Radon as a health hazard and a scientific topic

Jiří Hůlka

SURO - National Radiation Protection Institute,
Czech Republic, Praha, Bartoškova 28
jiri.hulka@suro.cz
www.suro.cz

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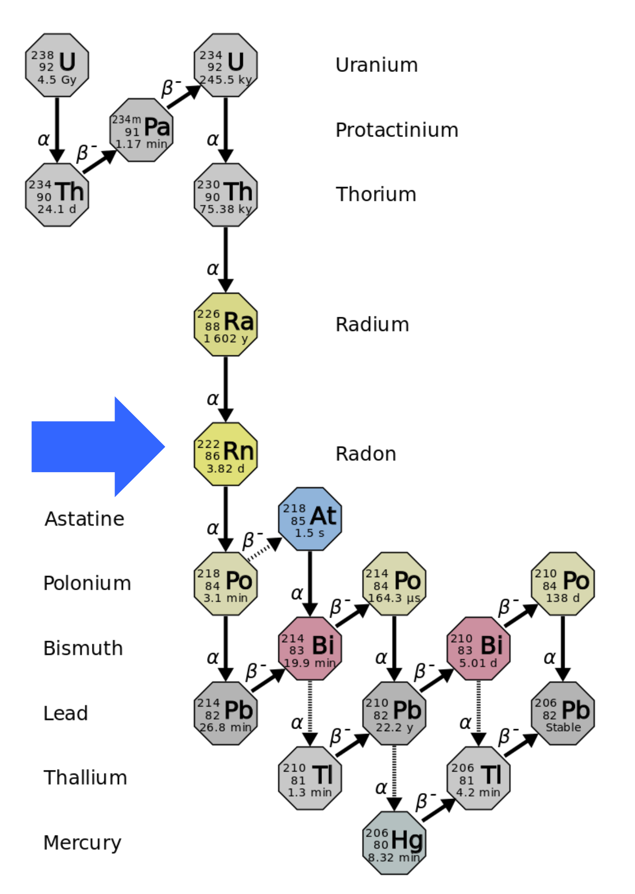
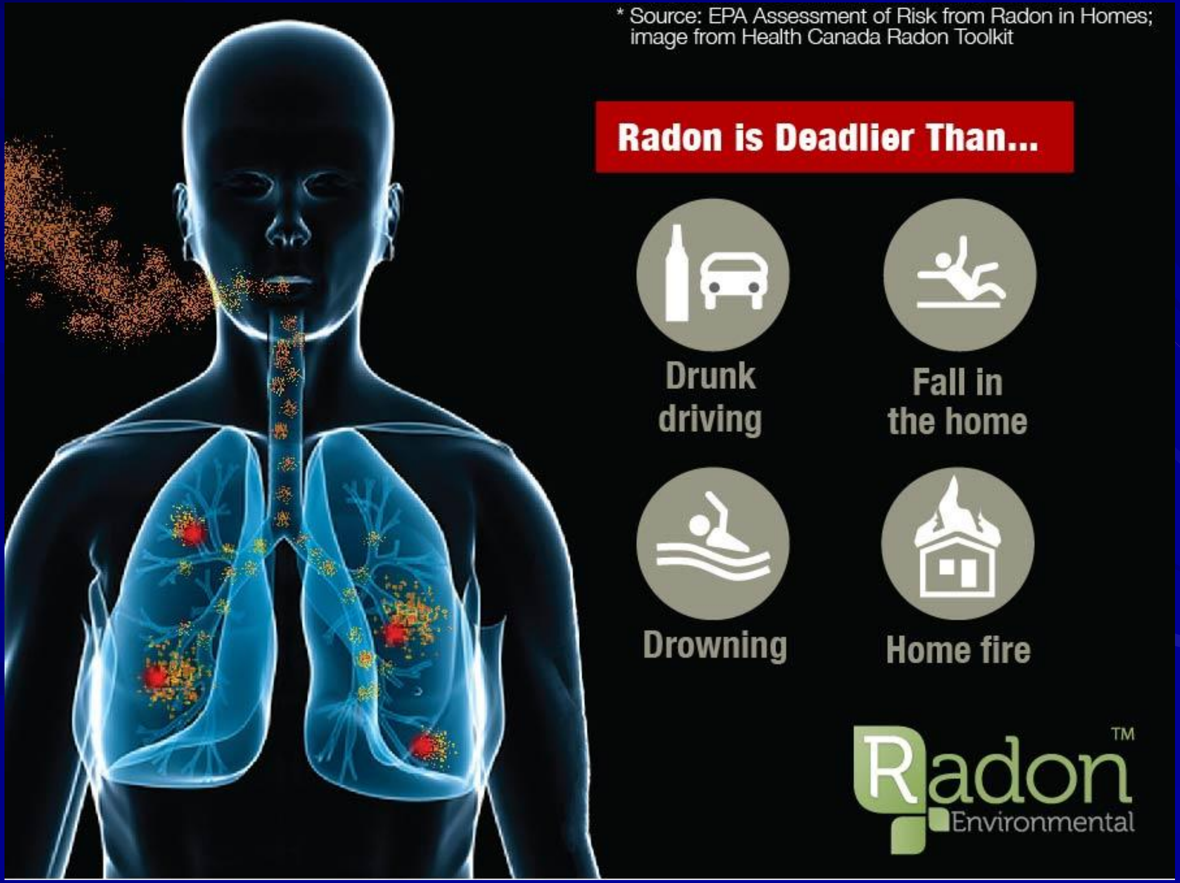
Why is radon (^{222}Rn) of concern?

Radon is a radioactive, odourless noble gas, occurs naturally in minute quantities as an step in the normal radioactive uranium decay chain.

Radon most stable isotope ^{222}Rn has a half-life of only 3.8 days

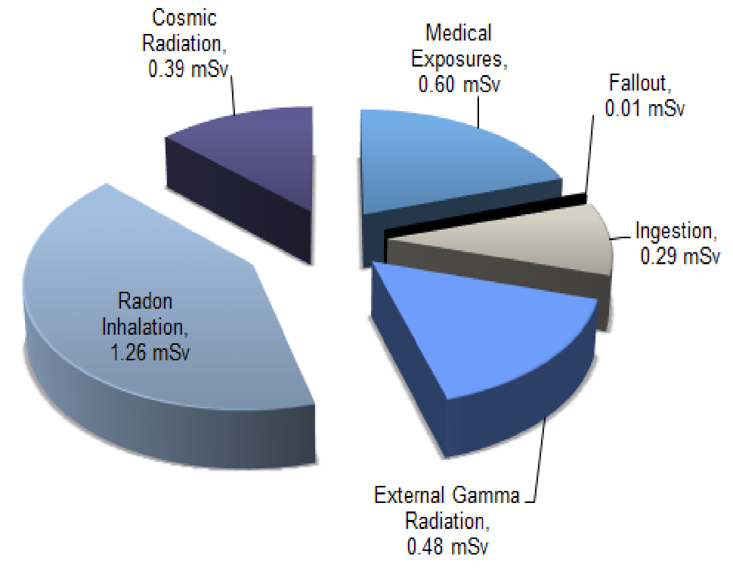




Why is radon of concern? Some details

- Radon is a known cause of lung cancer (Class 1 carcinogen*) *WHO - (*proven by the pooled epidemiological study from Europe, N.America, China*)*
- Radon is the second most important cause of lung cancer after smoking and the leading cause of cancer among non-smokers.
- Radon is responsible for almost one half of total ionising radiation dose received by the public each year.
- Extreme individual risk: Buildings with a radon concentration of up to 1000 times higher than the average value have been found all over the world
- Radon exposure can be controlled so as to reduce its health effects

**International Agency for Research on Cancer*

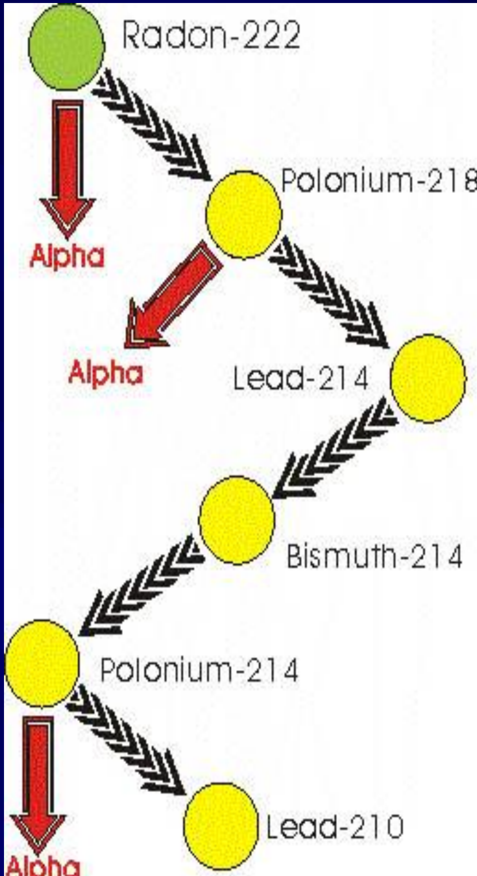


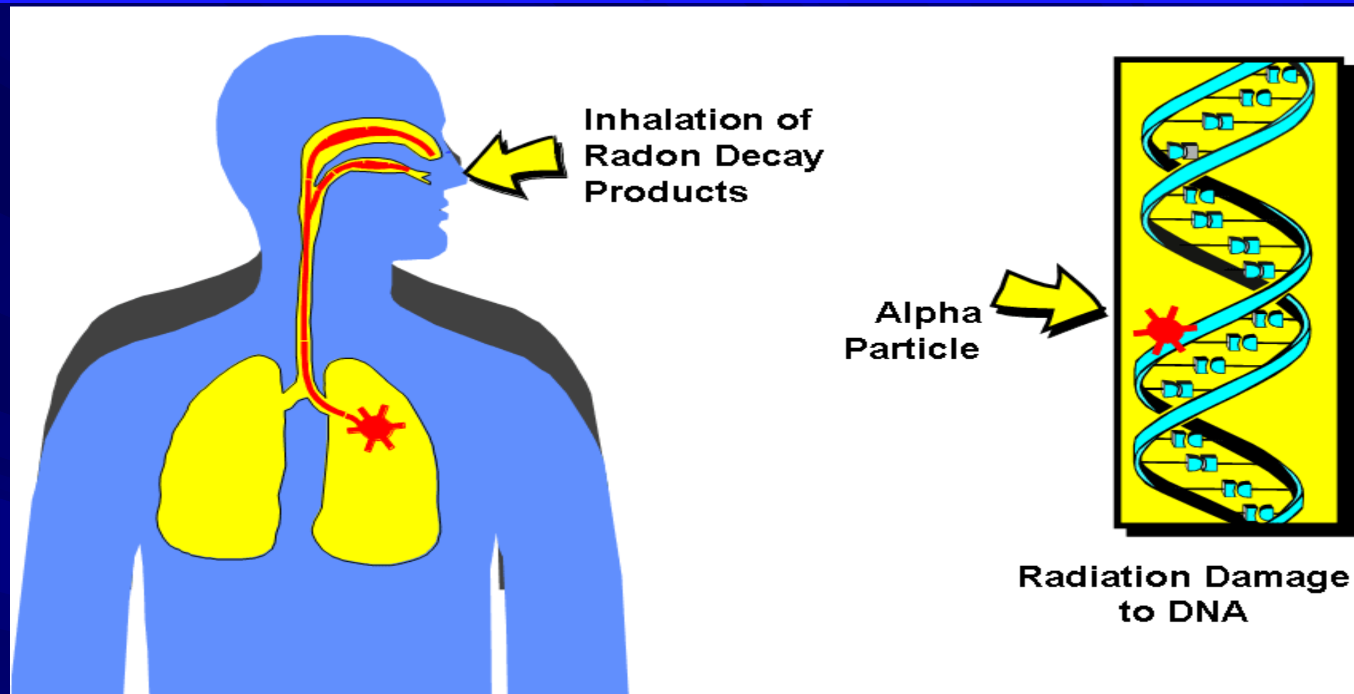
UNSCEAR, 2008 REPORT Vol. I Annex B

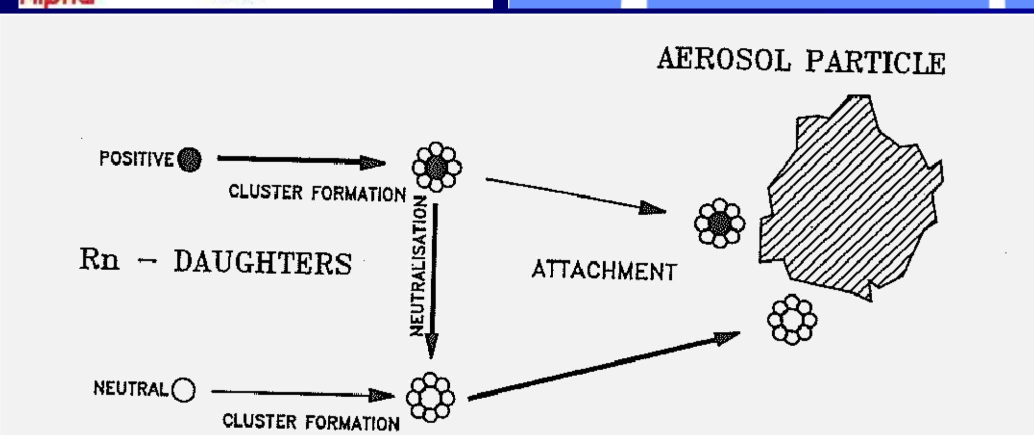
Worldwide radon accounts for 3% to 16% of all lung cancer deaths, depending on the average radon concentration in the country

(WHO Handbook on Radon, 2009)

Health effects of radon decay products exposure







When radon decay products are inhaled, alpha particles from radon decay products can interact with biological tissue in the bronchi epitel and lungs leading to DNA damage.

