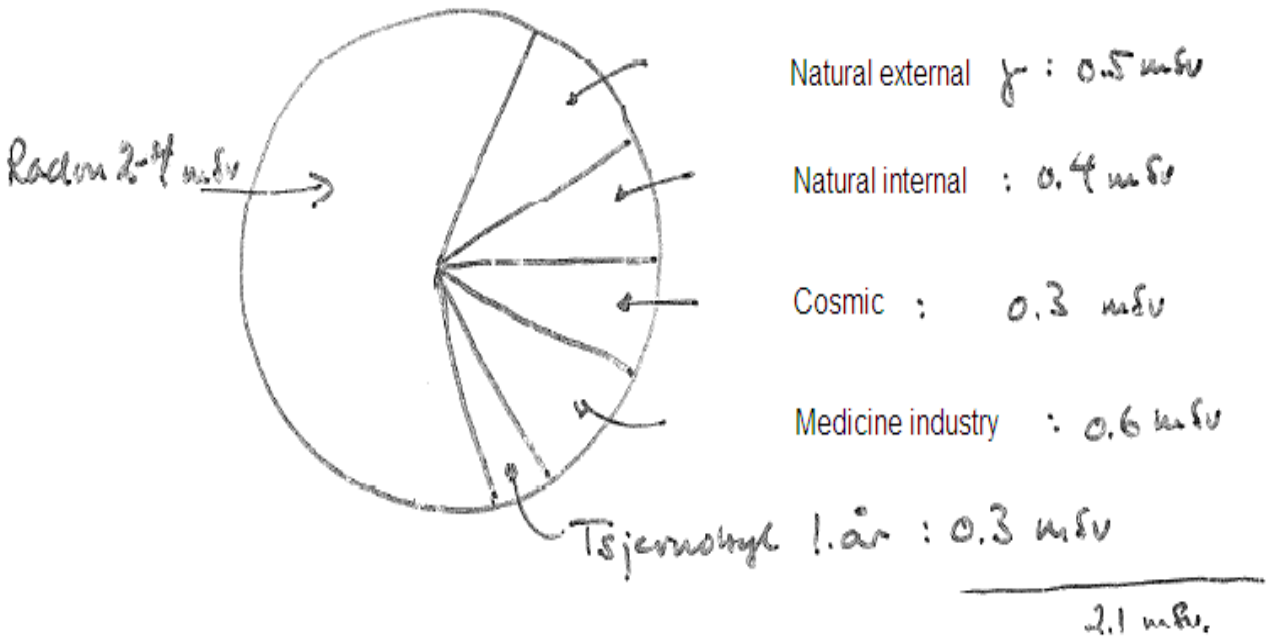
8.)
Our radiological environment

The average effective annual dose



Indoor radon

Rn-222 is the biggest problem, because of a relatively large abundance of its element of origin, U-238, and a relatively long lifetime compared to other Rn-isotopes (Rn-220 and Rn-219).

Building sites with high concentrations of Ra $[\frac{Bq}{kg}]$ ($Ra - 226 \rightarrow Rn - 222$) and high gas permeability represent the biggest problem.

Indoor Rn-concentration

$$\frac{d\chi_{Rn}}{dt} = \dot{u}(t) - \chi_{Rn}\left(\lambda_{Rn} + \lambda_v\right)$$

- $\chi_{Rn,air}$= the concentration of Rn-222 activity in air. $\left[\frac{Bq}{m^3}\right]$
- $\dot{u}(t)$ =the rate of flow of Rn-222 into the building. $\left[\frac{Bq}{m^3 \cdot s}\right]$
- λ_{Rn}= the disintegration constant. $[\frac{1}{s}]$
- λ_v = the rate of flow out of the building. $[\frac{1}{s}]$

