Transfer analysis of 210Po and 210Pb in the terrestrial environment

Persson, Bertil R

Published in:
Acta Scientiarum Lundensia

2013

Citation for published version (APA):
Persson, B. R. (2013). Transfer analysis of 210Po and 210Pb in the terrestrial environment. *Acta Scientiarum Lundensia*, *2013*(002), 1-42. https://www.researchgate.net/profile/Bertil_Persson

Volym ASL 2012-002

Citation: (Acta Scientiarum Lundensia)

Persson B. R. R., (2013). Transfer analysis of ^{210}Po and ^{210}Pb in the terrestrial environment, *Acta Scientiarum Lundensia*, Vol. 2013-002, pp. 1-42, ISSN 1651-5013

Corresponding author:

Bertil R.R. Persson,

Lund University, Dept. of medical radiation physics, Barngatan 2, S-22185 Lund Sweden

E-mail: bertil_r.persson@med.lu.se

Acta Scientiarum Lundensia
(open access) Vol V2013-002 2013-02-14

Transfer analysis of ^{210}Po and ^{210}Pb in the terrestrial environment

Bertil R.R. Persson PhD. MDhc
Professor em. of medical radiation physics
Lund University. SE-22185 Lund. Sweden

Abstract

The transfer of ^{210}Po and ^{210}Pb between various compartments in the terrestrial environment has been analysed by using various published data.

The average activity concentration of ^{210}Po in soil is 61 ± 14 Bq.kg^{-1} d.w. with a median (50%) value of 44 Bq.kg^{-1} d.w. Ground water concentrations of ^{210}Po in drilled wells might be as high as 6.5 Bq/l. But in regular drinking water it is just about 3-5 mBq/l.

The uptake of radionuclides from soil to plant is usually given as the ratio of radionuclide activity concentration per unit mass concentrations (Bq.kg^{-1} dry w.) of plant (AC_{plant}) and soil (AC_{soil}) respectively. This ratio is called the soil tranfer factor STF = AC_{plant} / AC_{soil}. The soil transfer factor vaires widely beween various types of crops with an average about 0.056±0.003.

Mean annual deposition and activity concentrations (mBq.l^{-1}) of ^{210}Pb ^{210}Po and in rainwater varies with latitudes (^{0}N to ^{0}S) with longitudes (^{0}W. ^{0}E). Between latitudes 20 and 60 ^{0}N a linear relation between the yje activity concentration of 210Pb was found: $A(^{210}Pb) = 2.17 * (^{O}N) - 22.2$ (mBq.l^{-1}). Lichens (Cladonia alpestris) collected at was used as a model for studying the sorpition and retention of atmospheric deposition in plants and the upper layer of soil.

The atmospheric deposition of ^{210}Pb and ^{210}Po. however. also affect the activity concentrations in leafy plants. By comparing the activity concentrations in plants grown on an open field with those grown on a field sheltered by a polyethylene tent it has been possible to estimate a deposition transfer factor : DTF= Difference of the activity concentration in plants grown in open field (Deposition+Soil "AC_{DS}") and tent shelter (Soil "AC_S") respectively. divided by the atmospheric deposition "AD" during the vegetation period (Bq.m^{-2}). The deposition transfer factor for ^{210}Pb thus estimated is in the order of 0.5-1 (m^2.Bq^{-1}) for leafy plants like grass and 0.1-0.5 for less leafy plant and straw. For various grains it is < 0.2 (Barley grains 0.2; wheat grains <0.001.). For root fruits it is < 0.003 (red beet 0.003; potatoes <0.001). Corresponding values for ^{210}Po are about a factor 3 higher. The fraction of ^{210}Pb firmly incorporated into the plant is about 82±20 % for atmospheric deposited ^{210}Pb and 60±20 % for ^{210}Pb taken up from soil.

A few studies have been performed to quantitatively study the transfer of the natural radionuclides ^{210}Pb and ^{210}Po from fodder to milk. The activity concentration ratios between milk and various types of forage was estimated to 1.4±0.7 for ^{210}Pb and 0.41±0.09 for ^{210}Po. By assuming a daily food intake of 16 kg dry matter per day the transfer coefficient F_m. that describes the fraction of the daily intake of radionuclides that is secreted per litre of milk has been estimated from these studies. The transfer coefficient F_m for ^{210}Pb thus obtained is 0.01±0.008 d.l^{-1} and for ^{210}Po 0.003 ± 0.0007 d.l^{-1}. These values are about 30 and 15 times higher than those estimated by IAEA for the elements respectively.

Key words: Transfer, terrestrial environment, ^{210}Po , ^{210}Pb

1. Introduction

After removal of the radioactive elements uranium and thorium from about 1000 kg of pitchblende, by Marie and Pierre Curie in 1898 they found another radioactive element (Curie & Curie 1898). The element was named Polonium after Marie Curie's native country of Poland. A few years later they also discovered radium. For these discoveries, the Curies shared 1903 Nobel Prize in physics with Henri Becquerel who discovered the radioactivity. In recognition of Marie Curie´s work in radioactivity she received the 1911 Nobel Prize in Chemistry,

Polonium has the chemical symbol Po and atomic number 84, and is chemically similar to bismuth and tellurium. All 33 known isotopes of polonium with atomic masses from 188 to 222 are radioactive. The naturally most widely occurring isotope is ^{210}Po with a half-life of 138.376 days. Long lived artificial isotopes ^{209}Po (half-life 103 a) and ^{208}Po (half-life 2.9 a) can be made by accelerator proton bombardment of lead or bismuth. Although the melting point of polonium is 254 ºC and its boiling point is 962 ºC, about 50% of it is vaporized at 50 ºC and become airborne within 45 hours as a radioactive aerosol.

Extensive research of the properties and production of polonium-210 was carried out at the top-secret Manhattan Project site established at the Bonebrake Theological Seminary in 1943 in Dayton, Ohio. The polonium was to be used in a polonium–beryllium neutron source whose purpose was to ignite the plutonium atomic-bombs (Sopka & Sopka 2010). After the first bomb had been dropped on Nagasaki, Japan, on August 9, 1945, a period of extensive atmospheric testing of new bombs occurred during 1950. This focused the interest to studying the ^{210}Po atmospheric fallout, and its potential health effect on mankind (Jaworowski 1969; Persson, B. R. 1970a). High activity concentrations of ^{210}Po were found in reindeer and caribou meat at high northern latitudes. This was, however, of natural origin and no evidence of significant contributions of ^{210}Po from the atomic bomb test was found. The most significant radionuclides in the fallout from the atmospheric atomic bomb-test of importance for human exposure were ^{137}Cs and ^{90}Sr (Persson, B. R. 1970a).

During the 1960 the presence of 210Pb and 210Po was studied in human tissues and particularly in Arctic food chains(Baltakmens 1969; Beasley & Palmer 1966; Blanchar.R.L & Moore 1969; Hill 1960,1965,1966b; Holtzman 1963,1966,1967; Kauranen & Miettinen 1967,1969; Kilibard.M, et al. 1966; Osborne 1963; Peirson, et al. 1966; Persson, B. R. 1970a; Persson, B. R. R. 1970b; Skrable, et al. 1964).

In December of 2006, former Russian intelligence operative Alexander Litvinenko died from ingestion of a few μg of Polonium-210. This incident demonstrated the high toxicity of polonium-210 and resulted in a renaissance for research of bio-kinetics and biological effects of Polonium-210. Already in 2009 there was an international conference on polonium (Po) and radioactive isotopes held in Seville Spain, which was attended by 138 scientists from 38 different countries The sessions covered all aspects on ^{210}Po and lead (^{210}Pb) such as radiochemistry, terrestrial and marine radioecology, kinetics, sedimentation rates, atmospheric tracers, NORM industries and dose assessment (Holm, Elis & Garcia-Tenorio 2011).

The present article is an deeper review and analysis of the transfer of ^{210}Po and lead (^{210}Pb) in the terrestrial environment.

2. Origin of ^{210}Po in the terrestrial environment

The presence of ^{210}Po in the ground can be traced to the decay of ^{238}U.

^{238}U $^{>234}$Th >^{234}Pa >^{234}U >^{230}Th >^{226}Ra >^{222}Rn (3.82 days).

After the first 5 decays Rn-222 is formed which is a nonle-gas diffusing out from ground into the atmosphere where it decays to the following short lived products which attach to airborne small particles

^{218}Po (RaA 3.10 min)>^{214}Pb (RaB 26.8 min) >^{214}Bi (RaC 19.9 min)>^{214}Po(RaC´164.3 μs).

The decay products following **^{214}Po** are longer lived

^{210}Pb (RaD 22.20 a) > ^{210}Bi (RaE 5.01 d) > ^{210}Po(RaF 138.4 d) > ^{206}Po(stable).

The concentration of those long lived products in air increase with height. and reach a maximum in the stratosphere.

3. Atmospheric deposition of ^{210}Po and ^{210}Pb

The atmospheric residence time of ^{210}Po has varies between 15 -75 days with a mean value in the order of 26 ± 3 days. ^{210}Pb is continuously deposited from the atmosphere in association with aerosols at a rate of about 55 Bqm^2/a over Scandinavia (Eldaoushy & Garciatenorio 1988). Generally. atmospheric ^{210}Pb concentrations are related to if the underlying surface is terrestrial area. oceanic areas including islands. Permafrost. ice and snow covered surface reduce the atmospheric ^{210}Pb concentrations (Eldaoushy & Garciatenorio 1988). Atmospheric fallout of ^{210}Po is normally assumed to be constant at any given site. measured on timescales of a year or more. The ^{210}Po flux may, however, vary spatially by an order of magnitude, depending on factors such as rainfall and geographical location. These basic concepts have been investigated by carrying out direct measurements of ^{210}Po fallout on both short and long timescales. and by developing mathematical models of ^{210}Po in the atmosphere (Piliposian & Appleby 2003). Direct measurements of ^{210}Po fallout on weekly or monthly timescales using bulk deposition collectors have been made at a number of sites in Europe and beyond. Indirect measurements of the mean atmospheric ^{210}Po flux over several decades have been made using cumulative deposits in selected soil cores. Simplified models of the evolution of the vertical distribution of ^{222}Rn. ^{210}Po and their daughter products ^{210}Bi and ^{210}Po in a vertical column of air moving over the Earth's surface have been developed and used to model geographical variations in the ^{210}Po flux long-range transport is of major importance when modelling atmospheric fallout in regional domains (Appleby 2008).

The natural radionuclide ^{210}Po was analysed in rainwater samples in Izmir by radiometric methods. The samples were collected continuously from January 2000 through December 2003 depending on the frequency of rain. The levels of ^{210}Pb in the samples were found to vary between 9 ± 1 and 198 ± 6 mBq.l^{-1}with an average value of 51 ± 0.5 mBq.l^{-1}. ^{210}Po activity concentration in total (wet and dry) deposition has also been investigated in the study from November 2001 to April 2003 and the results were found to vary between 2 ±0.4 and 35 ±3 mBq.l^{-1}. The average value of ^{210}Po activity concentration is found as 8 ± 0.5 mBq.l^{-1}. ^{210}Po /^{210}Pb activity ratios were derived as between 0.03 and 1.09. The annual ^{210}Po and ^{210}Pb fluxes were 12 and 48 Bq.m^{-2}.a^{-1} respectively (Ugur, Aysun, et al. 2011).

Bulk atmospheric deposition fluxes of ^{210}Po and ^{210}Pb were measured at three coastal regions of Japan. the Pacific Ocean coastal area of the Japanese mainland (Odawa Bay). the Chinese continental side of Japanese coastal area (Tsuyazaki). and an isolated island near Okinawa (Akajima). Wet and dry fallout collectors were continuously deployed from September 1997 through August 1998 for periods of 3 to 31 days depending on the frequency of precipitation events. Annual ^{210}Pb deposition fluxes at Odawa Bay . Tsuyazaki and Akajima were 73.3 +/- 8.0. 197 +/- 35 and 78.5 +/- 8.0 Bq.m^{-2}.a^{-1}. respectively. Higher Pb-210 deposition was observed at the Chinese continental side of Japanese coast than at the Pacific Ocean coastal site. The high ^{210}Pb atmospheric flux at the Chinese continental side coast was thought to be attributable to Rn-222-rich air-mass transport from the Chinese continent during the winter monsoon. In contrast. the annual ^{210}Pb deposition fluxes at the three study sites were 13.0 +/- 2.3 (Odawa Bay). 21.9 +/- 4.4 (Tsuyazaki) and 58.4 +/- 7.7 (Akajima) Bq.m^{-2}.a^{-1} respectively, indicating unusual high Po-210 deposition at Akajima during winter. Anomalous unsupported ^{210}Pb input was observed during summer 1997. suggesting unknown source of ^{210}Pb at this area (Tateda & Iwao 2008).

The Latitudw distribution of annual ^{210}Pb deposition summarized from various sources is displayed in **Figure 1** (Baskaran 2011; Persson, B.R.R. & Holm 2013).

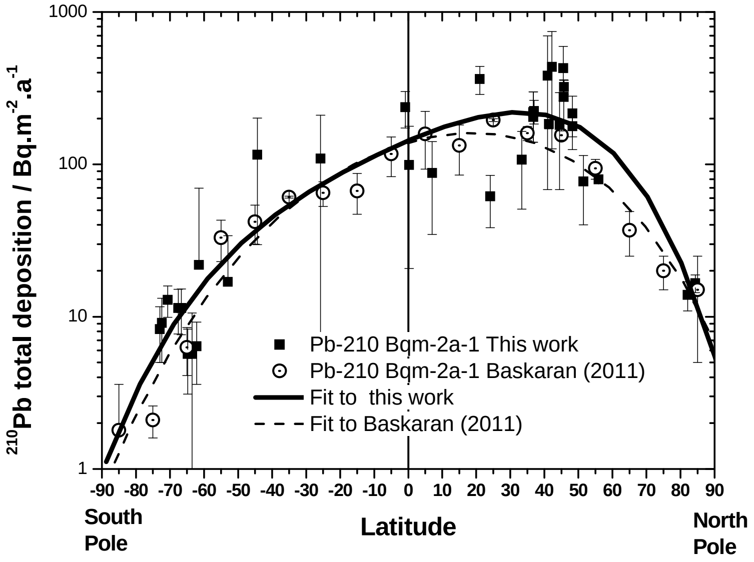


Figure 1.
Latitudinal distribution of all reported average values of deposition flux (Φ) of ^{210}Pb (Bq.m^{-2}.a^{-1}). The square dots are the data given in (Persson, B.R.R. & Holm 2013)and the open circles the data compilation of (Baskaran 2011; Persson, B.R.R. & Holm 2013).