The history of radon started on the border between the current Czech Republic and Germany:

The first reference to **negative health effects** of "something" in silver mines appeared in the 16th century: Paracelsus (1493 – 1514) described a specific "**miners disease**" that occurred in silver mines in Jachymov (Joachimstahl) and Schneeberg (pitchblende- Uraninite)

… today estimate up 500 000 Bq/m3

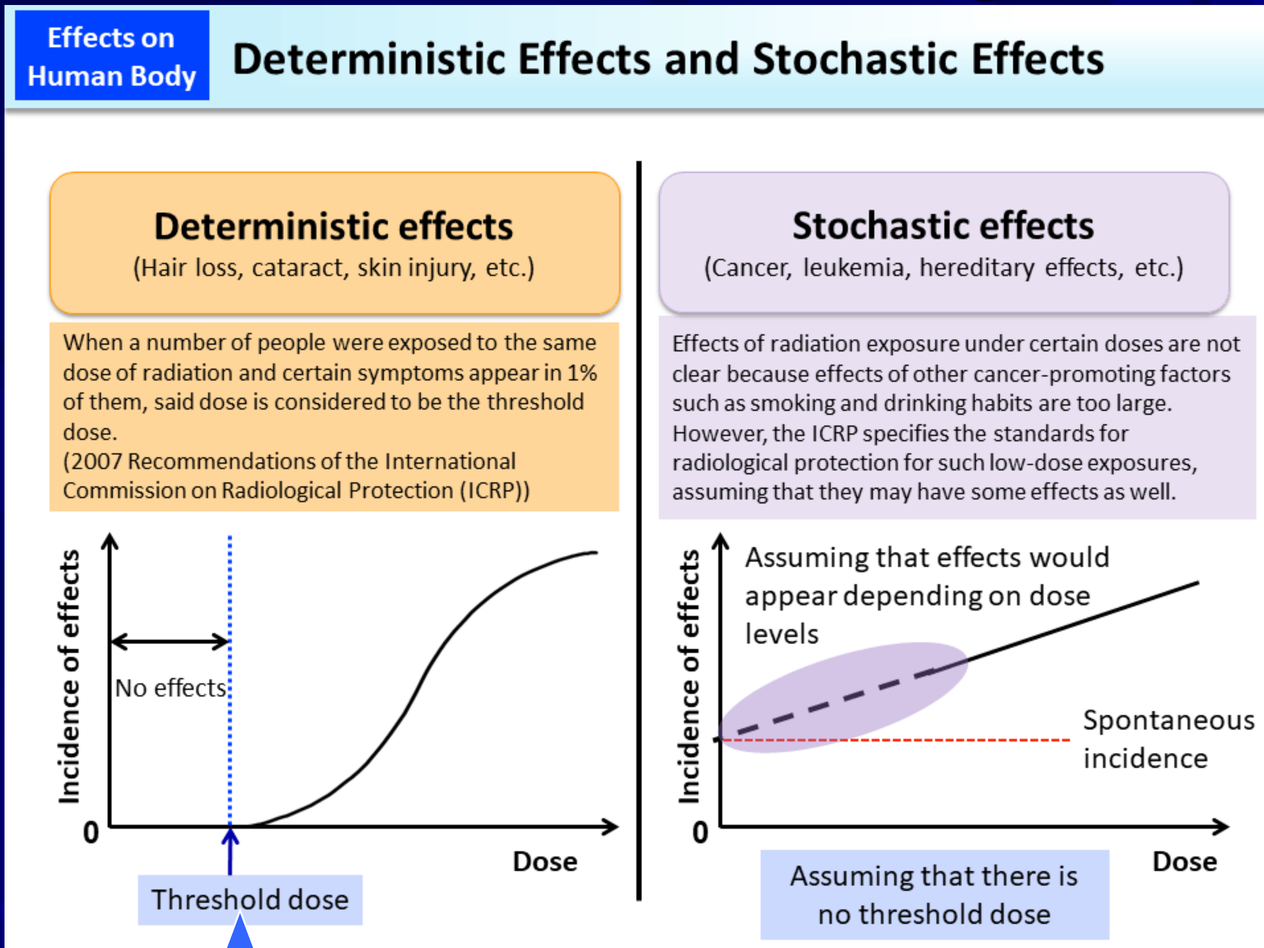
But as late as in 1952, was discovered the reason:

inhalation of short-term radon decay products.

In eighties of 20th century

High radon concentration was discovered surprisingly in the buildings in some countries

Health Risk from Ionizing Radiation and Radon



~ 0,5 Sv

Chest X-ray (dose ~ 0,1 mSv)

Risk 0,000 05

per 1 mSv (dose)

1 year living

in radon 30 Bq/m3

ef.dose ~ 1 mSv

50 years living

in „limit“ radon -300 Bq/m3

ef.dose ~ 500 mSv

~ 2,5% risk of lung cancer

there are also houses

with radon

100 000 Bq/m3

~ 3 000 mSv/annually

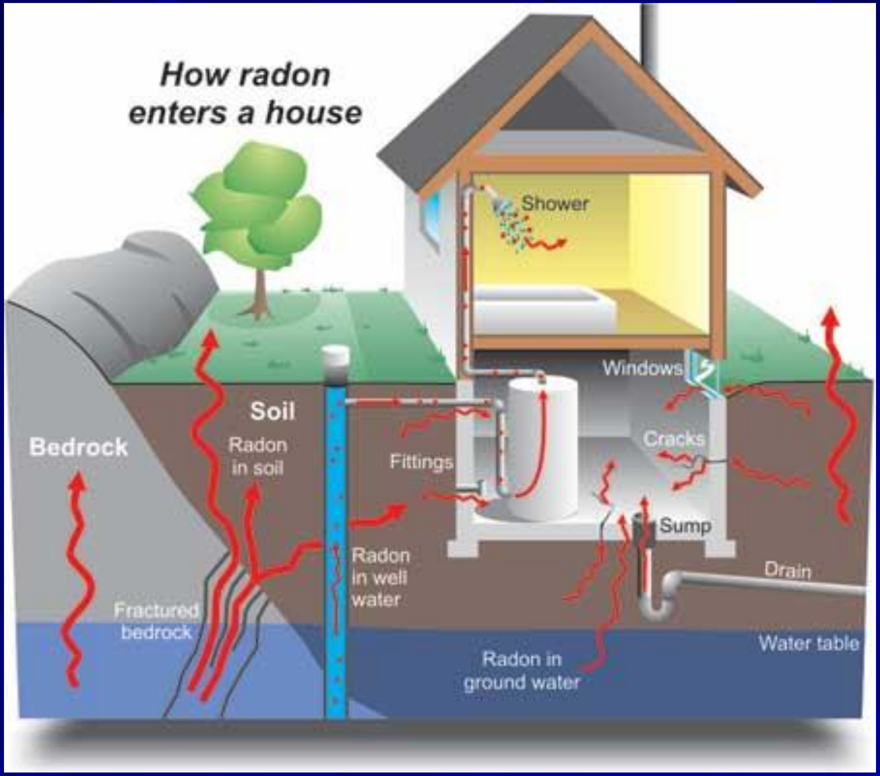
Radon origin and transport

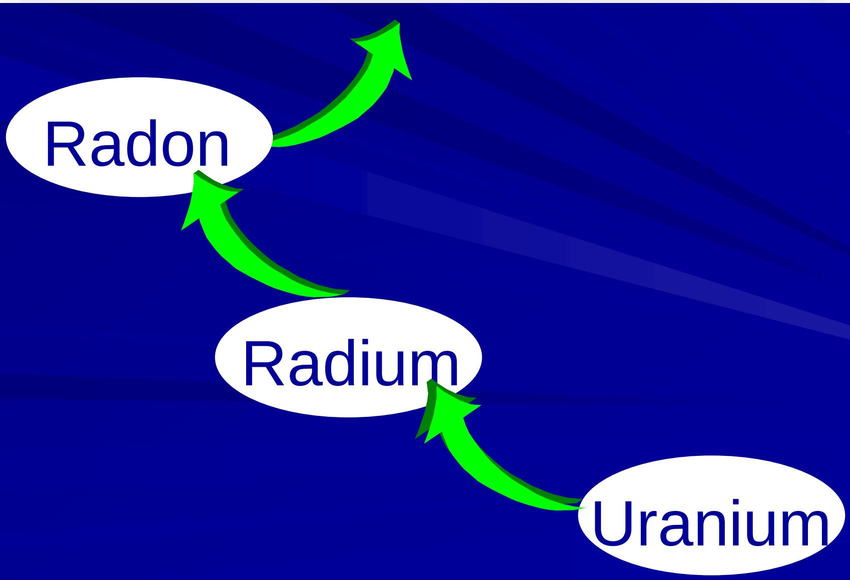
- Radon (noble radioactive gas half life 3,8 day) is continually produced by the decay of uranium, which occurs naturally in soils and rocks (everywhere)

- Once produced, radon escapes into the open air

unless

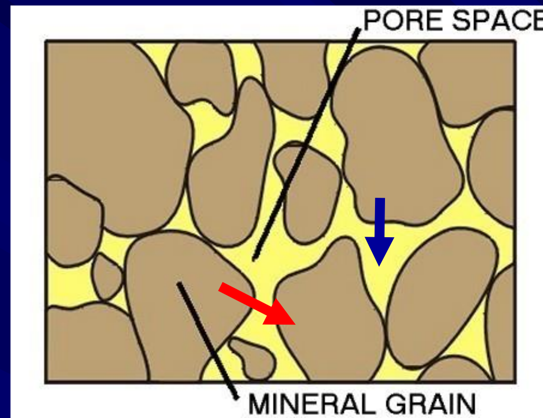
- it enters a building or enclosed space

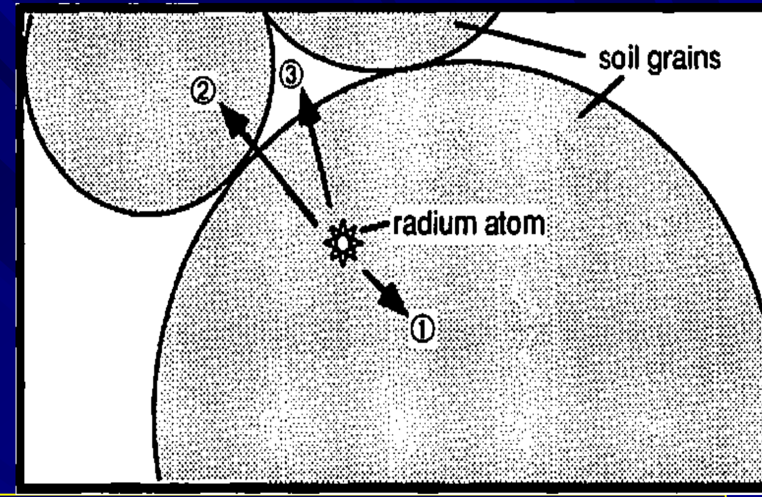




Rn emanation coefficient

U - 238 4,47.10^9 r → Th-234 24,1 d → Pa-234 1,17 m → U-234 2,46.10^5 r → Th-230 7,54.10^4 r → Ra-226 1600 r → Rn-222 3,82 d → Po-218 3,10 m → Pb-214 26,8 m → Bi-214 19,9 m





After Ra-226 decay Rn atom can escape by "back recoil" from mineral grain into the pores

Ra-226 > Rn-222 + alpha

The range of recoil distance for Rn 222 is

20-70 nm in common minerals, 100 nm in water, and 63 µm in air

The fraction of radon atoms released into rock or soil pore space from a radium-bearing grain is called the radon emanation coefficient in naturally-occurring rocks, minerals and soils varies over five orders of magnitude, often max some tenth %

(depends on grain size, radium concentrations in surface coatings, -humidity concentration of radon in the air-filled pores to be higher under moist conditions than under dry conditions …tempereture)

The concentration of radon in soil gas (or building material), C_{Rn} (in the absence of radon transport) is as follows:

$$C_{Rn} = C_{Ra}\, f\, \rho_s\, \varepsilon^{-1} (1-\varepsilon)\, (m\,[K_T - 1] + 1)^{-1}$$

where

C_{Ra} is the concentration of radium in soil (Bq kg$_{1}$),

f is the emanation coefficient , ρ_s is the density of the soil grains (2700 kg m$_{3}$), ε is the total porosity, including both water and air phases, m is the fraction of the porosity that is water-filled (also called the fraction of saturation),

K_T is the partition coefficient for radon between the water and air phases.

