

## Chapter 7

### The Natural Radiation Sources and doses to the people

1

#### *Cosmic radiation*

Myons, electrons and photons. In normal flying altitude the doselevel is about 40 times higher than that at ground level. The contribution from neutrons increases with altitude.

4

#### *Radon*

Rn-222 + "daughters"  
Po-218  
Pb-214  
Bi-214  
Po-214

The radon daughters give a dose to the bronchi and lungs

3

#### *Radioactivity in the body*

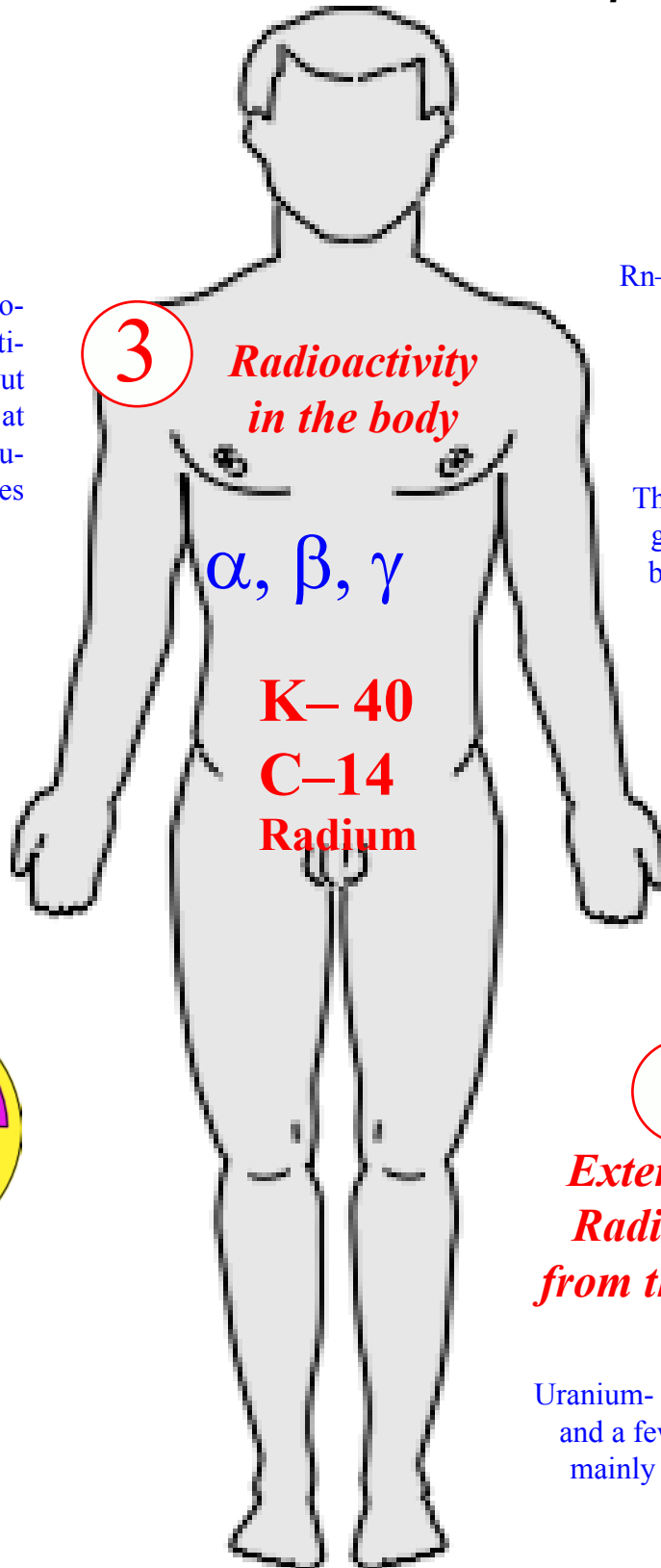
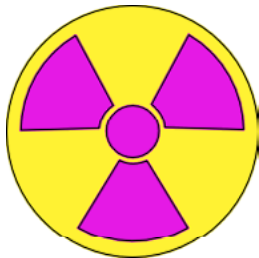
$\alpha, \beta, \gamma$

**K-40**  
**C-14**  
**Radium**

2

#### *External – $\gamma$ Radioactivity from the ground*

Uranium- and thorium-series and a few other isotopes, mainly K-40 and C-14.



## Introduction

There are radioactive isotopes in our bodies, houses, air, water and in the ground – and we are exposed to radiation from outer space. We divide all these radiation sources into four different groups:

1. Cosmic radiation.
2. External  $\gamma$ -radiation from natural radioactive sources.
3. Internal radioactive sources (radioactivity in the body).
4. Radon.

In this Chapter, we shall discuss the natural radiation in more detail. First of all, we shall give the physical aspects of the radiation sources and the level of radiation – both here in Norway and around the world.

UNSCEAR (United Nations Committee on the Effects of Atomic Radiation) has collected information about the distribution of the radiation sources around the world and doses to the public. We are largely using their data from the 2000 report.

<http://www.unscear.org/docs/reports/annexb.pdf>

We are exposed to natural radiation from cradle to grave – and the accumulated life-time dose, depends upon where you live as well as on your life style.

You can not go through life without radiation. It has been a silent rule that it would be good for you to keep your yearly dose to a minimum. However, new radiobiological experiments with cells and cell mechanisms seem to conclude that radiation in small amounts and with a low dose rate stimulate our defense mechanisms. The data suggests that radiation may protect you from cancer.

These very interesting data will be discussed later. Now we shall present the data for the environmental radiation. It can be mentioned that in the UNSCEAR report the doses are given in the Sv-system. However, it is very unclear what kind of RBE-values that are used for a mixture of neutron energies as found in the cosmic radiation.

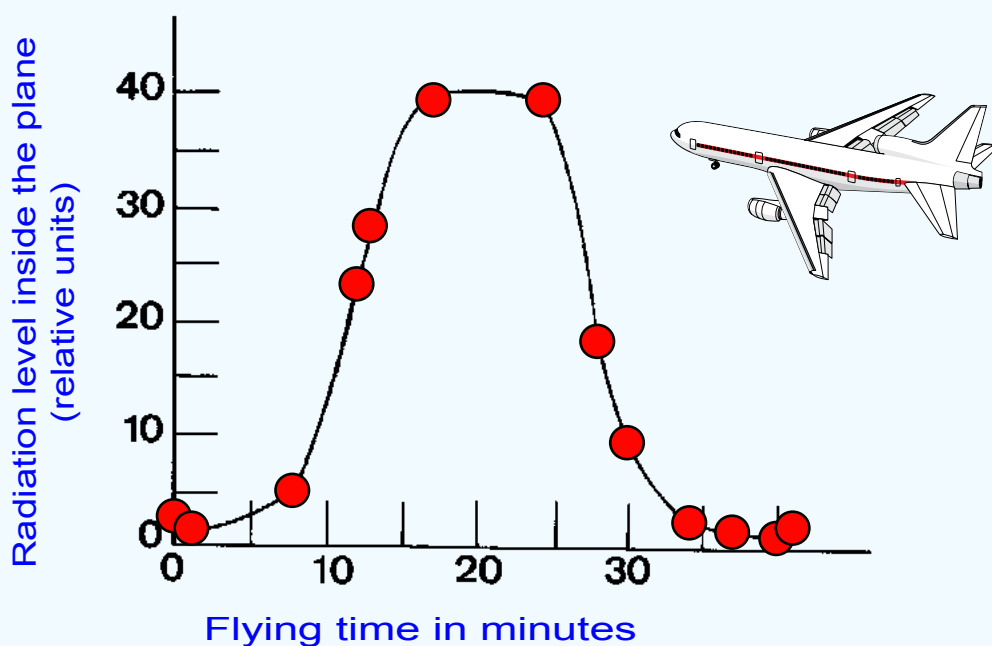
For the four different groups above, the radiation consists of a mixture of  $\gamma$ -radiation,  $\beta$ -particles, neutrons (in the cosmic radiation) and  $\alpha$ -particles (radon). This implies that for group 1. and 4. above, we have radiation with rather high LET. This suggests to use the Sv-dose units. The unsolved question is however to use the right RBE value in the conversion from Gy to Sv.

In the case of cosmic radiation different neutron energies are involved. This would involve different RBE-values according to ICRP. No debate on this issue is known and we have decided to use the UNSCEAR values for this group. In the case of radon a RBE-value of 20 was introduced and used. However, dose determinations turned out to be impossible to handle and all correlations between radon and lung cancer is now based, not on radiation dose, but rather on the Bq/m<sup>3</sup> in the home where you live or on the workplace in the case of miners.

# Cosmic Radiation

Victor F. Hess discovered the cosmic rays in 1912. In a series of balloon experiments with ionization chambers he found a noticeably increase from 1,000 m onwards, and at 5 km height the ionization level was several times that observed at sea level. He concluded that this ionization was due to radiation from the atmosphere. This radiation is called; *Cosmic radiation*.

The fact that the radiation level increases with height is clearly demonstrated in the figure below. Some of our colleagues at The University of Oslo carried a radiation detector on a flight from Trondheim to Oslo. A considerable fraction of the high energy radiation will penetrate airplanes, giving passengers and crew an extra dose during air travel. In this air travel, that lasted for 40 minutes, the plane was cruising at an altitude of 8500 meters (27,900 feet).



Before start, when the plane was on the ground, the radiation level is set equal to 1. This value represents the sum of cosmic radiation from above and  $\gamma$ -radiation emanating from natural sources at ground level.

You can see that when the plane reached the altitude of 8,500 meters (27,900 ft), the radiation level is approximately 40 times that observed at ground level.

From the figure you can see that the radiation level was slightly smaller just after take-off and just before landing. The reason for this is that, in both occasions, the plane was above water, which contains very low levels of  $\gamma$ -emitters.

It can be mentioned that the cosmic radiation was studied by a number of students in Norway in the 1940-ties, supervised by professor Bjørn Trumphy. They made their own Geiger tubes and used several tubes at the same time in a row. Coincidence measurements could give information about directions, and shielding gave information about penetration. The radiation had a *hard* and a *soft* component.



Bjørn Trumphy  
(1900 – 1974)

## The nature of the cosmic radiation

The atmosphere is continuously exposed to particles from outer space, about 98 % nucleonic and 2 % electrons. The nucleonic component is primarily protons (88%) and alpha particles (11%), whereas the remainder is heavier nuclei.

The energy of the primary cosmic radiation is from  $10^8$  to more than  $10^{20}$  eV (the highest value observed in cascades is  $3.2 \cdot 10^{20}$  eV). In this connection it can be mentioned that with the Large Hadron Collider in Geneva the scientists will accelerate protons to an energy of  $7 \cdot 10^{12}$  eV.

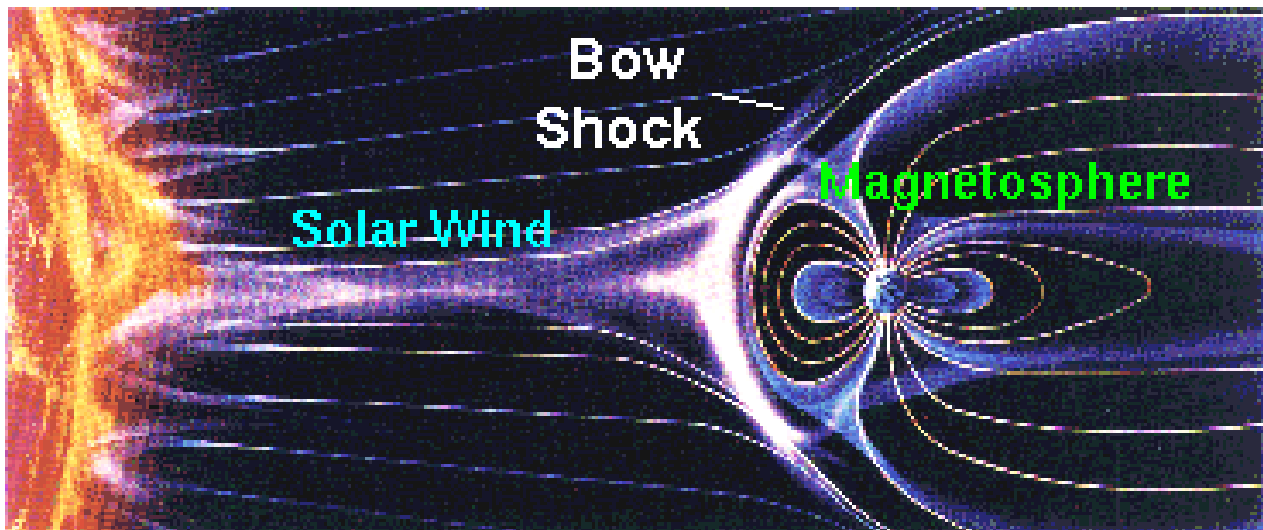
The amount of particles vary with the energy. Thus, for energies up to  $10^{15}$  eV the variation is as  $E^{-2.7}$  (E being the energy), and above this level it is as  $E^{-3}$ .

The origin of the high energy particles is from outer space. It is assumed that particles with an energy up to about  $10^{15}$  eV are coming from our own galaxy, whereas those with the highest energies probably have an extragalactic origin.

## Solar wind contribution

A small component of the cosmic rays is generated near the surface of the sun by magnetic disturbances. These solar particle events (solar flares) are comprised mostly of protons of energies below 100 MeV and only rarely above 10 GeV ( $10^{10}$  eV). These particles can produce significant dose rates at high altitudes, but only the most energetic ones affect the dose rates at ground level.

Solar flares are of short duration, typically a few hours, and highly variable in intensity. They have a negligible impact on long-term doses to the general population. Solar particle events can, in addition, disturb the earth's magnetic field in such a way as to change the galactic particle intensity. See the illustration below.



*An illustration of the solar wind and the magnetic field of the earth. The high energy particles coming into the atmosphere, will interact with the atmospheric atoms and molecules (mainly nitrogen and oxygen). A number of nuclear reaction will take place, and particles will be formed – both charged particles and neutrons. Some of the radiation may reach ground level, yielding a yearly dose of approximately 0.4 mGy. Furthermore, the particles will lead to excitations which again give us both "aurora borealis" and "aurora australis". Finally the combination of the Earths magnetic field and the charged particles (mainly protons and electrons) give the Van Allen belts.*

Another point that should be taken into consideration is the 11-year solar cycle. The periodic variation in solar activity produces a similar variation in the solar wind. The solar wind is a highly ionized plasma with associated magnetic field. The magnetic field of the earth partly reduces the intensity of cosmic radiation reaching the top of the atmosphere. Thus, at times with maximum solar activity the magnetic field is at its highest and the galactic cosmic radiation intensity is at its lowest. Furthermore, the magnetic field produces a geomagnetic latitude effect, with minimum intensities and dose rates at the equator and maximum near the geomagnetic poles.

## Cosmic radiation hit the atmosphere

The high-energy particles hitting the atmosphere interact with atoms and molecules in the air. This results in a complex set of secondary charged as well as uncharged particles, including protons, neutrons, pions and some other particles. These secondary nucleons in turn generate more particles, and we get a cascade in the atmosphere. Thus, cosmic rays seem to represent a theatre or a laboratory for high energy physics. Several elementary particles were discovered in experiments with cosmic radiation (see next page).