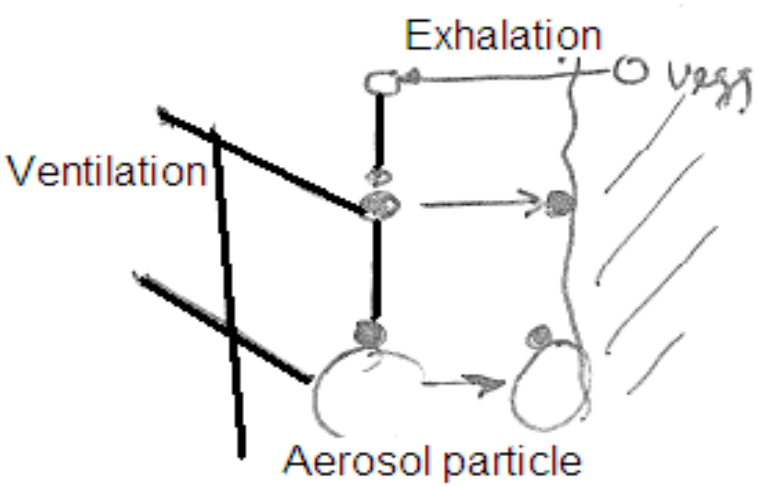
If $\dot{u}$ and λ_v are constant, the equilibrium concentration is:

$$\chi_{Rn,air} = \frac{\dot{u}}{\lambda_{Rn} + \lambda_v}$$

What contributes to $\dot{u}(t)$ is:

- Ground conditions
- Building materials
- Water (household water)
- Outdoor air (ventilation)

Rn and Rn-daughters get stuck to tiny particles of dust and surfaces (plate-out).



Rn-concentration in Norwegian houses

Most probable value:	$20\frac{Bq}{m^3}$
Mean value:	$88\frac{Bq}{m^3}$ in 2001
	3% of the houses had values $> 400\frac{Bq}{m^3}$ in 2001
	9% of the houses had values $> 200\frac{Bq}{m^3}$ in 2001

Rn dosimetry and risk limits (ICRP 50)

Contributions from Rn-222 (a gas) and its metal-like daughter nuclides have to be accounted for separately.

1.) Contributions from Rn:

Dose rate in soft tissue excluding the lungs (due to Rn dissolved in the tissue):

$$\dot{D}_{soft\ tissue} = S_{st} \cdot \chi_{Rn,air}, \qquad S_{st} = 0.005 \frac{\frac{nGy}{h}}{\frac{Bq}{m^3}}$$

For lung tissue, the contribution from Rn in the alveolar air comes in addition to the contribution from dissolved Rn:

Dose rate:	$\dot{D}_{lungs} = S_l \cdot \chi_{Rn,air}, \quad S_l = 0.04 \frac{\frac{nGy}{h}}{\frac{Bq}{m^3}}$
Equivalent dose rate:	$\dot{H}_T = \omega_R \dot{D}_{T,R}, \qquad \omega_R = 20$ for α
Effective dose rate:	$\dot{E} = \sum \omega_T \dot{H}_T = \omega_R(\omega_l \dot{D}_l + \omega_{st} \dot{D}_{st}), \qquad \omega_l = 0.12, \quad \omega_{st} = 0.88$
$\Rightarrow$	$\dot{E} = S_{tot,Rn} \cdot \chi_{Rn,air}, \qquad S_{tot,Rn} = 0.2 \frac{nSvh^{-1}}{Bqm^{-3}}$

2.) Contributions from short-lived Rn-daughter nuclei:

Chain of disintegrations:

No	Nuclide	$T_{\frac{1}{2}}$	E_α	ε_{pi}	$\frac{\varepsilon_{pi}}{\lambda_i}$
			$[MeV]$	$[MeV]$	$[\frac{MeV}{Bq}]$
0	^{222}Rn	3.82d	5.49		
1	^{218}Po	3.05m	6.00	13.7	3620
2	^{214}Pb	26.8m		7.69	17800
3	^{214}Bi	19.7m		7.69	13100
4	^{214}Po	164μ s	7.69	7.69	$2{\cdot}10^{-3}$
5	^{210}Pb	19.4yrs			

Where numbers 1 through 4 represent short-lived daughter nuclei.