Examples :

A warm, moist soil (25C, K_T = 0.23, m = 0.95) with typical soil parameters (C_{Ra} = 30 Bq kg$_{1}$, f = 0.2, ε = 0.25) will have a concentration of radon in pore air of 78 kBq m$_{3}$,

which is 3.7 times higher than

for the same soil under cold and dry conditions (0C, K_T = 0.53, m = 0.05, C_{Rn} = 21 kBq m$_{3}$)

[UNSCEAR 2002)

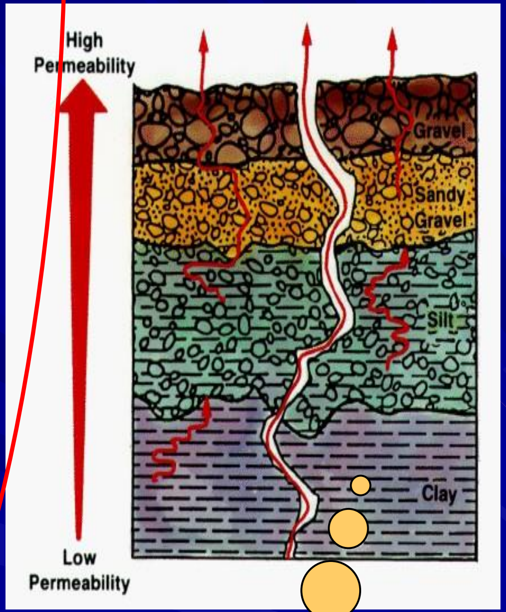
Radon Difusion

The main mechanism for the Rn entry into the atmosphere is molecular diffusion.

For a porous mass of homogeneous material semi-infinite the flux density of radon at the surface is given by the expression

$$J_D = C_{Ra} \lambda_{Rn} f \rho_s (1 - \varepsilon) L$$

Mean radon in atmosphere 10 Bq/m3 (range 1-100 Bq/m3)
(decay products cca 5 Bq/m3)



Example: With representative values of these parameters (C_{Ra}= 40 Bq kg^{-1}, f = 0.2, D_e = 2. 10^{-6} m^2 s^{-1}, ε = 0.25) the diffusion length ($L = \sqrt{\frac{D}{\lambda}}$)

J_D is 0.033 Bq m^{-2} s^{-1}.

Difusion lenght in porous materiál some tens of cm

„Mean worldwide" flux J_D is 0.016 Bq m^{-2} s^{-1}.

(Rn disperses in the atmosphere - some km)

Radon h = 1 m 10 000 - 100 000 Bq/m3 (even >1 000 000 Bq/m3)

Radioactivity of building materials - Typical Activity Concentrations (EU)

Material	Typical activity concentration (Bq/kg)			Maximum activity concentration (Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Concrete	40	30	400	240	190	1600
Aerated and light-weight concrete	60	40	430	2600	190	1600
Blast furnace slag	270	70	240	2100	340	1000
Coal fly ash	180	100	650	1100	300	1500

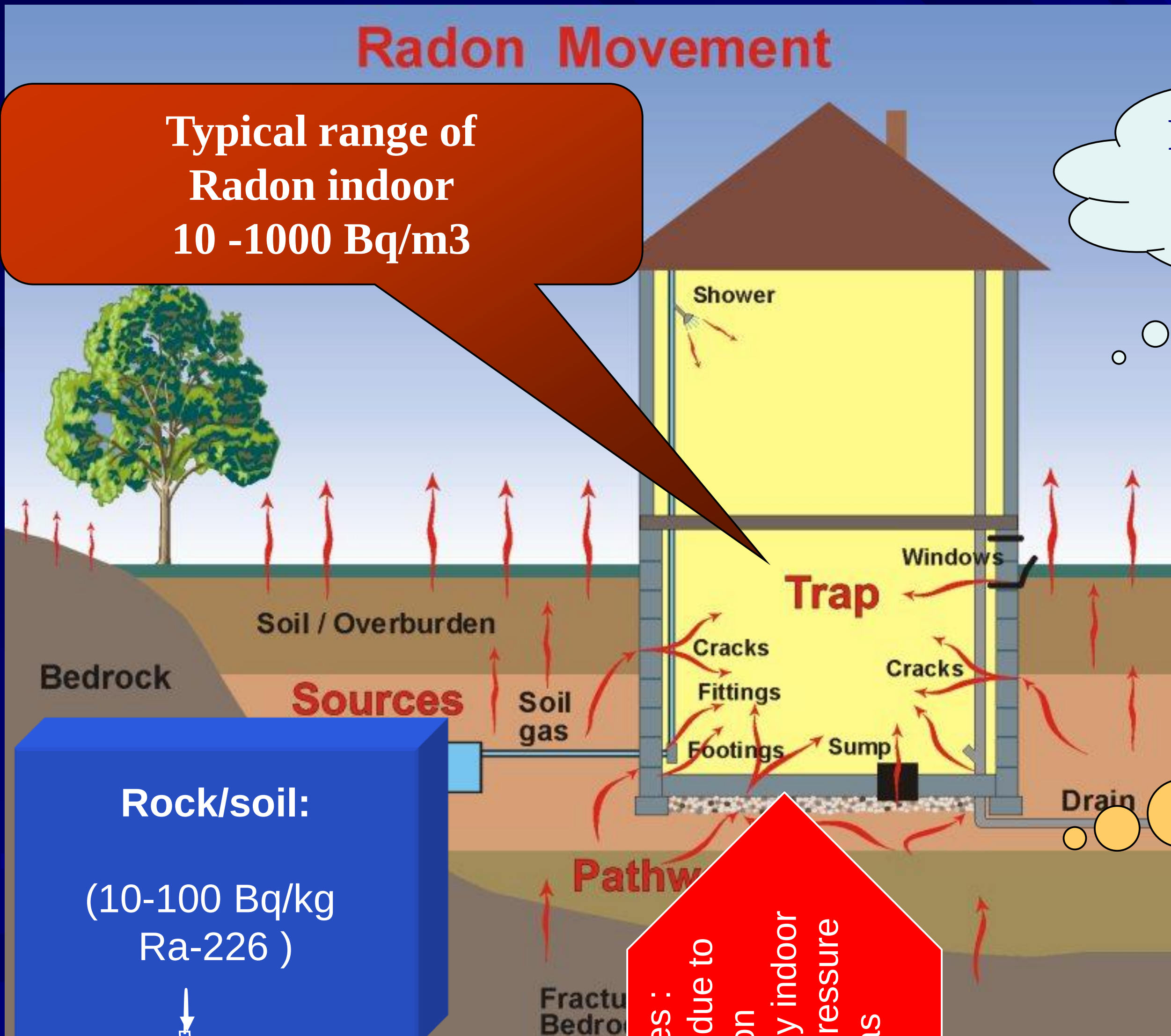
High ^{226}Ra content in building materials used

in the Czech Republic during 1900 -1985

1. **houses in town Joachimstahl (up to 1MBq/kg in plasters and mortars)**
2. **some 20 000 autoclaved aerated-concrete houses (1kBq/kg, emanat.coef. ≈ 15-30 %)**
3. **some 3000 houses from “slag-concrete” (up to 3kBq/kg)**

1 ppm U-238 …. ~ 12,4 Bq
Uraninite (formerly pitchblende) uranium-rich mineral largely UO_2 up 10 MBq/kg

Radon transport and entry in the building



Typical range of
Radon indoor
10 -1000 Bq/m3

Radon in atmosphere
10 Bq/m3

Radon
h = 1 m
10 000 - 100 000
Bq/m3
(even >1 000 000
Bq/m3)

Rock/soil:

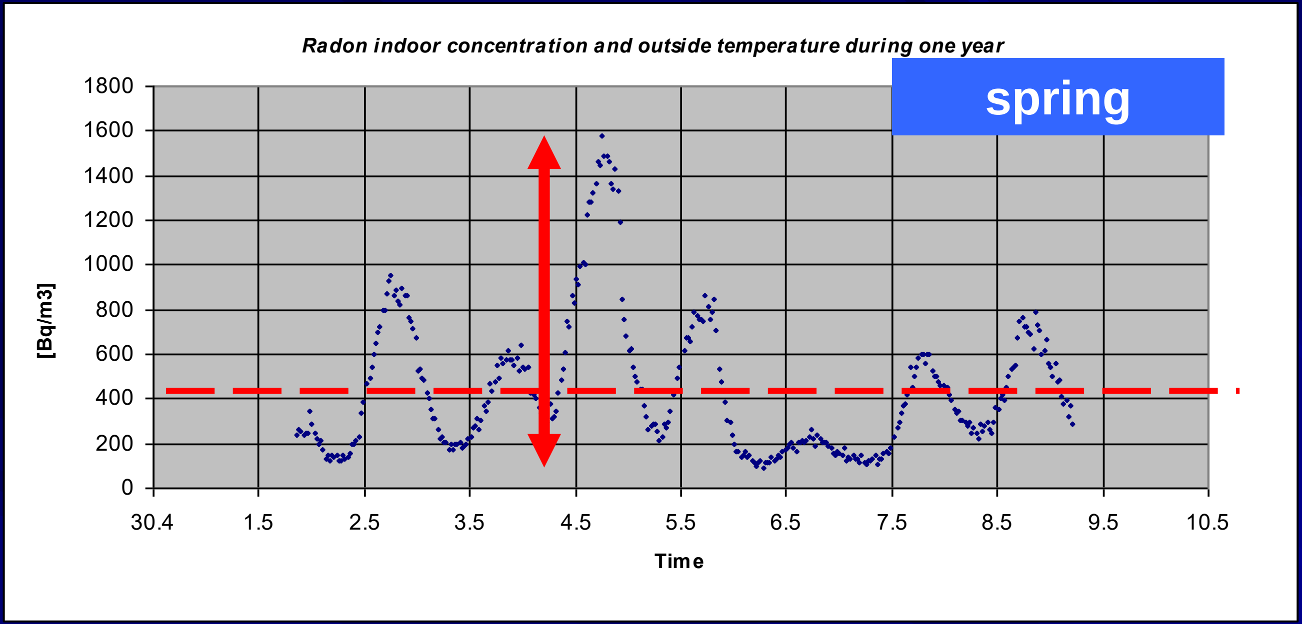
(10-100 Bq/kg
Ra-226)