Neutrons, which have a long free pathway, dominate the particle component at lower altitudes. The neutron energy distribution peaks between 50 and 500 MeV and with a lower energy peak, around 1 MeV.

The pions generated in the nuclear interactions are an important component of the cosmic radiation field in the atmosphere. The neutral pions decay into high-energy photons, which produce high-energy electrons, which in turn produce photons etc., thus producing the electromagnetic, or photon/electron, cascade. Electrons and positrons dominate the charged particle fluency rate at middle altitudes.

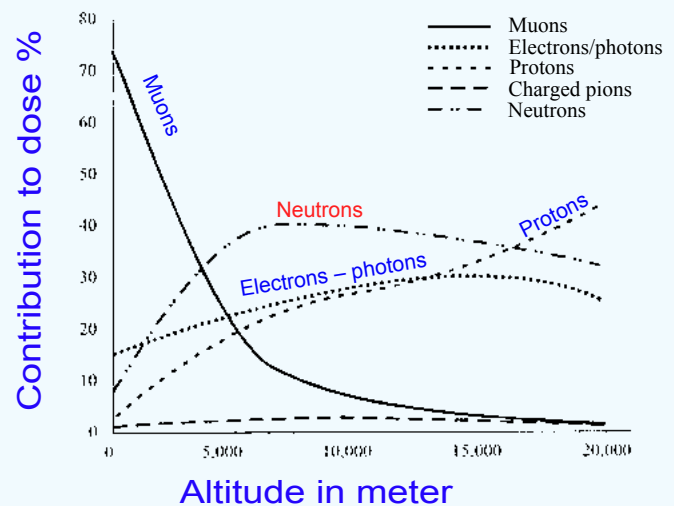
The charged pions decay into muons, whose long mean free path in the atmosphere makes them the dominant component of the charged-particle flux at ground level. They are also accompanied by a small flux of collision electrons generated along their path.

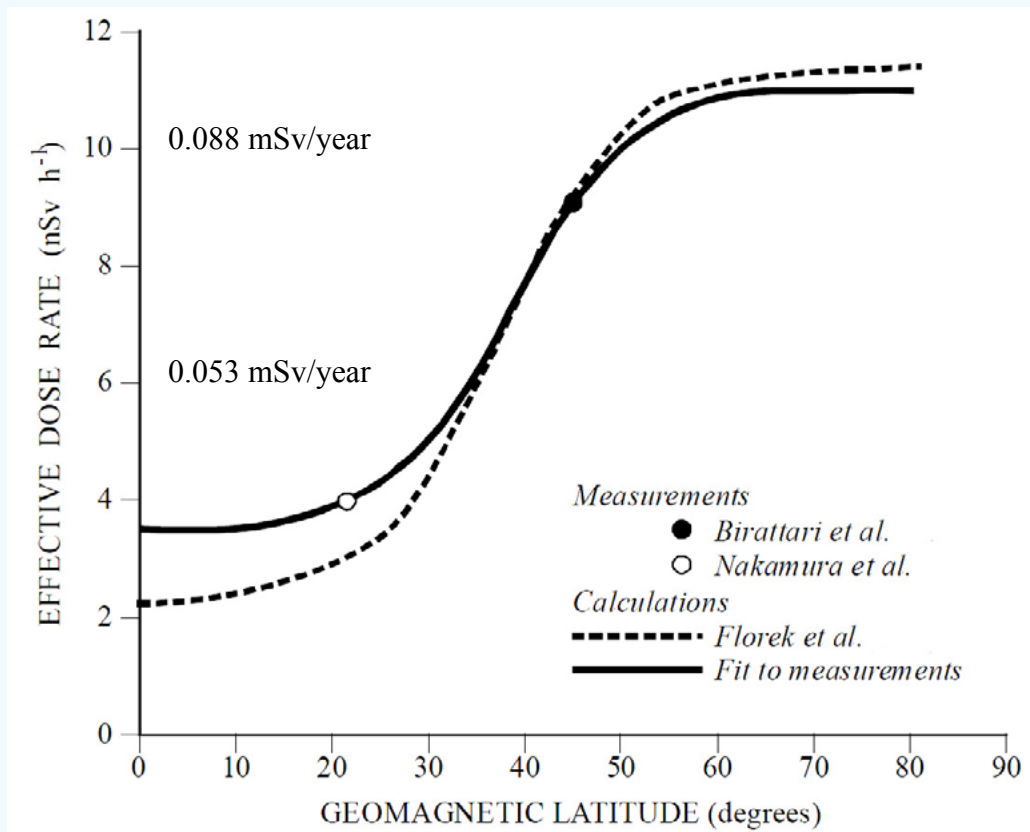
As you can see, we have a complex picture of radiation from ground level and up to the top of the atmosphere. In recent years the radiation intensity in the atmosphere has been measured – and we can give some details about doses at ground level – and also present information about doses at aircraft altitudes. Finally we shall discuss the Van Allen belts, even if they influence only space travellers.

*The figure is given by UNSCEAR and is an attempt to give the relative contribution to the dose by the different types of radiation. Consequently, at all altitudes the sum is 100 %.*

*At sea level myons and electrons/photons are the most important. At aircraft altitudes (8000 – 11000 m) neutrons are very important (about 40 %).*

*It is obvious that it is very difficult (impossible) to apply a radiation weight factor to the neutron radiation since it is a mixture of neutron energies involved.*





This figure is given by UNSCEAR and the dose is given in nSv per hour. You see that the dose around equator is about 0.03 mSv per year. For latitudes such as Oslo the contribution is about 0.09 mSv per year. Note also the discussion on RBE for neutrons.

## Cosmic rays – a laboratory for high energy physics

The cosmic rays were discovered in 1912 by Victor F. Hess. He received the Nobel prize in physics in 1936 for this discovery.

Before we developed the high energy accelerators, cosmic radiation was the source for high energy physics. Several particles were for the first time observed in experiments with cosmic radiation, such as the positron and the muon. The positron was proposed by P.A.M Dirac in 1928 and discovered by Carl D. Anderson in 1932.

Here we just summarize some of the particles found in the cosmic rays.



**Victor F. Hess**  
(1883 – 1964)

Pion (or pi meson) is any of the three particle denoted  $\pi^0$ ,  $\pi^-$  and  $\pi^+$ .  
The particles have a mass of about 270 electron masses, and have an extremely short life-time. Pions decay in the following way:

The negative pion decays into a negative muon and a neutrino.  $\pi^- \rightarrow \mu^- + \nu$

The positive pion decays into a positive muon and a neutrino.  $\pi^+ \rightarrow \mu^+ + \nu$

The neutral pion decays into two photons.  $\pi^0 \rightarrow 2 \gamma$

The muon (mass about 206 electron masses) was discovered by Carl Anderson in 1936 in the cosmic radiation. He called the particle for mesotron. This is the main product from the cosmic radiation reaching the sea level (see figure on opposite page).

Muons have been given (ICRP) a radiation weight factor of 1 and pions a factor 2.

Hideki Yukawa suggested in 1935 the existence of the meson and the charged pions were observed in the Cosmic radiation in 1947 by Cecil Powell using photographic emulsions placed on the top of mountains in the Pyrenees and later in the Andes.



**Carl David Anderson**  
(1905 – 1991)

Nobel prize in 1936 together with Victor Hess.



**Hideki Ykawa**  
(1907 – 1981)

Nobel prize in 1949.



**Cecil Frank Powell**  
(1903 – 1969)

Nobel prize in 1950.

## Doses at ground level

At ground level the muons, with energies mostly between 1 and 20 GeV, contribute about 75 % of the absorbed dose rate in free air. The remainder comes from electrons produced by the muons or present in the electromagnetic cascade. Furthermore, we have to include a dose from the neutrons (see figure on page 87).

In the early literature, the two components of the charged particle flux (muons and electrons) were referred to as the “*hard*” and “*soft*” components, respectively, because the electrons are much more readily absorbed by any shielding.

From some recent experiments, UNSCEAR assume the dose rate at sea level from muons and electrons to be 32 nGy h<sup>-1</sup>. This indicate a total yearly dose of 0.28 mGy. The geomagnetic latitude effect is about 10%. (Since in this case the radiation weighting factor is by ICRP set to 1, the equivalent dose is also 0.28 mSv.)

We also have to include the neutrons at ground level. This is however, much more difficult. Some data are available about the neutron fluency and energy distributions, but from recent measurements some information is available. According to UNSCEAR the fluency is 0.0123 cm<sup>-2</sup> s<sup>-1</sup> at sea level for a geomagnetic latitude of 45 N. Based on this, the effective annual dose from neutrons at sea level and at 50 degree latitude is estimated to be 0.08 mSv (see figure on page 88). For neutron radiation it is a stronger variation with latitude because the protons which yields the neutrons, are strongly affected by the earth’s magnetic field. The latitude variation for the neutron contribution is from 0.05 – 0.11 mSv per year.

With the above considerations we have established a dose level from the cosmic radiation at sea level. However the majority of people live at slightly higher altitudes where the radiation dose is larger. Furthermore, people spend a large fraction of time indoors, where the buildings attenuate the soft part of the cosmic rays.

An analysis has been made to combine the altitude dependence of dose with the altitude distribution of the worlds population. For the directly ionizing and photon component the population-weighted average dose rate is 1.25 times that at sea level, and for neutrons 2.5 times.

We have tried to outline some of the problems in order to arrive at an average public dose due to cosmic rays. We have some knowledge about the energy distribution of the neutrons – but it is still a guesswork to find the correct radiation factor to use. In order to end this discussion we give the values suggested by UNSCEAR for the population-weighted average in the table below.

Annual dose = 0.38 mSv

Conditions	Effective dose rate ( $\mu\text{Sv a}^{-1}$ )						
	Directly ionizing component			Neutron component			Total
	North	South	World	North	South	World	World
Outdoors, at sea level	272	265	270	49	35	48	320
Outdoors, altitude adjusted <sup>a</sup>	339	332	340	124	87	120	460
Altitude, shielding, occupancy adjusted <sup>b</sup>	285	279	280	104	73	100	380

<sup>a</sup> Altitude-weighting factors applied to sea level values: directly ionizing component 1.25; neutron component 2.5.  
<sup>b</sup> Building shielding factor 0.8; indoor occupancy factor 0.8.



## Air travel

The variation in cosmic radiation with the height above sea level can easily be observed when flying. This means that passengers as well as air crews receive an extra dose when flying. The majority of the world's population do not fly, but air crew members have an average of 500 hours per year in the air. Based on the types of radiation at flying altitudes (8000 – 12000 meter) some guidelines have been worked out.

For altitudes of 9 – 12 km at latitudes about 50°, the effective dose rate is in the range 5 – 8  $\mu\text{Sv}$  per hour. For a transatlantic flight from Europe to North America, the dose would be 30 – 45  $\mu\text{Sv}$  (0.03 – 0.045 mSv). At equatorial latitudes, the dose rates are lower and in the range of 2 – 4  $\mu\text{Sv}$  per hour.

For an altitude of 18 km the effective dose rates would be 10 – 12  $\mu\text{Sv}$  per hour. These data can give us some guidelines with regard to extra effective doses from cosmic radiation due to air travel.

We keep in mind the discussion about RBE and the conversion of dose from Gy to Sv – and give here the values used by the radiation authorities.

Exstra dose event	Dose in mSv
Pilot – annual dose	3 – 4
Oslo – Tromsø	0.01
Oslo – Hellas	0.025
Oslo – San Francisco	0.1



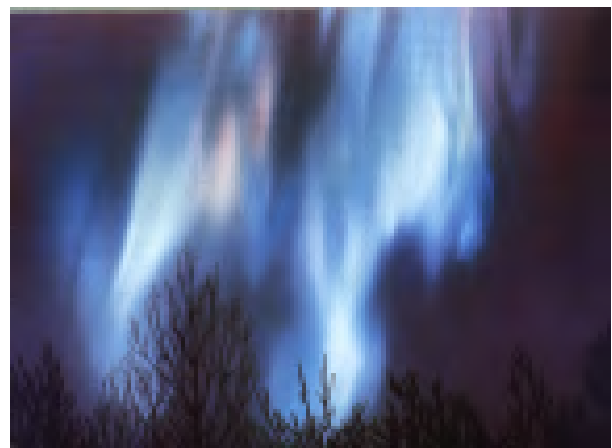
## Other results and effects of the cosmic radiation

We have to mention two other effects of the cosmic radiation, namely the beautiful northern and southern lights (*aurora borealis* and *aurora australis*), and the Van Allen radiation belts far out in space.

### Northern light

Due to the special form of the earth's magnetic field the cosmic particles penetrate to much lower altitudes in the polar regions. This makes Norway quite particular with regard to observation of Northern light.

Northern light is formed when charged particles from the cosmic radiation enter the earth's magnetic field. The magnetic field guides the particles to the regions around the earth's magnetic poles. High up in the atmosphere (above 90 km), the particles are



stopped by the gases in the atmosphere. Part of the particle energy is used for excitations of the atoms and molecules in the air (nitrogen and oxygen) – which result in specific light upon de-excitations. The colors of the aurora are determined by the gases present. When the solar activity is high, strong northern and southern lights can be observed.

Norwegian scientists, Kristian Birkeland and Carl Størmer are well known for their work with the Northern light. Their work is remarkable since it took place in a time before Hess had made his observation of the cosmic radiation. Birkeland's Terrella experiment, which in an elegant way explained the Northern light was carried out in the period **1900 – 1908 !**

Carl Størmer measured the height of the Northern light (90 – 125 km altitude). Furthermore, he was a brilliant mathematician – and he calculated the orbitals of the electric particles in the earth's magnetic field. As a result of these calculations the radiations belts – Van Allen belts – can be suggested.



**Kristian Birkeland**  
(1867 – 1917)



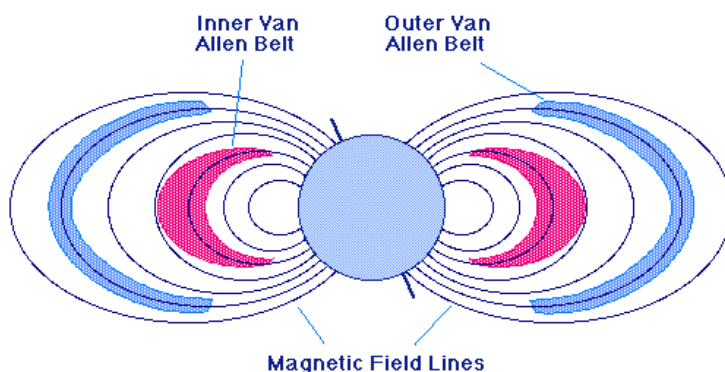
**Carl Størmer**  
(1874 – 1957)

### Van Allen radiation belts

In January 1958 the first American satellite, Explorer 1, was launched from Cape Kennedy center in Florida. James Van Allen, the instrument chief, had placed a Geiger counter on board. The goal was to measure the intensity of cosmic rays, fast ions that come from space, and in particular its variation with the distance from the magnetic equator. The hope was to observe particles that could not penetrate the full thickness of the atmosphere and reach the ground.

The data were puzzling – thus at low altitudes the number of counts was normal, then it rose rapidly.

At an altitude of 2000 km the counter could not follow. The counter discharged so frequently that it could not recover between the counts, with the result that the counting stopped. The radiation belt was discovered. The Van Allen belt is formed like a torus or doughnut above the equator at an altitude of about 6000 kilometers. It contains energetic protons in the 10-100 MeV range and





**James Van Allen**  
(1914 – 2006)

is a result of the cosmic radiation. The particles can readily penetrate spacecrafts and prolonged exposure can damage instruments and be a hazard to the astronauts.