The latitude distibution of ^{210}Po/^{210}Pb-activity ratio in the deposition was estimated from air filter studies during polar expeditions from the Arctic to Antactic oceans (Persson, B.R.R. & Holm 2013). The Latitude distribution of annual ^{210}Po deposition shown in **Figure 2** was estimated by applying this relation to the ^{210}Pb data displayed in **Figure 1**

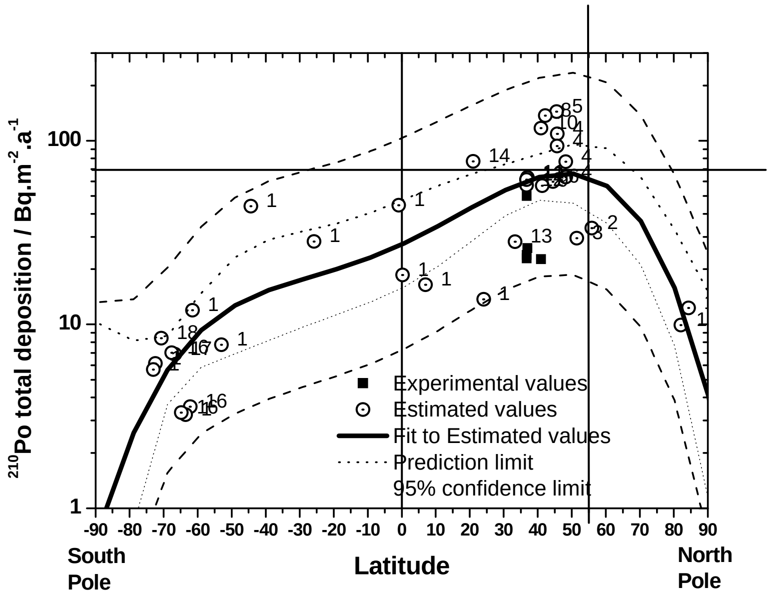


Figure 2 Latitudinal distribution of air concentrations of ^{210}Po (µBq.m^{-3}) Estimated from: [Latitudinal distribution of ^{210}Pb] ⊗ [^{210}Po/^{210}Pb-activity ratio] (Persson, B.R.R. & Holm 2013)

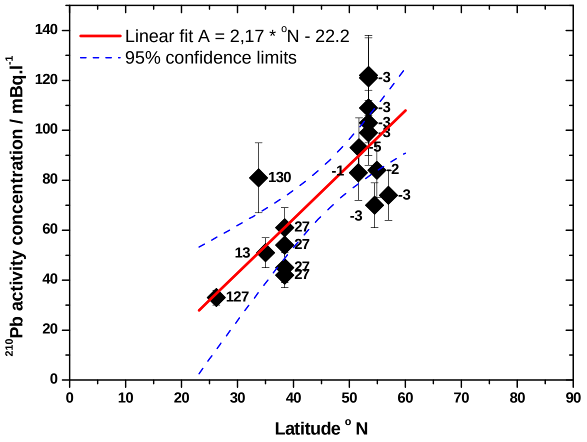


Figure 3 Mean annual ^{210}Pb concentrations (mBq.l^{-1}) in rainwater at various latitudes (^{0}N) with longitudes (:W. E) as labels.
Equation of fitted line: A(^{210}Pb) = -22.2 + 2.17 * (^{O}N)

Mean annual ^{210}Pb concentrations (mBq.l^{-1}) in rainwater reported by various authors are given in **Table 1** and displayed in **Figure 3** above.

Table 1: Mean annual ^{210}Pb concentrations (mBq.l^{-1}) in rainwater

Site	Latitude N(+)/S(-)	Longitude W(-)/E(+)	Period	^{210}Pb (mBq.l^{-1}) Annual Ave.	SD	Reference
Lochnagar	56.96	-3.24	1996/1998	74	10	(Appleby 2008).
Esthwaite	54.90	-1.54	1997/1998	84	11	(Appleby 2008)
Brotherswater	54.51	-2.92	1984	70	9	(Appleby 2008)
Liverpool	53.41	-2.99	2001	122	16	(Appleby 2008)
Liverpool	53.41	-2.99	2002	103	13	(Appleby 2008)
Liverpool	53.41	-2.99	2003	121	16	(Appleby 2008)
Liverpool	53.41	-2.99	2004	109	14	(Appleby 2008)
Liverpool	53.41	-2.99	2005	99	13	(Appleby 2008)
Milford Haven	51.71	-5.04	1966	93	12	(Appleby 2008).
Harwell	51.60	-1.29	1960	83	11	(Appleby 2008).
Izmir. Turkey	38.42	27.13	2000	54	7	(Ugur, Aysun, et al. 2011).
Izmir. Turkey	38.42	27.13	2001	61	8	(Ugur, Aysun, et al. 2011).
Izmir. Turkey	38.42	27.13	2002	45	6	(Ugur, Aysun, et al. 2011).
Izmir. Turkey	38.42	27.13	2003	42	5	(Ugur, Aysun, et al. 2011).
Odawa Bay	35	13	1997/98	51	6	(Tateda & Iwao 2008)
Tsuyazaki	33.79	130.46	1997/98	81	14	(Tateda & Iwao 2008)
Akajima	26.2	127.28	1997/98	33	3	(Tateda & Iwao 2008)

5. Levels of ^{210}Po in soil

Soil consists of particles of different minerals as well as organic matter in various stages of degradation. ^{210}Po in soils originates either as a product from the radioactive decay of radionuclides of ^{238}U series present in the soil (supported) or the result of the deposition of radon decay products from the atmosphere (unsupported). Airborne particles with attached ^{210}Pb and ^{210}Po are deposited on the earth's surface through fallout. which results in accumulation of the final long-lived ^{210}Pb (22.3 a) in plants and the top layer of soil. where it decays to ^{210}Bi (5 d) > ^{210}Po (140d) and finally to stable ^{206}Pb.

The levels of ^{210}Pb and ^{210}Po contained in the top layer of soil can be correlated with the amount of atmospheric precipitation. But the ingrowth from ^{238}U series present in the soil supported ^{210}Pb is the main source of ^{210}Po in soil and establish an equilibrium with a ratio close to 1. Due to the different amount of clay and organic colloids in various soils the ^{210}Po content varies with soil type (Parfenov 1974).

The of the activity concentrations of ^{210}Po in soils from various locations in the world are given in **Table 2** and displayed in **Figure 4**. The world average of the activity concentrations of ^{210}Po in soil is 60 ± 13 (SE) Bq.kg^{-1} dry weight and the median value is 44 (50%) Bq.kg^{-1} dry weight.

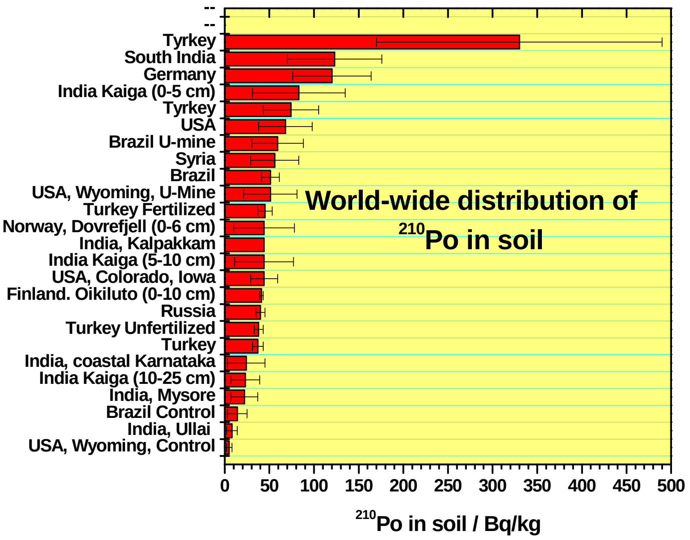


Figure4. The distribution of the activity concentrations of ^{210}Po in soils from various locations.

Table 2

The distribution of activity concentrations of ^{210}Po in soil from different countries Bq.kg^{-1} dry weight.

Country	210Po min Bq/Kg	210Po max Bq/Kg	210Po average Bq/Kg	s.e.	References
Russia	30	50	40	5	(Dowdall & O'dea 1999)
South India	17	228	123	53	(Hasanen 1977)
USA	8	128	68	30	(Myrick, et al. 1983)
Germany	33	207	120	44	(Schuttelkopf & Kiefer 1982)
Brazil	32	70	51	10	(Santos, R.C., et al. 1990)
Turkey	13	135	74	31	(Akyil, et al. 2002)
Turkey	10	870	330	160	(Akyil, et al. 2008)
Syria	1.2	110	56	27	(Al-Masri, et al. 2008)
Brazil U-mine	30	92	59	29	(Santos, P. L., et al. 1993)
Brazil Control	3	38	14	11	(Santos, P. L., et al. 1993)
Turkey	26	41	37	6	(Ekdal, et al. 2006)
India Kaiga (0-5 cm)	17	228	83	52	(Karunakara, et al. 2000)
India Kaiga (5-10 cm)	7	142	44	33	(Karunakara, et al. 2000)
India Kaiga (10-25 cm)	4	67	23	16	(Karunakara, et al. 2000)
Turkey Fertilized	37	57	45	8	(Bolca, et al. 2007)
Turkey Unfertilized	33	41	38	5	(Bolca, et al. 2007)
India. Kalpakkam			44		(Iyengar, et al. 1980)

Table 2 continued

India. Mysore	8	37	22	15	(Nagaiah, et al. 1995)
India. Ullai	1	14	8	6	(Radhakrishna, et al. 1993)
India. coastal Karnataka	4	45	24	21	(Siddappa, et al. 1994)
USA. Colorado. Iowa	29	59	44	15	(Usaec 1980)
USA. Wyoming. Control	2	9	5	3	(Ibrahim & Whicker 1987)
USA. Wyoming. U-Mine	21	81	51	30	(Ibrahim & Whicker 1987)
Finland. Oikiluto (0-10 cm)	40	43	41	2	(Brown, et al. 2011)
Norway. Dovrefjell (0-6 cm)	11	78	44	34	(Brown, et al. 2011)
World average	Min: 1	Max: 870	Mean: 60	Se 13	This work (SE)

The depth distributions of ^{210}Pb in cultivated soil and in a neighbourhood undisturbed flat reference site have been studied in Marchouch (6°42′ W, 33° 47′ N) 68 km south east from Rabat in Morocco. The profile in undisturbed soils shows a maximum activity at the surface due to the continuous inputs from atmospheric deposition As a result of mixing caused by cultivation processes abd yearly tillage activities an almost uniform distribution of ^{210}Pb is found throughout the plough layer (12 - 14 cm) (Benmansour, et al. 2013).

5.1 Fertilizer

About 85% of the phosphate rock used for fertilizers are formed mainly from organic residues which contain 50–200 ppm uranium and 2–20 ppm thorium. A minor fraction 15 % of the phosphate rock used for fertilizer are igneous phosphates of volcanic origin containing less than 10 ppm uranium but with a higher concentration of thorium and rare earths. Thus most phosphate fertilizers also contain the decay products radium and polonium and lead. The distribution of activity concentrations of ^{210}Pb and ^{210}Po in 28 samples of phosphate fertilizers in Italy is displayed in **Figure 5** (Roselli, et al. 2009). Continued application of phosphate fertilizers to soil over a period of many years could eventually increase the content of ^{210}Pb and ^{210}Po the soil which would result in an increased transfer of these radionuclides to the crops. The absorbed dose equivalent to the population due to the application of phosphate fertilizer for 10, 50 and 100 years has been estimated to be below 1 mSv.a^{-1} (Saueia & Mazzilli 2006).

In 1999 di-hydrate phosphor-gypsum samples were collected from two important Brazilian phosphoric acid producers. For each company a stack was chosen, recorded as A and B, In the phosphogypsum the activity concentration of ^{210}Po ranged within 1-m intervals from 364±47 to 900±28 Bq.kg–1 (mean value of 581±97 Bq.kg–1) for stack A and 149±15 to 803±21 Bq.kg–1 (mean value of 325±114 Bq.kg–1) for stack B (Taddei 2001)

.

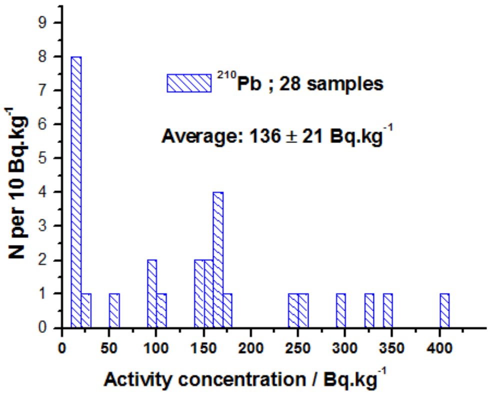


Figure 5a ^{210}Pb concentration in phosphate fertilizers (Bq kg−1)

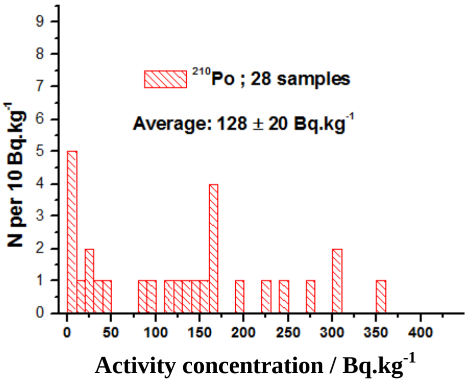


Figure 5b ^{210}Po concentration in phosphate fertilizers (Bq kg−1)

6. Transfer of of ^{210}Po to Ground Water

The average activity concentrations of ^{210}Po in water sources are given in **Table 3**. ^{210}Po concentrations in household water from private drilled wells have been observed to be quite high (maximum 6500 but median 48-107 mBq.l^{-1}). In water from dug wells. the concentrations ^{210}Po are lower (maximum 120 but median 5 mBq.l^{-1}). But from public water supplies the concentrations of ^{210}Po is usually very low (median 3-5 mBq.l^{-1}).

Table 3; Estimates of the ^{210}Po activity concentrations in ground water and drinking water at different locations around the world (Vesterbacka, et al. 2005)

Type of plant	Location	^{210}Po min mBq.l^{-1}	^{210}Po max mBq.l^{-1}	^{210}Po average mBq.l^{-1}	Reference
Reference value	World wide			5	(Unscear 2000)
Recommendation	EU			100	(Who 2004)
Surface water	Finland	1.6	2.0	1.9	(Vesterbacka 2007)
Lake water	Finland	1.0	6.5		(Vesterbacka 2007)
Drilled wells	Finland			48	(Vesterbacka 2007)
Water works	Finland			3	(Vesterbacka 2007)
Ground water	Brazil			3	(Bonotto & Bueno 2008)
Mineral Water	Italy	<0.04	21	1.8	(Desideri, et al. 2007)
Ground water	California USA	0.25	555	< 26	(Ruberu, et al. 2007)
Drilled wells	N. Nevada. USA	0.4	6500	107	(Seiler 2011)
Mineral water	Italy	0.12	11.3	3	(Jia & Torri 2007)
Mineral water	Austria	0.4	6.1	1.9	(Wallner, et al. 2008)

Activity concentration ratio water/soil varies widely depending on the treatment of the water.

7. Transfer of ^{210}Po to vegetation

7.1. Polonium soil-to-plant transfer factor

Uptake of radionuclides from soil to plant is characterized by the ratio of radionuclide activity concentration per unit mass concentrations (Bq.kg^{-1} dry w.) of plant (AC_{plant}) and soil (AC_{soil}) respectively. This activity ratio is called the Soil tranferfactos STF = AC_{plant} / $AC_{soil.}$

In **Table 4** is given estimated average values of soil transfer factors for ^{210}Po (mBq.kg^{-1} dry wt. plant/Bq.kg^{-1} dry wt. soil) for various crop groups. crop compartments and crop/soil combinations. The upper part of **Table 4** shows the current established values (Iaea 1994). The lower data are compiled from an extensive compilation of recent published data on transfer factors (Vandenhove, et al. 2009).

The STF for a given type of plant and for a given radionuclide can vary considerably from one site to depending on several factors such as the physical and chemical properties of the soil. environmental conditions. and chemical form of the radionuclide in soil. The overall average in **Table 4** including and excluding deposition are shown by the two lowest beams indicate that about 7-8 % of ^{210}Po present in the soil is transferred to plants. Although the transfer factor for non leafy plants. maize and cereals are extremely low.

The general accepted word wide average of the trasfer factor for ^{210}Po in vegetables and fruit are 1 (mBq.kg^{-1} dry wt. plant/ Bq.kg^{-1} dry wt. soil) and for grain 2 (mBq.kg^{-1} dry wt. plant/ Bq.kg^{-1} dry wt. soil) with corresponding values for ^{210}Pb 0.1 and 5 (Staven, et al. 2003). In soils with high content of ^{226}Ra and its daughters ^{210}Pb and ^{210}Po . however. the transfer factors can be much higher (Al-Masri, et al. 2008; Al-Masri, et al. 2010).

Table 4. Average Polonium soil-to-plant transfer factor (mBq.kg^{-1} dm plant/ Bq.kg^{-1} dm soil) for crop groups. crop compartments and crop/soil combinations (Iaea 1994; Vandenhove, et al. 2009).

Plantgroup	min.	Max.	Average TF*1000	Rel. SD
Wheat grain-grain			2.30	
Potato			7.00	
Vegetables			1.20	
Grasses			0.90	
Cereals-Grain	0.224	0.26	0.24	0.11
Maize-Grain	0.018	0.466	0.24	1.31
Rice-Grain			17	
Leafy vegetables			19	0.91
Non-leafy vegetables	0.016	0.37	0.19	1.30
Legumes-pods	0.06	1.02	0.48	0.96
Root crops-roots	0.24	49	12	1.38
Root crops-shoots	58	97	77	0.35
Tubers	0.143	34	8.0	1.44
Natural pastures	22	1020	259	1.25
All cereals	0.018	16.8	3.6	2.09
Pastures/grasses	18	1020	259	1.25

Table 4. Continued

odder	0.016	97	25	1.40
All excluding deposition	0.016	1020	56	2.86
All including deposition	0.016	1020	74	2.16

The soil transfer factor varies widely beween various types of crops with an average about 0.056 exluding deposition and 0.074 including deposition.