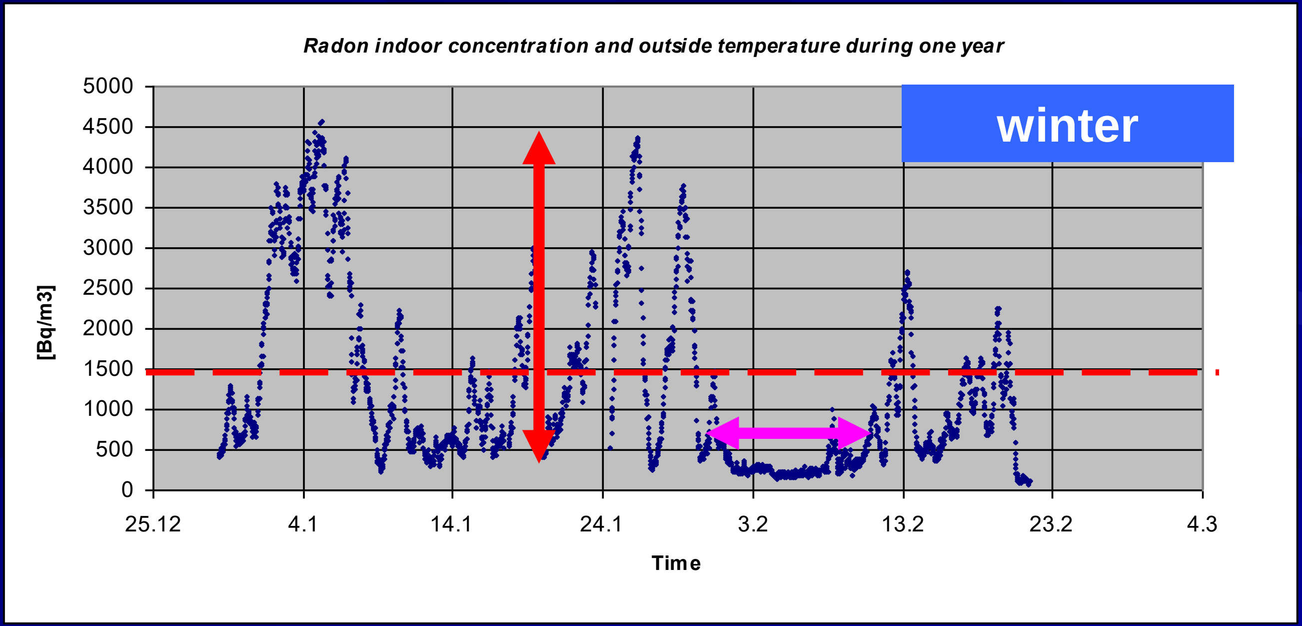
Dominates :
Rn entry due to
convection
caused by indoor
negative ressure
vs.soil gas

underground water Rn^{222} in
range 10 - 100 Bq/l

Estimate : 1 Bq/m3 indoor
from 10 Bq/l in water

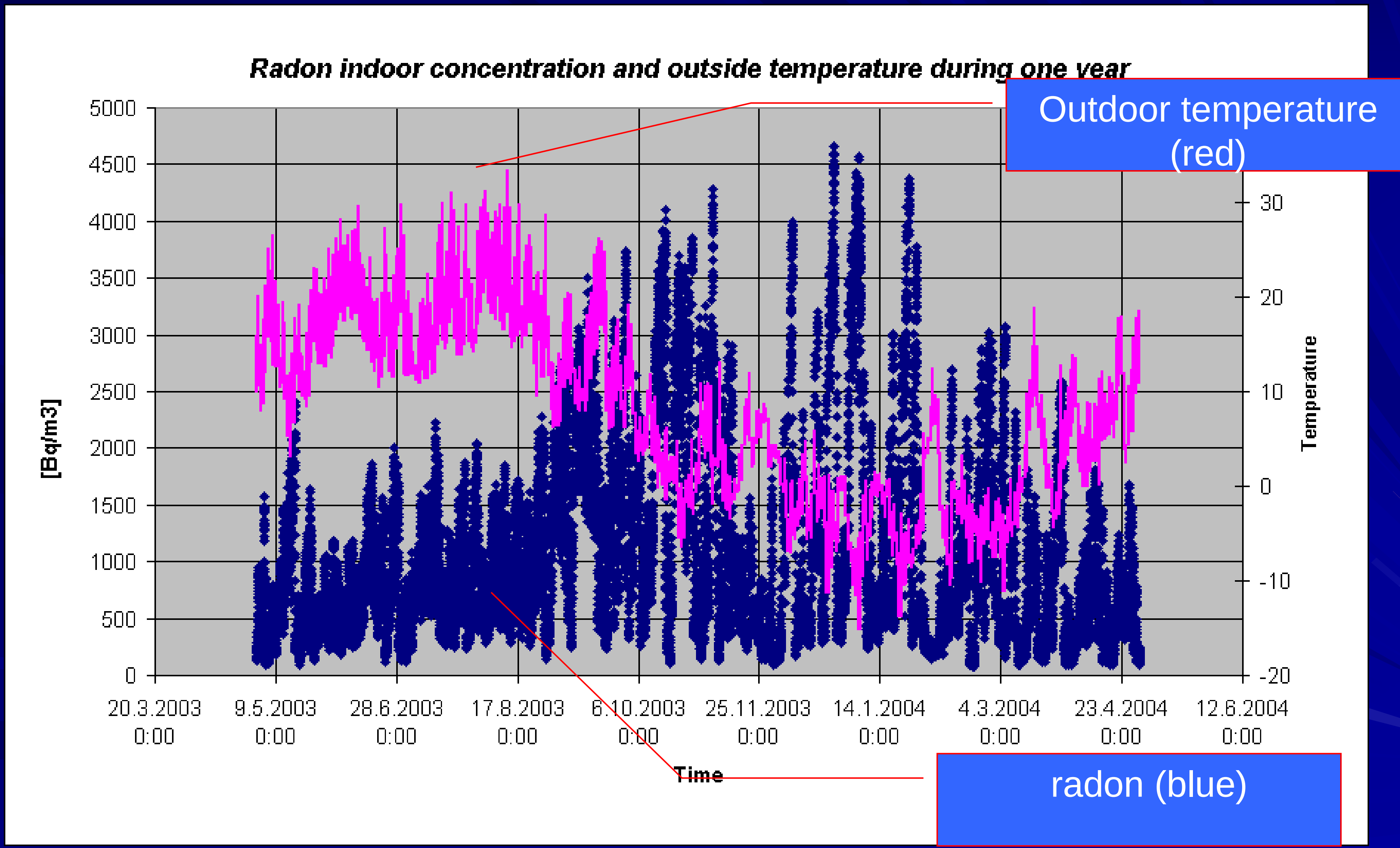
Rn concentration variation - Close room condition – extreme case



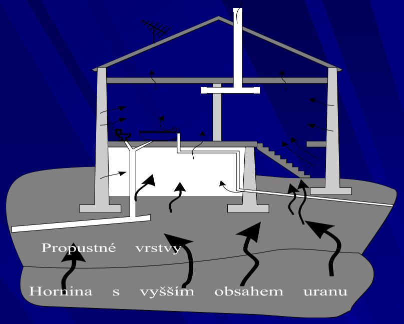


continuous Rn measurement during 1 year

in the building (without inhabitants)



Indoor radon variation (simplified theory)



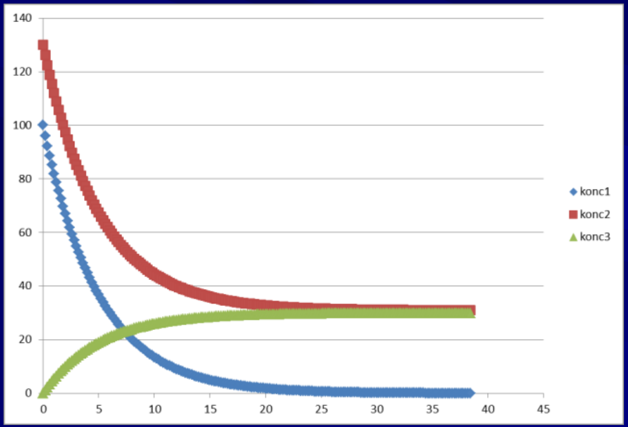
$$\frac{da(t)}{dt} = \frac{Q(t)}{V} - k(t).a(t) - \lambda.a(t)$$

λ..radon decay
0,007 h^{-1}

k…ventlation rate (0,1-0,5) h^{-1}

Q… total radon entry rate

$$a(t) = ao.\exp(-k.t) + \frac{Q}{k.V}(1-\exp(-k.t))$$



Solution for
- Zero initíal concetration
- Constant radon entry rate and ventilation rate
- mix

Steady state

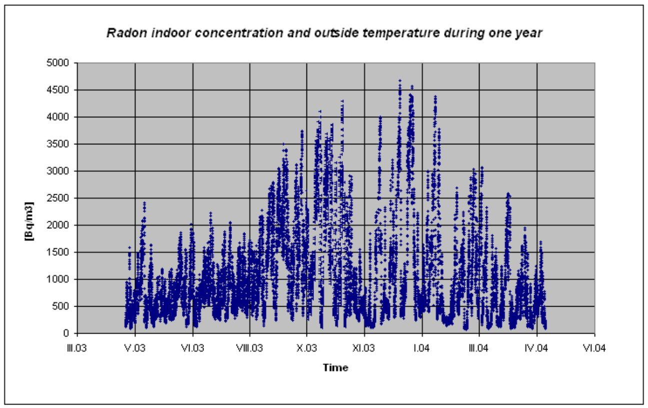
$$a = \frac{Q}{k.V}$$

Q,k are influenced by

- Meteorological changes (temperature difference, wind, b) → **Δp**
- human behaviour (ventilation and radon entry)
- long-term changes (soil moisture below house , subsoil water level, construction changes , window sealing, cracks …., global warming…

How to properly measure and assess indoor Rn concentration

("uncertainty" caused by physical phenomena - short and long term variations)



Well known radon variations

- Hour-to-hour,
- Week to week,
- Month-to-month,
- Season-to season (seasonal correction?)
- Year-to-year

cause issue of due measurement and interpretation

- Instrumental uncertainty (< 30%) …not a big problem
- Spatial uncertainty (how many and which rooms)
- Time factor (when and how long)

the most complicated for interpretation,

- data distributions are hardly normal/lognormal

- time series and frequency analysis necessary

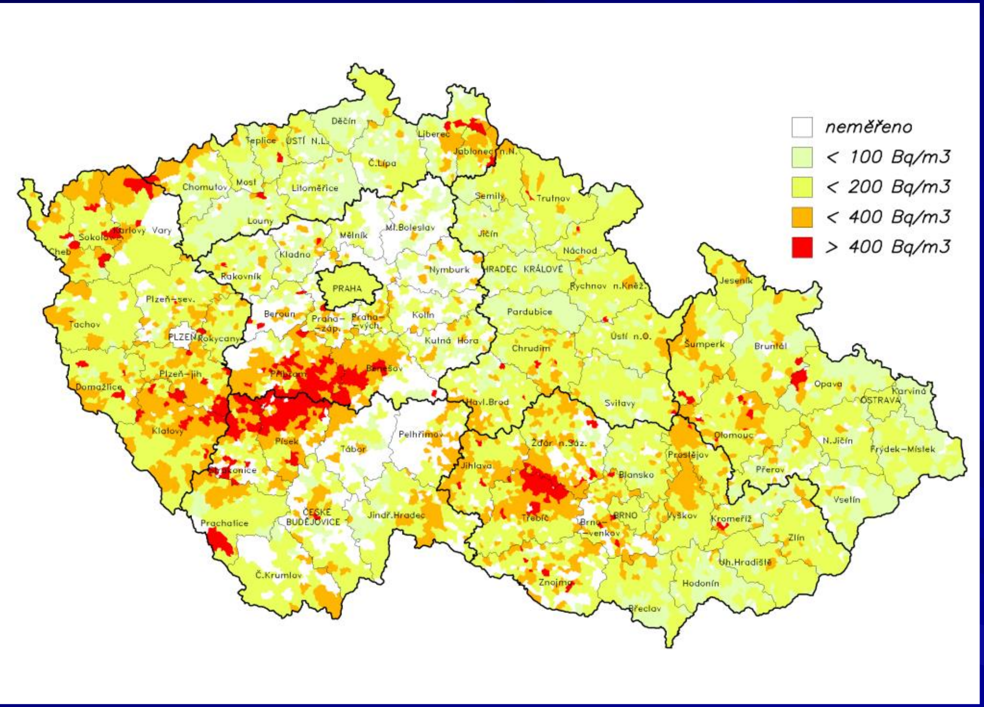
Radon Measurements and Detectors

- Measurement types
  - Spot
  - Integrated
  - Continuous
- Passive and Active
- Exposure duration
  - Short term
  - Long term
- Sensitivity