In experiments with Pioneer 3 and 4 an outer radiation belt was discovered. It is part of the plasma trapped in the magnetosphere. The outer radiation belt extends from an altitude of about three to ten Earth radii (ER), and its greatest intensity is usually around 4-5 ER. The trapped particle population of the outer belt is varied, containing electrons and various ions.

A lot of research is still going on in order to attain more information about these particular radiation belts.

If you are interested in the possibilities to observe Northern light the periods with high solar activity is important. The daily variation in the solar activity can be followed.

See the address: <http://www.solarcycle24.com/>

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## 2. External Gamma-radiation from natural sources

Gamma-radiation, emitted by radioactive isotopes in building materials and the ground, produces an annual dose of about 0.5 mGy – or 0.5 mSv. In certain areas the  $\gamma$ -radiation can be much larger, particularly in areas where the ground contains thorium and radium. Let us consider, in more detail, the sources of  $\gamma$ -radiation.

### Natural Radioactive Sources

A long time ago, when the earth was created, a number of radioactive elements were formed. Some of these isotopes have very long half-lives, billions of years, and are still present. Since radioactive isotopes are unstable, a disintegration eventually occurs, resulting in a different type of atom. This continues until a stable (non-radioactive isotope) is formed.

Because most of the natural radioactive isotopes are heavy (found in the fifth row or higher in the periodic table), more than one disintegration is necessary before a stable atom is reached. This radioactive series is called a *radioactive family*. It is not unusual for the number of disintegrations comprising a series to be around 11 to 14 different nuclides. The two most important radioactive series today are the *Uranium-radium-series* and the *Thorium-series*. There are two other series, but they have almost disappeared from the Earth because they have much shorter half-lives. The four possible series are given in the table on the next page.

### The radioactive series



Name	Start	End	Half-life in year
Uranium – radium	U - 238	Pb - 206	$4.47 \cdot 10^9$
Neptunium	Np - 237	Bi - 209	$2.14 \cdot 10^6$
Uranium – actinium	U - 235	Pb - 207	$7.038 \cdot 10^8$
Thorium	Th - 232	Pb - 208	$1.405 \cdot 10^{10}$

The first radioisotope in the Thorium-series has a half-life of  $1.4 \cdot 10^{10}$  years. This is why there is still a lot of thorium in the ground. On the other hand, neptunium with its short half-life has disappeared. However, it can be produced in the laboratory. Thus, all four radioactive series are well understood. The starting element in the Uranium-actinium series has a half-life of  $7.038 \cdot 10^8$  years. This is short compared to the age of the earth (5 billion years or about 7 half-lives), and therefore the content of U-235 is only 0.71 % of the Uranium isotopes.

In addition to these radioactive series, there are a number of other radioactive isotopes. The most important is K-40 with a half-life of 1.27 billion years. This half-life is shorter than the age of the earth and only a few percent of the original K-40 remains today. The half-lives given in the table indicate that the natural radioactivity has decreased considerably since the formation of the earth. This is of interest when speculating about the origin of life and discussing the possible effects of radiation when the Earth was younger. We can conclude that early life existed with a much higher level of natural radiation.

### Distribution of Natural Radioactivity

Natural radioactivity varies from place to place. With regard to doses from external  $\gamma$ -radiation, the most significant contributions come from the elements in the uranium-radium-series, the thorium-series and K-40.



**Anders Storruste**  
(1917 – 2001)

In order to give a quantitative measure for the presence of radioactive elements, the number of becquerel per kilogram (Bq/kg) can be obtained for different types of rock and soil. Of course, this varies from place to place. In the table next page are presented some data from measurements carried out at the University of Oslo under supervision of Anders Storruste.

Storruste also developed the TLD - method for determination of the radon content in the air in buildings. He was responsible for the first mapping of the radon level in Norwegian dwellings.

## The concentration of isotopes (given in Bq/kg)

in some species of rock and soil.



Species of rock/soil	Ra – 226	Th – 232	K – 40
Granite	20 – 200	20 – 80	600 – 1800
Thorium and uranium rich granite	100 – 500	40 – 350	1200 – 1800
Gneiss	20 – 120	20 – 80	600 – 1800
Sandstone	5 – 60	4 – 40	300 – 1500
Limestone	5 – 20	1 – 10	30 – 150
Slate	10 – 120	8 – 60	600 – 1800
Shale (from cambrium)	120 – 600	8 – 40	1000 – 1800
Shale (lower ordovicium)	600 – 4500	8 – 40	1000 – 1800
Shale rich soil	100 – 1000	20 – 80	600 – 1000
Moraine soil	20 – 80	20 – 80	900 – 1300
Clay	20 – 120	25 – 80	600 – 1300
Sand and salt	5 – 25	4 – 30	600 – 1200
<b>Average (Norway)</b>	<b>50</b>	<b>45</b>	<b>850</b>

The table above gives the concentrations of Ra-226, Th-232 and K-40 in different species of rock found in Scandinavia. It appears that certain types of shale exhibit concentrations of Ra-226 up to 4,500 Bq/kg. The concentration of Th-232 also varies considerably from one mineral to another. In certain areas of the world, such as India, Brazil and Iran, the thorium concentration in the soil can be 10 to 100 times above the average (see below).

Potassium is everywhere. It is in soil, plants, animals and humans. The element potassium makes up 2.4 percent by weight of all elements. However, the abundance of the radioactive isotope K-40 is only 0.0118%.

It can be noted that the variation of K-40 between different types of rock is much smaller than that for radium and thorium. K-40 emits both a  $\beta$ -particle and a  $\gamma$ -ray (see the decay scheme on page 26).

Each isotope contributes a different amount to the total external  $\gamma$ -dose: approximately 40 % from K-40, 40 % from Th-232 and about 20 % from Ra-226.

## Outdoors

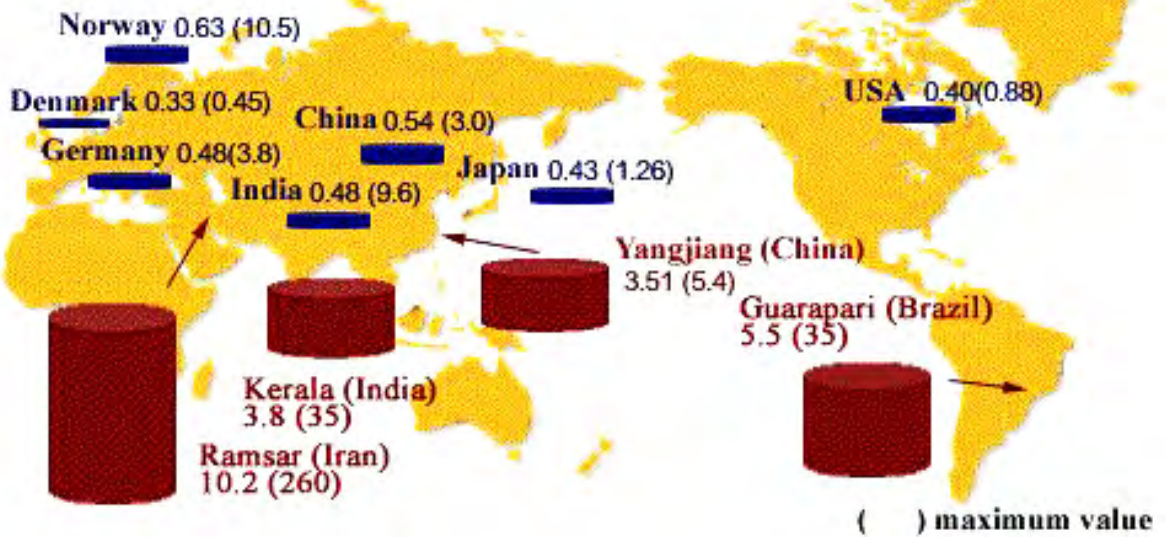
Direct measurements of absorbed dose rates in air have been carried out in the last few decades in many countries of the world. According to UNSCEAR the population-weighted average doserate is  $59 \text{ nGy h}^{-1}$ . *This yields an annual exposure dose of 0.52 mGy.*

The lowest average values are found in Cyprus, Iceland, Egypt, the Netherlands, Brunei, and the United Kingdom and the highest values are in Australia, Malaysia, and Portugal. The average value for Norway is 0.63 mGy per year.

We shall mention some places with very high values with external  $\gamma$ -radiation.



## Places with high external gamma-radiation



The above figure is adapted from Health Research Foundation, Kyoto, Japan. Four areas with very high background radiation is outlined. The values are given in mGy/year with maximum values in parenthesis.

It can also be mentioned that several places in Italy with volcanic soil the outdoor dose level is about 1.7 mGy per year. Lets us show some of the places with high background radiation (HBR).

### Guarapari Brasil

The city is 375 km north of Rio and have about 100 000 inhabitants. The beaches are full of radioactivity from the thorium-series.

On the beach you can get a whole body dose of 10 mGy in a week.

In the picture to the right you see a couple on the beach with a Geiger counter.



The whole region along the coast with monazite sand, has a high dose level. A large amount of dose measurements have been carried out. However, no personal doses can be given – and no special cohorts have been studied with regard to health effects.

## Kerela India



The coastal belt of Karunagappally, Kerala in India, is a well known high background radiation (HBR) area. Again it is the monazite sand with the thorium series. For a large area the median outdoor radiation level is more than 4 mGy/year. In certain locations on the coast, it is as high as 70 mGy/year.

A study of the cancer incidence in the area has been performed. A cohort of 173 067 residents have been followed for 15 years, both with regard to dose as well as cancer incidence. No excess cancer risk due to exposure from the gamma-radiation was found. According to the LNT-hypothesis a significant increase should be expected.

## Ramsar Iran



In Ramsar we find the highest level of background radiation, measured to up to 260 mGy/year. The areas of highest background are found in discrete locations, corresponding to specific geologic features.

The radioactivity in Ramsar is due to Ra-226 and its decay products, which have been brought to the surface by the waters of hot springs.

There are more than 9 hot springs with different concentrations of radium in Ramsar that are used as spas by both tourists and residents.

Since the houses have been built by materials containing  $\text{RaCO}_3$  the radon level inside the buildings are extremely high – about 3700 Bq/m<sup>3</sup>.

People within the LNT-group have suggested relocation of some of the families with the highest level of radon and radiation. This suggestion has not been followed since the health situation for these people is not different from others, in fact the opposite.

## Yangjiang China



People living in the town of Yangjiang, located in China's southern Guangdong province, have traditionally built their homes from bricks made of sand and clay. Trouble is, the sand in the region has eroded from hills containing monazite and once incorporated in bricks and mortar, thorium in the monazite sand continues to decay into radioactive radium, radon and actinium. The residents in these areas live with a radiation level far above average.

Some studies have been carried out with two cohorts within this area. The two groups have an average annual dose of 6.4 mGy and 2.4 mGy – a difference of about 3. More than 100 000 people have been included and the studies involve more than 1.7 million person-years.

All these studies have failed to reveal any significant health effects that could be attributed to living in these areas of high natural background radiation. The LNT theory does not work! This holds true also for the Kerala-studies.

**CONCLUSION:** An increased cancer risk associated with the high levels of natural radiation in HBRA was not found. On the contrary, the mortality of all cancers in HBRA was generally lower than that in control areas, but not significant, statistically. This turned out to be – 0.11 per sievert (Sv) or Gy. Although the value is not significant, this indicates that mortality from cancer in HBRA tends to be slightly lower than in the other area – no excess cancer risk from exposure to terrestrial radiation far above normal.

It can be noted that in Ramsar they have carried out studies on chromosome aberrations after an extra dose of 1.5 Gy. The result was **fewer** chromosome aberrations compared to other residents in nearby control areas. The conclusion of this is that high level of natural radiation may induce a radio adaptive response. The radio adaption was found for individuals who received doses up to hundred times more than inhabitants of nearby control area.

Another observation from Ramsar is that 2000 people living in the highest radon areas show slightly lower rates of lung cancer compared to the control areas.

### Summary

A large amount of people are living with background radiation far above the average. All studies on the health effects seem to indicate **no increased** detrimental effects – rather the opposite. According to the LNT-theory we should expect a clear effect and an increased cancer ratio.

The observed data from the high background radiation areas (HBRA) may have some bearing to the panic evacuations in combination to Chernobyl and Fukushima.

The counters in Pripjat close to the reactor reads now about 4.8 mGy per year. For the most contaminated areas around Fukushima the reading in May 2013 is about 2.9 mGy per year. Both places are evacuated in spite of the facts that they have a much lower radiation level than the HBRA areas.



# Indoors

When inside houses and buildings, people may think they are shielded from much of the radiation coming from the outside. This is not always true.

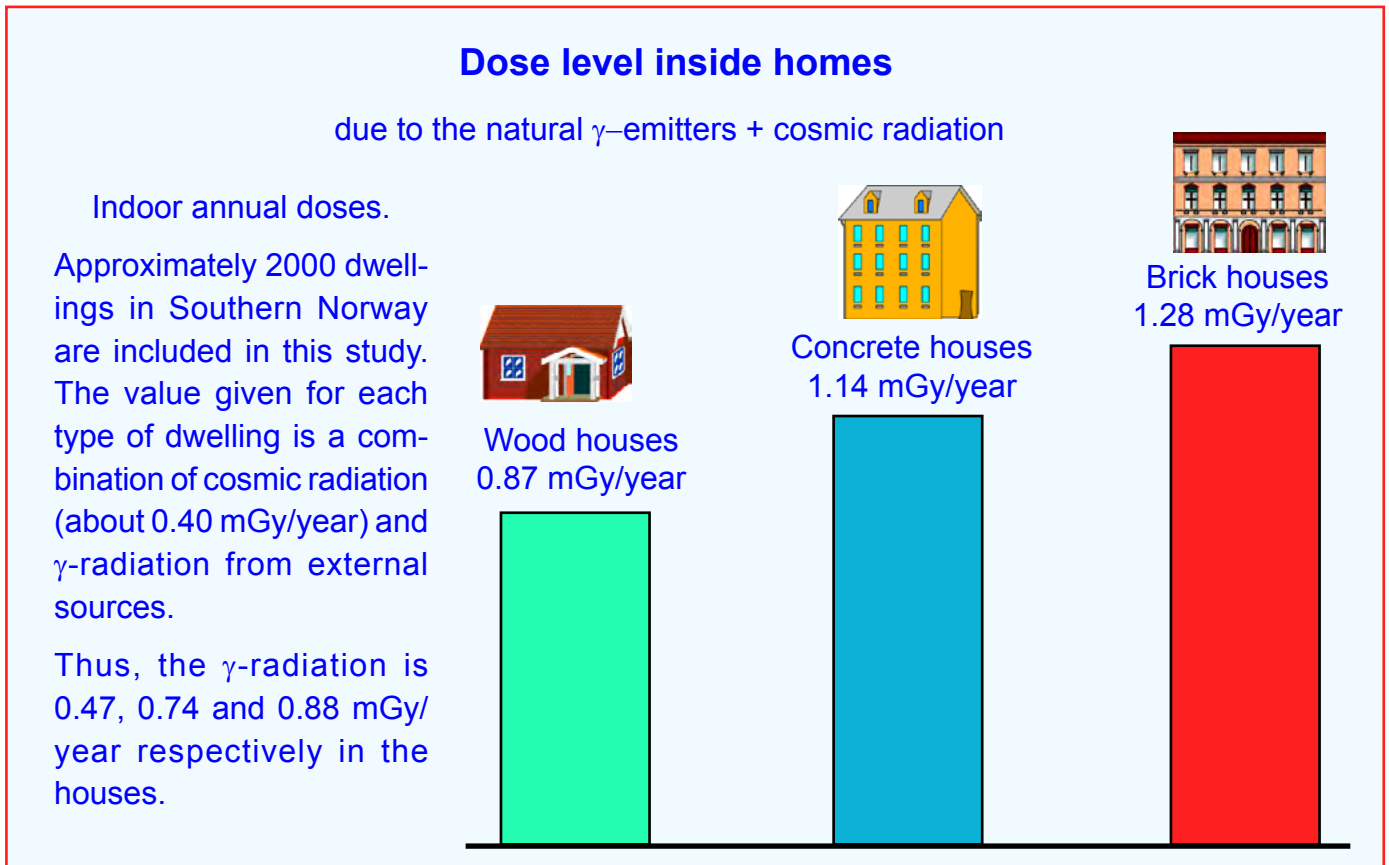
Since the building materials also contain radioactive elements, the dose generally does not go down. More often it goes up. Since the concentration of radioactive isotopes varies from one region to another, it is also true that the radioactivity in building materials, such as concrete, depends on where it is made.

