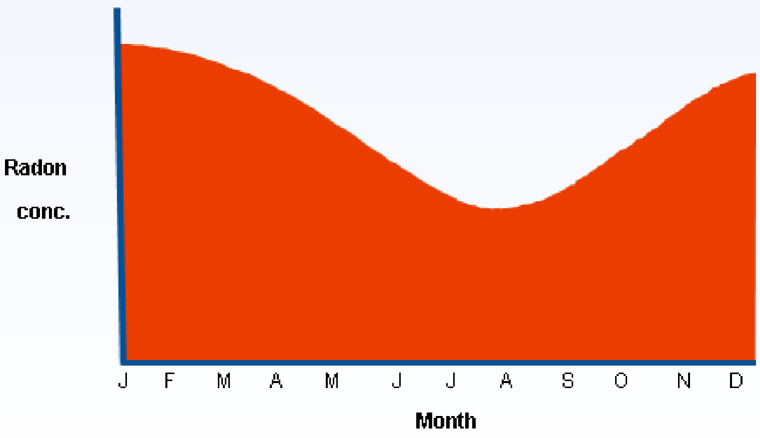
Radon levels vary appreciably from time to time, so prolonged measurements are required for reliable results. Short measurements can be misleadingly low or alarmingly high.

Variations

Diurnal variations

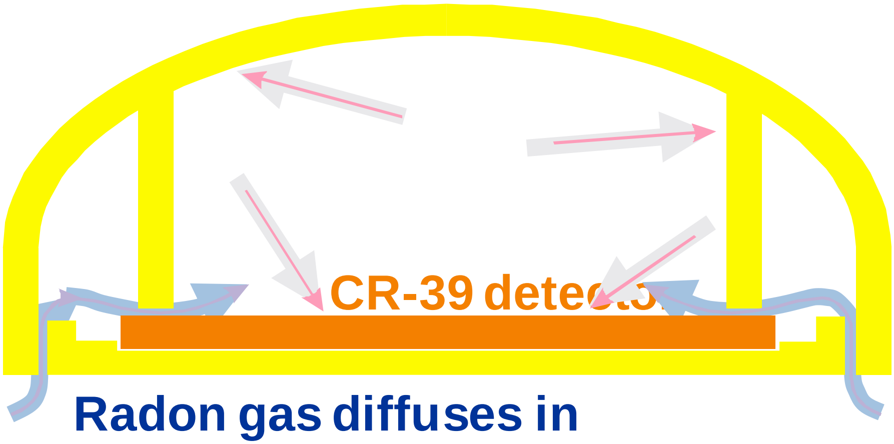


Seasonal variations



Radon gas passive monitor

- Some alpha particles emitted by radon and daughters strike detector



Workplace monitoring – radon gas

- Grab sampling: Lucas cells
- Grab sampling: pulse ionization chambers
- Grab sampling: two filter method
- Integrated measurements using nuclear track detectors (radon cup)
- Continuous monitoring

Types of radon detectors

Workplace monitoring – radon progeny

- Air is drawn through a filter
- The particulate progeny are collected
- The gross alpha (and/or beta) decay is measured

or

- Alpha spectrometry can be used to measure each radon progeny

Sampling strategies

- Sampling strategies require to be statistically based – random/ extensive screening
- Usually assessed by grab sampling (10–30 minutes)
- Requires a documented monitoring programme
- The monitoring frequency depends upon:
  - The level of concentration
  - The variability of concentration

Sampling strategies

The sampling frequency is increased when:

- measured concentrations exceed the usual range
- major changes are made to the ventilation system
- reference levels are exceeded
- the effectiveness of corrective actions is to be assessed
- ingress of radon into the working area is suspected

Individual passive radon monitoring

Radon gas

- Personal radon monitors are usually passive devices
- Passive monitors rely on radon diffusion into the detector
- Track-etch detectors are solid state devices, i.e. plastic
- Radon decays through alpha decay
- The alpha particle marks the detector
- Passive detectors are integrating devices
- Their exposure periods can range up to three months