Radon Survey and Mapping



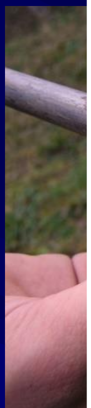
Radon indoor

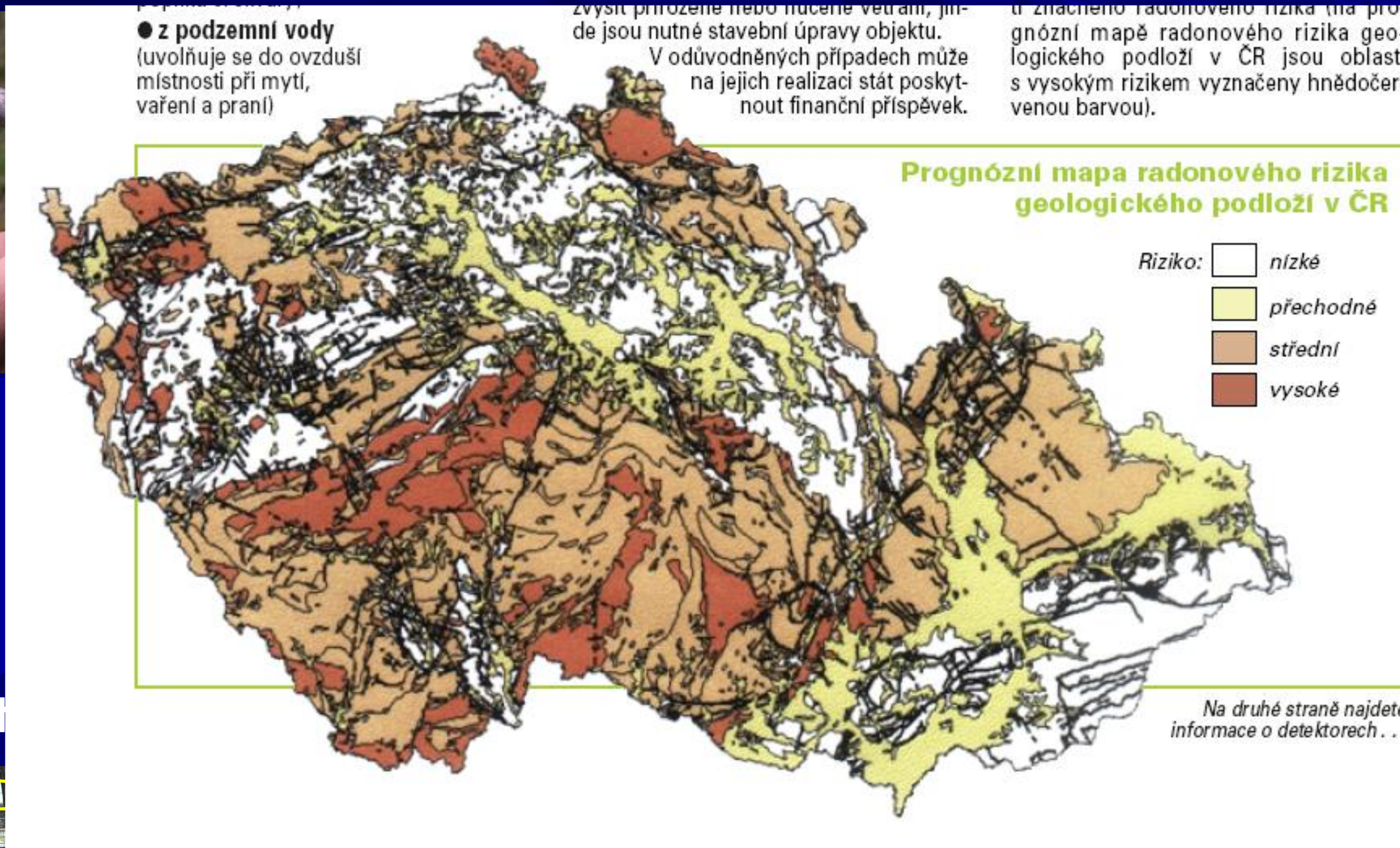
(200 000 family houses

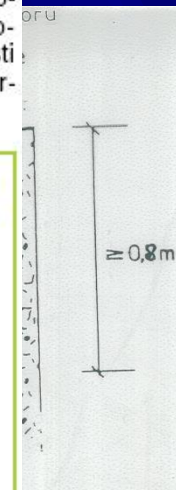
+ schools +kindergartens)

Radon In the soil bedrock

Soil-gas and permeability sampling (The end result of continuous simplification)







a)

b)

c)

m) +

Det

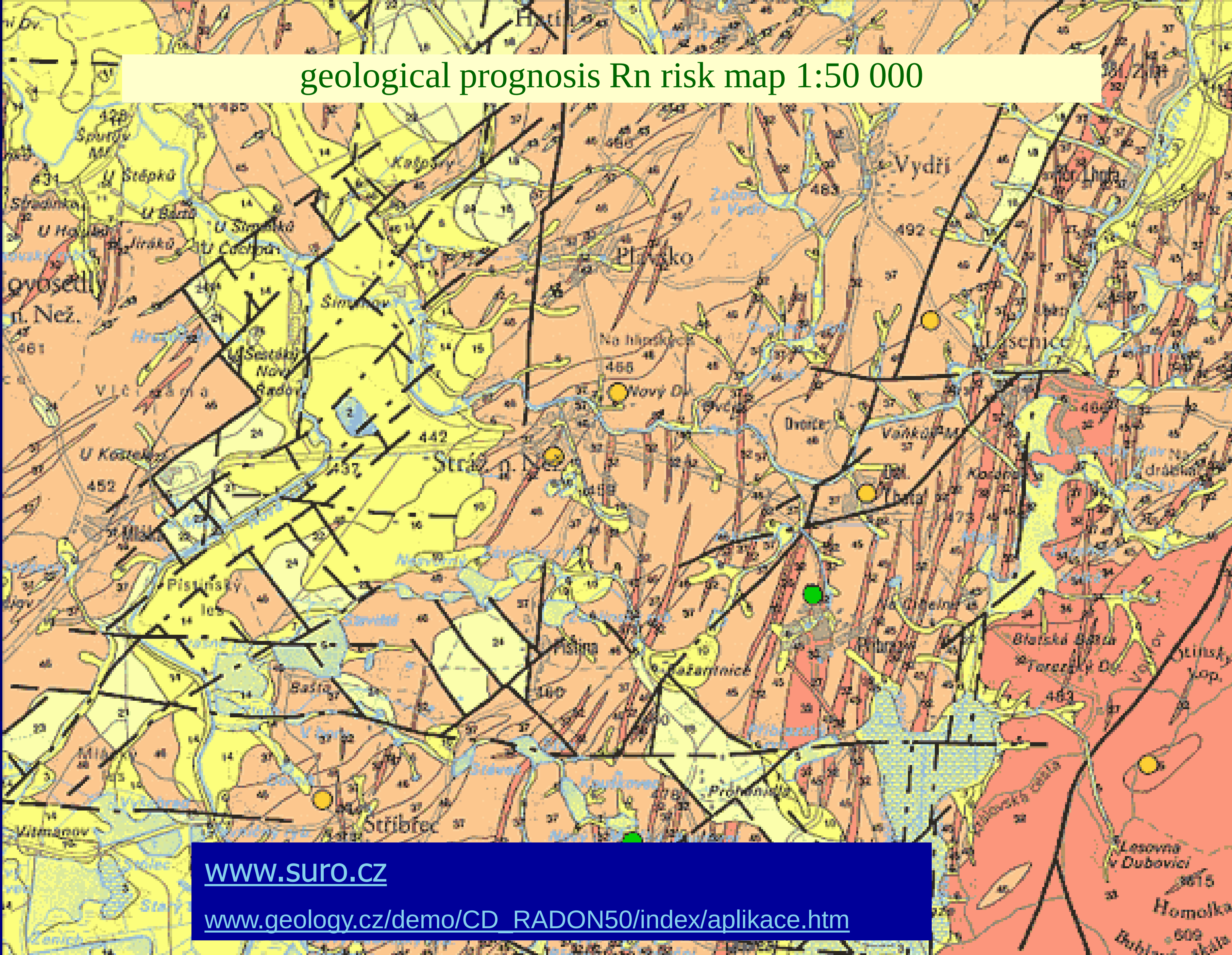
RAD

oil

Principle: air withdrawal by means of negative pressure

	permeability	Permeability	High permeability
Low	<30	<20	<10
Medium	30-100	20-70	10-30
High	>100	>70	>30

geological prognosis Rn risk map 1:50 000

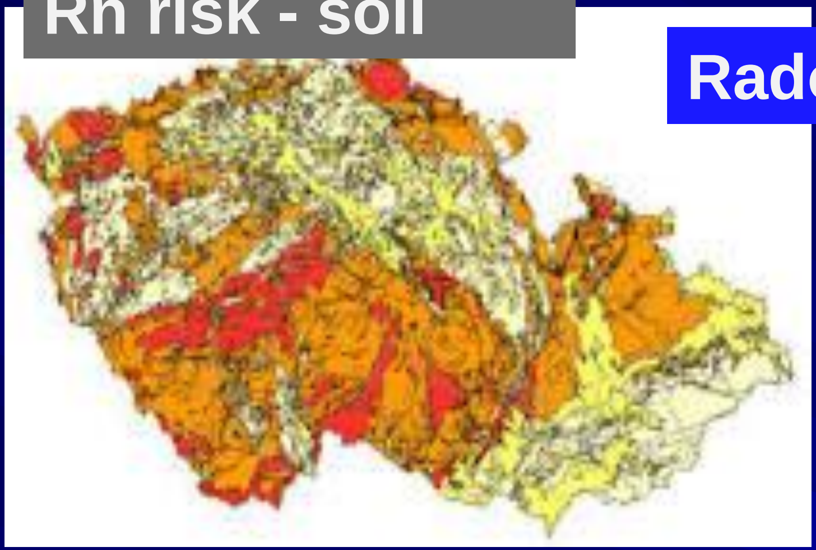


www.suro.cz

www.geology.cz/demo/CD_RADON50/index/aplikace.htm

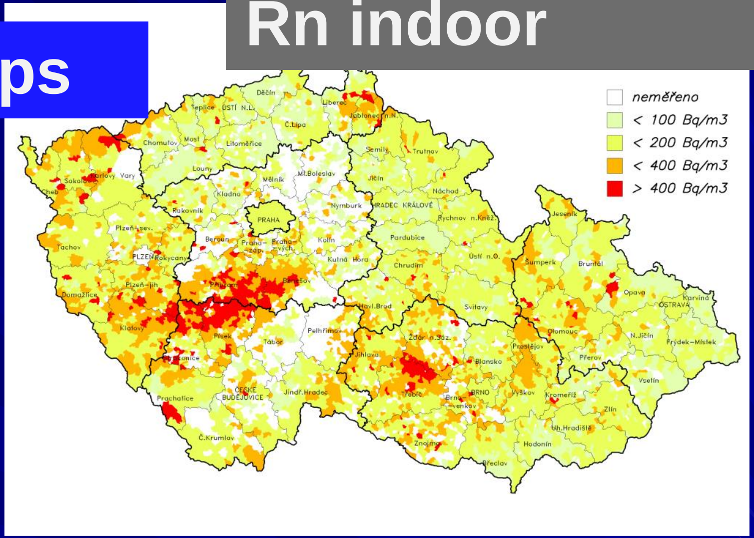
Radiometric vs. Radon maps
(gamma dose rate or uranium/Ra-226 concentration)
(not enought for Rn indoor prediction)