7.2. Transfer of Pb-210 and Po-210 to plants from atmospheric deposition

The effect of atmospheric deposition of ^{210}Pb and ^{210}Po on their transfer to various types of plants used as food (potatoes. vegetables. cereals) or as fodder (grass. alfalfa) has been studied by comparing the activity concentrations in plants grown on an open field with those grown on a field sheltered by a polyethylene tent (Pietrzak-Flis & Skowronskasmolak 1995). ^{210}Pb and ^{210}Po were determined both in the total deposition, as well as in soils and plants. The difference between the activity concentrations in the plants grown on the open field and those grown in the tent was takes as measure of the contamination via the above ground parts of the plants. The ratio of this difference to the total content of the radionuclides under open field conditions was taken as a measure of the contribution from atmospheric deposition.

The fractional uptake from deposition was calculated by dividing this difference with the local deposition of ^{210}Pb and ^{210}Po (Bq.m^{-2}) throughout the vegetative period. The data displayed in those figures indicate that atmospheric deposition is the main source of ^{210}Pb and ^{210}Po in the above-ground parts of the plants. For the leafy parts of the plants DTF of ^{210}Pb and ^{210}Po were higher than in the grains. stem and roots. The data demonstrate that atmospheric deposition is an important source of ^{210}Pb and ^{210}Po in the above-ground parts of plants. Thus it is of importance to consider in the discussion of the transfer factors.

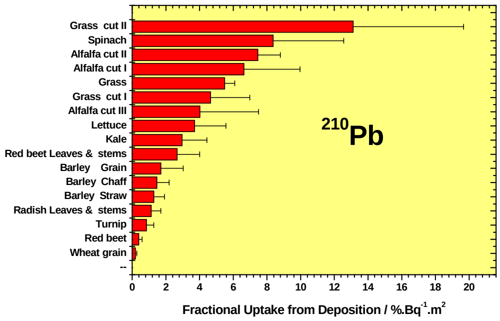


Figure 6a
The fractional uptake of ^{210}Pb for various corps from deposition calculated by dividing the difference with the local deposition of ^{210}Pb (Bq.m-2) throughout the vegetative period.

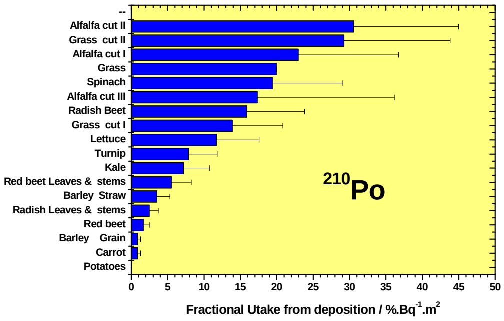


Figure 6b
The fractional uptake of ^{210}Po for various corps from deposition calculated by dividing the difference with the local deposition of ^{210}Po (Bq.m-2) throughout the vegetative period.

One has to consider soil transfer factor “STF” and the deposition transfer factor “DTF” separately in modelling the activity concentration ^{210}Pb and ^{210}Po in plants used i diet and a fodder.

STF$_{dw}$ = The ratio of the Activity concentration in plant (AP$_S$ Bq.kg^{-1} dry weight) grown in shelter and AS is the Activity concentration in the soil (Bq.kg^{-1} dry weight).

DTF= Difference of the activity concentration in plants grown in open field (Deposition+Soil “AP$_{DS}$”) and tent shelter (Soil “AP$_S$”) respectively. divided by the atmospheric deposition “AD” during the vegetation period (Bq.m^{-2}).

$$STF_{dw} = \frac{AP_S}{AS} \quad \left[\frac{Bq.kg^{-1}\ dry\ weight}{Bq.kg^{-1}\ dry\ weight}\right]$$

$$DTF_{dw} = \frac{AP_{DS} - AP_S}{AD}\ ; \left[\frac{Bq.kg^{-1}\ dry\ weight}{Bq.m^{-2}}\right]; \left[\frac{m^2}{kg\ dry\ weight}\right];$$

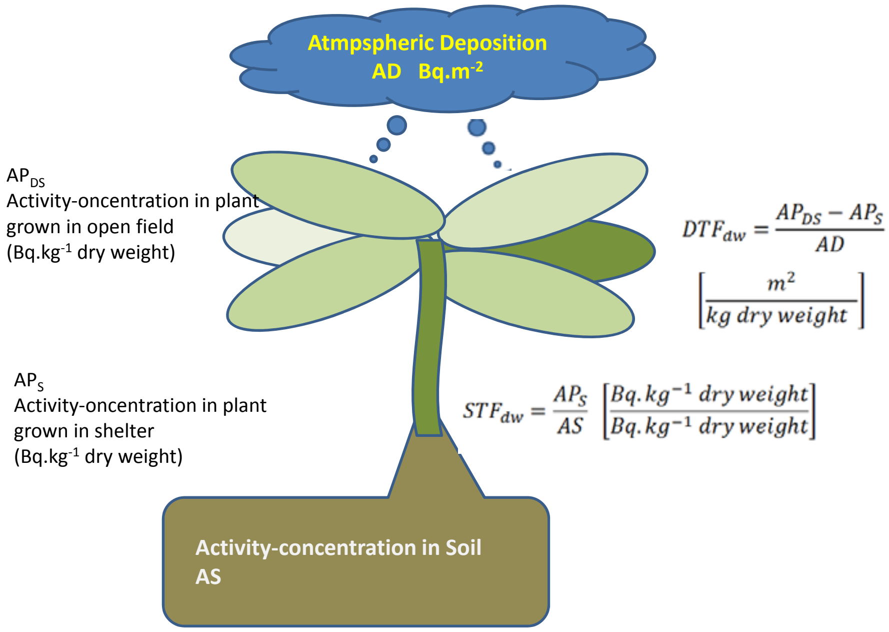


Figure 7
Model for transfer of ^{210}Pb and ^{210}Po to plants from atmospheric deposition (AD) and soil (AS)

The deposition transfer factor DTF for various types of plants was calculated from the published data and is displayed in **Figures 8a** and **8b**.

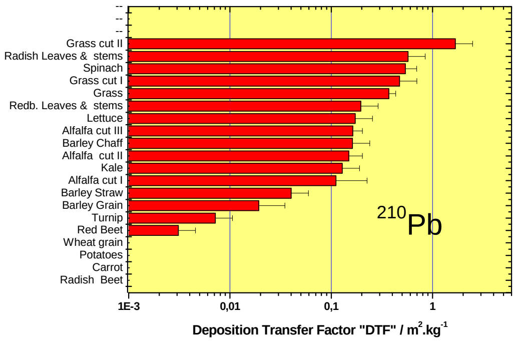


Figure 8a Deposition transfer factor of ^{210}Pb

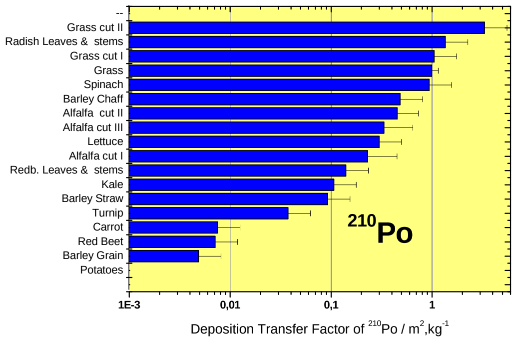


Figure 8b Deposition transfer factor of ^{210}Po

The fraction of ^{210}Pb firmly incorporated into the plant measured after thorough washing, as displayed in **Figure 9**, is about 82±20 % for atmospheric deposited ^{210}Pb and 60±20 % for ^{210}Pb taken up from soil.

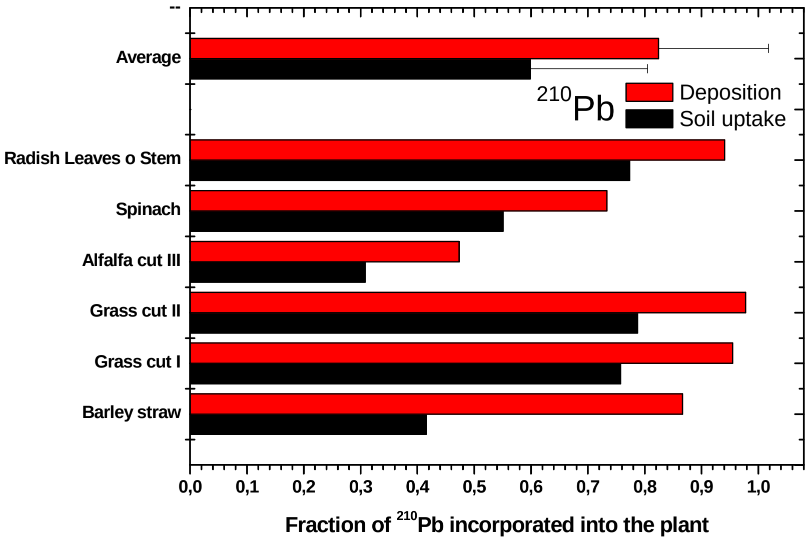


Figure 9 The fractions of ^{210}Pb firmly incorporated into various corps from atmospheric deposition and up-take from soil.

8. ^{210}Po and ^{210}Pb in food chains grass-cattle-milk

8.1 Activity concentration of ^{210}Pb and ^{210}Po

The activity concentrations of ^{210}Pb and ^{210}Po in various types of milk and meat products mBq.kg^{-1} fresh weight are given in **Table 5**.

For ^{210}Pb in milk products the minimum was 5 mBq.kg^{-1} and maximum 88 mBq.kg^{-1} and average of all reported values was 81 ± 19 mBq.kg^{-1} which is twice the UNSCEAR`s reference value of 15 mBq.kg^{-1}. For ^{210}Po in milk products the minimum was 2 mBq.kg^{-1} and maximum 80 mBq.kg^{-1} and average of all reported values was 59 ± 13 mBq.kg^{-1}. which is 4 times the UNSCEAR´s reference value of 15 mBq.kg^{-1}.

For ^{210}Pb in meat the minimum was 15 mBq.kg^{-1} and maximum 140 mBq.kg^{-1} and average of all reported values was 32 ±13 mBq.kg^{-1} which is the same as the UNSCEAR`s reference value of 80 mBq.kg^{-1}. For ^{210}Po in meat the minimum was 21 mBq.kg^{-1} and maximum 120 mBq.kg^{-1} and average of all reported values was 70 ± 39 mBq.kg^{-1}. which does not differ significantly from the UNSCEAR´s reference value of 60 mBq.kg^{-1}. The dietary intake of milk and meat products is 170 kg.a^{-1}. the highest of all food items of terrestrial origin (Unscear 2000).

Table 5. Activity concentration of ^{210}Pb and ^{210}Po in various milk and meat products Bq.kg^{-1} fresh weight

Country	^{210}Pb min mBq.kg^{-1}	^{210}Pb max mBq.kg^{-1}	^{210}Pb ave mBq.kg^{-1}	SD	^{210}Po min mBq.kg^{-1}	^{210}Po max mBq.kg^{-1}	^{210}Po ave mBq.kg^{-1}	SD	Reference
Milk products									
World wide	5	88	25	10	2	80	23	10	(Unscear 2000)
Syria			22.5				194		(Al-Masri, et al. 2004)
India. Kalpakkam					8	12	10	1	(Kannan, et al. 2001)
Poland	18	29	24	6	16	23	20	4	(Pietrzak-Flis, et al. 1997)
Slovenia	43	60	54	6	30	65	48	16	(Štrok & Smodiš 2010)
UK			35	1					(Smithbriggs & Bradley 1984)
Average			32	13			59	77	This work
Reference value			15				15		(Unscear 2000)
Meat products									
World wide	15	140	67	17	37	120	81	13	(Unscear 2000)
India. Kalpakkam					21	100	28	6	(Kannan, et al. 2001)
Poland	98	106	102	15	99	102	101	15	(Pietrzak-Flis, et al. 1997)
UK			74	1					(Smithbriggs & Bradley 1984)
Average			81	19			70	38	This work
Reference value			80				60		(Unscear 2000)

A few studies have been performed to quantitatively study the transfer of the natural radionuclides ^{210}Pb and ^{210}Po from fodder to milk (Amaral, et al. 1988; Staples, et al. 1994; Strok & Smodis 2012). In **Table 6** is given the average concentrations and Activity-concentration ratios fodder/milk of : ^{226}Ra. ^{210}Pb and ^{210}Po in fodder and milk sampled on Days 1. 15. and 30 of lactation of Holstein cows fed control corn silage (CSC). corn silage (CSR) and alfalfa (AR) grown on phosphate clay soil (Staples, et al. 1994).

Table 6. The average concentrations (Bq/kg dry matter) in fodder and milk, sampled on days 1. 15, and 30 of lactation of Holstein cows fed control corn silage (CSC). corn silage (CSR) and alfalfa (AR) grown on phosphatic clay soil and transfer factors fodder/milk of : ^{226}Ra. ^{210}Pb and ^{210}Po (Staples, et al. 1994).

Fodder	^{226}Ra Bq/kg d.m.	Sd.	^{210}Pb Bq/kg d.m.	Sd.	^{210}Po Bq/kg d.m.	Sd.
Control	0.15	0.04	0.52	0.22	1.26	0.15
Corn Silage	0.26	0.07	0.63	0.22	0.59	0.11
AlfaAlfa	2.44	0.18	1.04	0.22	1.59	0.18

Table 6. continued

Milk	^{226}Ra Bq/kg d.m.	Sd.	^{210}Pb Bq/kg d.m.	Sd.	^{210}Po Bq/kg d.m.	Sd.
Control	0.13	0.03	0.92	0.19	0.45	0.07
Corn Silage	0.22	0.03	1.38	0.19	0.3	0.07
AlfaAlfa	0.27	0.03	0.94	0.19	0.58	0.07

Acivity Concentration ratios (Bq/kg d.m.)/(Bq/kg d.m.) Milk / fodder	^{226}Ra ACR	Sd.	^{210}Pb ACR	Sd.	^{210}Po ACR	Sd.
Control	0.87	0.31	1.77	0.83	0.36	0.07
Corn Silage	0.85	0.26	2.19	0.82	0.51	0.15
AlfaAlfa	0.11	0.01	0.90	0.26	0.36	0.06

Table 7. The average concentrations (Bq/kg dry matter) in soil. forage and milk and Activity-cocentration ratios fodder/milk of : ^{226}Ra. and ^{210}Pb (Amaral, et al. 1988).

	^{226}Ra Bq/kg d.m.	Sd.	Min.	Max.	^{210}Pb Bq/kg d.m.	Sd.	Min.	Max.
Soil	135	1.6	68	262	104	1.7	60	253
Forage (grass)	8.2	3	2	57	26	2	9.4	83
Milk (fresh)	0.081	0.012	0.029	0.210	0.016	3	5	60

Activity concentration ratios (Bq/kg d.m.)/(Bq/kg d.m.)	^{226}Ra ACR	Sd.	^{210}Pb ACR	Sd.

Table 7. Continued

Forage (grass)/Soil	0.06	0.37		0.25	0.08
Milk/forage	9.88	0.37		0.62	0.20

Table 8 . The average concentrations (Bq/kg dry matter) in fodder

Fodder dry mattet	^{226}Ra Bq/kgdm	sd	^{210}Pb Bq/kgdm	sd	^{210}Po Bq/kgdm	sd	reference
Control	0.15	0.04	0.52	0.22	1.26	0.15	(Staples, et al. 1994)
Corn Silage	0.26	0.07	0.63	0.22	0.59	0.11	(Staples, et al. 1994)
AlfaAlfa	2.44	0.18	1.04	0.22	1.59	0.18	(Staples, et al. 1994)
Forage d.m.	8.20	3.00	26.00	2.00			(Amaral, et al. 1988)
Silage	1.28	0.08	14.7	0.9	22.6	0.85	(Strok & Smodis 2012)
Hay	0.60	0.04	14.4	0.9	4.54	0.19	(Strok & Smodis 2012)
Ave. Salage. Hay	0.94	0.47	14.6	0.2	13.57	12.77	(Strok & Smodis 2012)

Table 9. The average transfer factors Fm for ^{226}Ra. ^{210}Pb and ^{210}Po.to cow milk from various fodder with 16 kg intake per day.