In houses made of wood, the  $\gamma$ -radiation in the ground floor is approximately the same as that outdoors. This is because most of the radiation comes from the masonry materials in the cellar and the ground just outside. Wood materials contain less radioactivity than rocks and soil and the radiation level decreases as you go to higher floors.

In houses made of concrete, the indoor radiation level will be like that of outdoors if the concrete is made from materials found locally. But it is not unusual for the concrete or cinder blocks to contribute to an increase in the radiation level over that found outdoors.

In Sweden, a number of houses were built using uranium rich shale. Because these houses have a radiation level that is unacceptable, construction using this type of building material was stopped in 1979. Houses made of red brick very often have a high radiation level, mainly because of the content of K-40. Brick houses are more common in cities than in the country; consequently, people living in cities tend to be exposed to more radiation than those living in the countryside.

Examples of the radiation level inside different types of houses in the same area are given in the figure below. The data are collected by graduate students at the University of Oslo, supervised by Anders Storruste. More than 2000 houses in southern Norway yield these data.



For different types of houses, the radiation level may vary by a factor 2. The lowest levels were found for wood houses. Here the annual indoor dose is 0.87 mGy from external  $\gamma$ -radiation and cosmic radiation combined.

It appears from the figure that, if you move from one house to another, you will also change your radiation environment. Your background dose will either increase or decrease. Consequently, if small environmental doses, either natural or artificial, are of some concern, it would be of interest to have information about the sources that contribute to the annual dose.

We can conclude that the external  $\gamma$ -radiation dose (coming from sources external to the human body) varies within large limits from place to place, and even from one house to another house in the same area.

UNSCEAR have collected data from almost all countries. It appears that the ratios of indoor to outdoor exposure are in the range from 0.6 to 2.3, with a population-weighted value of 1.4. Thus indoor exposures (absorbed dose rate in air from terrestrial gamma radiation) are, in general, 40% greater than outdoor exposures. If you look into the figure again you will see that the indoor  $\gamma$ -dose for brick houses is 87 % greater than that for the wooden houses.

UNSCEAR have also made attempts to estimate annual effective doses from the measurements of the radiation level outside as well as inside houses. One must take into account the conversion coefficient from absorbed dose in air to effective dose – and furthermore the indoor occupancy factor. These parameters vary with the age of the population and the climate at the location considered.

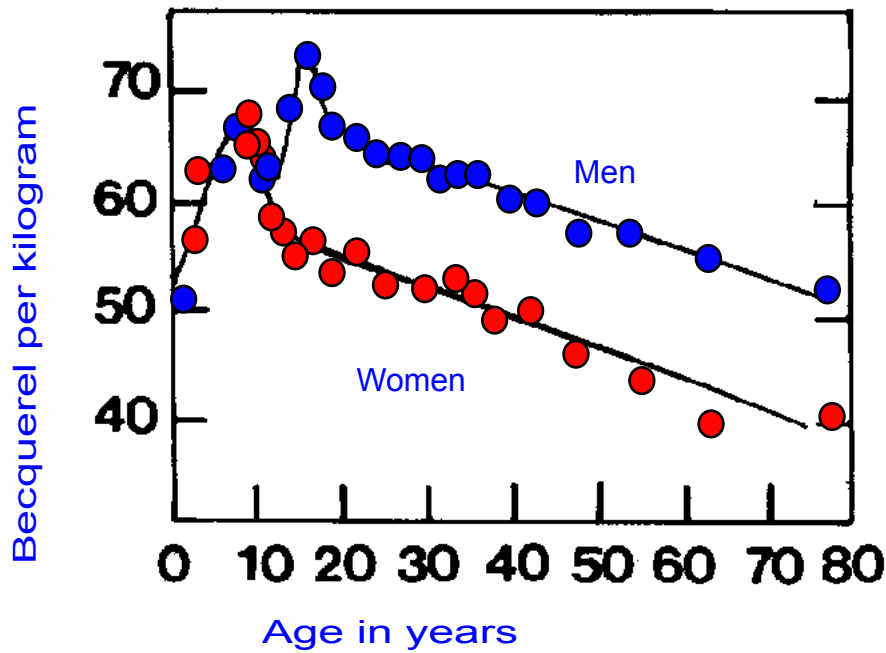
The result of such calculations yields a worldwide average of an annual effective dose of 0.48 mSv – within the range 0.3 – 0.6 mSv.

### 3. Internal Radioactivity (sources inside the body)

The food we eat and the air we breathe contains radioactive isotopes. Dust particles in the air contain isotopes of both the U-238 and the Th-232 series. We have therefore small amounts of radioactivity in our bodies.

The most important isotope with regard to dose is K-40. The daily consumption of potassium is approximately 2.5 gram. From this you can calculate that each day you eat about 75 Bq of K-40. Potassium is present in all cells making up soft tissue. The potassium content per kilogram body weight will vary according to sex and age (see figure next page). The dose due to K-40 will of course also vary in a similar way. Muscular young men receive a larger dose than older persons and men receive a larger dose than women.

**Inhalation.** The dominant component of inhalation exposure is the short-lived decay products of radon. They will be treated separately in the next section. The content of the other isotopes in the air (like U-238, Ra-226) is on average about 1  $\mu\text{Bq}/\text{m}^3$ . However, the content of Pb-210 and Po-210 are 500 and 50  $\mu\text{Bq}/\text{m}^3$ . Pb-210 is a  $\beta$ -emitter whereas Po-210 is an  $\alpha$ -emitter.



The concentration of potassium in the body varies with age and sex. Consequently the amount of K-40 (the abundance of the K-40 isotope is 0.0118%) varies in a similar way. In the figure the K-40 level is given as becquerel per kilo.

### A simple calculation of the K-40 dose

Based on a K-40 level of 70 Bq/kg we can do a simple calculation of the annual dose from this isotope. You have to use the decay scheme for K-40 (see page 26). In 89.3 % a  $\beta$ -particle with average energy  $1/3 \cdot 1.31$  MeV is emitted, and in 10.7 % a  $\gamma$ -photon with energy 1.46 MeV is emitted.

We calculate the energy to the body for one disintegration (in average) of K-40.

The  $\beta$ -particle energy is as follows: 
$$\frac{89.3 \cdot 10^{-2} \cdot 1.31 \cdot 10^6}{3} = 42.92 \cdot 10^4 \text{ eV}$$

The  $\gamma$ -photon energy is: 
$$\frac{10.7 \cdot 10^{-2} \cdot 1.46 \cdot 10^6}{2} = 7.81 \cdot 10^4 \text{ eV}$$

**The sum of the two is:**  $1 \text{ Bq} \approx 51 \cdot 10^4 \text{ eV}$

For  $\beta$ -particles the average energy is approximately 1/3 of maximum – therefore the 3 in the denominator. All  $\beta$ -energy is deposited within the body.

For  $\gamma$ -rays a rather significant part will go out of the body. Thus, it is possible to use counters outside the body to observe K-40. In the expression above we have assumed that about half of the  $\gamma$ -energy is absorbed in the body. This is the reason for the 2 in the denominator. You see that the calculation is rather rough, but it gives you an idea how to use your knowledge.

1 Bq in a year represents  $31.536 \cdot 10^6$  disintegrations (seconds per year).

Furthermore since 1 eV is  $1.6 \cdot 10^{-19}$  J we have:

1 Bq/kg/year is  $51 \cdot 10^4 \cdot 31.5 \cdot 10^6 \cdot 1.6 \cdot 10^{-19} = 2.6 \cdot 10^{-6} \text{ J/kg} = 2.6 \text{ } \mu\text{Gy}$

For 70 Bq per kg the annual dose would be; 182  $\mu\text{Gy}$  or (in line with ICRP) 182  $\mu\text{Sv} = 0.18 \text{ mSv/year}$ .

UNSCEAR give a value of 0.165 – 0.185 mSv per year.

The other naturally occurring radioactive isotopes which come into our bodies are C-14 and a number of isotopes from the Uranium family (U-238, Th-230, Ra-226, Pb-210 and Po-210). From the thorium family (Th-232, Ra-228, Th-220 and U-235). A large amount of work and experiments have been carried out to find the average concentrations of these isotopes in our food products. With regard to annual doses we can give the following.

### **C-14**

This isotope is formed in the atmosphere when neutrons react with nitrogen. C-14 is taken up by plants in the form of carbon dioxide, CO<sub>2</sub>. The amount of C-14 in the body is about 35 Bq/kg. C-14 emits a β-particle with maximum energy 156 keV – an average energy of 52 keV per disintegration.

This would yield a body dose of approximately 10 μGy per year = 0.01 mGy/year or 0.01 mSv/year. You can carry out this calculation which is similar to that for K-40 (see page above).

### **Uranium and thorium series radio nuclides**

UNSCEAR have, based on a large number of investigations, presented values about the annual intake by humans of the different isotopes. We can mention the following; Ra-226 (22 Bq/year), Pb-210 (30 Bq/year), Po-210 (58 Bq/year) and Ra-228 (15 Bq/year). The other isotopes have smaller intake.

Based on the concentrations of radioisotopes in foods and the consumption rates for infants, children, and adults the concentrations in the body have been calculated. Furthermore, the distribution throughout the body has been calculated based on models. U-isotopes, Ra-isotopes, Pb-210 and Po-210 are concentrated mainly to the bone (about 70 %).

Based on all the data from the different countries the UNSCEAR 2000 report arrive at an annual effective dose of 0.12 mSv. The main contributor to this dose is Po-210 (for this α-emitter UNSCEAR uses a weight factor of 20).

The amount of polonium in food varies. It is particularly high in reindeer and caribou meat because it concentrates in lichen, an important food source for these animals. Some people living in Lappland eat a lot of reindeer meat and, consequently, have Po-210 concentrations much higher than average.

The tobacco plant also takes up Po-210; thus, smokers get an extra radiation dose to their lungs.

If we sum up this, we can conclude that the world average effective dose due to the natural isotopes is;

301 μSv per year – or 0.3 mSv/year

## 4. Radon

We intend to treat the field with radon in 2 sessions:

1. The physical background, measurements as well as radon in homes.
2. Radon and lung cancer; dosimetry and epidemiological studies.

Radon is formed when radium disintegrates. Radon and its first 4 decay products, with rather short half-lives, are called the "*radon family*". We find one radon family in the uranium-radium series (see page 21) and one family in the thorium-series (also called the "*thoron family*").

Radon is a ***noble gas and does not combine chemically with other atoms or molecules***. The radon gas may be released from the place where it is formed and come into the atmosphere, both outside and into houses.

The half-lives for the two radon isotopes are 3.82 days and 55.6 seconds respectively. Both radon isotopes disintegrate into negative metal ions (called "*radon daughters*"). These ions become attached to water molecules and other molecules in the air and get a diameter of about 5 nm. In this form the radon daughters are considered to be ***free***. The majority of the radon daughters become attached to larger aerosol particles in the air (from 50 – 500 nm in diameter). Both the free and the bound daughters will deposit on the walls, roof and floor inside and to the ground, trees, houses, etc. outside. Consequently, it will never be equilibrium between radon and radon daughters in the air we are breathing, For the air inside the houses the equilibrium factor is about 0.4 whereas for the outside air it is about 0.8.

The radiation from radon and its decay products is a mixture of  $\alpha$ -particles and  $\beta$ -particles as well as  $\gamma$ -radiation. As long as these isotopes are outside the body, only the  $\gamma$ -radiation will be able to give a dose. However, when the isotopes come inside the body, all types of radiation contribute. Since the  $\alpha$ -particles have the largest energy (in the range from 5 to 8 MeV) they are the most important for the dose (more than 80 % of the absorbed energy is due to the  $\alpha$ -particles).

The amount of isotopes ingested with the food is negligible, and all concern is about the breathing and the deposition of radon daughters in the bronchi and in the lungs. For a long time we have been aware of the health risks associated with high radon exposures in underground mines, but relatively little attention was paid to environmental radon exposures until the 1970s, when some scientists began to realize that indoor radon exposures could be quite high, because the local concentration of uranium and/or thorium is high. At the same time the radiation weight factor of 20 was introduced for the  $\alpha$ -particles in the radon family.

In the following we shall try to give you some information about the radon families – the physical aspects, measurements in dwellings, estimations of annual doses and the relation to lung cancer.

### **The Radon Family – physical aspects**

Most of the physical aspects are given in the two tables on the next page. In the second column is given the decay type. We know that  $\gamma$ -radiation very often is emitted together with the particle (see the decay schemes in Chapter 2).

The energy of the different particles and  $\gamma$ -radiation is given in the last column. In the case of the  $\beta$ -particles the maximum energy is given. We would remind you that the average  $\beta$ -energy is approximately 1/3 of the maximum energy. The  $\alpha$ -particles have the largest energies (in the range from 5.49 to 8.78 MeV). The range in soft tissue is about 50 to 100  $\mu\text{m}$ .

(It is a long way to go from the measurements of radon in the air to an estimation of the effective doses from the radon and thoron families. In the following we shall try to give you some information about radon in the atmosphere, how it is measured, and how effective doses have been estimated.

### The Uranium – radium series

Isotope	Decay type	Half-life	Energy released (in MeV)
Rn-222	$\alpha$	3.82 days	$\alpha$ with energy 5.49
Po-218	$\alpha$	3.05 minutes	$\alpha$ with energy 6.0
Pb-214	$\beta$	26.8 minutes	$\beta$ with maximum 0.59 and 0.65 $\gamma$ with energy 0.053 and 0.35
Bi-214	$\beta$	19.6 minutes	$\beta$ with maximum 1.51, 1.0 and 3.18 $\gamma$ with energy 0.61 and 2.42
Po-214	$\alpha$	0.164 msec	$\alpha$ with energy 7.69
Pb-210	$\beta$	22.3 years	$\beta$ with maximum 0.015 and 0.061
Bi-210	$\beta$	5.01 days	$\beta$ with maximum 1.16
Po-210	$\alpha$	138.4 days	$\alpha$ with energy 5.3
Pb-206	Stabile	Stabile	

In this table Rn-222 and the 4 decay products (Po-218, Pb-214, Bi 214 and Po-210) are members of the radon family. However, when Po-214 decays the radioactive decay product Pb-210 is formed. The half-life is 22,3 years and Pb-210 and the following two decay products are not considered to be members of the radon family.