Individual active radon progeny monitoring

Radon progeny

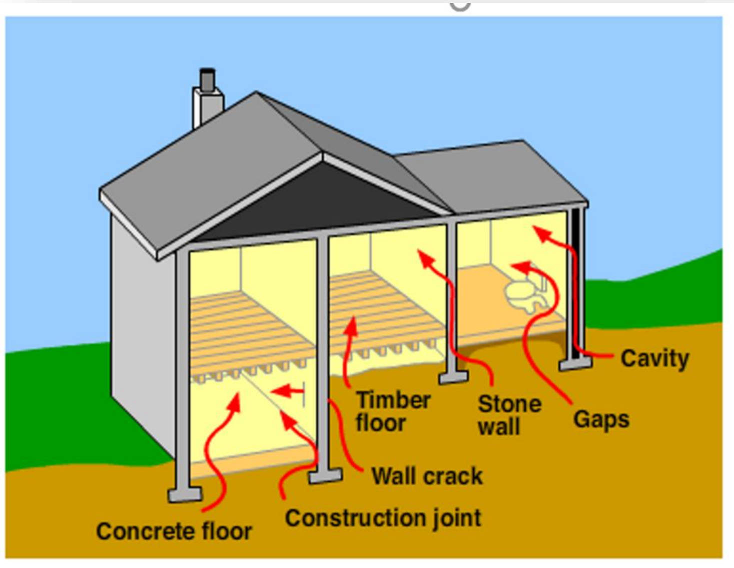
- Active monitors use pumps and filters
- Known volumes of air are sampled
- Short term integrating devices, e.g. full shift
- Collects the particulate radon progeny

Types of detector:

- Solid state silicon detectors
- Track etch

Radon in buildings

- Ingress mainly from underlying soil through cracks in floor:
  - Indoor air pressure usually lower than outside
    - Indoor air is warmer — convective flow
    - Wind blowing over chimneys and other openings
  - Other factors affecting ingress through floor:
    - Relative humidity
    - Soil moisture
    - etc.



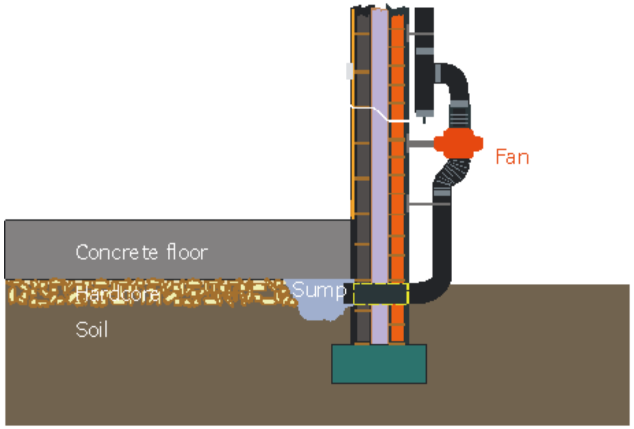
Radon in buildings (2)

- Other (usually less prominent) forms of ingress:
  - Emission from building materials:
    - Type of material
    - Porosity
    - ^{226}Ra concentrations
  - Emission from water supply:
    - ^{222}Rn concentration in water usually low
    - May be higher if originating from groundwater
  - Minerals and raw materials in workplaces, depending on:
    - ^{226}Ra concentrations, surface area (particle size), porosity, radon emanation coefficient

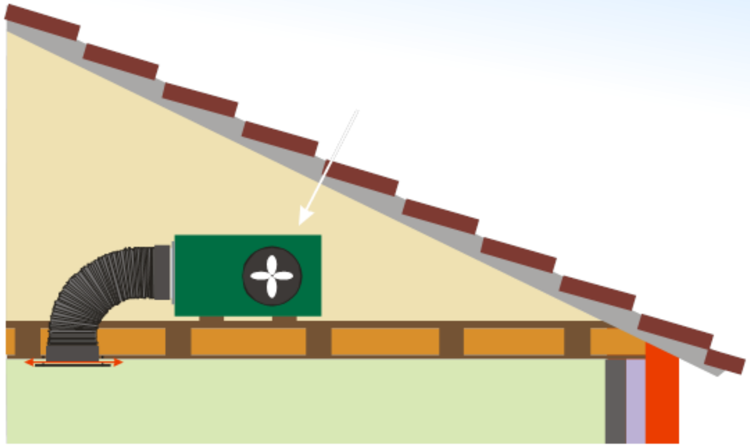
Radon in buildings (3)