Fm 16 kg fodder /day	226Ra day/litre		210Pb day/litre		210Po day/litre		reference
Control	6.90E-03	5.97E-03	1.41E-02	6.88E-03	2.84E-03	3.72E-03	(Staples, et al. 1994)
Corn Silage	6.74E-03	3.41E-03	1.74E-02	6.88E-03	4.05E-03	5.07E-03	(Staples, et al. 1994)
AlfaAlfa	8.81E-04	1.33E-03	7.20E-03	6.88E-03	2.90E-03	3.10E-03	(Staples, et al. 1994)
Forage d.m.	6.17E-04	2.50E-05	3.85E-05	9.38E-05			(Amaral, et al. 1988)
Silage	4.10E-04	5.18E-04	1.64E-04	7.70E-04	8.84E-05	1.78E-04	(Strok & Smodis 2012)
Hay	8.72E-04	1.04E-03	1.67E-04	7.70E-04	4.40E-04	7.96E-04	(Strok & Smodis 2012)
Ave. Silage. Hay	5.58E-04	8.64E-05	1.65E-04	3.27E-03	1.47E-04	1.18E-05	(Strok & Smodis 2012)
Average	2.42E-03	3.01E-03	5.61E-03	7.46E-03	1.75E-03	1.72E-03	This work
IAEA	5.10E-04	3.80E-04	3.30E-04	3.50E-04	2.30E-04	9.70E-05	(I.A.E.A. 2010)
Ave. /IAEA	5		17		8		

Table 10. The average Activity-Concentrations Ratios (Bq/kg dry matter) milk /fodder of ^{226}Ra. ^{210}Pb and ^{210}Po

Activity Concentration Ratios (Bq/kg d.m.)/(Bq/kg d.m.)	^{226}Ra		^{210}Pb		^{210}Po	
Milk / fodder	ACR	Sd.	ACR	Sd.	ACR	Sd.
Control	0.87	0.31	1.77	0.83	0.36	0.07
Corn Silage	0.85	0.26	2.19	0.82	0.51	0.15
AlfaAlfa	0.11	0.01	0.9	0.26	0.36	0.06
Grass	9.88	0.37	0.62	0.20		
Average	2.93	4.65	1.37	0.73	0.41	0.09

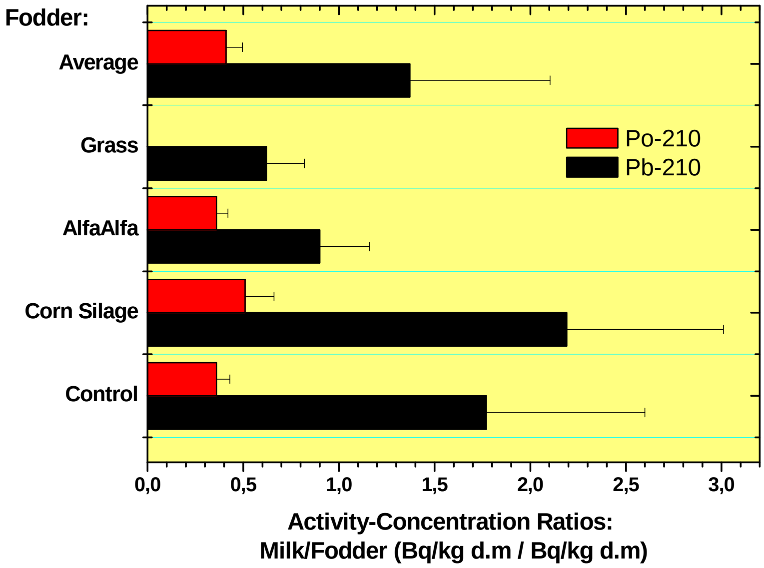


Figure 10 Activity Concentration ratios (Bq/kg d.m.)/(Bq/kg d.m.) between milk and different kinds of fodder

8.2 Transfer coefficient F_m of cow milk

The transfer coefficient F_m describes the fraction of the daily intake of radionuclides that is secreted per liter of milk.

$$F_m(d/l) = \frac{\text{Activity concentration of Milk}}{\text{Daily Radionuclide Intake}} = \frac{\left(Bq.litre^{-1}\right)}{\left(Bq.day^{-1}\right)} = \frac{day}{litre} = d.l^{-1}$$

The daily radionuclide intake = Activity concentration of fodder ($Bq.kg^{-1}$) × Daily Intake of fodder ($kg.d^{-1}$).

The estimation of this parameter requires data of the activity concentration in fresh milk and the activity concentrations in fresh fodder. Unfortunately most reported activity concentration for ^{210}Pb and ^{210}Po values are given for dry mass which limit the use of the transfer coefficient F_m.

A Fresh weight to dry matter ratio of 7.8 ± 0.8 (s.d) has been calculated from literature data (Yazgan, et al. 2010).

By assuming a daily food intake of 16 kg dry matter per day. From these studies the transfer coefficient F_m. that describes the fraction of the daily intake of radionuclides that is secreted per liter of milk has been estimated.

A few studies have been performed to quantitatively study the transfer of the natural radionuclides ^{210}Pb and ^{210}Po from fodder to milk (Amaral, et al. 1988; Staples, et al. 1994; Strok & Smodis 2012).

By assuming a daily food intake of 10 kg dry matter per day the transfer coefficient F_m. that describes the fraction of the daily intake of radionuclides that is secreted per litre of milk has been estimated from these studies.

The transfer coefficient F_m for ^{210}Pb thus obtained is 0.01 d.l^{-1} and for ^{210}Po 0.003 d.l^{-1}. These values are about 17 and 8 times higher than those estimated by IAEA for the elements respectively (I.A.E.A. 2009,2010).

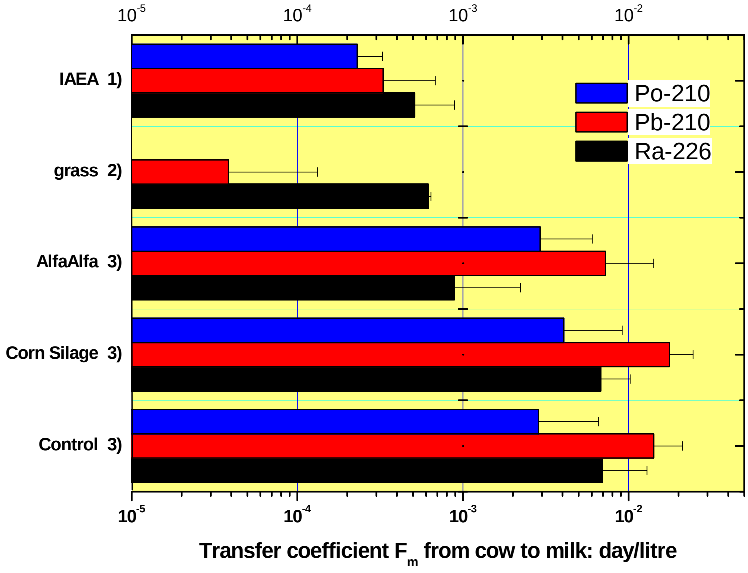


Figure 11 The transfer coefficient F_m describes the fraction of the daily intake of radionuclides that is secreted per liter of milk.

$$F_m(d/l) = \frac{\text{Activity concentration of Milk}}{\text{Daily Radionuclide Intake}} = \frac{\left(Bq.litre^{-1}\right)}{\left(Bq.day^{-1}\right)} = \frac{day}{litre} = d.l^{-1}$$

The daily radionuclide intake = Activity concentration of fodder (Bq.kg^{-1}) × Daily Intake of fodder (kg.d^{-1}).

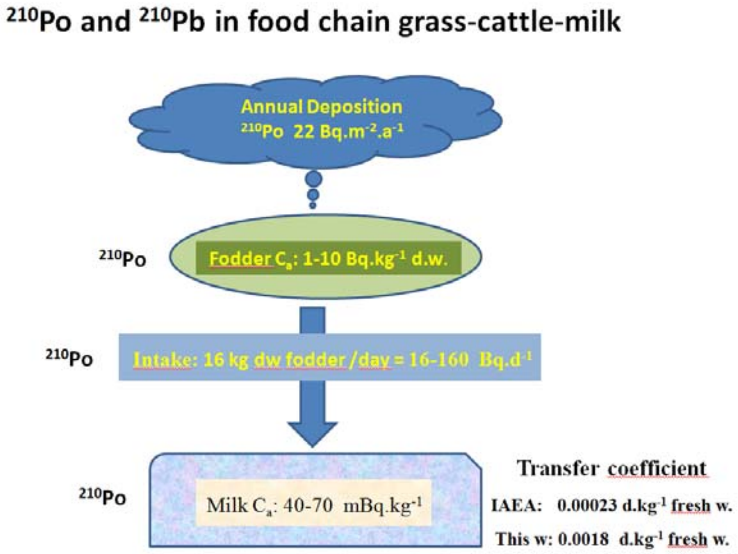


Figure 12. Transfer Model for ^{210}Po: Fodder (grass)–cattle -milk

8.2 ^{210}Po and ^{210}Pb transfer grass-meat

Activity concentrations of ^{210}Pb and ^{210}Po in meat products are given in **Table 11**

Table 11. Activity concentration of ^{210}Pb and ^{210}Po in meat products Bq.kg^{-1} fresh weight

Country	^{210}Pb min mBq.kg^{-1}	^{210}Pb max mBq.kg^{-1}	^{210}Pb ave mBq.kg^{-1}	SD	^{210}Po min mBq.kg^{-1}	^{210}Po max mBq.kg^{-1}	^{210}Po ave mBq.kg^{-1}	SD	Reference
Meat products									
World wide	15	140	67	17	37	120	81	13	(Unscear 2000)
India. Kalpakkam					21	100	28	6	(Kannan, et al. 2001)
Poland	98	106	102	15	99	102	101	15	(Pietrzak-Flis, et al. 1997)
UK			74	1					(Smithbriggs & Bradley 1984)
Average			81	19			70	38	This work
Reference value			80				60		(Unscear 2000)

The transfer of ^{210}Pb and ^{210}Pb from fodder to meat can be estimated by the activity concentration ratio (ACR) which is the equilibrium ratio between the radionuclide activity concentration in the fresh animal food product (Bq.kg^{-1} fresh weight) divided by the dry mass radionuclide activity concentration in the feedstuff ingested (Bq.kg^{-1} dm) (Howard, et al. 2009a).

$$ACR = \frac{\text{Activity concentration of fresh Meat}}{\text{Dry mass Activity concentration in food}} = \frac{\left(Bq.kg^{-1}\right)}{\left(Bq.kg^{-1}dm\right)}$$

The transfer coefficient F_{meat} describes the fraction of the daily intake of radionuclides that is accumulated in meat.

$$F_{meat}(d/l) = \frac{\text{Activity concentration of Meat}}{\text{Daily Radionuclide Intake}} = \frac{\left(Bq.kg^{-1}\right)}{\left(Bq.day^{-1}\right)} = \frac{day}{kg} = day.kg^{-1}$$

The daily radionuclide intake = Activity concentration of fodder ($Bq.kg^{-1}$) × Daily Intake of fodder ($kg.d^{-1}$).

A compilation of activity concentration ratios and transfer coefficients for Pb and Po are given in **Table 12** (Howard, et al. 2009b).

Table 12 A compilation of activity concentration ratios and transfer coefficients for Pb and Po (Howard, et al. 2009b).

Transfer factor $day.kg^{-1}$	Pb Average $day.kg^{-1}$	SD	min	max	Po Average $day.kg^{-1}$	SD	min	max
Cow meat	0.0009	0.0006	0.0002	0.0016				
Sheep meat	0.0071		0.004	0.01				
Poultry meat					2.4			
Poultry Egg					2.1			

Concentration Ratios	Pb Average	SD	min	max	Po Average	SD	min	max
Beef	0.077	0.180	0.0010	0.62	0.14	0.13	0.037	0.41
Sheep	0.012	0.004	0.0092	0.016				
Pork	0.066		0.23	1.1				

9. ^{210}Po and ^{210}Pb in Arctic food chains

9.1 Uptake of Atmospheric ^{210}Po deposition in mosses and Lichen

Mosses and Lichens are slow growing perennials that have high interception potentials for aerosols in precipitation. and therefore contain significantly higher ^{210}Po and ^{210}Pb concentrations than vascular plants and fungi. The median activity concentrations are in

Mosses 2000 Bq.kg^{-1} dry weight. Lichens 200 Bq.kg^{-1} dry weight. and in leafy plants 2-20 Bq.kg^{-1} dry weight.

Peat bogs are characterized of being covered by primitive plants that grows from the top while the dead bottom develops to peat. Peat is a heterogeneous mixture of partially humified remains of several groups of plants together with some inorganic material. Estimates of the ^{210}Po activity concentrations in Mosses. Lichens and Peat at different locations are given in **Table 13.**

The ^{210}Po/^{210}Pb activity ratio in lichens is typically equal to 1 as ^{210}Po approaches secular equilibrium with ^{210}Pb. The activity concentrations in lichens of *Cladonia family* which is grazed by reindeer and caribou. varies between 110 to 430 Bq.kg^{-1} dry weight with an average of 243±11 Bq.kg^{-1} dry weight (Persson, B. R. 1970a,1972; Persson, Bertil R. R. & Holm 2011; Persson, B. R. R., et al. 1974).

In a previous study the sorpition and retention of atmospheric deposition of ^{210}Pb in lichen was modelled (Persson, B. R. R., et al. 1974).

$$\frac{\delta C(z)}{\delta t} = K(z)\cdot\frac{\delta^2 C}{\delta t^2} + I_0\cdot f(z) - \lambda\cdot C + \kappa\cdot C - \theta\cdot C \ \ [\text{Bq.kg}^{-1}.\text{a}^{-1}]$$

$$\frac{\delta C(z)}{\delta t} = K(z)\cdot\frac{\delta^2 C}{\delta t^2} + I_0\cdot f(z) - \kappa_{eff}\cdot C \ [\text{Bq.kg}^{-1}.\text{a}^{-1}]$$

Table 13; Estimates of the ^{210}Po activity concentrations in Mosses. Lichens and Peat at different locations.

Type of plant	Location	^{210}Po min Bq.kg^{-1} dry wt	^{210}Po max Bq.kg^{-1} dry wt	^{210}Po average Bq.kg^{-1} dry wt	se	Ref
Mosses:						
Polytrichum	N. Sweden	300	960	630	330	(Holm, E., et al. 1981)
Sphagnum	N. Sweden	185	700	443	258	(Holm, E., et al. 1981)
Alectoria	N. Sweden	570	640	605	35	(Holm, E., et al. 1981)
Pterobryopsis tumida.	S. India			2724	13	(Karunakara, et al. 2000)
Grimmia pulvinata	W. Turkey.	1228	1228	1228		(Ugur, A., et al. 2003)
Lycopodium cernuum	Syria			1322		(Al-Masri, et al. 2005)
Funaria hygrometrica	Syria			2392		(Al-Masri, et al. 2005)
Lichens:						
Cladonia alpestris	Ctr. Sweden			250	30	(Persson, B. R. 1970a) (Persson, B. R. R., et al. 1974)
Cladonia arbuscula	Vågå Norway			140	27	(Skuterud, et al. 2005)
Cladonia arbuscula	E Namdal Norway			141	11	(Skuterud, et al. 2005)
Cladonia arbuscula	Dovrefjell Norway			138		(Brown, et al. 2011)

Cladonia stellaris	Dovrefjell Norway	30		(Brown, et al. 2011)

Table 13; continued

Peat:				
Sphagnum	N Sweden	192	37	(Malmer & Holm 1984)
Sphagnum	S Sweden	439	117	(Malmer & Holm 1984)

Where

C(z) = the activity concentration at z [Bq.kg^{-1}]
z = the mass depth [kg.m^{-2}]
K(z) = the diffusion koefficient. which varies with depth
I_0 = input-rate from the atmosphere [Bq.m-^{2}.a^{-1}]
f(z) = The deposition distribution function which multiplied by I_o. gives the increase of activity concentration in mass layer δz at the mass depth z
λ = physical decay constant [a^{-1}]
κ = rate constant for chemical fixation [a^{-1}]
θ = rate constant for biological degradation through growth and decomposition [a^{-1}]
k_{eff} = the effective rate-konstant for changing of the radioactivity concentration by first order kinetics [a^{-1}]

$$\left(\frac{\delta C(z)}{\delta t}\right)_{Air} + \left(\frac{\delta C(z)}{\delta t}\right)_{Lichen/Soil} = \kappa_{eff} \cdot C(z) \qquad [\mathrm{Bq.m^{-2}.a^{-1}}]$$

By assuming zero recycling contribution from soil in the top layer the lichen plant the effective rate-constant for changing of the radioactivity concentration by first order kinetics is 2.1 a^{-1} and in the deepest soil layer the the effective rate-konstant for changing of the radioactivity concentration by first order kinetics is 0.03 a.