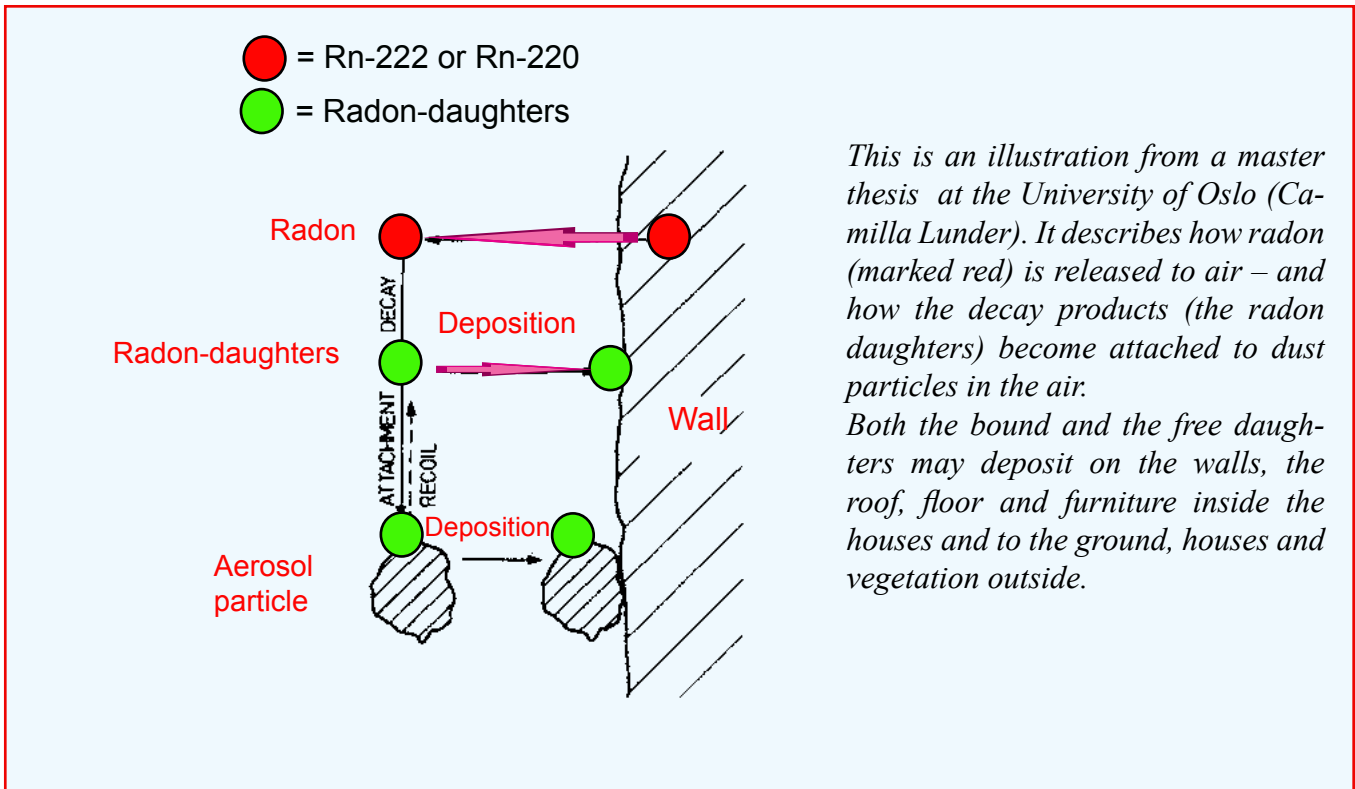
### The Thorium series

Isotope	Decay-type	Half-life	Energy released (in MeV)
Rn-220	$\alpha$	55.6 sek	$\alpha$ with energy 6.28
Po-216	$\alpha$	0.156 sek	$\alpha$ with energy 6.78
Pb-212	$\beta$	10.6 timer	$\beta$ with maksimum 0.34 and 0.58 $\gamma$ with energy 0.239
Bi-212	$\alpha$ (34 %) $\beta$ (66 %)	60.6 min	$\alpha$ with energy 6.05 $\beta$ with maksimum 2.25 $\gamma$ with energy 0.04
Po-212	$\alpha$	$3 \cdot 10^{-7}$ sek	$\alpha$ with energy 8.78
Pb-208	Stabile	Stabile	

### Comments on thorium series

You see from the table that Bi-212 has two possibilities for decay; either  $\alpha$ -decay (34 %) or  $\beta$ -decay (66 %). The  $\alpha$ -decay yield Tl-208 which then by  $\beta$ -decay reach Pb-208. The other possibility goes via Po-212 followed by  $\alpha$ -decay and reach again the stable Pb-208 isotope.

The Tl-208 isotope decays via  $\beta$ -particles (energies of 1,79, 1,28 and 1,52 MeV) and accompanying  $\gamma$ -radiation. One of these  $\gamma$ -lines have an energy of 2.61 MeV. This line is used to identify the thorium series in a mixture of  $\gamma$ -radiation (see for example chapter 14).



*This is an illustration from a master thesis at the University of Oslo (Camilla Lunder). It describes how radon (marked red) is released to air – and how the decay products (the radon daughters) become attached to dust particles in the air.*

*Both the bound and the free daughters may deposit on the walls, the roof, floor and furniture inside the houses and to the ground, houses and vegetation outside.*

## The radon sources

The two radon isotopes Rn-222 and Rn-220 are formed from the radium isotopes Ra-226 and Ra-224. The distribution of radium follows the distribution of uranium (U-238) and thorium (Th-232).

It is important to note that radon is a **noble gas**, whereas all the other isotopes in the two families are metals. The gas may be trapped in the soil until it decays, but it is the only isotope that also has a chance to be released to the air. When radon disintegrates, the metallic daughters are ions that will be attached to other molecules like water and to aerosol particles in the air.

The radon concentrations in the soil within a few meters of the surface are important for the entry into the atmosphere. The main mechanism for this is molecular diffusion.

The concentrations of Rn-222 in soil vary over many orders of magnitude from place to place and show significant time variations at any given site. Because of the short half-life of thoron (Rn-220) in the soil, a large fraction of the atoms will disintegrate before they reach the surface.

## Radon measurements

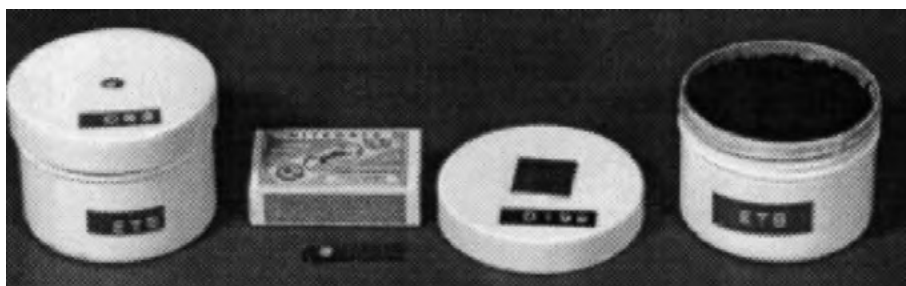
The methods for measuring radon has developed considerable during the latter years. Today we have instruments that make it possible to follow the radon concentration as a function of time, the concentration of the different radon daughters, as well as the fraction not bound to particles.

For indoor radon measurements we can use charcoal canister sampling and thermoluminescence dosimeters (TLD). This method consists of a small box with carbon powder and two TLD crystals. One crystal is placed in the middle of the box whereas the other is outside the box. Radon daughters from the air will become trapped in the carbon powder and subsequently expose the crystal in the box. The crystal outside the box serves as a control for the cosmic radiation and gamma radiation from the walls of the room.

The difference between the two TLD-crystals yields information on the average radon concentration during the exposure period. The first mapping of radon in Norwegian dwellings were performed using this method by A. Storruste and his students at the University of Oslo around 1960.

Another new and popular method is the solid-state nuclear track detectors. The method is based on the fact that  $\alpha$ -particles make tracks in certain materials such as polymers, minerals or glass. The tracks are made visible upon etching and then examined microscopically. The size and shape of these tracks yield information about the mass, charge, energy and direction of motion of the particles.

Radon concentrations are determined by measuring the emitted alpha particles and the track detector has become the state-of-the-art for environmental radon monitoring.



*Above is a picture of the coal box method used by Storruste in the first Norwegian measurements. Below is a modern nuclear track detector. These pictures give rather little information about the measurements, but are presented to give an impression of the size of the detectors.*

*Both detectors are used for indoor measurements – and give information about the average radon concentration for the period measured.*

## **Radon into the houses**

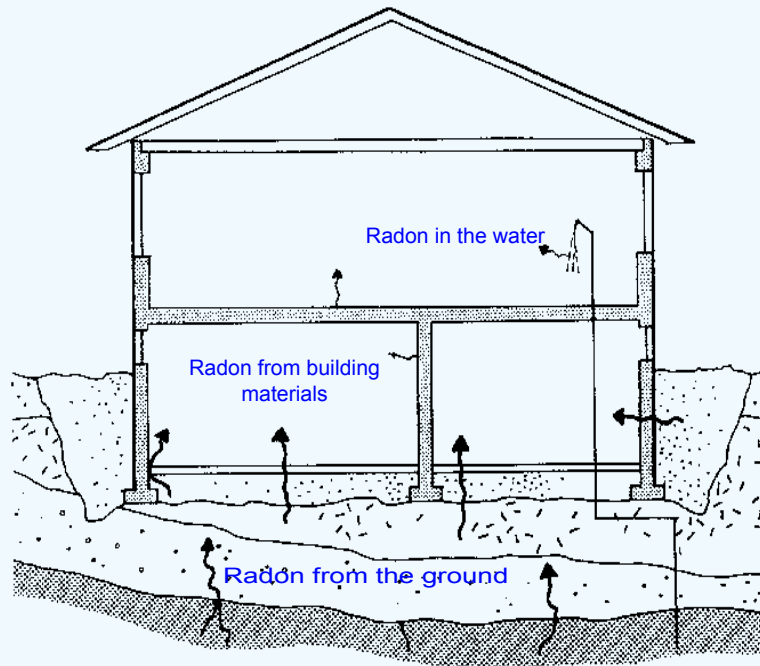
Several possibilities exist for the release of radon into houses (see illustration on the next page).

The main sources are the rock or soil on which the house is built, as well as the water supply. The rock formations under a house always contain some radium and the radon gas can penetrate into the house through cracks in the floor and walls of the basement. Furthermore, the building materials is also a source for radon.

Another source for radon is the water supply. Water from wells, in particular in regions with radium-rich granite, may contain high radon concentrations. When water is the carrier, the radon gas is readily released.

The indoor radon concentrations usually show an annual variation with the largest values during the winter. This is quite usual in places with frost and snow on the ground. The frost makes it difficult for the gas to diffuse out of the surrounding ground and to be released directly into the air. Consequently, the radon gas is more likely to seep into the house. It is the radon concentration averaged over a long-time that is important with regard to health risk and, consequently, remediation. Decisions on what action to take are generally based on an average annual level.





*This drawing illustrates how radon may enter a house. The radon gas (originating from radium) comes into the house from the ground, from the building materials and sometimes from the water. Well water contains in some areas (for example in Finland) quite large amounts of radon which is released when used in showers or in the kitchen. Drinking the water increases the amount of radiation to the body. In this connection we are interested in inhaled radon daughters.*

(Courtesy of Terje Strand, Norwegian Protection Agency)

## Radon measurements around the world

The UN organization UNSCEAR has collected measurements carried out around the world and presented data in several reports. Some of the data presented in the report from 2000, will be given.

The main mechanism for the entry of radon into the atmosphere is diffusion. In the outdoor atmosphere, there is also some advection caused by wind and changes in barometric pressure. Furthermore the concentrations of Rn-222 in the soil gas vary over many orders of magnitude from place to place and show significant time variation at any given site.

According to UNSCEAR, the flux of Rn-222 to the atmosphere is of the order  $0.02 - 0.03 \text{ Bq m}^{-2}\text{s}^{-1}$ . From the outdoor radon measurements it appears that the concentrations of Rn-222 and Rn-220 are approximately  $10 \text{ Bq m}^{-3}$  for each. There is, however, a wide range of long-term average concentrations of Rn-222, from approximately 1 to more than  $100 \text{ Bq m}^{-3}$ .

### Radon (world average)

#### UNSCEAR 2000

Outdoor:  $10 \text{ Bq m}^{-3}$

Indoor:  $46 \text{ Bq m}^{-3}$

## Indoor measurements

Radon measurements are carried out in all countries around the world and UNSCEAR presents tables of the values like the one below. In the report from 2000 the world average indoor value is  $46 \text{ Bq m}^{-3}$ . In the table below we have quoted the values for some selected countries – the values may change when more measurements are carried out.



*In Kinsarvik in the western part of Norway the highest radon values have been measured – both inside the houses as well as for the outside air:*

*Values above  $50\,000 \text{ Bq m}^{-3}$  inside and up to  $287 \text{ Bq m}^{-3}$  outside (1 meter above the ground) have been measured*

### Indoor Radon values (UNSCEAR 2000)

Country	Average $\text{Bq m}^{-3}$	Maximum $\text{Bq m}^{-3}$
United States	46	
Canada	34	1720
China	24	380
India	57	210
Iran	82	3070
Denmark	53	690
Finland	120	20 000
<b>Norway</b>	<b>73</b>	<b>50 000</b>
Sweden	108	85 000
France	62	4690
Germany	50	10 000
United Kingdom	20	10 000
Australia	11	420

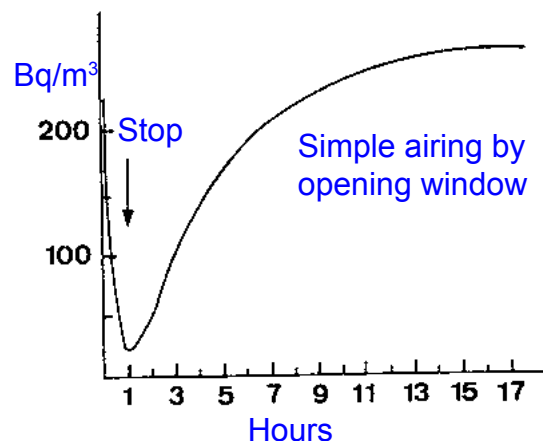
## Some comments on the indoor radon level

The inside radon level vary considerable with weather, time of the year and even time of the day – and of course with the airing system. For example, sleeping with an open window can reduce the radon content considerable. An example of airing is given below. After 1 hr the radon level was reduced by a factor 5 – 10. Afterwards the radon content increased and reached the old values in about 8 – 10 hours.

In places where water is the source for the radon release, the use of water for cooking, for showers, etc. will increase the radon level.

A reducing factor is air-condition. The radon level can be reduced by a large factor.

In conclusion. The radon level inside homes and other buildings can be measured with good accuracy. Old methods like ventilation and new methos with air-condition can reduce the radon content.