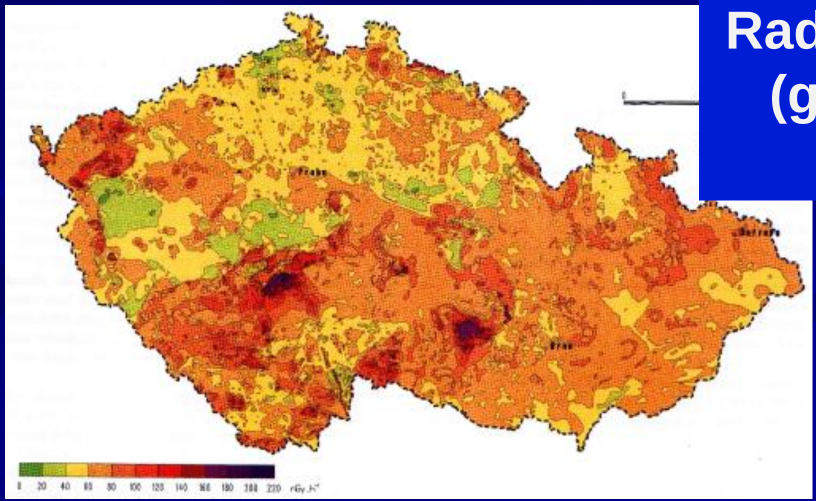
Rn risk - soil



Radon risk maps

Rn indoor

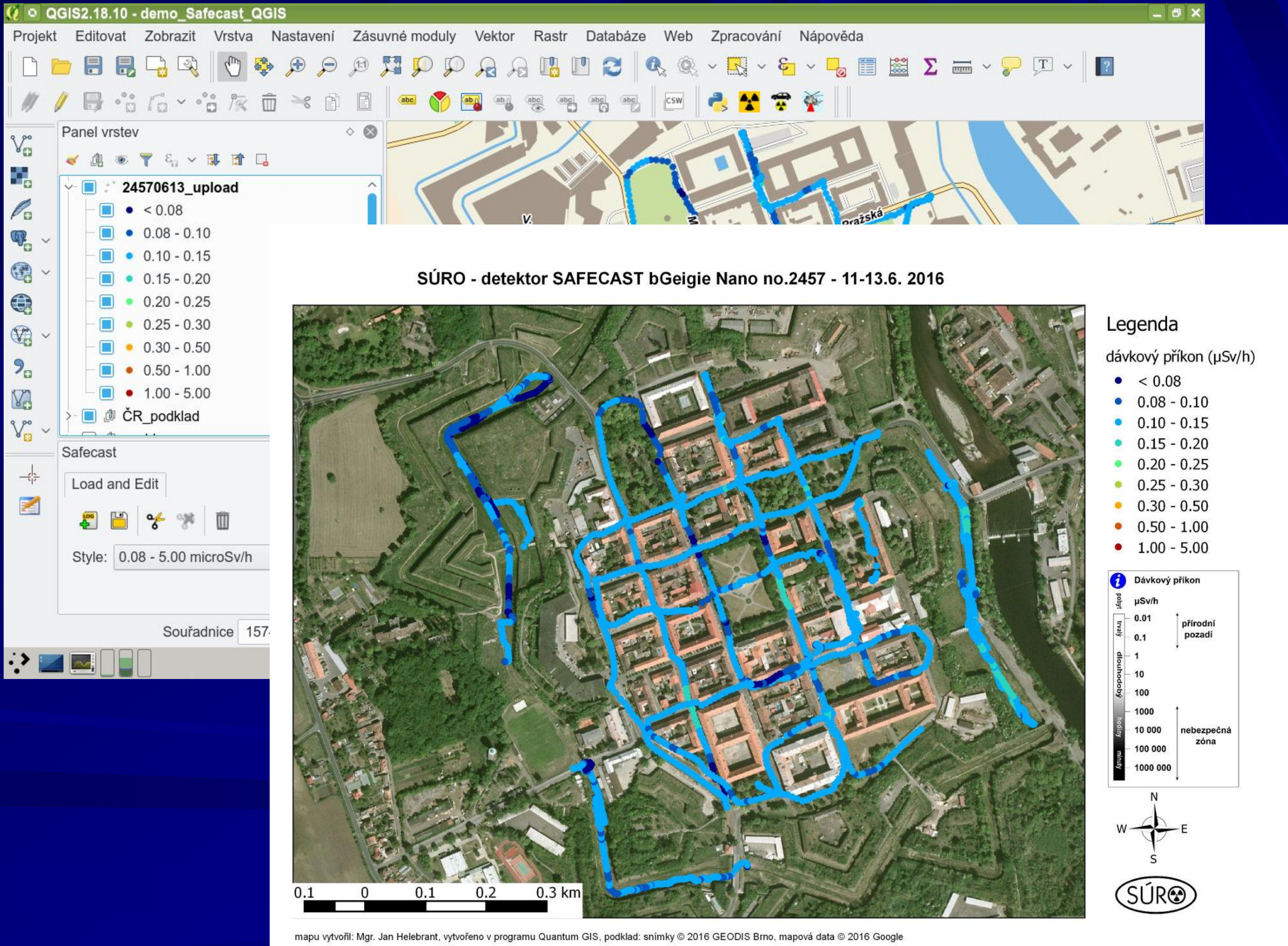




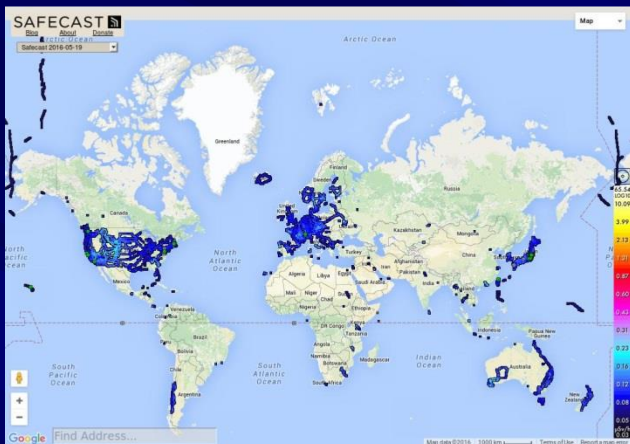
Radiometric map (gamma dose outdoor)

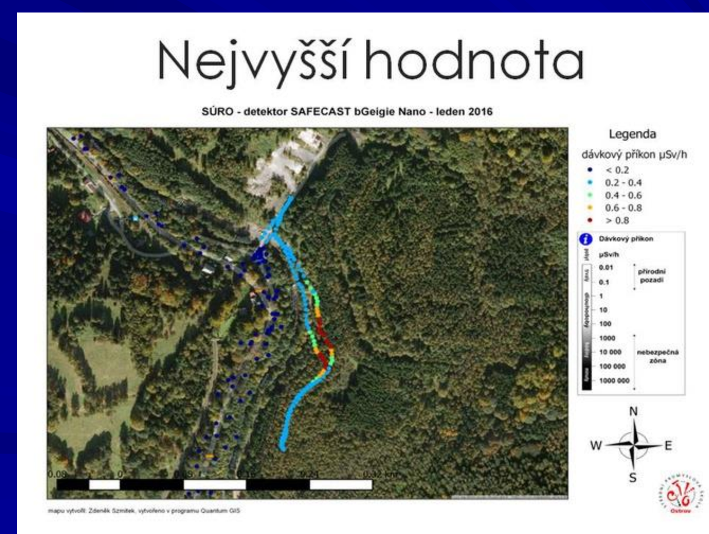
How to simply prepare national (gamma) radiometric map?

Citizen dose rate measurements SAFECAST


QGIS2.18.10 - demo_Safecast_QGIS
Projekt Editovat Zobrazit Vrstva Nastavení Zásuvné moduly Vektor Rastr Databáze Web Zpracování Nápověda
Panel vrstev
24570613_upload
< 0.08
0.08 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.50
0.50 - 1.00
1.00 - 5.00
ČR_podklad
Safecast
Load and Edit
Style: 0.08 - 5.00 microSv/h
Souřadnice
SÚRO - detektor SAFECAST bGeigie Nano no.2457 - 11-13.6. 2016
Legenda
dávkový příkon (μSv/h)
< 0.08
0.08 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.50
0.50 - 1.00
1.00 - 5.00
Dávkový příkon
μSv/h
0.01
0.1
1
10
100
1000
10 000
100 000
1000 000
přírodní pozadí
nebezpečná zóna
N
W
E
S
SÚRO
0.1 0 0.1 0.2 0.3 km
mapu vytvořil: Mgr. Jan Helebrant, vytvořeno v programu Quantum GIS, podklad: snímky © 2016 GEODIS Brno, mapová data © 2016 Google

SURO v.v.i. borrow it to schools, tourist, fire brigade etc



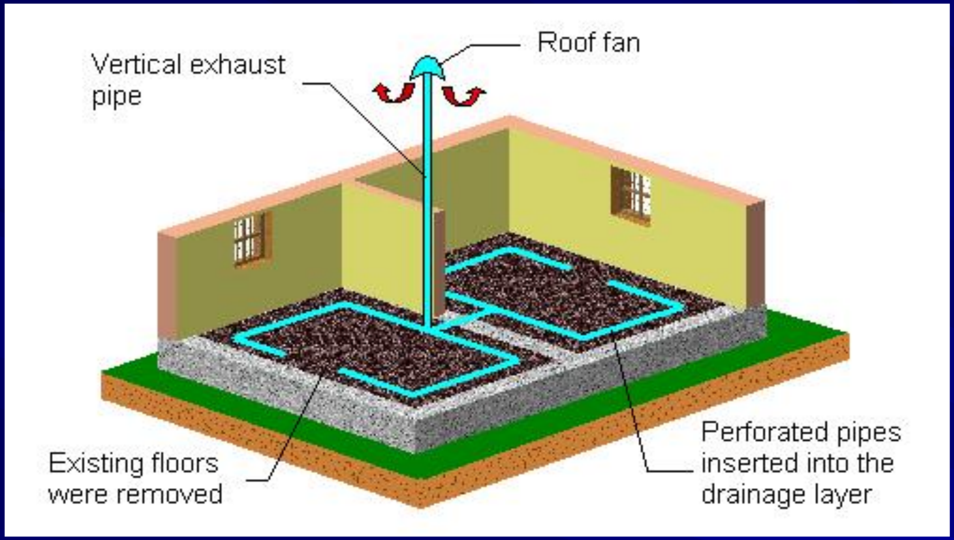


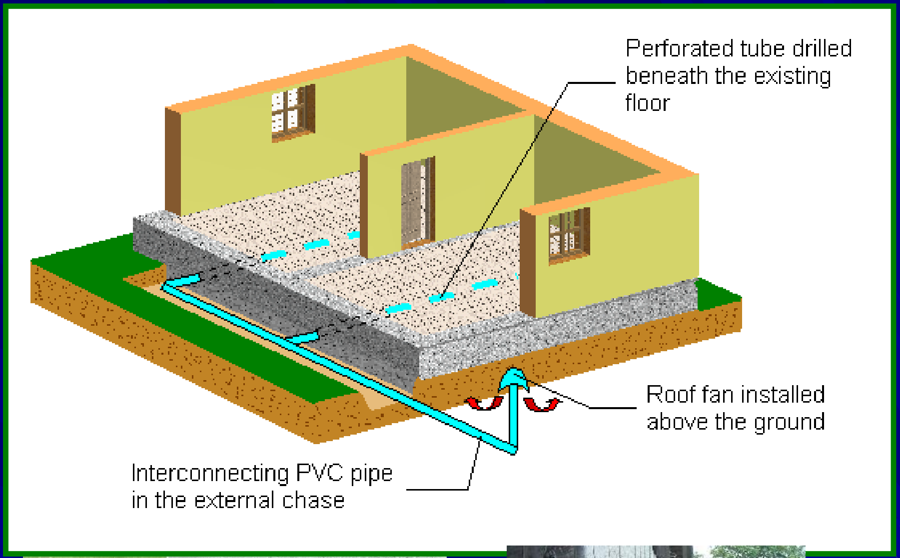
Corrective Actions
in existing buildings

- New insulation against soil radon (special membranes -radon barriers)
- Pressure air-exchange of the building (controlled by Rn sensor)
- Sub-soil ventilation (passive or active) or soil suction

Sub-soil ventilation or soil suction

Network of flexible perforated pipes



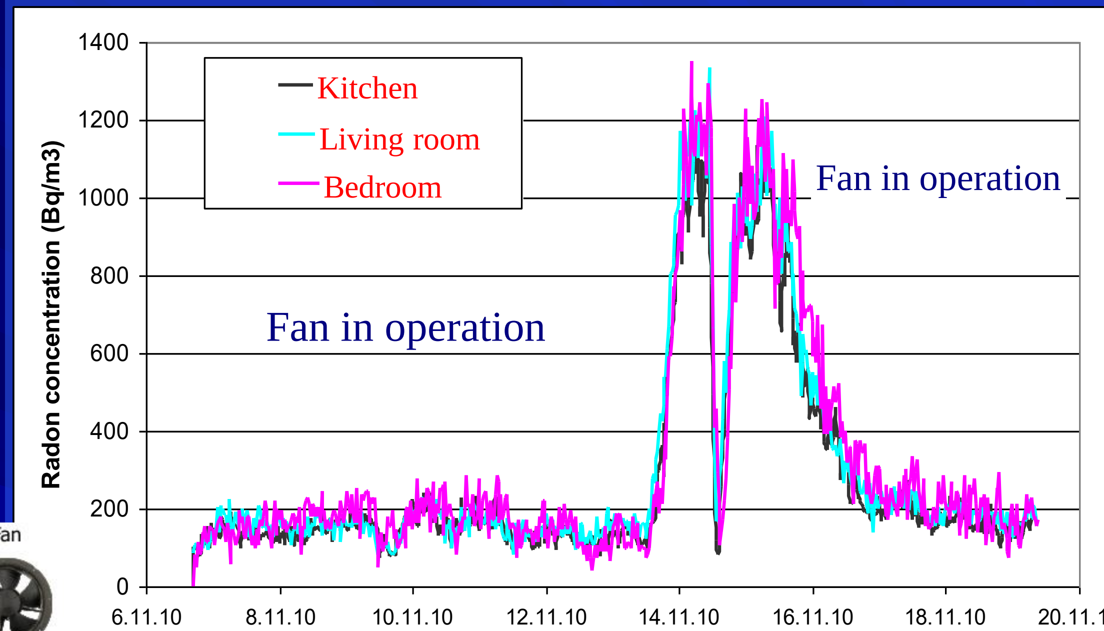


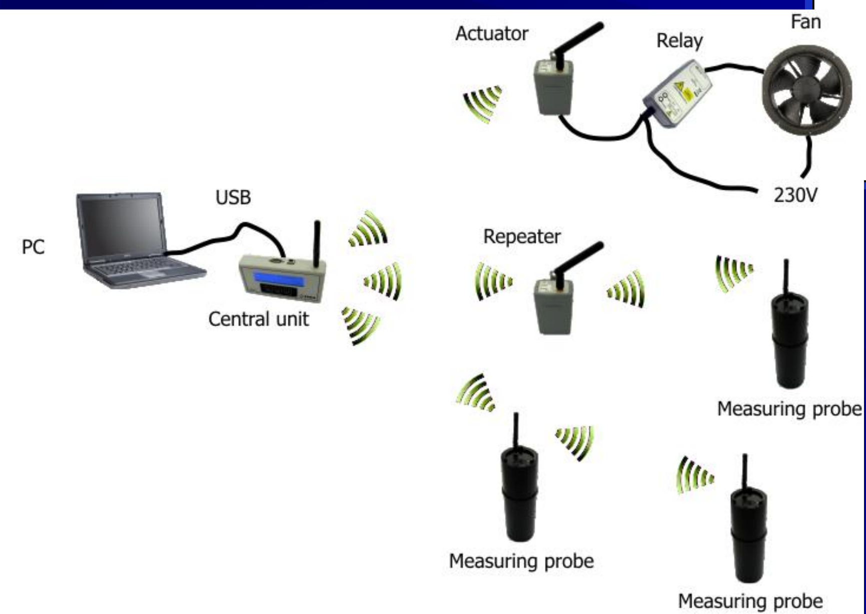
Example: radon concentration after the active corrective action, IoT