- Indoor concentrations:
  - Variation between countries:
    - Geology
    - Climate
    - Construction techniques
    - Domestic habits
    - National mean values: 7–200 Bq/m^3
    - Population weighted worldwide mean: 39 Bq/m^3
  - Variation within individual countries
    - High background areas: 112 – 2745 Bq/m^3
    - Up to 84 000 Bq/m^3 in some parts of northern Europe

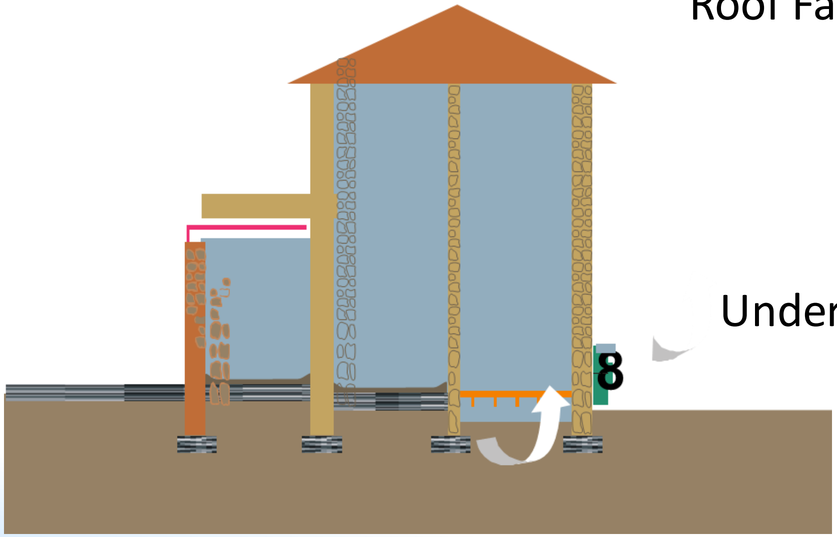
Mitigation - buildings



Radon Sump



Roof Fan



Underfloor Ventilation

Radon in underground workplaces

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- Examples:
  - Tunnels
  - Basement storage & parking facilities
  - Underground water treatment plants
  - Caves and former mines open to the public
  - Spas
  - Underground mines
- Causes of high concentrations:
  - Large areas of interface with the ground
  - Practical limitations on ventilation
  - Ingress of water laden with ^{222}Rn
  - High ^{226}Ra concentrations in the ground (certain mines)

Radon in underground workplaces

- Concentrations:
  - Caves and mines open to the public: 20 to >20 000 Bq/m^3
  - Workplaces in tunnels: 200 to 7000 Bq/m^3
  - Even higher values possible in underground mines
    - Particularly uranium mines

Calculation of dose

- Reference levels are expressed in terms of ^{222}Rn concentrations rather than dose
- Conversion to dose is however necessary when exposure to ^{222}Rn progeny is treated as a planned exposure situation
  - UNSCEAR recommend a dose factor of 9 nSv per $Bq{\cdot}h{\cdot}m^{-3}$
  - 1.6 Sv per $J{\cdot}h{\cdot}m^{-3}$ potential alpha energy exposure
- Dose due to ^{222}Rn progeny has to be added to doses from external gamma and inhaled or ingested dust

Thoron

- Thoron (^{220}Rn) is not normally of concern in NORM industries, except where material with a high thorium content is processed, e.g. monazite
- Short lived progeny are likely to be severely out of equilibrium with the parent
- In enclosed workplaces, the short half-life of thoron (55.6 s) means that the spatial distribution of thoron is much different from that of its progeny
  - Assessment of equilibrium factor is difficult
  - For dose assessment, an approach based on measurement of progeny concentration is easier and more appropriate than an approach based on measurement of thoron concentration

Thoron

- Dose factors:
  - The UNSCEAR value for dose from inhalation of thoron is 40 nSv per Bq·h·m^{-3} equilibrium equivalent exposure
  - Using this value:
    - A thoron progeny potential alpha energy exposure of 1 mJ·h·m^{-3} gives a committed effective dose of about 0.5 mSv

      (Compared with 1.6 mSv for ^{222}Rn progeny)

Key messages

- Radon is everywhere and concentrations can vary significantly
- Exposure is subject to regulation
- Dose comes from the radon progeny
- Special quantities for concentrations and exposures
- Many measurement methods exist and vary from simple to complex
- Selection depends upon the situation and the possible concentration