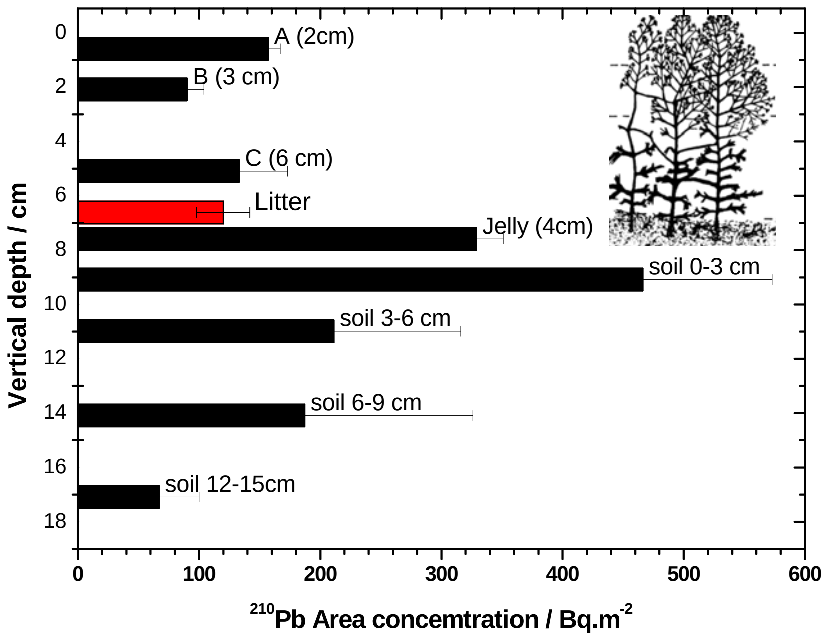


Figure 13 Distribution of 210Pb in the lichen-Jelly-soil profile

9. 1 ^{210}Po and ^{210}Pb in food chains lichens-reindeer

The activity concentrations of ^{210}Pb in reindeer meet varies between 200 and 1200 mBq.kg^{-1} fresh weight with an average of 500±100 mBq.kg^{-1} fresh weight. The activity concentrations of ^{210}Po in reindeer meet varies between 1700 and 13300 mBq.kg^{-1} fresh weight with an average of 7800±1300 mBq.kg^{-1} fresh weight. This maintains about 10 times higher ^{210}Po concentration in soft tissues of residences regularly consuming caribou or reindeer meet than the 80 mBq.kg fresh weight estimated for the general population (Hill 1966a; Persson, B. R. R. 1970b) .

In bone of reindeer the concentrations of ^{210}Pb in varies between 111 to 481 Bq.kg^{-1} fresh weight with an average of 282±48 Bq.kg^{-1} fresh weight (Holtzman 1966; Kauranen & Miettinen 1969; Persson, B. R. 1972; Persson, B. R. R. 1970b). The ^{210}Pb in bone of caribou varies between 160 to 870 Bq.kg^{-1} fresh weight with an average of 450±80 Bq.kg^{-1} fresh weight (Beasley & Palmer 1966; Blanchar & Moore 1970; Holtzman 1966; Macdonald, et al. 1996).

Results of ^{210}Pb and ^{210}Po activity concentrations in reindeer and caribou meet samples collected in various countries are summarized in **Table 14**.

Samples from Finnish Lapland showed activity concentrations of about 3 Bq/kg w.w. in autumn, 5 Bq/kg w.w. in winter and 12 Bq/kg w.w. in spring. For ^{210}Pb the annual average activity concentrations in reindeer meet was ten times lower, 0.22±0.04 Bq/kg ww , with less seasonal fluctuation.

This maintains a high ^{210}Po concentration in soft tissues of reindeer breeding Lapps (about 12 times higher than in southern Finns (P. Kauranen and J. K. Miettinen, 1969). This was shown to be true also for Alaskan residents consuming caribou or reindeer meat (Blanchar.Rl and J. B. Moore, 1970).

^{210}Po average activity concentrations in Swedish reindeer meet samples from animals slaughtered in March 1970 and 1971 was 10.6±0.6 Bq/kg ww. These animals, two years old, had grazed within the same reindeer breeding district where the lichen sampling area is situated (L.J.S. Mattsson and R.B.R. Persson, 1971; B. R. Persson, 1972; R.B.R. Persson, 1970, 1974)

In bone of reindeer from the island Novaya Zemlya in the arctic sea, the concentrations of the natural ^{210}Po and ^{210}Pb in bone of the recent reindeer (570 +/- 190 Bq/kg) is similar to that which was in the teeth of reindeer a hundred years ago (650-750 Bq/kg) and significantly higher than in the recent mainland reindeer from different regions (180-170 Bq/kg) (G. A. Klevezal et al., 2001). The ^{210}Pb in bone of caribou from 1989-74 was around 610 (490-800) Bq/kg (McDonald 1966).

This compares well with the level of 170 +/- 190 Bq/kg wet weight found in Finnish reindeer during 1964-67 (P. Kauranen and J. K. Miettinen, 1969) **.** By letting 14 volunteers consume 2.0 kg of caribou meat containing 9–40 Bq. kg w.w. And collecting urine and faeces the average GI absorption factor was estimated to 56 +/- 4% . This value agree well with the value of 50% recommended that by the ICRP (P. A. Thomas et al., 2001; ICRP, 1994)

A study of concentrations of Po-210 and Pb-210 in Norwegian reindeer during 2000-2003 focused on potential differences in concentrations of these nuclides in reindeer of different ages. Concentrations of ^{210}Po and ^{210}Pb in muscle and liver tissues were comparable to those reported for reindeer in other Nordic areas, with no significant difference in ^{210}Po and ^{210}Pb concentrations between adults and calves or between reindeer from the two different study areas. Mean ^{210}Po activity concentrations in muscle tissue, December 2000 at Vargå, were 23.7±3.7 and 35.5±9.2 Bq/ kg dry weight in calves and females (7 years) respectively, not significantly different from those in 2002. These value corresponds to 6 ± 1 and 9.2 ±2.3 Bq/ kg wet weight respectively, which is in agreement with the values recorded in Sweden 1970-71(ICRP, 1994; L.J.S. Mattsson and R.B.R. Persson, 1971; B. R. Persson, 1972; R.B.R. Persson, 1970, 1974)

The ^{210}Pb and ^{210}Po activity concentrations determined in muscle and liver tissue from Norway were similar to values reported from other Nordic areas (B. R. Persson, 1972; R.B.R. Persson, 1974; L. Skuterud et al., 2005; J. P. Gwynn et al., 2006; P. Kauranen and J. K. Miettinen, 1969; B.L. Tracy, 1993; P. Kauranen and J. K. Miettinen, 1967).

The transfer coefficient Ff (i.e., the amount of the animal's daily radionuclide intake that is transferred to 1 kg of the animal product at equilibrium) (Ward & Johnson 1986,1989) for ^{210}Po to reindeer meat could be estimated from the determined ^{210}Po concentrations in lichen and reindeer muscle and an estimated lichen intake during winter of about 1.2 kg d.m. per day (Gaare & Staaland 1994). This gave Ff values in the range 0.04-0.06 day/kg fresh w.

Table 14. Results of ^{210}Pb and ^{210}Po activity concentrations in reindeer and caribou meet samples collected in various countries.

Country	Species	Year of collection	210Pb meat Bq/kg ww		210Po meat Bq/kg ww		Po/Pb	Ref
Finland	reindeer	1961	0,6		1,7		3,0	Holzman 1966
Finland	**reindeer**	1964-7	0,2	0,1	5,3	1,9	**27,0**	**Kauranen 1969**
Finland	reindeer	1966	0,3					Kauranen 1970
Norway	reindeer	2000			6,0			Skuterud 2005
Norway	reindeer	2002			9,2			Skuterud 2005
Russia	reindeer	1967	1,4	0,2	3,0	0,4	2,1	Ramzaev 1967
Sweden	reindeer	1968			6,3	0,4		Persson 1972
Sweden	reindeer	1969			6,5	1,5		Persson 1972
Sweden	reindeer	1970			8,3	1,6		Persson 1972
Sweden	reindeer	1971			9,3			Persson 1972
Sweden	reindeer	1970	0,4	0,1	12,2	1,1	31,7	Mattsson o Persson 1974
Average	reindeer		0,6	0,2	6,8	1,0	16,0	
Alaska	caribou	1967	0,3	0,1	7,5	2,1	29,0	Holzman 1966
Alaska	caribou	1965	1,1	0,2	12,2	2,0	11,0	Beasly 1966
Canada	caribou	1967	0,4	0,1	11,0	4,0	27,0	Holtzman 1971
Canada	Caribou	1992	3,7	2,6	6,8	2,1	1,9	McDonald 1996
Canada	Caribou	1993	2,4	1,1	8,4	3,9	3,6	McDonald 1996
Canada	Caribou	1994	1,8	0,5	13,7	10,3	7,4	McDonald 1996
Canada	Caribou fw	1999	1,3	1,2	1,9	2,3		Thomas
Average	Caribou		1,6	0,5	8,8	1,5	13,3	

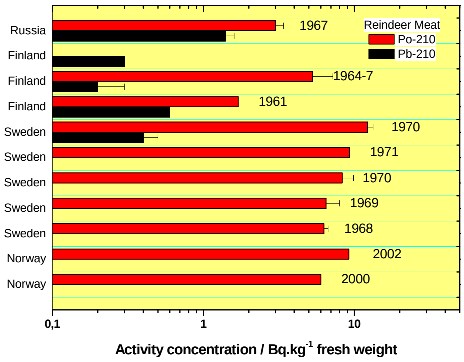


Figure 14a
^{210}Pb and ^{210}Po activity concentrations in reindeer meet samples collected in various countries. The average activity concentration of ^{210}Pb is 0.6 ±0.2 Bq.kg^{-1} and for ^{210}Po 6.8 ±1.0 Bq.kg^{-1}

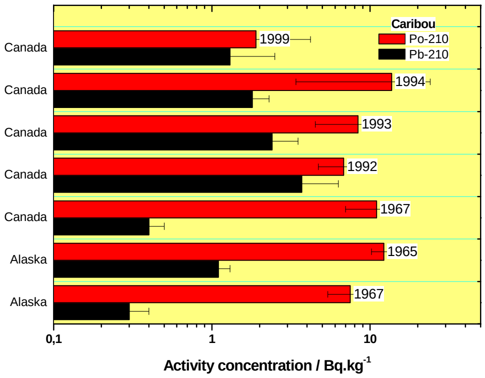


Figure 14b
^{210}Pb and ^{210}Po activity concentrations in caribou meet samples collected in various countries. The average activity concentration of ^{210}Pb is 1.6 ±0.5 Bq.kg^{-1} and for ^{210}Po 8.8 ±1.5 Bq.kg^{-1}

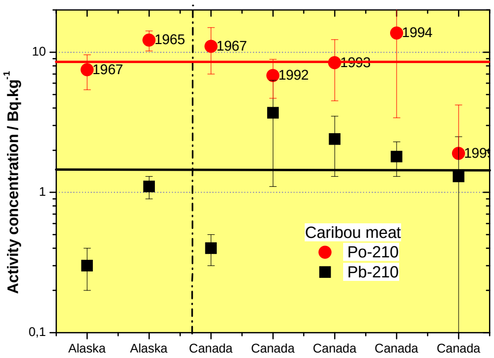


Figure 15a
^{210}Pb and ^{210}Po activity concentrations in caribou meet samples collected in various countries. The average activity concentration of ^{210}Pb is 1.6 ±0.5 Bq.kg^{-1} and for ^{210}Po 8.8 ±1.5 Bq.kg^{-1}

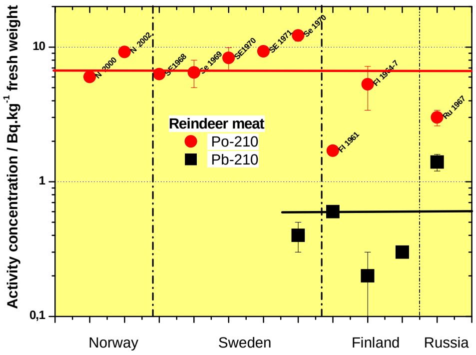


Figure 15b
^{210}Pb and ^{210}Po activity concentrations in reindeer meet samples collected in various countries. The average activity concentration of ^{210}Pb is 0.6 ±0.2 Bq.kg^{-1} and for ^{210}Po 6.8 ±1.0 Bq.kg^{-1}

Table 15.
Results of ^{210}Po activity transfer from lichen to reindeer meet samples collected in various countries.

Country	species	Ref	Year	210Po Meat Bq/kg fW Average	SD	210Po Lichen Bq/kg dm Average	SD	Lichen Intake kg dm /day	Activity intake Bq/day	Transfer coefficient day/kg fw	Activity ratio fw meat / dm lichen
Norway	reindeer	Skuterud 2005	2000	6		130	18	1,2	155	0,039	0,046
Norway	reindeer	Skuterud 2005	2002	9,2		139	18	1,2	166	0,055	0,066
Sweden	reindeer	Persson 1972	1968	6,3	0,4	352		1,2	422	0,015	0,018
Sweden	reindeer	Persson 1972	1969	6,5	1,5	115		1,2	138	0,047	0,056
Sweden	reindeer	Persson 1972	1970	8,3	1,6	241		1,2	289	0,029	0,035
Sweden	reindeer	Persson 1972	1971	9,3	1,8	235		1,2	282	0,033	0,039
Finland	reindeer	Holzman 1966	1961	1,7							
Finland	reindeer	Kauranen 1971	1964-67	6,0	2,0						
Finland	reindeer	Kauranen 1970	1966								
Finland	reindeer	Kauranen 1969	1961			283		1,2	339		
Finland	reindeer	Kauranen 1969	1964	4,8		235	24	1,2	282	0,017	0,020
Finland	reindeer	Kauranen 1969	1965	5,4		218					
Finland	reindeer	Kauranen 1969	1966	3,2		234	72	1,2	281	0,011	0,014
Finland	reindeer	Kauranen 1969	1967	7,7		216	34	1,2	259	0,030	0,036
Avverage				6.8						**0,031**	**0,037**
Sd										**0,015**	**0,018**
Se										**0,002**	**0,002**

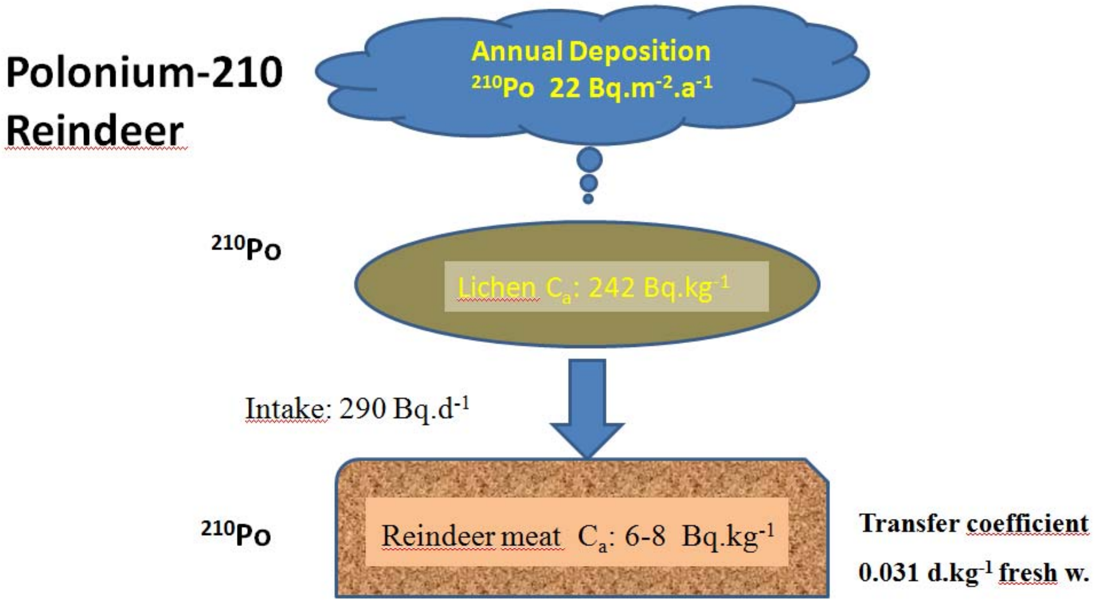


Figure 16
Transfer of ^{210}Po from deposition to lichen and reindeer

9.2 Transfer of 210Po from lichen to caribou

Results of ^{210}Pb and ^{210}Po activity concentrations in caribou meet samples collected in various countries are given in **Table 16** as well as the ^{210}Po activity transfer coefficient from lichen to caribou meet samples collected in various countries are compiled in **Table 16**. The average values of the transfer coefficients (0.035) and activity ratios (0.04) agree well with corresponding values for reindeer (0.031 and 0.037)

Table 16.
Results of ^{210}Po activity transfer from lichen to caribou meet samples collected in various countries. The Transfer coefficient is based on an lichen-intake if 1.2 kg dry mass per day.