# Radon and lung cancer



In chapter 13 we discuss the mechanisms for cancer development – in particular radiation induced cancer. However, it seems reasonable – at this point – to present some of the discussions and studies carried out to evaluate the connection between the radon level in homes and lung cancer.

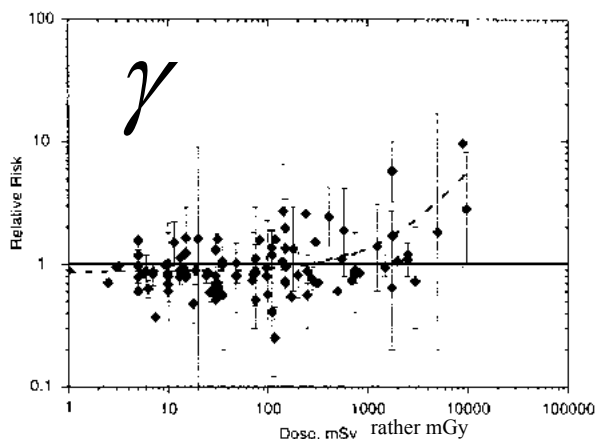
The fundamental for radiation induced cancer is the **radiation dose**. It is the ionizations and excitations formed when radiation is absorbed that initiate the chain of reactions that finally give an observed tumor.

In the studies of radiation induced cancer it is often easier to observe the medical result – namely the cancer – compared to observe the physical part, namely the radiation dose. This holds true for all internal dose calculations such as radon and also the intake of radioactive isotopes via food. On page 101 we have given an example how to calculate the dose from K-40 in the body, and in the next chapter we calculate the doses from intake of Cs-137 via food.

## External exposure

Radiation induced lung cancer can be observed after **external exposure** to x- and  $\gamma$ -radiation. A number of different groups have been irradiated with small and larger doses that can be measured fairly well. The results of this give us some information about radiation induced lung-cancer. The published data are given in the figure.

### *Low LET external radiation*



*Here you see a number of epidemiological studies of the correlation between lung cancer and radiation dose.*

*In these studies the radiation is external and consists mainly of  $\gamma$ -radiation and a small fraction of  $\beta$ -particles. It is low LET-radiation.*

*Although the data are heterogeneous, they indicate some type of radiation protection (radiation hormesis) for doses below 1 Sv or rather 1 Gy.*

*The figure is from the book of Charles L. Sanders: "Radiation Hormesis and the Linear-No-Threshold Assumption"*

Let us note that in the case of external low LET-radiation there is no linear correlation between lung cancer and radiation dose. Both parameters are fairly well determined. A question that can be raised is if high LET-radiation would give another result.

Since we have no human results we would like to present an experiment with dogs.

## Experiments with lung cancer formation by $\alpha$ -particles in dogs

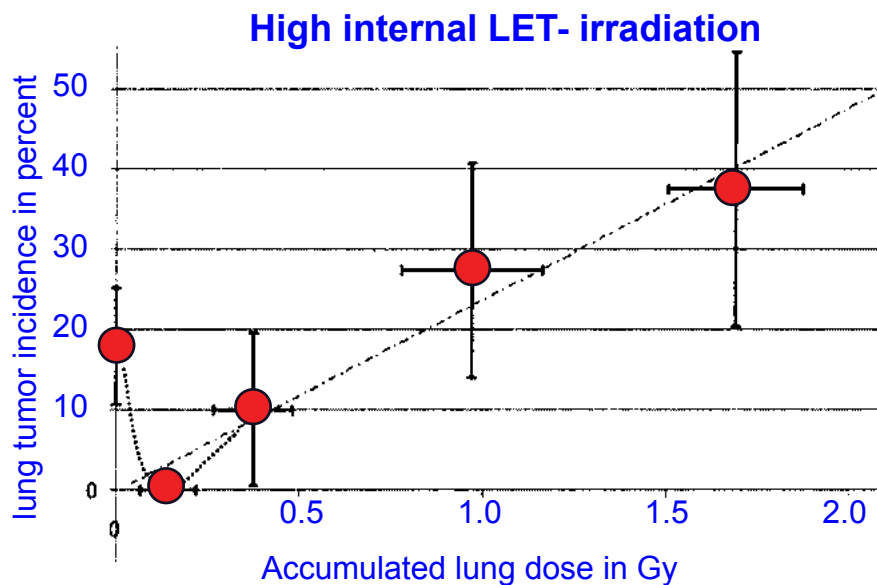


Since about 1970 a group connected to Pacific Northwest National Laboratory in Oregon have carried out life-span studies of dogs that inhaled plutonium oxide. The radioactive isotope is Pu-239, with half-life 24400 years. The decay scheme of Pu-239 is  $\alpha$ -particles with energy 5.15 MeV and  $\gamma$ -radiation with a line of 53 keV, which makes it possible to observe the isotope from outside the body with a  $\gamma$ -camera.

The biological half-life was 3.26 years – and the dogs were exposed until death.

The dose in Gy was fairly well determined – we can not give any dose in Sv since we operate with dogs.

The overall lung cancer incidence in 137 exposed dogs was best represented by a pure-quadratic equation. However, for accumulated doses below 2 Gy some interesting results appeared as shown in the figure below.



The data for doses below 2 Gy supported a threshold effect for  $\alpha$ -particle induced lung cancer. Un-irradiated dogs (the controls) exhibited a higher lung cancer level than those irradiated with doses up to about 0,7 Gy. The data showed that chronic low doses may be beneficial and give an advantage effect compared to unirradiated subjects.

The data indicated the likelihood that low doses of  $\alpha$ -particle radiation protected and reduced the incidence of lung cancer relative to the controls.

We would like to have these results for low and high LET-radiation in mind when we embark on the much more complicated issue to evaluate the effect of the indoor radon level on the induction of lung cancer.

The, by far most important cause of lung cancer, is smoking. Furthermore, smoking has an important effect on destroying the lungs cleaning system. This implies that the radon daughters connected to the aerosol-particles will not be stopped in the same way for smokers compared to non-smokers.

## Radon Doses – system I

Several attempts have been made to calculate the energy deposited in the lungs. These calculations are not easy since several important factors are unknown. We shall now go through some of the efforts done to arrive at the dose level from inhaled radon daughters.

***We have the following situation:*** You are exposed to radon and radon daughters from cradle to grave. Each time you breathe, more radioactive daughters are inhaled. The half-lives for the daughters are very short and the radiation dose is given within the day. If, however, some of the particles in the uranium series remain within the lung system, we will eventually have a small contribution from the decay of Po-210 ( $\alpha$ -particle) as well as from Pb-210 and Bi-210.

Let us try to describe how radon doses may be *estimated* based on human models. The models take into account both physical and biological parameters.

***Dose estimations.*** We breathe in an atmosphere consisting of radon and radon daughters. Since the daughters are attached to aerosol particles, they are easily deposited both indoors and outdoors. Consequently, the number of daughters in the air is approximately 40 – 60 % compared to radon itself. We do not know the correct number.

Radon and radon daughters will follow the air into the lungs when breathing. Radon itself will mostly follow the air out again. If we assume that the average air volume in the lungs is 1 – 2 liter, about 0.1 to 0.2 radon atoms may disintegrate in the lungs per second (0.1 – 0.2 Bq). This gives a minor contribution to the dose. Consequently, it is the radon daughters that give the radiation dose.

Some of the factors that are important for the amount of radon daughters inhaled are:

**1.** The aerosol size distribution as well as the equilibrium factor between free and bound radon daughters are important. The free radon daughters will penetrate and deposit deeper into the lungs. UNSCEAR is using an equilibrium indoor factor of 0.4 and an outdoor factor of 0.6.

**2.** The amount of radon daughters that enter the bronchi and lungs depend on the intake of air by breathing. In one of the models used by UNSCEAR it is assumed that an adult man breathe 22.4 m<sup>-3</sup> air per day and a woman 17.7 m<sup>-3</sup> per day.

**3.** The important target cells may be reached by the  $\alpha$ -particles. The depth in tissue for the target cells have been observed, and a value of 27  $\mu\text{m}$  for men and 18  $\mu\text{m}$  for women has been used.

**4.** In order to convert absorbed energy; i.e. the dose in Gy to Sv we have to apply a radiation weight factor. ICRP recommends a radiation weight factor of 20 for the  $\alpha$ -particles. This value is highly uncertain. The weight factor for the  $\beta$ -particles and  $\gamma$ -radiation is 1.

It can be noted that when the radiation weight factor of 20 was introduced (in the 1970-ties) the equivalent dose (in Sv) increased by a factor 20, and this changed our concern about radon completely.

**5.** Only the lungs are irradiated by the radon family and in order to arrive at an *effective dose*, we have to apply the tissue weight factor for lungs (ICRP suggests 12 % for the lungs).

**6.** Since the radon content is much higher inside the houses we have to assume a value for the indoor occupancy. UNSCEAR use an indoor occupancy of 80 % – about 19 hours which is much larger than average.

**Result:** In the UNSCEAR 2000 report a world average person obtain an accumulated annual dose from the radon and thoron families of the order 1.2 mSv. The Rn-222 family accounts for more than 90 % of the dose. Using the same estimation procedure the **annual effective** dose in Norway would according to this, be approximately 2.0 – 2.3 mSv. The **lung dose** would be about 16 – 18 mSv – or **0.8 – 0.9 mGy** when the weight factor between Gy and Sv is omitted.

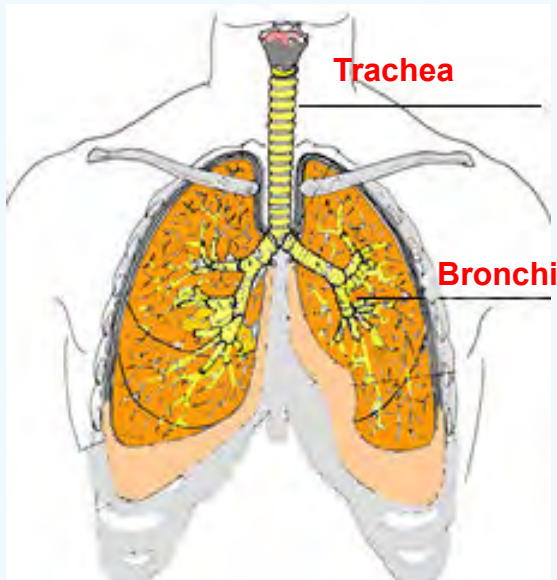
The accumulated lung dose of  $\alpha$ -particles over a period of 50 years would be 40 – 45 mGy. We use the unit Gy in order to compare this dose to the  $\alpha$ -dose for the dogs mentioned above. Such a dose would give the dogs a significant protection!

## The lungs cleaning system

A very important point in all dose estimations is the fact that the airways and lungs has a cleaning system. ***This seems to have been ignored in all epidemiological studies. Consequently all dose estimations become more or less a guesswork.***

Let us give some facts about the lungs cleaning system. The bronchial tubes are lined with ***cilia*** (like very small hairs) that have a wave-like motion. This motion carries mucus (sticky phlegm or liquid) upward and out into the throat, where it is either coughed up or swallowed. The mucus catches and holds much of the dust, germs, and other unwanted matter that has invaded the lungs. You get rid of this matter when you cough, sneeze, clear your throat or swallow.

With regard to radon it is evident that parts of the aerosol particles are swept out of the lung system before the radiation is emitted. ***However, we have no information about how effective this systems works – and how it changes from one person to another.***



**Smoking** destroys cilia – the lungs' natural cleaning and repair system. This system in general, and the cilia in particular, are paralyzed and destroyed by the poisons in cigarette smoke. However, functioning cilia can begin regenerating within a few days of quitting smoking, and may completely return to their original functioning after an extended period; statistics show that people who have quit smoking reduce their risk of developing lung cancer to that of a person who has never smoked, within 10 to 15 **years** after quitting.

*Above is an illustration of the lungs and bronchi. Radon and radon daughters (both free and bound) enter this system when breathing. Radon itself will not be stopped in the lungs, but follow the air out again. The radon daughters may be deposited in the walls of the bronchi and down in the lungs.*

***The lungs cleaning system consists of cilia that move in a sweeping motion to keep the air passages clean. Since the cilia and their function are damaged by cigarette smoke it implies that smokers get a larger radon dose than non-smokers. We have no quantitative information about this. However, two persons living in the same house get different lung doses. This uncertainty in radon dose are connected to all dose estimations – however it is not mentioned in any of the epidemiological studies.***

## Radon dose system II – used for underground miners

We know that radon in old mines involved a health risk for the miners. As early as around 1500, lung disease was found in two regions of Germany and Czechoslovakia, Schneeberg and Joachimsthal, among miners. The miners developed a deadly disease, called "Bergkrankheit". Between 1876 and 1938, 60 % to 80% of all miners died from the disease which, on average, lasted 25 years. Certain regions of the mines were known as "death pits," where all workers got sick. Bergkrankheit was mainly lung cancer and a result of their work and was recognized as an occupational disease.

It was mainly silver in the mines and it was made silver coins (called "thaler"). However, the mines contained pitchblende and consequently uranium, which at that time was considered to be of no value. From uranium the way to radon is clear and the mines contained radon and radon daughters.

The atmosphere in underground mines contains several *other* carcinogenic compounds, like arsenic and silica dust and diesel exhaust from mining machinery. Furthermore, the majority of the miners were smokers.

The radon concentration in the old mines are unknown, but they may be very large. Thus, measurements published in 1924 confirmed that the air in the mines contained high concentrations of radon gas, the highest more than 18 000 picocuries per liter – or 666 000 Bq m<sup>-3</sup>. It would therefore be of interest to arrive at the exposure rate and accumulated lung doses – or effective radon doses for those who worked for years in the mines. All the dosimetry is carried out in recent years and consists of exposure level and the product of the exposure level and time on work.

### Exposure

The unit for exposure was called "*Working Level*" (WL). The working level unit was defined as the amount of radon and radon daughters in 1 liter air that give a total  $\alpha$ -particle energy of  $1,3 \cdot 10^5$  MeV.

For an equilibrium factor between radon and radon daughters of 1.0, one WL correspond to 100 pCi per liter (or 3700 Bq m<sup>-3</sup>), whereas for an equilibrium factor of 0.5 the WL unit correspond to 200 pCi per liter (7400 Bq m<sup>-3</sup>).

### Dose

The workers in those days worked 40 hours per week, or 170 hours per month. This gives the unit for total exposure or "dose"; called "*Working Level Month*" (WLM).



$$1 \text{ WLM} = 1 \text{ WL in 170 hours}$$

Several attempts have been made to estimate a dose of 1 WLM into the more usual dose units such as Gy and Sv. Using the dose models suggested by UNSCEAR, it appears that 1 WLM is equivalent with an **effective dose** of the order 4 – 5 mSv. This again corresponds a **lung dose** of the order 1.6 mGy to 2.0 mGy! An accumulated dose of 200 WLM may be considered with a lung dose of the order 400 mGy or 0.4 Gy (compare with the doses to the dogs on page 110).

## Lung cancer for the miners

Several retrospective cohort studies have been made and some conclusions can be drawn. An excess number of lung cancers have been found – even for nonsmokers. The risk increases with dose. In some of the reported studies it is possible to draw a straight line between the dose given in WLM and the relative risk. The straight lines indicate a threshold value of from 300 to 700 WLM.

Another point that should be mentioned is that the old German data seem to indicate that the risk was at a maximum in the period 15 – 24 years after exposure – indicating a latency period of that length.