Example: Rn sensors (Tera Tesla) for automatic regulation of radon concetration

Including for monitoring and regulation :
VOC, CO, CO_2, T, humidity etc

During active sub soil ventilation radon concentration decreased to the mean value





Short intensive ventilation by window

Preventive measures (new buildings)

Legislation : What should be obligatory ?

- Estimation of **<u>Rn index (risk) of each building site</u>** before siting of the new building.
- Building protection according Technical Building Standard (obligatory for building owner)

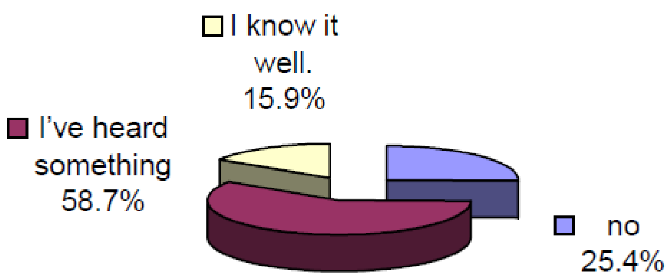
- Monitoring of natural radioactivity of **<u>building materials</u>** (obligatory for producers of building materials)
  (Stop delivery above limit values).

- Monitoring of natural radioactivity of supplied **<u>water</u>** (obligatory for water providers)
  (Stop delivery above limit values).

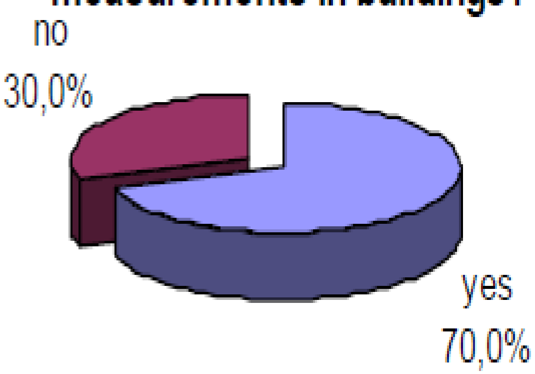
Evaluation of information campaign

SURVEY OF RADON AWARENESS AMONG CZECH REPUBLIC RESIDENTS

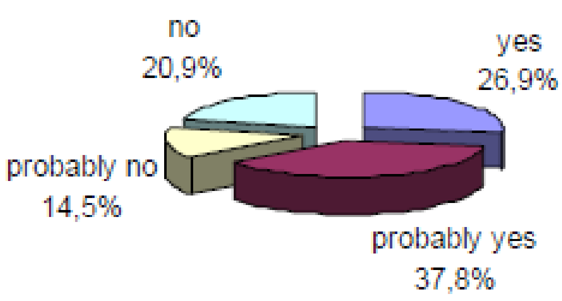
Have you ever heard of a naturally occurring gas named radon?



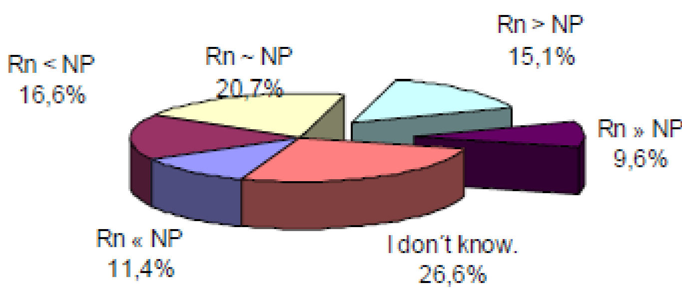
Do you know that there exist Rn measurements in buildings?



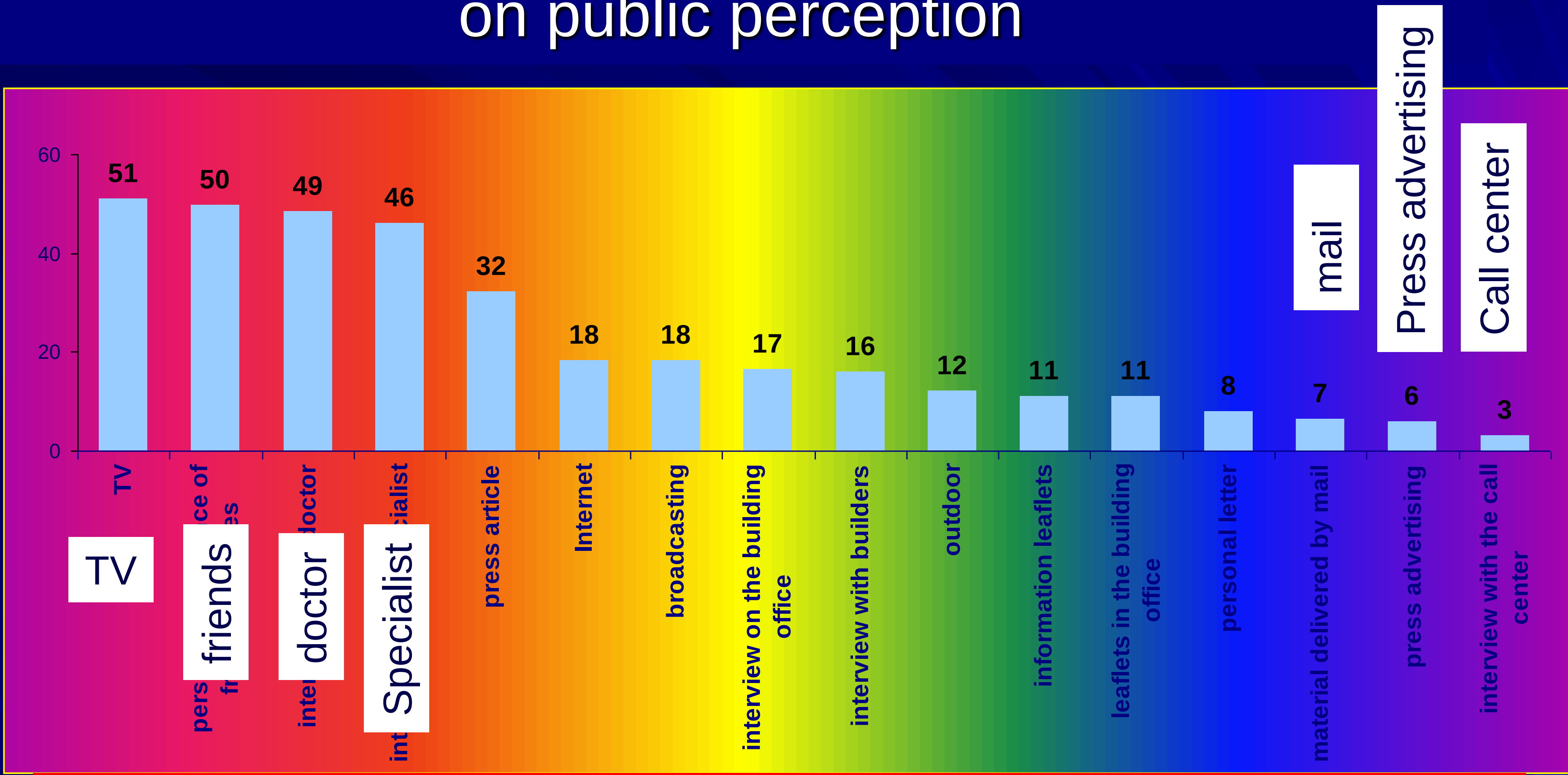
Do you want to measure Rn in your house?



compare the danger (exposure) from radon and a nuclear power station (NP)



Qualitative survey:
impact of the different information channels
on public perception



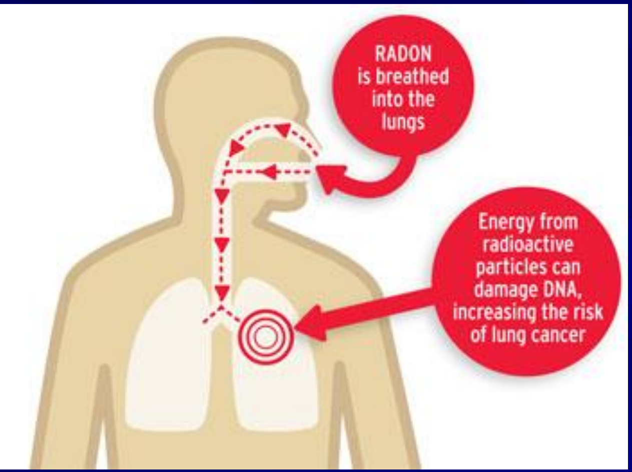
Who is (in the family) responsible for the radon exposure and corrective actions?

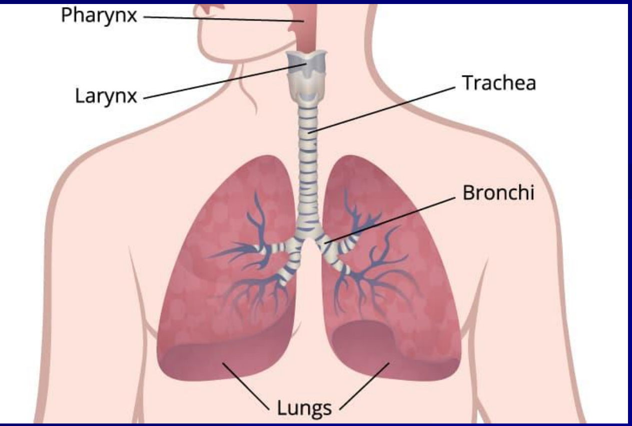
Radon as a scientific topic

Selected subjects:

- Rn and carcinogenesis
- Rn as Earthquake Precursor
- Rn and atmosphere (tracer)
- *Low Rn activity issue: Rn as confounding factor in ultra-sensitive detection and radiobiology*

Rn and carcinogenesis - microdosimetry and nanodosimetry - bronchial epithelium





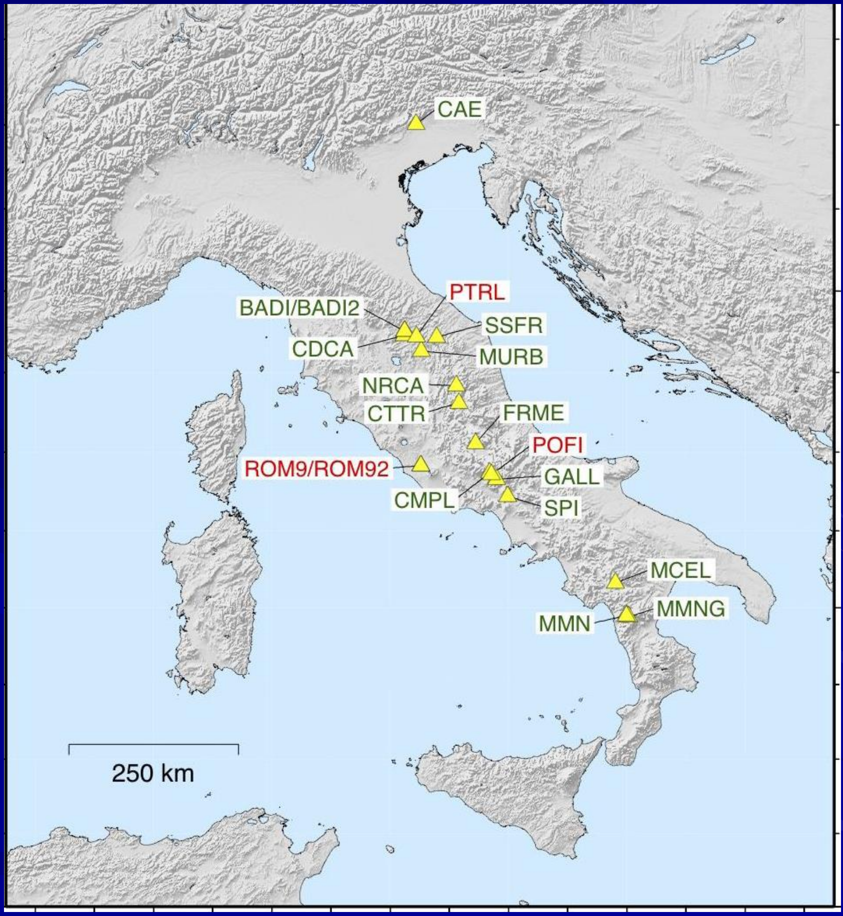
- transformation of a cell after irradiation into a cancer cell (in bronchial epithelium), **has not been fully elucidated**, online tissue tracking in vitro
- stages of carcinogenesis
- individual radiosensitivity - which genes are responsible for it?