Year of collection	210Po meat Bq/kg ww Average	SD	210Po Lichen Bq/kg dm Average	SD	Lichen Intake kg d^{-1} dry	Activity intake Bqd^{-1}	Transfer koefficient dkg^{-1} fresh	Ref
1967	7,5	2,1	281,2	84	1,2	337	0,022	(Holtzman 1966)
1965	12,6	1,6	551,3	165	1,2	662	0,019	(Beasley & Palmer 1966)
1967	11,0	4,0	270	81	1,2	324	0,034	(Holtzman & Ilcewicz 1971)
1992	6,8	2,1	155	47	1,2	186	0,037	(Mcdonald, et al. 1996)
1993	8,4	3,9	152	46	1,2	182	0,046	(Mcdonald, et al. 1996)
1994	13,7	10,3	148	44	1,2	178	0,077	(Mcdonald, et al. 1996)
1999	1,9	2,3	133	40	1,2	160	0,012	(Thomas, P. A., et al. 2001)
Average	8,9		242			290	0,035	This work
SD	4,0		150			180	0,022	
SE	1,5		57			68	0,008	

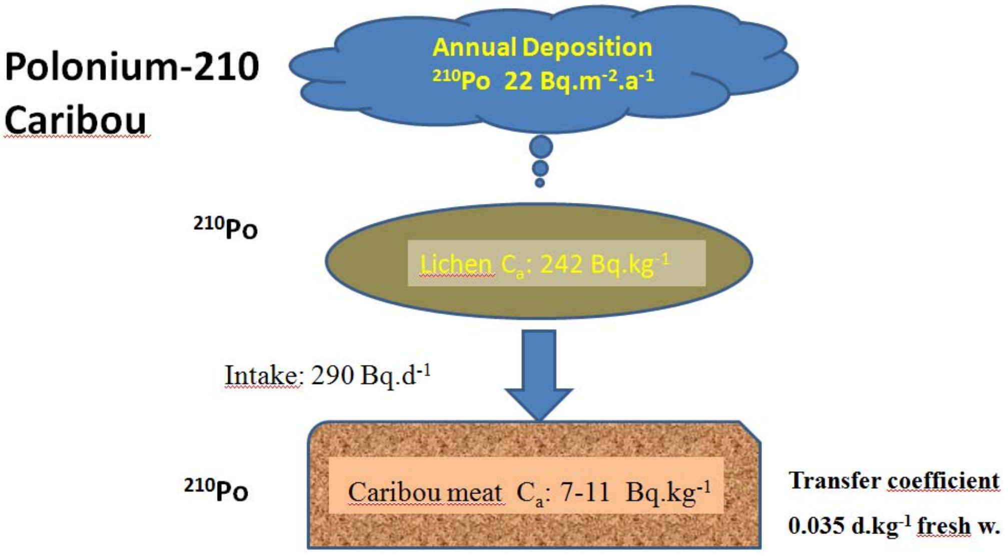


Figure 17
Transfer of ^{210}Po from deposition to lichen and caribou meat

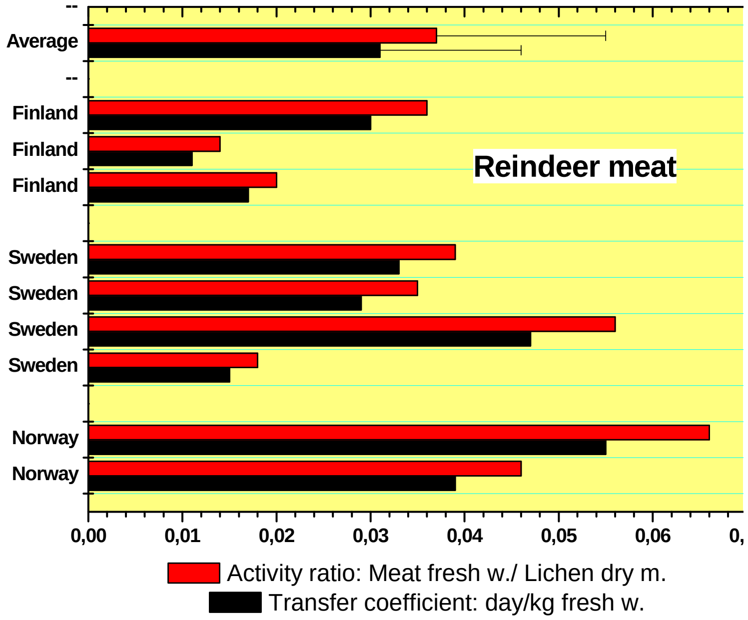


Figure 18 ^{210}Po activity transfer from lichen to reindeer meet samples collected in various countries.

9.3 Transfer of 210Pb and 210Po to Moose

Lead-210 (^{210}Pb), and polonium-210 (^{210}Po) was studied in tissues from 45 moose and 4 cattle were collected to assess the health of country foods near uranium mines in northern Saskatchewan. The results of ^{210}Pb and ^{210}Po activityconcentration and Concentation ratios meat/ rumen content in Moos and cattle are given in **Table 17** (Thomas, P., et al. 2005). In liver and muscle the activity concentration of ^{210}Po declined significantly with distance from tailings within the most active mining area, possibly influenced by nearby natural uranium outcrops. In some edible soft tissues of moose from this area the activity concentration of ^{210}Pb and ^{210}Po was was significantly increased compared to a control area.

But soil type and type of diet may influence concentrations as much as uranium mining activities. Thus the activity concentration of ^{210}Po in liver was similar to a second positive control area with mineral-rich shale hills. In cattle kidneys the activity concentration of ^{210}Po was higher than in all samples of moose.

Although radiological doses to moose in the main mining area were 2.6 times higher than doses to control moose or cattle, low moose intakes yielded lowhuman doses (0.0068 mSv y_1), a mere 0.3% of the dose from intake of caribou (2.4 mSv y_1), the dietary staple in the area. (Thomas, P., et al. 2005)

Table 17

Results of ^{210}Pb and ^{210}Po activity-concentration and Concentation ratios meat/ rumen content in Moos and cattle (Thomas, P., et al. 2005).

	210Pb meat Bq/kgww		210Po meat Bq/kgww		^{210}Pb CR fw		^{210}Po CR fw	
Moose								
Wollastone	3		1,6		0,45	0,28	0,47	0,26
Key Lake	0,7		0,95		0,11	0,06	0,24	0,21
Uranium city	0,6		6		0,13		1,5	
Medow	0,9		0,69		0,13	0,05	0,18	0,04
Average-se	**1,3**	**±0,6**	**2,3**	**±1,2**	**0,2**	**±0,1**	**0,6**	**±0,3**
Cattle	0,9		0,5		1,08	0,34	0,45	0,17

10. Model of the transfer of ^{210}Pb and ^{210}Po in an arctic food chain

A steady state model considering the fraction of annual or daily intake of ^{210}Pb or ^{210}Po in a specific step of the food chain concerned to be equal to the average elimination rate from this step has been applied to the food chain lichen reindeer and man (Persson, B. R. 1972),

$$\mathbf{R_i \cdot C_i \cdot f_a \approx k_a \cdot C_a \cdot M_a}$$

where

R_i = rate of mass transfer into the step of food chain in question (kg.a^{-1})
C_i = activity concentration of ingested material (Bq.kg^{-1})
I = ingested activity ($R_i \cdot C_i$) Bq/a or Bq/d
f_a = fraction of ingested activity I which is absorbed by the consumer, in the step of the food chain in question
C_a = activity concentration in the tissue of the consumer concerned (Bq.kg^{-1})
M_a = mass of the tissue or organ of the of the consumer concerned (kg)
A = Activity in the actual step ($M_a \cdot C_a$) Bq
k_a = fraction of the amount of activity in the actual step which is eliminated per unit of time (a^{-1}) or (d^{-1})

If in equilibrium condition the fraction of ingested activity in the step concerned which is retained can be assumed to be about the same as the activity eliminated from that step during the same period of time, the following relation arise:

$$\mathbf{R_i \cdot C_i \cdot f_a \approx M_a \cdot C_a \cdot k_a \;\; (Bq.a^{-1}) \text{ or } (Bq.d^{-1})}$$

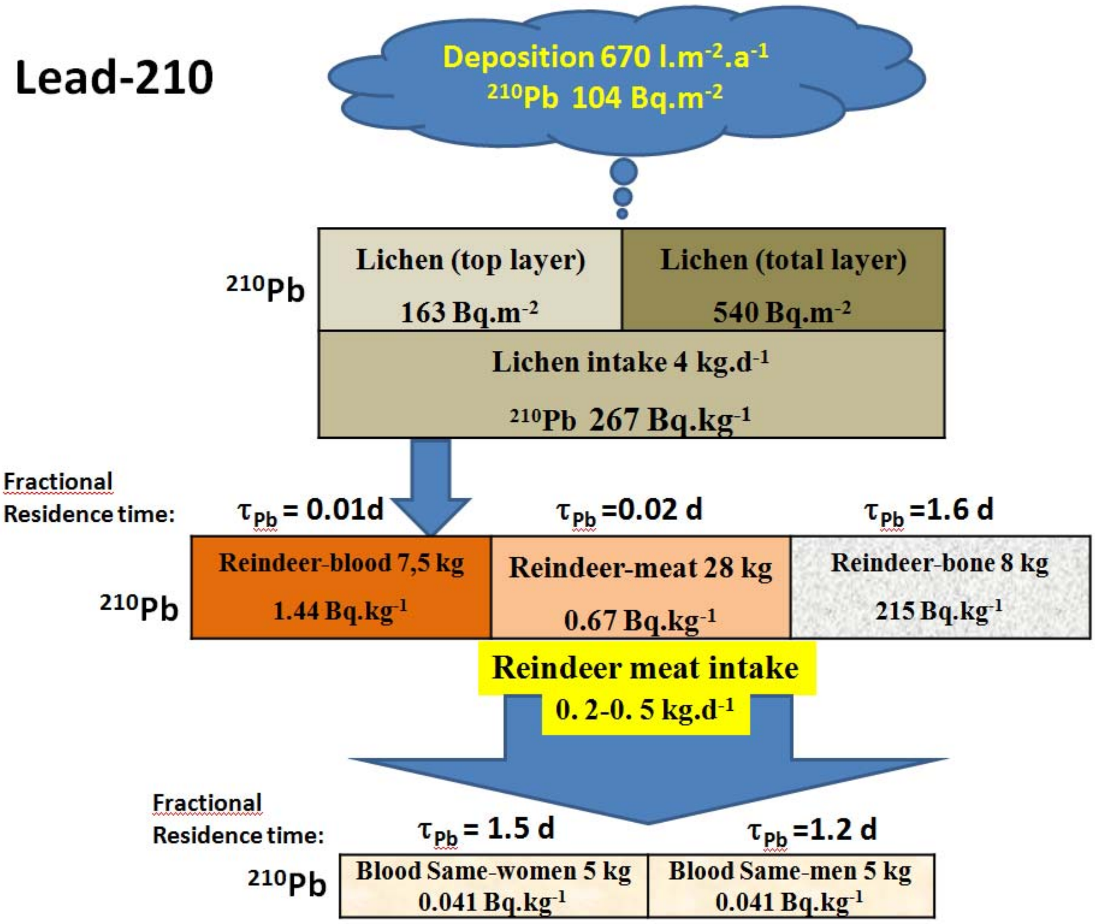
The ratio f_a / k_a characterize the “metabolic” behaviour of the actual step in the chain is called “fractional residence time τ”

$$\tau \approx f_a / k_a = (M_a \cdot C_a) / (R_i \cdot C_i) = A / I; \ (Bq/Bq.a^{-1}; Bq/Bq.d^{-1}); \text{(a) or (d)}$$

The ^{210}Po activity depends both on the ^{210}Po originating from ^{210}Pb predent and of the ingested ^{210}Po which is retained in the current step. The fractional residence tion of ^{210}Po it thus given by the expression:

$$\tau \approx (f_a + g)/ k_a = A_{Po} / I_{Po}; \ \text{(a) or (d)}$$

Where **g** is the ratio between ^{210}Po originating from ^{210}Pb present and the amount of ingested activity. In lichen and reindeer bone where the biological elimination of ^{210}Pb is relatively slow the value of **g** > **f**. But **g<<f** in reindeer blood and flesh due to rapid biological elimination,.



T **Figure 19a**
ransfer of Lead-210 and Polonium-210 in the food chain: Deposition→Lichen→Reindeer→man (blood).
R_i=The mass transfer or ingestion rate.
M_a= the total mass of the current step.
C_a=Activity concentration
Fractional residence time τ = A/I; for different steps

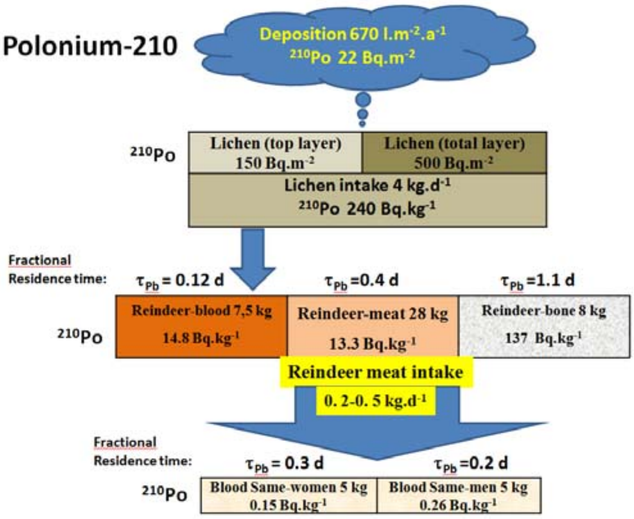


Figure 19b
Transfer of Lead-210 and Polonium-210 in the food chain:
Deposition→Lichen→Reindeer→man (blood).
R_i=The mass transfer or ingestion rate.
M_a= the total mass of the current step.
C_a=Activity concentration
Fractional residence time τ = A/I; for different steps

Table 18

Calculation of the fractional residence time τ = A/I; for different steps in the food chain: Deposition→Lichen→Reindeer→man (blood). R_i=The mass transfer or ingestion rate. M_a= the total mass of the current step. C_a=Activity concentration (Burton & Stewart 1960; Kauranen & Miettinen 1967,1969; Lidén & Gustafsson 1967; Rühling & Tyler 1972; Rühling & Tyler 1973).