Equilibrium activity concentration: $C_{act,eq} = \lambda_{Rn} \cdot C_{Rn} = \lambda_i \cdot C_i, \quad i = 1, ..4$

Where C_{Rn} is the number of Rn atoms per unit volume of air.
Now, in a real situation, the activity concentration of Rn-daughters will be lower than the equilibrium Rn activity concentration. This is because of ventilation and plate-out, which affect the daughters more than it affects Rn itself.
The potential α-energy per Rn-daughter atom ($\varepsilon_{pi}, \quad i = 1, ..4$) is the sum of α-disintegration energies for one atom of the nuclide and its short-lived daughter nuclei:

$$\varepsilon_{pi} = \sum_{j \geq i}^{4} E_{\alpha j}$$

Potential α-energy per unit activity: $\frac{\varepsilon_{pi}}{\lambda_i} = \frac{N_i \varepsilon_{pi}}{\lambda_i N_i} = \frac{\varepsilon_{pi} T_{\frac{1}{2},i}}{\ln 2}$

Potential α-energy concentration: $C_p = \sum_{i=1}^{4} C_{act,i} \cdot \frac{\varepsilon_{pi}}{\lambda_i} [\frac{J}{m^3}]$

Equivalent equilibrium Rn-concentration in air: $EEC_{Rn} \equiv \chi_{eq,Rn} = \frac{\sum_{i=1}^{4} C_{act,i} \cdot \frac{\varepsilon_{pi}}{\lambda_i}}{\sum_{i=1}^{4} \frac{\varepsilon_{pi}}{\lambda_i}}$

$$= \frac{C_p}{\sum_{i=1}^{4} \frac{\varepsilon_{pi}}{\lambda_i}} = K \cdot C_p$$

EEC_{Rn} is the concentration of activity of Rn in equilibrium with its short-lived daughter nuclei, which would have the same potential α-energy per unit volume air as the mixture of interest:

$$\chi_{eq,Rn} = 0.10 \cdot C_{act,Po-218} + 0.51 \cdot C_{act,Pb-214} + 0.38 \cdot C_{act,Bi-214}$$

Note! Contribution from $C_{act,Po-214}$ is extremely small because $\frac{\varepsilon_{pi}}{\lambda_i} \ll 1$ for Po-214.

Empirical value of the equilibrium factor: $F = \frac{EEC_{Rn}}{\chi_{Rn,air}} \simeq 0.5$

Heavy duty ventilation results in a smaller F-value.

Intake of potential α-energy during a time interval T:

$$I_{pot} = \frac{E}{A}\dot{V}_{in}T \cdot \chi_{eq,Rn}, \qquad \frac{E}{A} = \sum_{i=1}^{4} \frac{\varepsilon_{pi}}{\lambda_i} = 55.5 \cdot 10^{-10} \quad J/Bq$$

Assume the inhalation rate to be: $\dot{V}_{in} = 0.8\frac{m^3}{h}$ during the time interval T.

The trachea-bronchial region: $\frac{D_{T-B}}{I_{pot}} = 1.5\frac{Gy}{J} \equiv K_{T-B}$

Pulmonal region: $\frac{D_P}{I_{pot}} = 0.2\frac{Gy}{J} \equiv K_P$

T-B dose rate: $\dot{D}_{T-B} = \frac{D_{T-B}}{T} = S_{T-B} \cdot \chi_{eq,Rn} = F \cdot S_{T-B} \cdot \chi_{Rn,air}$

where $S_{T-B} = K_{T-B}\frac{E}{A}\dot{V}_{in} = 7\frac{nGyh^{-1}}{Bqm^{-3}}$

P dose rate: $\dot{D}_P = \frac{D_P}{T} = S_P \cdot \chi_{eq,Rn} = F \cdot S_P \cdot \chi_{Rn,air}$

where $S_P = K_P \cdot \frac{E}{A} \cdot \dot{V}_{in} = 0.9\frac{nGyh^{-1}}{Bqm^{-3}}$

Equivalent dose rate: $\dot{H}_T = \omega_R \dot{D}_{T,R}, \qquad$ for α $\omega_R = 20$

Effective dose rate: $\dot{E} = \sum \omega_T \dot{H}_T = \omega_R[\omega_{T-B}\dot{D}_{T-B} + \omega_p \dot{D}_p]$

When taking into account the tissue weighting factors, it is assumed that T-B and P contribute equally to the total lung tissue weighting factor.