**The observation of lung cancer among miners seem to indicate a threshold value.** Thus no cancers have been observed for non-smokers for accumulated doses below 100 WLM.

An  $\alpha$ -particle dose of 300 WLM (probably a threshold dose) is equivalent with a lung dose of about 600 mGy. This is quite interesting when we compare with the experiments on dogs (page 110). For the dogs the threshold dose was about 700 mGy.

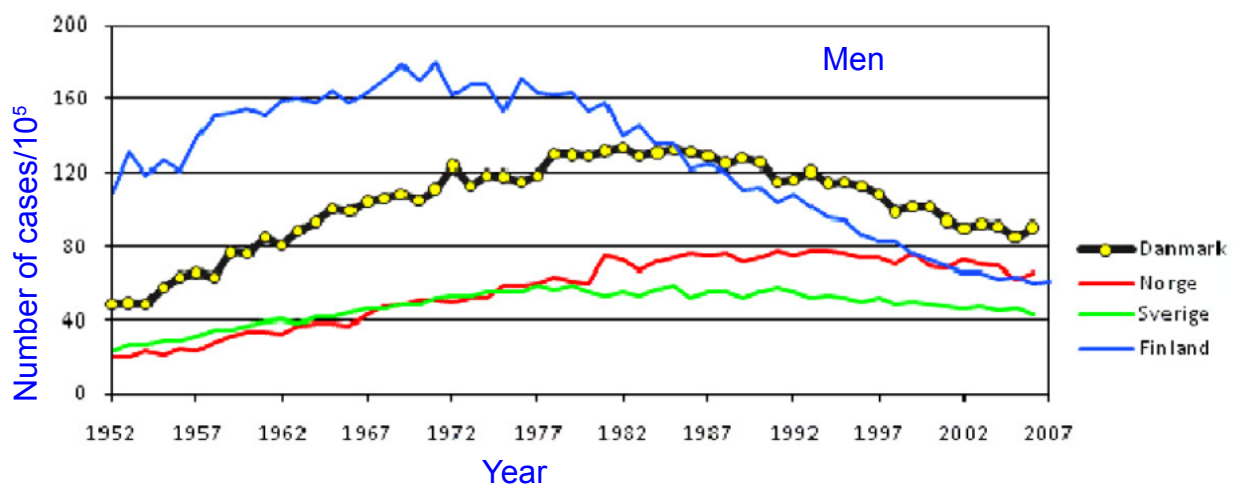
## Radon dose system III – radon in homes

We know that exposure to large radon doses may give lung cancer. However, we can not extrapolate the observations for the underground miners to the radon values observed in most houses. For example if we live in a house with a constant radon level of 100 Bqm<sup>-3</sup> the accumulated annual dose is about 0.4 – 0.7 WLM (assuming an equilibrium factor of 0.5). The accumulated lifetime radon dose is about 20 WLM. This is much lower than the threshold values for the underground miners.

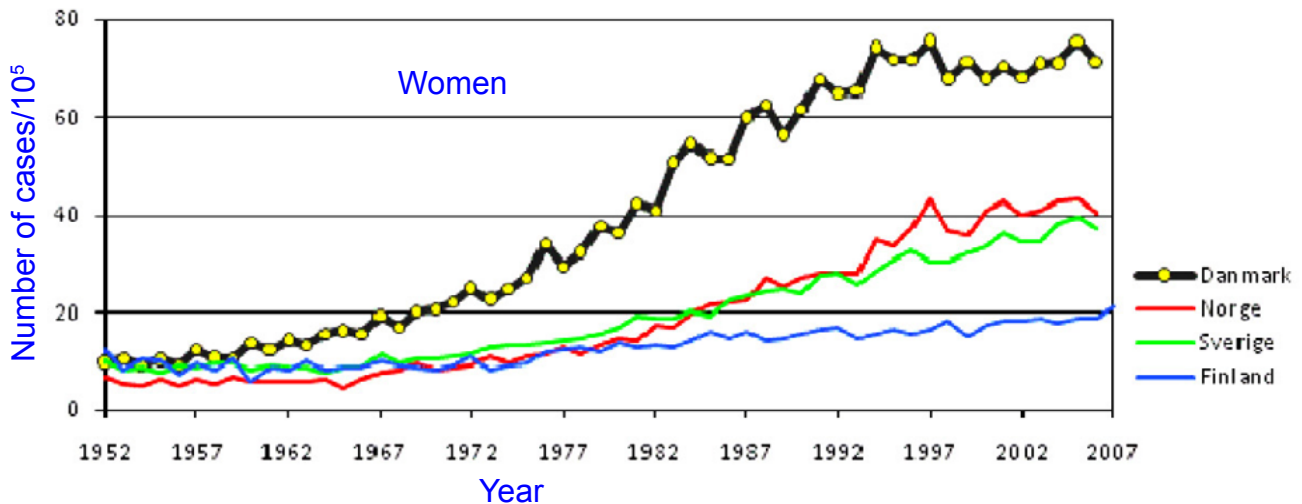
A large number of epidemiological studies on radon in homes and lung cancer have been published during the last 30 years. **The aim of such studies is to give a plot with the radiation dose to the lungs along the horizontal axis and the radiation induced lung cancer along the vertical axis.**

### First a few words on lung cancer

Lung cancer is by far the leading cause of cancer death among both men and women (see the figure below for the Nordic countries).







The two figures show the lung cancer deaths in the Nordic countries for the period 1952 to 2007 given as cases per 100 000 persons. It was an increase after the second world war, which has flattened out for men and started to go down again. For women the curves are somewhat different, but seem to have reached a maximum and may hopefully go down again together with the smoking habits.

The main cause for lung cancer is smoking. We assume that about 90 % (in the range from 80 to about 95 %) of the cases are due to smoking. The other causes are asbestos, diesel fumes, radiation and nature itself (see a more extensive discussion on DNA-damages and cancer in chapter 13). It is impossible to identify and determine those cases that are caused by radiation. Consequently in a plot on lung cancer versus radon, all lung cancers cases are plotted along the vertical axis.

## Dose

Along the horizontal dose axis the radiation dose to the lungs should be given. The lung dose from inhaled radon daughters is unknown and, as discussed above, impossible to arrive. In the epidemiological studies another parameter – hopefully equivalent to the dose – has been introduced. The dose parameter introduced is **the radon level in Bq per cubic meter**. This parameter is more or less equivalent to the old WL exposure. In the case of the miners the dose was given in units of WLM where a WLM was the dose after 170 hrs at the exposure level of 1 WL. In most of the epidemiological studies the dose is given by the bequerel-level you have lived with for about 30 years. Since no one carry a personal dosimeter a number of assumptions are made:

1. The time inside the home is set to 80 % of the total. This may hold true only for retired people.
2. The radon level outside the home – in your work and your outdoor time is not recorded.
3. **The lungs cleaning system** is not mentioned. Consequently, two or more people living with the same radon level – **will not** be exposed to the same radiation dose!

We are here faced with a parameter that to a large extent seems to abolish the epidemiological studies. It is by far not enough to divide between smokers and nonsmokers – even though smoking has a large effect on the cleaning system.

**Furthermore, the power of case-control studies disappears since it is impossible to arrive at a control group with the same radiation dose.**

The ecological studies are not hampered by the cleaning system in a similar way – and become more important due to the large number of persons included.

**In conclusion:** For the many epidemiological studies carried out, the physical part (the radiation doses to the lungs) are extremely poorly determined. It is a surprise to the present author that the epidemiologists dare to draw firm conclusions based on this.

## **An overview of the epidemiological studies of radon and lung cancer**

A large number of epidemiological studies have been carried out for the correlation between lung cancer and radon in houses. We shall present some of these studies – 3 case-control studies and 1 ecological study.

As mentioned above the radiation dose is replaced by the radon level in the houses, given in  $\text{Bq m}^{-3}$ . *No attempts have been made to take into consideration the cleaning system of the lungs. The smoking habit is not enough.*

### **Case-control studies**

In general, we assume that the case-control studies give the most and best information. However, in the case of radon and lung cancer, it is more or less impossible to arrive at control groups mainly because we can not evaluate the lungs cleaning system. Thus, two persons living with equal becquerel level may obtain very different radiation dose to the lungs – even if they are non-smokers.

The "dose" in the case-control studies is usually given as the average radon level during 25 – 30 years, ending 5 years before diagnosis. The radon level is determined both by measurements and assumptions about the radon level for periods without measurements.

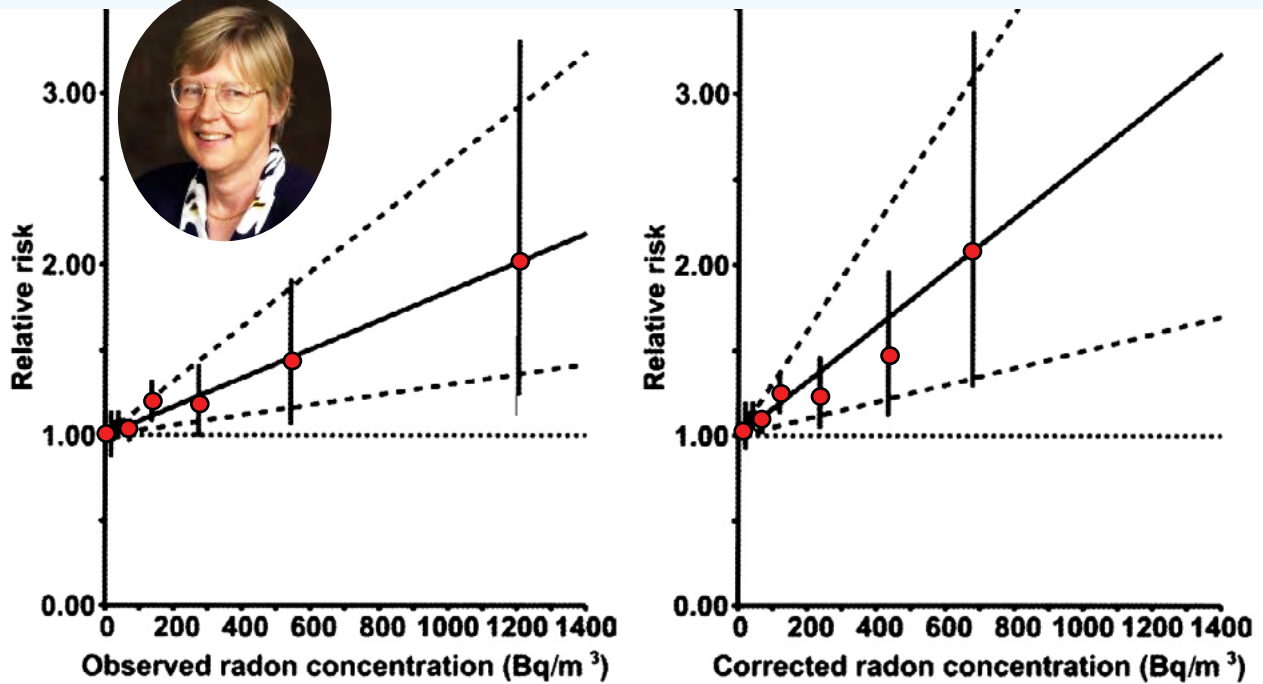
We would like to present 3 groups of case-control studies which yield different results.

### **1. Sarah Darbu and Daniel Krewski – pooled studies**

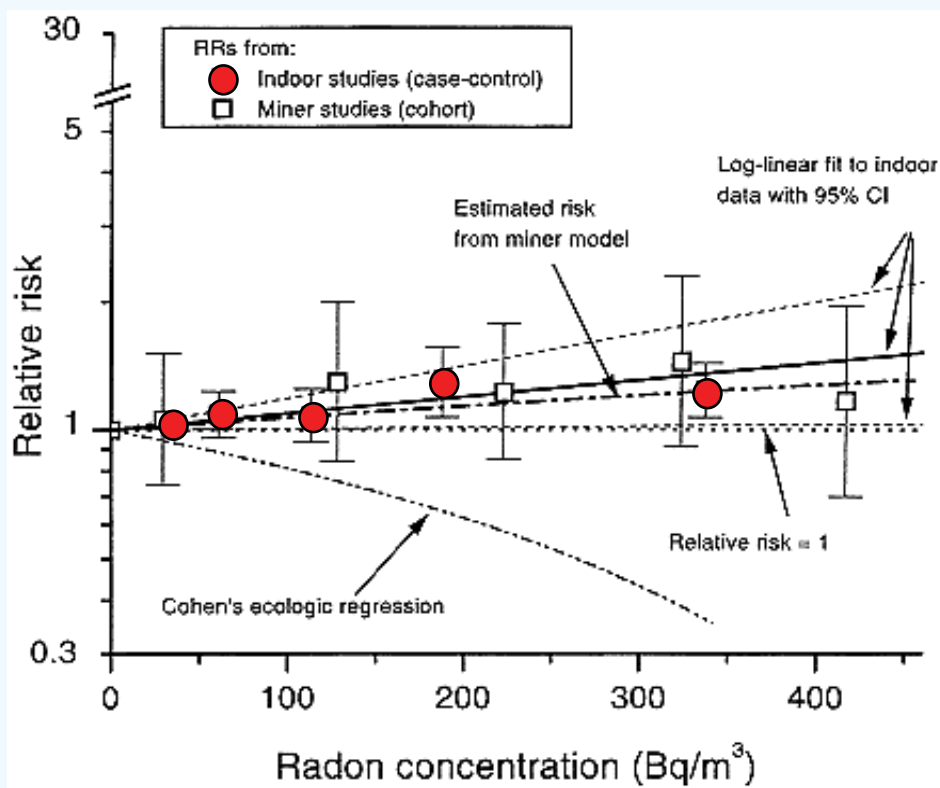
Sarah Darbu et. al.(2005) presented pooled data from 13 studies in 9 European countries including 7148 cases and 14208 controls. Daniel Krewski et.al. presented data from 7 studies in USA including 4420 cases and 5707 controls.

These studies can be presented together since they both have based the studies on the LNT-theory. Thus, they assume that the data should be given in a linear plot between lung cancer and the level of Bq per square meter in the homes. *The purpose of the studies is to determine the increase in cancer incidence per 100  $\text{Bq/m}^3$  increase in radon level.*

The main results are given in the figures on the next page. The weakness in these studies is the radiation dose – or the Bq-level measured. No discussion is made on the radon level and the time spent outside the home, and no discussions are presented on the effect of the lungs cleaning system as well as the validity of the LNT-model.



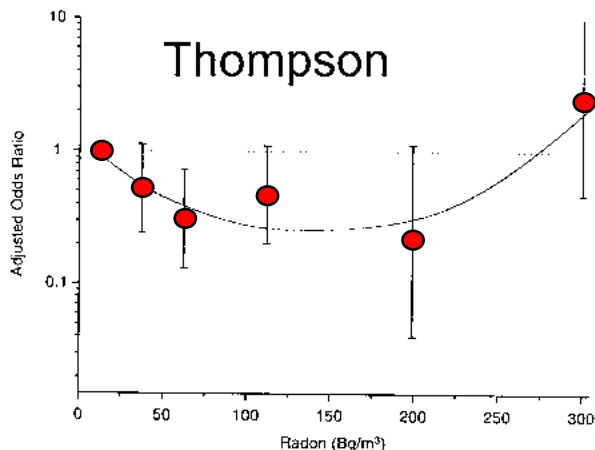
Above Darbus data are given. To the left is given the measured amount of radon in the homes in Bq per cubic meter. In the figure to the right the same data are given, but the "dose-axis" are corrected to imply the long term average of the radon content. In these plots the risk for lung cancer increases by 8 % per 100 Bq/m<sup>3</sup> whereas in the right figure the increase is 16% per 100 Bq/m<sup>3</sup>. For non-smokers no measurable increase was found.