Current step in the food chain	**Rate of mass Transfer** R_i	**Mass of the tissue or organ** M_a	**Activity Conc.** ^{210}**Pb** C_i	**Res. time** ^{210}**Pb** τ_{Pb}	**Activity Conc.** ^{210}**Po** C_i	**Res. time** ^{210}**Po** τ_{Po}
Deposition	670 $l.m^{-2}.a^{-1}$		104 $Bq.m^{-3}$		22 $Bq.m^{-3}$	
Lichen (top layer)			163 $Bq.m^{-2}$		150 $Bq.m^{-2}$	
Lichen (total layer)			540 $Bq.m^{-2}$		500 $Bq.m^{-2}$	
Lichen intake	4 $kg.d^{-1}$		267 $Bq.kg^{-1}$		240 $Bq.kg^{-1}$	
Reindeer-blood		7.5 kg	1.44 $Bq.kg^{-1}$	0.01 d	14.8 $Bq. kg^{-1}$	0.12 d
Reindeer-flesh		28 kg	0.67 $Bq.kg^{-1}$	0.02 d	13.3 $Bq. kg^{-1}$	0.4 d
Reindeer-bone		8 kg	215 $Bq.kg^{-1}$	1.6 d	137 $Bq. kg^{-1}$	1.1 d
Reindeer meat intake	0. 2-0. 5 kg. d^{-1}		0.67 $Bq.kg^{-1}$		13.3 $Bq. kg^{-1}$	
Blood Same-women		5 kg	0.041 $Bq.kg^{-1}$	1.5 d	0.15 $Bq. kg^{-1}$	0.3 d
Blood Same-men		5 kg	0.078 $Bq.kg^{-1}$	1.2 d	0.26 $Bq. kg^{-1}$	0.20 d

A general compartment model of the transfer of the radionuclide “R” in the terrestrial food chain "lichen reindeer-man" is outlined below with a system of exponential functions with short-term and long-term effective ecological half-lives (Golikov, et al. 2004). It´s mathematical description correspond to the difference equations used in the present work:

$$\frac{\partial C_{\mathrm{L}}(t)}{\partial t} = f_{\mathrm{L}} A(t) - C_{\mathrm{L}}(t)(\lambda_{\mathrm{L}} + \lambda_r)$$

$$\frac{\partial C_{\mathrm{R}}(t)}{\partial t} = a_{\mathrm{L,R}} C_{\mathrm{L}}(t) - C_{\mathrm{R}}(t)(\lambda_{\mathrm{R}} + \lambda_{\mathrm{r}})$$

$$\frac{\partial C_{\mathrm{M}}(t)}{\partial t} = a_{\mathrm{R,M}} C_{\mathrm{R}}(t) - C_{\mathrm{M}}(t)(\lambda_{\mathrm{M}} + \lambda_{\mathrm{r}})$$

where

A(t)	is the annual rate of radionuclide deposition (kBq.m^{-2}.a^{-1});
f_L	is the annual mass interception fraction of radionuclide deposition on lichen (m^{2}.a.kg^{-1}); i.e Ratio of activity concentration (Bq.kg^{-1}) to annual deposition (Bq.m^{-2}.a^{-1})
C_L(t),	is the radionuclide activity concentration lichen (Bq.kg^{-1}) at time t after deposition
C_R(t),	is the radionuclide activity concentration reindeer meat (Bq.kg^{-1}) at time t after deposition
C_M(t)	is the radionuclide activity concentration in, the body of reindeer-breeders (Bq.kg^{-1}), at time t after deposition respectively, at time t after deposition (kBq.kg^{-1})
a_{L-R}	is the lichen consumption rate by reindeer kg.a^{-1}.per kg body weight
a_{R-M}	is the reindeermeat consumption rate by reindeer herders kg.a^{-1}.per kg body weight
λ_r	is the decay constant of radionuclide R (a^{-1}).

Radiation Absorbed dose to man from intake of ^{210}Po

According to the model recommended by the International Commission on Radiological Protection (ICRP). about 10–50% of ingested ^{210}Po is absorbed by the intestine into the bloodstream and deposits mostly in the liver, kidneys, spleen, red bone marrow (Icrp 1993). To distinguish between ingestion of the organic and inorganic forms of polonium, ICRP recommended that 10% of ingested ^{210}Po material of workers was in a form with fast or moderate absorption to the blood. But for members of the public, 50% of ingested ^{210}Po material is of a form with slow absorption to the blood. For intake by inhalation, ICRP recommended that 10% is absorbed by the blood for both workers and 1% for members of the public (Icrp 1994,1996).

The committed effective dose by dietary intake of and ^{210}Po for adult members of the public recommended by ICRP is 1.2 µSv.Bq^{-1} respectively, considering a transfer coefficient of 50% for ingestion of ^{210}Po (Hunt & Rumney 2007; Icrp 1993). That is the highest value for any of the natural radionuclides ^{3}H, ^{7}Be, ^{14}C, ^{23}Na, ^{40}K, ^{238}U(series); ^{232}Th(series) or ^{235}U(series) (Unscear 2000). In **Table 19** is given the minimum and maximum annual dose equivalent of ^{210}Po from drinking water and various food products estimated in this work compared with the reference levels given by UNSCEAR displayed in the most right column of **Table 19** (Unscear 2000).

For inhalation of ^{210}Po aerosols, assuming 10% absorption to the blood, the recommended effective dose coefficient is 3.3 µSv.Bq^{-1} (Icrp 1996). The committed effective dose equivalent by breathing inhalation of natural ^{210}Po aerosols (50 µBq.m^{-3}) has been estimated to be about 1.2 µSv.a^{-1} (Unscear 2000).

The average median daily dietary intakes of ^{210}Po for the adult world population from terrestrial products is estimated to be in the range of 20-300 Bq.a^{-1} with an average of 80±60 Bq.a^{-1}. That corresponds to a committed annual effective dose of 91±70 µSv.a^{-1} for ^{210}Po from terrestrial products. The dietary intakes of ^{210}Po and ^{210}Pb from vegetarian food, however, was estimated to correspond to annual effective doses of only about 30 µSv.a^{-1} and 10 µSv.a^{-1}. respectively (Persson, Bertil R. R. & Holm 2011).

Since the activity concentrations of ^{210}Po in seafood are significantly higher than in terrestrial food products. the world average effective doses estimated for ^{210}Po from marine products is higher (260±120 µSv.a^{-1}). The effective dose to populations consuming a lot of seafood is estimated to be up to 4-8 times higher than this world average (Carvalho 1995; Sugiyama, et al. 2009).

Table 19

The minimum and maximum annual dose equivalent of ^{210}Po from drinking water and various food products estimated in this work compared with the reference levels given by UNSCEAR2000 in the most right column(Unscear 2000).

	^{210}Po min µSv.a^{-1}	^{210}Po max µSv.a^{-1}	^{210}Po Average µSv.a^{-1}	SE	210Po Reference level (Unscear 2000)
Drinking water	0,02	3900	13	23	3
Cereals	15	152	40	13	10
Leafy vegetables	2	150	23	14	7
Root vegetables and fruit	7	39	17	4	8
Milk products	0	10	7	4	2
Meat products	1	7	4	1	4
Terrestrial Products	**25**	**358**	**91**	**70**	**31**
Marine products	1	2160	261	122	36
Total	26	6418	352	141	70

Table 20
Estimated annual activity intake and annual dose-equivalent of ^{210}Pb and ^{210}Po for various type of diet

	^{210}Pb	^{210}Po
World average:		
Annual intake (Bq.a^{-1})	40	58
Annual DE (μSv.a^{-1})	30	70
Vegetarians intake:		
Annual intake (Bq.a^{-1})	15	26
Annual DE (μSv.a^{-1})	10	30
Marine Food Intake		
Annual DE (μSv.a^{-1})	321	467
Annual DE (μSv.a^{-1})	222	561
Reindeer Meat Intake:		
Annual intake (Bq.a^{-1})	90	1700
Annual DE (μSv.a^{-1})	60	2000

References

Akyil S., Aslani, M. A. A., Gurboga, G., Aytas, S., and Eral, M., (2002). Activity concentration of radium-226 in agricultural soils, *Journal of Radioanalytical and Nuclear Chemistry*, Vol. 254, pp. 9–14,

Akyil S., Gurboga, G., Aslani, M. A. A., and Aytas, S., (2008). Vertical distribution of Ra-226 and Po-210 in agricultural soils in Buyuk Menderes Basin, Turkey, *Journal of Hazardous Materials*, Vol. 157, pp. 328-334, 0304-3894

Al-Masri M. S., Al-Akel, B., Nashawani, A., Amin, Y., Khalifa, K. H., and Al-Ain, F., (2008). Transfer of K-40, U-238, Pb-210, and Po-210 from soil to plant in various locations in south of Syria, *Journal of Environmental Radioactivity*, Vol. 99, pp. 322-331, 0265-931X

Al-Masri M. S., Al-Hamwi, A., Eadan, Z., and Amin, Y., (2010). Transfer factors of Polonium from soil to parsley and mint, *Journal of Environmental Radioactivity*, Vol. 101, pp. 1038-1042, 0265-931X

Al-Masri M. S., Mamish, S., Al-Haleem, M. A., and Al-Shamali, K., (2005). Lycopodium cernuum and Funaria hygrometrica as deposition indicators for radionuclides and trace metals, *Journal of Radioanalytical and Nuclear Chemistry*, Vol. 266, pp. 49-55, 0236-5731

Al-Masri M. S., Mukallati, H., Al-Hamwi, A., Khalili, H., Hassan, M., Assaf, H., Amin, Y., and Nashawati, A., (2004). Natural radionuclides in Syrian diet and their daily intake, *Journal of Radioanalytical and Nuclear Chemistry*, Vol. 260, pp. 405-412, 0236-5731

Amaral E. C. S., Carvalho, Z. L., and Godoy, J. M., (1988). Transfer of Ra-226 and Pb-210 to forage and milk in a Brazilian high natural radioactivity region, *Radiation Protection Dosimetry*, Vol. 24, pp. 119-121, 0144-8420

Appleby P. G., (2008). Three decades of dating recent sediments by fallout radionuclides: a review, *Holocene*, Vol. 18, pp. 83-93, 0959-6836

Baltakmens T., (1969). Lead-210 in New Zealand milk., *Aust. 5. Sci.*, Vol. 31, pp. 111-114,

Baskaran M., (2011). Po-210 and Pb-210 as atmospheric tracers and global atmospheric Pb-210 fallout: a Review, *Journal of Environmental Radioactivity*, Vol. 102, pp. 500-513, 0265-931X

Beasley T. M., and Palmer, H. E., (1966). Lead-210 and Polonium-210 in Biological Samples from Alaska, *Science*, Vol. 152, pp. 1062-1064, 00368075

Benmansour M., Mabit, L., Nouira, A., Moussadek, R., Bouksirate, H., Duchemin, M., and Benkdad, A., (2013). Assessment of soil erosion and deposition rates in a Moroccan agricultural field using fallout Cs-137 and Pb-210(ex), *Journal of Environmental Radioactivity*, Vol. 115, pp. 97-106, 0265-931X

Blanchar R. L., and Moore, J. B., (1970). Pb-210 and Po-210 in tissues of some alaskan residents as related to consumption of caribou or reindeer meat, *Health Physics*, Vol. 18, pp. 127-&, 0017-9078

Blanchar.R.L, and Moore, J. B., (1969). 210Pb and 210Po in tissues of Alaskan Eskimo, *Health Physics*, Vol. 17, pp. 387-&, 0017-9078

Bolca M., Sac, M. M., Cokuysal, B., Karali, T., and Ekdal, E., (2007). Radioactivity in soils and various foodstuffs from the Gediz River Basin of Turkey, *Radiation Measurements*, Vol. 42, pp. 263-270, 1350-4487

Bonotto D. M., and Bueno, T. O., (2008). The natural radioactivity in Guarani aquifer groundwater, Brazil, *Applied Radiation and Isotopes*, Vol. 66, pp. 1507-1522, 0969-8043

Brown J. E., Gjelsvik, R., Roos, P., Kalas, J. A., Outola, I., and Holm, E., (2011). Levels and transfer of (210)Po and (210)Pb in Nordic terrestrial ecosystems, *Journal of Environmental Radioactivity*, Vol. 102, pp. 430-437, 0265-931X

Burton W. M., and Stewart, N. G., (1960). Use of long-lived natural radioactivity as an atmospheric tracer, *Nature*, Vol. 186, pp. 584-589, 0028-0836

Carvalho F. P., (1995). Po-210 and Pb-210 Intake by The Portuguese Population - The Contribution of Seafood in the Dietary-Intake of Po-210 and Pb-210. , *Health Physics*, Vol. 69, pp. 469-480, 0017-9078

Curie P., and Curie, M., (1898). Radiations from Compounds of Uranium and of Thorium, *Comptes Rendus*, Vol. 126,

Desideri D., Meli, M. A., Feduzi, L., and Roselli, C., (2007). Po-210 and Pb-210 inhalation by cigarette smoking in Italy, *Health Physics*, Vol. 92, pp. 58-63, 0017-9078

Dowdall M., and O'dea, J., (1999). Comparison of point estimation techniques in the spatial analysis of radium-226 and potassium-40 in soil, , *Environ. Monit.Assess.*, Vol. 50, pp. 191–209,

Ekdal E., Karali, I., and Sac, M. M., (2006). Po-210 and Pb-210 in soils and vegetables in Kucuk Menderes basin of Turkey, *Radiation Measurements*, Vol. 41, pp. 72-77, 1350-4487

Eldaoushy F., and Garciatenorio, R., (1988). Speciation of Pb-210/Po-210 in aquatic systems and their *Science of the Total Environment*, Vol. 69, pp. 191-209, 0048-9697

Gaare E., and Staaland, H., (1994). In: *Pathways of fallout radiocaesium via reindeer to man*, H. Dahlgaard,0166-1116

0-444-81617-8 0166-1116

0-444-81617-8).pp. 303-334 ^

Golikov V., Logacheva, I., Bruk, G., Shutov, V., Balonov, M., Strand, P., Borghuis, S., Howard, B., and Wright, S., (2004). Modelling of long-term behaviour of caesium and strontium radionuclides in the Arctic environment and human exposure, *Journal of Environmental Radioactivity*, Vol. 74, pp. 159-169, 0265-931X

Hasanen E., (1977). Dating of sediments, based on ^{210}Po measurements, *Radiochem. Radianal. Lett.*, Vol. 31, pp. 207,

Hill C. R., (1960). Lead-210 and Polonium-210 in grass., *Nature*, Vol. 187, pp. 211-212, 0028-0836

Hill C. R., (1965). Polonium-210 in man, *Nature*, Vol. 208, pp. 423-&, 0028-0836

Hill C. R., (1966a). Polonium-210 Content of Human Tissues in Relation to Dietary Habit, *Science*, Vol. 152, pp. 1261-1262, 00368075

Hill C. R., (1966b). *Routes of uptake of 210Po into human tissues.*(Academic Press, Stockholm).

Holm E., and Garcia-Tenorio, R., (2011). Journal of Environmental Radioactivity special issue: international topical conference on Po and radioactive Pb isotopes, *Journal of Environmental Radioactivity*, Vol. 102, pp. 413-414, 0265-931X

Holm E., Samuelsson, C., and Persson, R. B. R., (1981). *Natural Radioactivity around a prospected Uranium mining site*(A Halsted Press book., Bhabha Atomic Research Centre, Bombay 400 085, India).