$\Rightarrow$ $\omega_{T-B} = \omega_P = \omega_{\frac{1}{2}} = 0.06$

$\Rightarrow$ $\dot{E} = S_{tot,Rn-daughters} \cdot \chi_{eq,Rn} = F \cdot S_{tot,Rn-daugthers} \cdot \chi_{Rn,air}$

$S_{tot,Rn-daughters} = 9.5\frac{nSvh^{-1}}{Bqm^{-3}}$

Finally, the total contribution from both Rn and its daughters becomes:

$$\dot{E}_{tot} = [S_{tot,Rn} + F \cdot S_{tot,Rn-daughters}]\chi_{Rn,air}$$
$$\dot{E}_{tot} = \overline{S} \cdot \chi_{Rn,air}$$

If one assumes that F=0.5 $\Rightarrow \overline{S} = [0.2 + 0.5 \cdot 9.5]\frac{nSvh^{-1}}{Bqm^{-3}} = 5\frac{nSvh^{-1}}{Bqm^{-3}}$

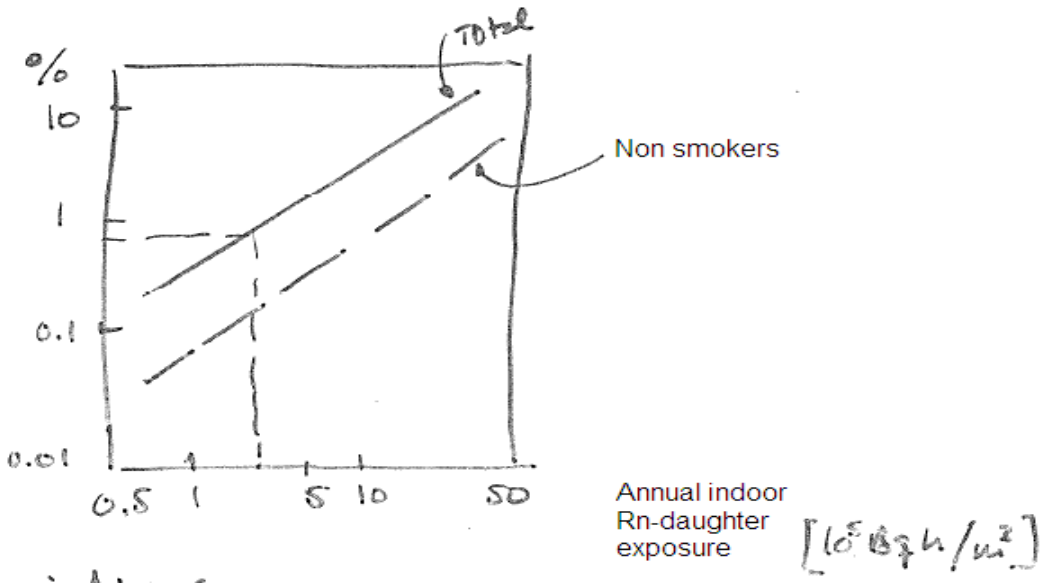
Yearly, one can assume that an average person stays indoors about 80% of the time. This becomes about 7000 hours per year. Further on, assuming that the Rn exposure outdoors can be neglected:

$\Rightarrow$ $\overline{S}_{yr} = 5\frac{nSvh^{-1}}{Bqm^{-3}} \cdot 7000\frac{h}{yr} = 35\frac{\frac{\mu Sv}{yr}}{Bqm^{-3}}$

The mean Rn-concentration in Norwegian houses was $\chi_{Rn,air} = 88\frac{Bq}{m^3}$ in 2001. From this, it follows that the effective dose rate becomes:

$$\Rightarrow \qquad \dot{E}_{tot} = 35 \cdot 88 \frac{\mu Sv}{yr} = 3.0 \frac{mSv}{yr}$$

Cancer risk due to Rn exposure



Concentration limits in Norway

Limits have been revised: If radon concentration is above 100 Bq/m3, actions should be taken. Maximum limit is 200 Bq/m3.

~~$\chi_{Rn,air} < 200$: It is not necessary to take action.~~

~~$200 < \chi_{Rn,air} < 400$: Simple actions required.~~

~~$\chi_{Rn,air} > 400$: Expensive actions required~~

Measuring the amount of Rn and Rn-daughters

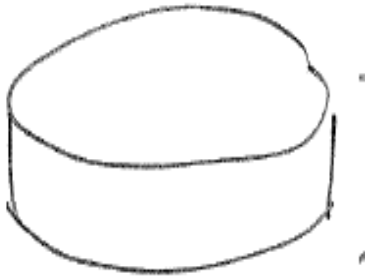
Important conditions to take into account

1.) The measuring device must not be affected by deposited Rn-daughters.
For example on the surface of the detector.