The data presented by Krewski et. al. In this figure is also presented the data from the BEIR VI report. The miner data are extrapolated to the very low values of radon. The extrapolation is based on LNT. Furthermore, the dotted line include the data from Bernhard Cohens ecological studies (see later). The straight line indicate an increase in lung cancer of 9.6 % per 100 Bq/m<sup>3</sup>.

## 2. Richard Thompsons and Donald Nelsons studies from Massachusetts 2008

The number of cases in this study was much smaller than those above. Thus 200 cases and 397 controls. They divided the cases in 6 groups with regard to radon content in the homes. The lowest value 25 Bq/m<sup>3</sup> was used as reference. No preassumption about LNT was made. The results are given below.



*Here are the results from Massachusetts. It was a surprise that the data showed a clear hormetic effect. The range in "dose" or Bq/m<sup>3</sup> is rather very limited.*

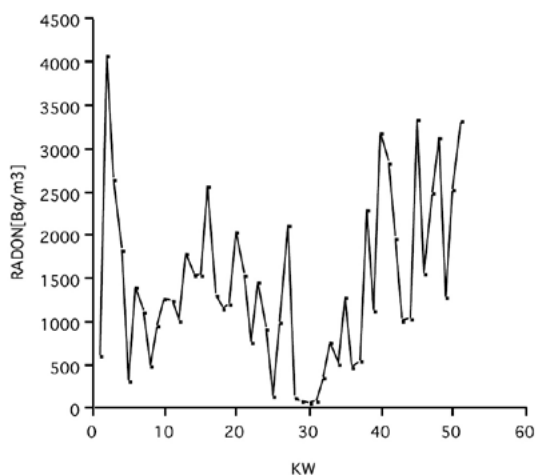
## 3. The Schneeberg studies

Schneeberg is a small German city close to the border of the Czech Republic. The city is known for high level of radon in the homes. Thus the radon level varied from 50 Bq/m<sup>3</sup> to more than 3000 Bq/m<sup>3</sup>. The studies include only women that lived in these homes for 25 years.

Most of the women were non-smokers (only 22 % smokers). It can be mentioned that the self-reported smoking behaviour of the women are made at time of diagnosis. Consequently, the data may be biased due to an obvious tendency to repress and minimise their smoking habit.

Only those with low mobility are included.

The radon level is measured by track-dosimeters for several years. The data could vary significantly through the year as shown in the figure. Along the abscissa is given weeks through the year.

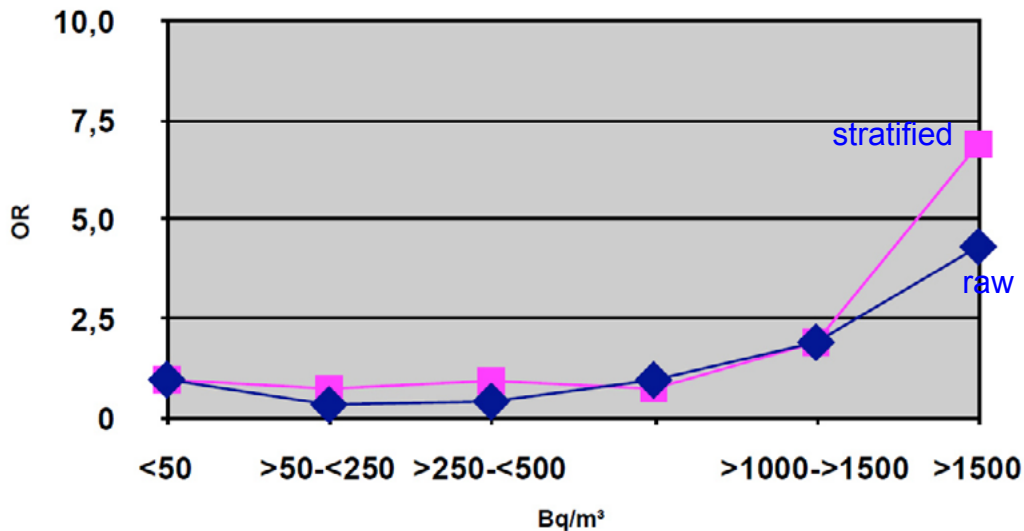


It was assumed that the time spend inside the homes are 68 % of the total. Furthermore the equilibrium factor was set to 0.4.

A number of cases were found not to fit the requirements and are therefore omitted.

It was 4 controls for each case.

The results are given in several tables and given in the figure on the next page.



The reference is the group with a radon level below 50 Bq/m<sup>3</sup>. It is clear that these data do not follow an increase of about 10 % per 100 Bq/m<sup>3</sup> as found for Darbu and Krewskis studies. Only for values above 1000 Bq/m<sup>3</sup> the risk seems to increase.

The risk estimation of the Schneeberg study for lung cancer from indoor radon is not in accordance with the results from miners and population studies by Darbu and Krewski, which state an excess risk of about 10% per 100 Bq/m<sup>3</sup> radon exposure. If such risk estimates are true, in the highly exposed population of Schneeberg such lung cancer risks must have been easily established. That is not the case. From the risk estimate of the Schneeberg study even a safe threshold value was found and a significantly elevated risk appeared at >1.500 Bq/m<sup>3</sup> only.

It was not the purpose of this study to test the LNT model. However, the evidence of the Schneeberg study strongly indicates that its results are not in accordance with the LNT assumption. The risk estimations for lung cancer due to indoor radon exposure are derived by direct observation in a key population for such research. The Schneeberg study is considered by its authors as a contribution to the growing body of scientific evidence that the LNT model might not be valid in the low dose range.

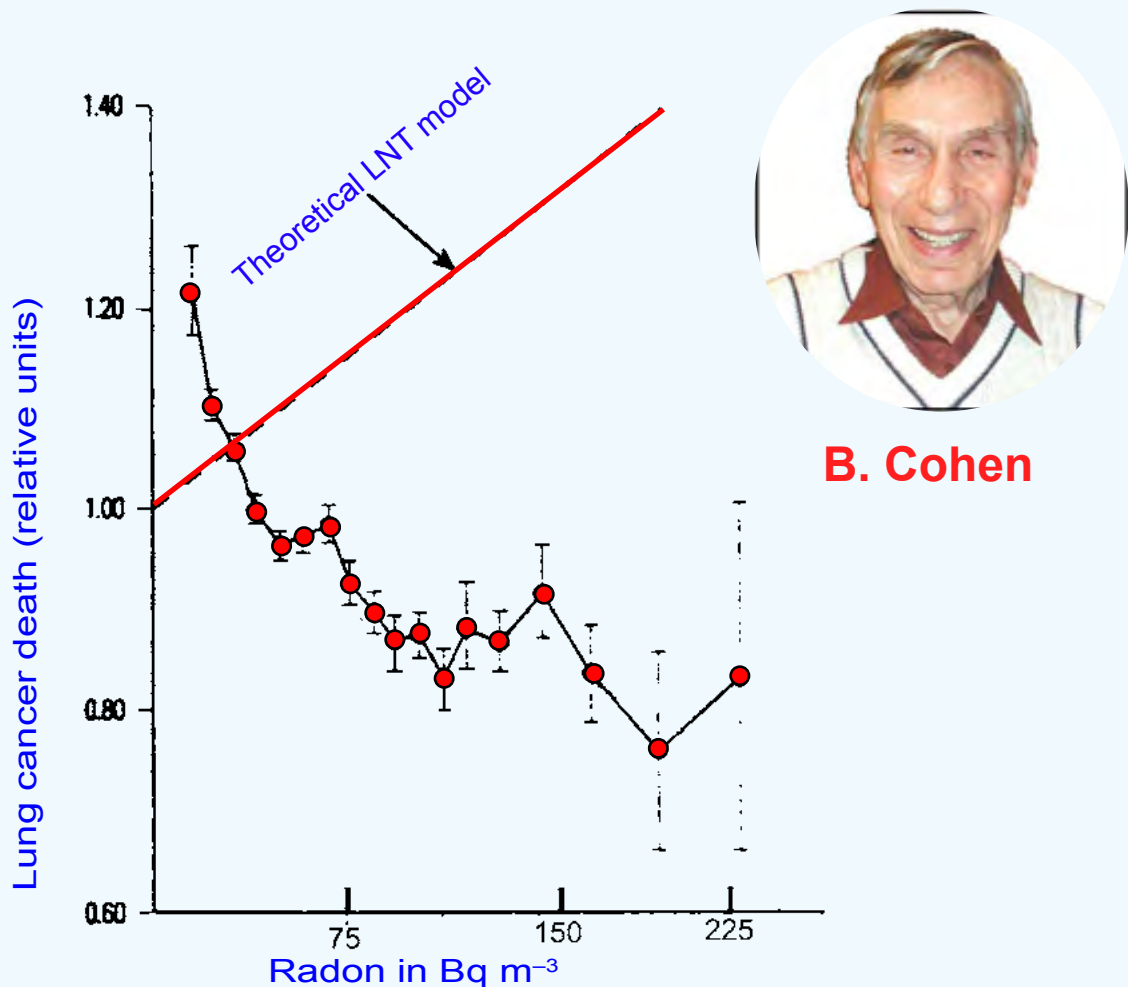
### Summary of the case-control studies

Thompsons study and the Schneeberg study strongly indicates that its results are not in accordance with the LNT assumption. In the Schneeberg studies an increase in risk was observed only for a radon level above 1000 Bq/m<sup>3</sup>.

If we assume you are exposed to a radon level of 1000 Bq/m<sup>3</sup> for a full year (68 % of the time and an equilibrium factor of 0.5), it would correspond to about 5 WLM. The accumulated dose for 25 years would be of the order 125 WLM. Consequently, the threshold dose for radon in houses would be quite equal to the threshold dose for miners. Furthermore, the external  $\gamma$ -radiation and the dog  $\alpha$ -particle radiation both exhibited threshold lung doses of about 0.7 to 1.0 Gy.

## Bernhard Cohens ecological studies

The last epidemiological study to be presented is the ecological study by Bernhard L. Cohen (1995 and 2000). This study involve more persons that all the other studies combined, and involve about 90 % of the US population and about 330 000 radon measurements. In this study Cohen divided the country in 1729 counties or regions. The average radon level within each region was determined and compared to the incidence of lung cancer. No control groups, no assumptions on the cleaning system. It is an average for each county. The main results of these studies are given in the figure below.



*The figure shows the main results of Bernhard L. Cohens investigations from 1995 and 2000 . The main data are published in Health Physics 68 (2), 157 – 174 (1995).*

*The data points from counties with almost the same radon level have been grouped together.*

*The data from 2000 include more recent cancer data. Furthermore, data for Florida and California have been deleted because deaths there are frequently due to retirees who received their radon doses elsewhere. The results are however, not changed but are more or less equal to those presented above.*

## Radon summary

We know that radiation can give cancer. The cancer formation depend on both radiation dose and dose-rate. We have no information about cancer formation for doses below 500 mGy. Furthermore, we have no information about any differences between low and high LET radiation.

On the pages above we have given some of the many epidemiological studies presented about radon as a factor for lung cancer. It is of course not radon itself, but the ionizing radiation from the radon daughters that are able to get into the lungs – the aerosol particles with radon daughters that is not cleaned out again.

We have pointed out the problems connected to case-control studies with regard to dose determination. All studies include a discussion on smoking and smoking is an important factor for the cleaning system. We have little information about other factors that may damage this system – but assume that diesel fumes and nitric oxides are important. May be age is a factor.

A combined result of the studies are: for radon levels up to about 400 – 500 Bq/m<sup>3</sup> we can not observe any increase in lung cancer incidence. The combined data on radiation and lung cancer indicate a threshold level of about 0.6 – 1.0 Gy.

The data can not be associated with the LNT-hypothesis. This interesting question will be further discussed in chapters 12 and 13 when we discuss the mechanisms for cancer including all the defense mechanisms.

## Radon regulations

ICRP (*International Committee on Radiation Protection*) as well as radiation authorities in most countries use the LNT-theory for the deleterious effect of ionizing radiation. With regard to radon this implies that S. Darbus data are considered valid and the other studies are disregarded. EPA (United States Environmental Protection Agency) is also using the LNT-theory and based on the BEIR VI report assumes that radon in US-homes is responsible for about 20 000 lung cancer deaths per year (between 6 000 and 30 000).

In USA they have introduced regulations for the radon level in houses. For schools and public buildings the radon level should be below 4 pCi per liter which is 148 Bqm<sup>-3</sup>.

WHO assume LNT and use the data from Darbu, Krewski and Lubin. In Norway the radiation authorities have decided to use Darbus data and neglect all other information. Thus they state that the level should be below 200 Bqm<sup>-3</sup>, and it should be possible to introduce remedial action for the site of the building if and when the radon concentrations in the inside air is above 100 Bqm<sup>-3</sup>.

The other European countries the remedial action level is suggested to be 400 Bq/m<sup>3</sup> for old houses and 200 Bq/m<sup>3</sup> for new houses. In general, it is possible to reach a set level, but the cost may be very large. In the particular case of lung cancer it is more wise to give the money to actions against smoking – and in particular to stop young people from beginning.

The costs for remedial actions for existing dwellings within OECD countries above the action level of 400 Bq/m<sup>3</sup> have to be more than 10 Billion ECU. As long as Public Health effects are dubious, no new regulations should be imposed on the public causing billions of ECU without a certain Public Health effect.

## Summary

In this chapter we have presented the four main natural radiation sources which are responsible for the natural background radiation. We are exposed to this radiation from the time of conception until we die.

The annual background dose vary from place to place as well as with lifestyle. It is of interest to get more information about the health situation in the areas with high background radiation.

The most discussed source is radon, which exhibits a variation from 10 – 60 000 Bqm<sup>-3</sup> in the homes. Another important aspect of the radiation emitted by radon is that a large fraction consists of  $\alpha$ -particles. The  $\alpha$ -particles result in high density of ionizations along the track (high LET radiation). ICRP and the radiation authorities give this radiation a large radiation weight factor. We meet the high LET radiation only in the case of radon. The results presented above with lung cancer induction by low LET radiation and the dog experiments with high LET radiation are in fact very equal. Both dataset involve a dose limit of about 1 Gy for low LET and about 0.6 Gy for high LET. This suggests a radiation weight factor for  $\alpha$ -particles of about 2! It is of interest to note that this is more in line with the weight factors observed for cell-killing.

Members of the public often seem to ignore the natural doses of radiation, whereas they are very concerned about smaller doses from anthropogenetic sources such as nuclear accidents (Windscale, Three Mile Island, Chernobyl, Fukushima, etc.) and radioactive waste products from the nuclear industry.

With regard to health effects from the natural radiation sources we have introduced two opposite models. According to the LNT hypothesis all dose levels are harmful to the society – whereas the other model suggests some beneficial effect from the radiation.

According to newer biological research (including defense mechanisms such as stimulated repair and apoptosis) the natural radiation is positive with regard to health and may save life. This will be discussed in a later chapter.