Holtzman R. B., (1963). MEASUREMENT OF THE NATURAL CONTENTS OF RaD (Pb210) and RaF (Po210) IN HUMAN BONEESTIMATES OF WHOLE-BODY BURDENS*, *Health Phys.*, Vol. 9, pp. 385-400,

Holtzman R. B., (1966). Natural levels of Lead-210 Polonium-210 and Radium-226 in humans and biota of Arctic, *Nature*, Vol. 210, pp. 1094-&, 0028-0836

Holtzman R. B., (1967). The determination of Pb-210 and Po-210 in biological and environmental materials, *Journal of Radioanalytical and Nuclear Chemistry-Articles*, Vol. 115, pp. 59-70, 0236-5731

Holtzman R. B., and Ilcewicz, F. H., (1971). Renal excretion rates of Pb-210 and Po-210 of northern Canadians, *Health Physics*, Vol. 21, pp. 61-&, 0017-9078

Howard B. J., Beresford, N. A., Barnett, C. L., and Fesenko, S., (2009a). Quantifying the transfer of radionuclides to food products from domestic farm animals, *Journal of Environmental Radioactivity*, Vol. 100, pp. 767-773, 0265-931X

Howard B. J., Beresford, N. A., Barnett, C. L., and Fesenko, S., (2009b). Radionuclide transfer to animal products: revised recommended transfer coefficient values, *Journal of Environmental Radioactivity*, Vol. 100, pp. 263-273, 0265-931X

Hunt G. J., and Rumney, H. S., (2007). The human alimentary tract transfer and body retention of environmental polonium-210, *Journal of Radiological Protection*, Vol. 27, pp. 405-426, 0952-4746

I.A.E.A., (2009). *Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, IAEA-TECDOC-1616*International Atomic Energy Agency (IAEA), VIENNA,, 978–92–0–104509–6, ,).

I.A.E.A., (2010). *Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Technical reports series, no. 472* International Atomic Energy Agency (IAEA), Vienna, ISSN 0074–1914).

Iaea, (1994). *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments. Technical Report Series 364.*IAEA (International Atomic Energy Agency), Vienna).

Ibrahim S. A., and Whicker, F. W., (1987). Plant accumulation and plant/soil concentration ratios of ^{210}Pb and ^{210}Po at various sites within a uranium mining and milling operation. , *Environmental and Experimental Botany*, Vol. 27, pp. 203-213,

Icrp, (1993). Age-dependent doses to members of the public from intake of radionuclides: Part 2 ingestion dose coefficients., *Annals of ICRP*, Vol. 23,

Icrp, (1994). *Limits for Intakes of Radionuclides by Workers*96-97 Pergamon Press, Oxford).

Icrp, (1996). Age-dependent doses to members of the public from intake of radionuclides: Part 5 compilation of ingestion and inhalation dose coefficients., *Annals of ICRP*, Vol. 26, Iyengar M. A. R., Rajan, M. P., Ganapathy, S., and Kamath, P. R., (1980). *Sources of natural radiation exposure in a low monazite environment.*(Oak Ridge TN: Technical Information Centre, US Department of Energy., Houston, 1978,).

Jaworowski Z., (1969). Radioactive lead in the environment and in the human body, *Atomic Energy Rev.*, Vol. 7, pp. 3-45,

Jia G., and Torri, G., (2007). Estimation of radiation doses to members of the public in Italy from intakes of some important naturally occurring radionuclides (^{238}U, ^{234}U, ^{235}U, ^{226}Ra, ^{228}Ra, ^{224}Ra and ^{210}Po) in drinking water, *Applied Radiation and Isotopes*, Vol. 65, pp. 849–857,

Kannan V., Iyengar, M. A. R., and Ramesh, R., (2001). Dose estimates to the public from 210Po ingestion via dietary sources at Kalpakkam (India), *Applied Radiation and Isotopes*, Vol. 54, pp. 663-674, 0969-8043

Karunakara N., Avadhani, D. N., Mahesh, H. M., Somashekarappa, H. M., Narayana, Y., and Siddappa, K., (2000). Distribution and enrichment of Po-210 in the environment of Kaiga in South India, *Journal of Environmental Radioactivity*, Vol. 51, pp. 349-362, 0265-931X

Kauranen P., and Miettinen, J. K., (1967). In: *^{210}Po and ^{210}Pb in environmental smples in Finland*, B. Åberg, &Hungate, F. P. Pergamon Press, Oxford Stockholm 25-29 April1966).pp. ^

Kauranen P., and Miettinen, J. K., (1969). ^{210}Po and ^{210}Pb in Artic Food Chain and Natural radiation exposure of Lapps, *Health Physics*, Vol. 16, pp. 287-295, 0017-9078

Kilibard.M, Petrovic, D., Panov, D., and Djuric, D., (1966). CONTAMINATION WITH POLONIUM-210 URANIUM AND RADIUM-226 DUE TO SMOKING, *Health Physics*, Vol. 12, pp. 1808-&, 0017-9078

Lidén K., and Gustafsson, M., (1967). In: *Relationships and annual variation of 137Cs in lichen, reideer and man in northern Sweden 1961-1965.*, B. Åberg, &Hungate, F. P. Pergamon Press Oxford).pp. 193-208 ^

Macdonald C. R., Ewing, L. L., Elkin, B. T., and Wiewel, A. M., (1996). Regional variation in radionuclide concentrations and radiation dose in caribou (Rangifer tarandus) in the Canadian Arctic; 1992-94, *Science of the Total Environment*, Vol. 182, pp. 53-73, 0048-9697

Malmer N., and Holm, E., (1984). Variation in the C/N-quotient of peat in relation to decomposition rate and age determination with ^{210}Pb, *OIKUS*, Vol. 43, pp. 171-182,

Mcdonald P., Baxter, M. S., and Scott, E. M., (1996). Technological enhancement of natural radionuclides in the marine environment, *Journal of Environmental Radioactivity*, Vol. 32, pp. 67-90, 0265-931X

Myrick T. E., Berven, B. A., and Haywood, F. F., (1983). Determination of concentrations of selected radionuclides in surface soil in the United States,, *Health Phys.*, Vol. 45 pp. 631–642,

Nagaiah N., Malini, S., Paramesh, L., Venkataramaiah, P., and Raghavayya, M., (1995). *Dependence of Po-210 to Ra-226 ratio on soil characteristics.* (Anna University., Chennai).

Osborne R. V., (1963). LEAD-210 AND POLONIUM-210 IN HUMAN TISSUES, *Nature*, Vol. 199, pp. 295-&, 0028-0836

Parfenov Y. D., (1974). Polonium-210 in Environment and in Human Organism., *Atomic Energy Review*, Vol. 12, pp. 75-143, 0004-7112

Peirson D. H., Cambray, R. S., and Spicer, G. S., (1966). LEAD-210 AND POLONIUM-210 IN ATMOSPHERE, *Tellus*, Vol. 18, pp. 427-&, 0040-2826

Persson B. R., (1970a). Pb-210 atmospheric deposition in lichen-carpets in northern Sweden during 1961-1969, *Tellus*, Vol. 22, pp. 564-&, 0040-2826

Persson B. R., (1972). *Lead-210, Polonium-210, and stable Lead in the Food-Chain lichen Reindeer and man*(Rice University , Houston, Texas, USA).

Persson B. R. R., (1970b). *^{55}Fe, ^{90}Sr, ^{134}Cs, ^{137}Cs and ^{210}Pb in the Biosphere. Radiological Health Aspects of the Environmental Contamination from Radioactive Materials in Northern Sweden*(Lund University, Lund).

Persson B. R. R., and Holm, E., (2011). Polonium-210 and lead-210 in the terrestrial environment: a historical review, *Journal of Environmental Radioactivity*, Vol. 102, pp. 420-429, 0265-931X

Persson B. R. R., and Holm, E., (2013). ^{7}Be. ^{210}Pb. and ^{210}Po in the surface air from the Arctic to Antarctica, *INCOPoPb-2013 conference, Mangalore University*, Vol.,

Persson B. R. R., Holm, E., and Lidén, K., (1974). Radiolead (Pb-210) and stable lead in lichen Cladonia-alpestris, *Oikos*, Vol. 25, pp. 140-147, 0030-1299

Pietrzak-Flis Z., and Skowronskasmolak, M., (1995). Transfer of Pb-210 and Po-210 to plants via root-system and above ground interception, *Science of the Total Environment*, Vol. 162, pp. 139-147, 0048-9697

Pietrzak-Flis Z., Suplinska, M. M., and Rosiak, L., (1997). The dietary intake of U-238, U-234, Th-230, Th-232, Th-228 and Ra-226 from food and drinking water by inhabitants of the Walbrzych region, *Journal of Radioanalytical and Nuclear Chemistry*, Vol. 222, pp. 189-193, 0236-5731

Piliposian G. T., and Appleby, P. G., (2003). A simple model of the origin and transport of Rn-222 and Pb-210 in the atmosphere, *Continuum Mechanics and Thermodynamics*, Vol. 15, pp. 503-518, 0935-1175

Radhakrishna A. P., Somashekarappa, H. M., Narayana, Y., and Siddappa, K., (1993). A new natural background-radiation area on the southwest coast of India, *Health Physics*, Vol. 65, pp. 390-395, 0017-9078

Roselli C., Desideri, D., and Meli, M. A., (2009). Radiological characterization of phosphate fertilizers: Comparison between alpha and gamma spectrometry, *Microchemical Journal*, Vol. 91, pp. 181-186, 0026-265X

Ruberu S. R., Liu, Y. G., and Perera, S. K., (2007). Occurrence and distribution of Pb-210 and Po-210 in selected California groundwater wells, *Health Physics*, Vol. 92, pp. 432-441, 0017-9078

Rühling A., and Tyler, G., (1972). *Fallout of heavy metals over Scandinavia (in Swedish),*(Lund University, Dept of Ecological Botany Report, Lund, Sweden).

Rühling A., and Tyler, G., (1973). Heavy metal pollution and decomposition of spruce needle litter., *Oikos*, Vol. 24, pp. 402-416,

Santos P. L., Gouvea, R. C., and Dutra, I. R., (1993). Pb-210 in vegetables and soils from an area of high natural radioactivity in Brazil., *Science of the Total Environment*, Vol. 138, pp. 37-46, 0048-9697

Santos R. C., Gouvea, I. R., Dutta, V. A., and Gouvea, R. C., (1990). Accumulation of Po-210 in foodstufs cultivated in farms around the Brazilian mining and milling facilities on Pocos de Caldas Plateau,, *J. Environ. Radioac.* , Vol. 11, pp. 141–149.,

Saueia C. H. R., and Mazzilli, B. P., (2006). Distribution of natural radionuclides in the production and use of phosphate fertilizers in Brazil, *Journal of Environmental Radioactivity*, Vol. 89, pp. 229-239, 0265-931X

Schuttelkopf H., and Kiefer, H., (1982). In: *The radium-226 and polonium-210 concentration of the Black Forest,* , K. G. Vohra, et al. Wiley Eastern, New Delhi, Bombay)).pp. 194-200 ^

Seiler R. L., (2011). Po-210 in Nevada Groundwater and Its Relation to Gross Alpha Radioactivity, *Ground Water*, Vol. 49, pp. 160-171, 0017-467X

Siddappa K., Balakrishna, K. M., Radhakrishna, A. P., Somashekarappa, H. M., and Narayana, Y., (1994). *Distribution of natural and artixcial radioactivity components in the environs of coastal Karnataka, Kaiga and Goa (1991-94).* (Mangalore University, , Mangalore, India.).

Skrable K. W., Haughey, F. J., Little, J. B., Hunt, V. R., Radford, E. P., and Alexande.El, (1964). POLONIUM-210 IN CIGARETTE SMOKERS, *Science*, Vol. 146, pp. 86-&, 0036-8075

Skuterud L., Gwynn, J. P., Gaare, E., Steinnes, E., and Hove, K., (2005). Sr-90, Po-210 and Pb-210 in lichen and reindeer in Norway, *Journal of Environmental Radioactivity*, Vol. 84, pp. 441-456, 0265-931X

Smithbriggs J. L., and Bradley, E. J., (1984). Measurement of natural radionuclides in UK diet, *Science of the Total Environment*, Vol. 35, pp. 431-440, 0048-9697

Sopka K., and Sopka, E., (2010). The Bonebrake Theological Seminary: Top-Secret Manhattan Project Site, *Physics in Perspective (PIP)*, Vol. 12, pp. 338-349, 1422-6944

Staples C. R., Umana, R., Stricker, J. A., Shibles, D., Hayen, M. J., Hissem, C. D., Lough, D. S., and Demorest, D. L., (1994). Radionuclides in milk of dairy heifers raised on forages harvested from phosphatic clay soils on reclaimed mined land, *Journal of Environmental Quality*, Vol. 23, pp. 663-667, 0047-2425

Staven L. H., Rhoads, K., Napier, B. A., and Strenge, D. L., (2003). *A Compendium of Transfer Factors for Agricultural and Animal Products.*(Pacific Northwest National Laboratory, Richland, Washington.).

Strok M., and Smodis, B., (2012). Transfer of natural radionuclides from hay and silage to cow's milk in the vicinity of a former uranium mine, *Journal of Environmental Radioactivity*, Vol. 110, pp. 64-68, 0265-931X

Štrok M., and Smodiš, B., (2010). Natural radionuclides in milk from the vicinity of a former uranium mine, *Nuclear engineering and design*, Vol. 241, pp. 1277-1281, 0029-5493

Sugiyama H., Terada, H., Isomura, K., Iijima, I., Kobayashi, J., and Kitamura, K., (2009). Internal exposure to (210)Po and (40)K from ingestion of cooked daily foodstuffs for adults in Japanese cities, *Journal of Toxicological Sciences*, Vol. 34, pp. 417-425, 0388-1350

Taddei M. H. T., (2001). The natural radioactivity of Brazilian phosphogypsum, *Journal of Radioanalytical and Nuclear Chemistry*, Vol. 249, pp. 251-255,

Tateda Y., and Iwao, K., (2008). High Po-210 atmospheric deposition flux in the subtropical coastal area of Japan, *Journal of Environmental Radioactivity*, Vol. 99, pp. 98-108, 0265-931X

Thomas P., Irvine, J., Lyster, J., and Beaulieu, R., (2005). Radionuclides and trace metals in Canadian moose near uranium mines: Comparison of radiation doses and food chain transfer with cattle and caribou, *Health Physics*, Vol. 88, pp. 423-438, 0017-9078

Thomas P. A., Fisenne, I., Chorney, D., and Baweja, A. S., (2001). Human absorption and retention of polonium-210 from caribou meat, *Radiation Protection Dosimetry*, Vol. 97, pp. 241-250, 0144-8420

Ugur A., Ozden, B., and Filizok, I., (2011). Determination of (210)Po and (210)Pb concentrations in atmospheric deposition in Izmir (Aegean sea-Turkey), *Atmospheric Environment*, Vol. 45, pp. 4809-4813, 1352-2310

Ugur A., Ozden, B., Sac, M. M., and Yener, G., (2003). Biomonitoring of Po-210 and Pb-210 using lichens and mosses around a uraniferous coal-fired power plant in western Turkey, *Atmospheric Environment*, Vol. 37, pp. 2237-2245, 1352-2310

Unscear, (2000). *United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risk of ionizing radiation*(United Nation, New York).

Usaec, (1980). *Po-210 in soils and plants.*(United States Atomic Energy Commission).

Wallner G., Wagner, R., and Katzlberger, C., (2008). Natural radionuclides in Austrian mineral water and their sequential measurement by fast methods, *Journal of Environmental Radioactivity*, Vol. 99, pp. 1090-1094, 0265-931X

Vandenhove H., Olyslaegers, G., Sanzharova, N., Shubina, O., Reed, E., Shang, Z., and Velasco, H., (2009). Proposal for new best estimates of the soil-to-plant transfer factor of U, Th, Ra, Pb and Po, *Journal of Environmental Radioactivity*, Vol. 100, pp. 721-732, 0265-931X

Ward G. M., and Johnson, J. E., (1986). Validity of the term transfer-coefficient, *Health Physics*, Vol. 50, pp. 411-414, 0017-9078

Ward G. M., and Johnson, J. E., (1989). Assessment of milk transfer-coefficients for use in prediction models of radioactivity transport, *Science of the Total Environment*, Vol. 85, pp. 287-294, 0048-9697

Vesterbacka P., (2007). Natural radioactivity in drinking water in Finland, *Boreal Environment Research*, Vol. 12, pp. 11-16, 1239-6095

Vesterbacka P., Makelainen, I., and Arvela, H., (2005). Natural radioactivity in drinking water in private wells in Finland, *Radiation Protection Dosimetry*, Vol. 113, pp. 223-232, 0144-8420

Who, (2004). *Guidelines for drinking water quality: radiological aspects*(World Health Organization, Geneva).

Yazgan K., Makulska, J., Weglarz, A., Ptak, E., and Gierdziewicz, M., (2010). Genetic relationship between milk dry matter and other milk traits in extended lactations of Polish Holstein cows, *Czech Journal of Animal Science*, Vol. 55, pp. 91-104, 1212-1819