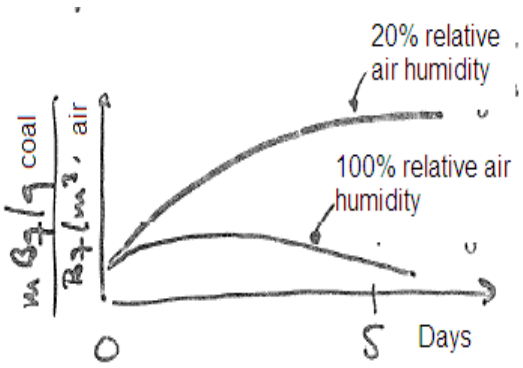
2.) It must be known to which degree it measures Rn, and to which degree it measures Rn-daughters.

3.) Integration over long time is necessary to obtain good accuracy.

Measuring methods for air-borne Rn



1.) The CB (Coal Box)-method, consists of a box containing active coal, which absorbs Rn-gas. The box is open only during exposure when Rn gas is adsorbed to the active coal. Measuring the activity of Rn-daughters, originating from the absorbed Rn-gas, is done using a NaI scintillation crystal via γ spectroscopy. A problem here is that the coal adsorbs air humidity more efficiently than Rn-gas. This means that the measuring results are more accurate in dry places. Another inaccuracy of this method is that it does not integrate over very long time.



Other sources of radiation

Cosmic radiation

Particle radiation (85% protons, 15% α-particles) from space, and particle radiation as well as γ-radiation from the sun. These primary particles are transformed into secondary cosmic radiation consisting of various particle types and some γ-radiation, due to interactions and reactions in the atmosphere. Cosmic radiation increases with altitude above sea level.

Ground-level:	$0.35\frac{mSv}{yr}$ i.e. 0.04 $\frac{\mu Sv}{h}$
Air-traffic altitude: (10.000m)	$5\frac{\mu Sv}{h}$

External γ-radiation

External γ-radiation is mostly due to the existence of radioactive minerals in the ground. The following nuclides constitute the main contributions to dose:

^{40}K	40%
^{232}Th	40%
^{226}Ra	20%

The average effective dose from external γ is around $0.55\frac{mSv}{yr}$

Naturally occuring internal radiation

Natural internal radiation is mainly due to radiation from ^{40}K (β-emitter, $T_{\frac{1}{2}}$=10^9yrs). Natural K consists of about a fraction of 10^{-4} ^{40}K. The amount of K inside our bodies is regulated by the metabolism. This again implies that the dose contribution is kept at a constant level.
Average effective dose from internal radiation is about $0.37\frac{mSv}{yr}$.

The Tsjernobyl accident

The outburst resulted in a release of about 3.5% of the total amount of activity contained in the reactor. All the gaseous nuclei (^{85}Kr and ^{133}Xe) were released. The fall-out consisted mainly of ^{137}Cs and ^{134}Cs. The mean ^{137}Cs fall-out in Norway was $7\frac{kBq}{m^2}$, but some places had more than $80\frac{kBq}{m^2}$.

Dosimetry

Total transfer factor for effective dose due to all the nuclides, based on ^{137}Cs ground deposition. For northern areas, in units of $\frac{\mu Sv}{kBqm^{-2}}$:

	Year 1	Total
External	10	86
Internal	27	59
Sum	$\simeq 40$	$\simeq 150$

Internal dosimetry is based on averaged transfer coefficients, assumptions concerning diet-composition and biokinetical models for up-take of radioactive substances.

Average dose based on Norwegian conditions:

Year 1 $40\frac{\mu Sv}{kBqm^{-2}} \cdot 7\frac{kBq}{m^2} = 0.28mSv$

Total $150\frac{\mu Sv}{kBqm^{-2}} \cdot 7\frac{kBq}{m^2} = 1.0mSv$

Dose-reducing measures

Use of Cs-binders (as feed-admixture and tablets) reduces the up-take of Cs in domestic animals by up to 50-80%.