Radon changes as Earthquake Precursor

A) Rn in soil gas (example : IRON Italian Radon mOnitoring Network)

..over 50 stations in the central-Southern Apennines following the distribution of Italian seismicity ….
.
IRON stations have recorded radon concentration time series for more than 5 years, (sampling interval of about two hours),

the IRON dataset consists of more 440,000 single radon concentration measurements



- *IRON: Italian Radon mOnitoring Network*

Radon changes as Earthquake Precursor

B) Ground-Water Radon Anomaly (Kobe Earthquake in Japan)

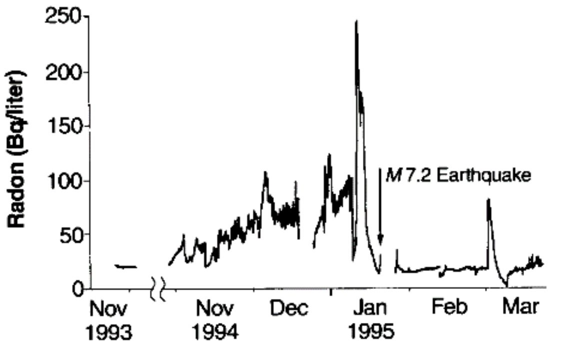


Fig. 2. Radon concentration data at the well in the southern part of Nishinomiya city, Hyogo prefecture, Japan.

Rn concentration in ground water increased for several months before the 1995 southern Hyogo Prefecture (Kobe) earthquake on 17 January 1995. From October 1994 the beginning of the observation, to the end of December 1994, Rn concentration increased about fourfold.

On 8 January, 9 days before the earthquake, the Rn concentration reached a peak of more than 10 times that at the beginning of the observation, before starting to decrease . These radon changes are likely to be precursory phenomena of the disastrous earthquake.

- *Igarashi, G.; Saeki, S.; Takahata, N.; Sumikawa, K.; Tasaka, S.; Sasaki, Y.; Takahashi, M.; Sano, Y. Groundwater radon anomaly before the Kobe earthquake in Japan. Science 1995, 269, 60–61.*
- *Earthquake forecasting: a review of radon as seismic precursor A. Riggio and M. Santulin*, Bollettino di Geofisica Teorica ed Applicata Vol. 56, n. 2, pp. 95-114; June 2015*
- *Recent progress in radon-based monitoring as seismic and volcanic precursor: A critical review Nury Morales-Simfors, Ramon A. Wyss & Jochen Bundschuh; Critical Reviews in Environmental Science and Technology, (2019) ; DOI: 10.1080/10643389.2019.1642833*

Radon in the atmosphere

The 3.8-day half-life of radon-222 makes it useful in physical sciences as a natural tracer

Radon concentration in the atmosphere varies widely from place to place. In the open air, it ranges (the most common) from 1 to 100 Bq m^{-3}, even less (0.1 Bq m^{-3}) above the ocean.

Average radon concentration in the atmosphere is 10 Bq m^{-3} (UNSCEAR, 2000).

Rn concentration increases during the night when the atmosphere is stable reaching a maximum at dawn.

Less well known are the effects *of* mountain-valley air drainage on radon concentrations in the outflow system.

1. Moses, H., A. Stehney, and H. Lucas, The effect of meteorological variables upon vertical and temporal distributions of atmospheric radon, J. Geophys. Res., 65, 1223-1238, 1960.
2. Fontan, J., A. Birot, D. Blanc, A. Bouville, and A. Druilhet, Measure of the diffusion of radon, thoron and their radioactive daughter products in the lower layers of the earth's atmosphere, Tellus, 18, 623-632,1966.
3. Cohen, L., S. Barr, R. Krablin, and H. Newstein, Steady-state vertical turbulent diffusion of radon, J. Geophys. Res., 77,2654-2668, 1972
4. Radon in Atmospheric Studies: A Review, MARVIN WILKENING, 1981, Bombay

Radon in the atmosphere

Global radon emissions to atmosphere annually are estimated $1{,}10 \times 10^{17}$ Bq *(compare to total emission Chernobyl 10^{19} Bq , Fukushima 10^{18} Bq)*

Components:

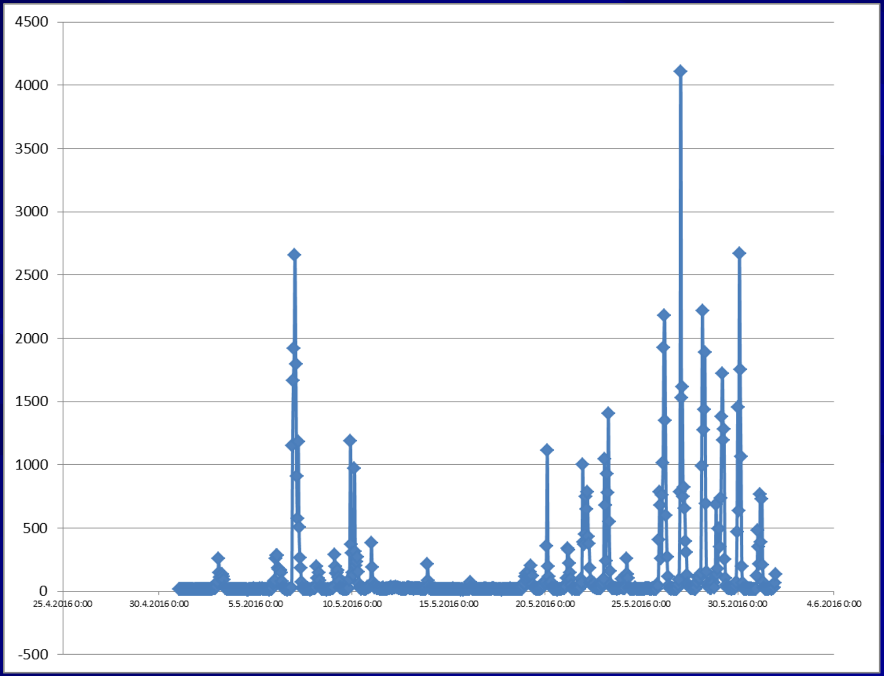
- from soil (81,7 %),
- from groundwater (17%),
- oceans (1,15%),
- phosphate residues (0.1%),
- uranium mill tailings (0.07%),
- coal residues (0.0007%),
- natural gas emissions (0.0003%),
- coal combustion (0.0003%),

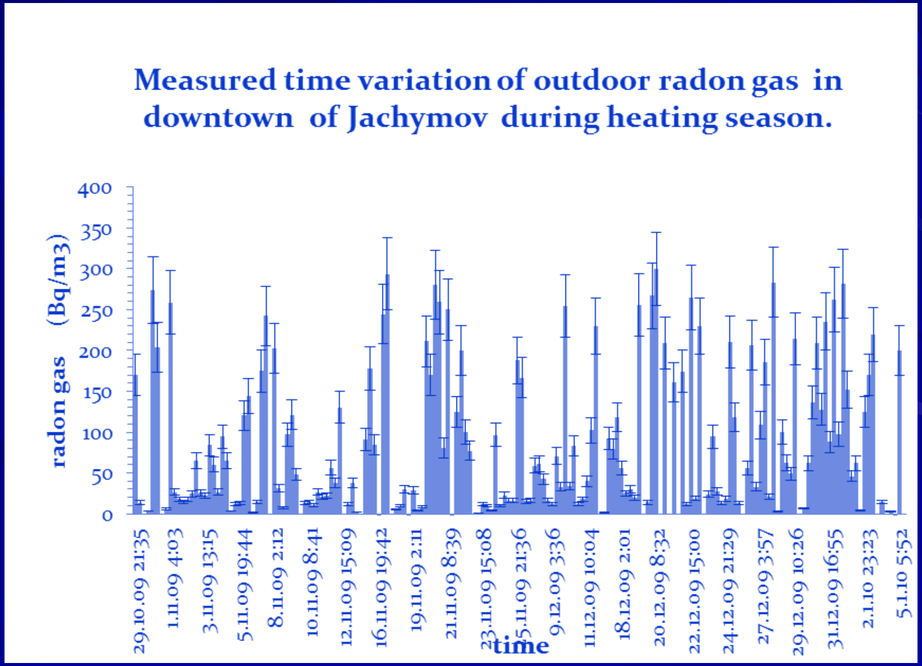
(Fishbein 1992).

Radon in the atmosphere - results

Rn and Rn progeny continuous monitoring in the enviromnent (uranium tailings, deep valey , Rn in ground layer of the atmosphere at the time of inversion)

(RAMONIS) Modular Station for Continuous Measurement of Natural Radioactivity in Air, Soil and Water





Rn as confounding factor in ultra-sensitive detection (and Low level Rn clean room)

REASON

to suppress radioactivity caused by Rn/Rn decay product in the air for special cases:

ultrasensitive detectors, radiobiology (behaviour of cells or DNA in the radiation free environment) contamination in nano-electronics.

Rn concentrations in buildings … 10-100 000 Bq/m^3

atmosphere some 10 Bq/m^3

We need mBq/m^3

with very low aerosol concentration

(„Clean room") ISO 5 highest class of cleanliness

+ Including entry of persons

Clean and „radon free“ room (SURO + IEAP)

Principle of the “CLEAN ROOM”:

to join

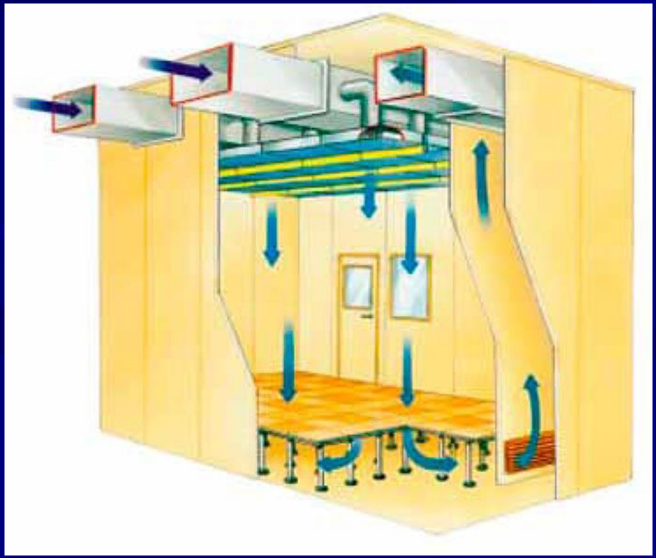
The room is intensively ventilated and filtered by HEPA filtration system with filtration rate of 8000 m^3/h to reach highest class of cleanliness (ISO 5)

laminar air flow - to reach aerosol free space

Normal outdoor air is used for filtration

Principle of the “RADON FREE ROOM”:

- Clean uncontaminated building material (metal sandwich panels with termal insulation)
- sealed against radon from soil and **<u>outdoor radon</u>**
- delivery of **<u>only radon free air</u>** (20 m3/h - 150 m3/h) (< 10 mBq/m3 from Radon reduction system facility
- Minimize Rn exhalation from persons



Indoor clean room 10-100 mBq/m3

Outdoor 10-100 Bq/m3

Thank you