^{210}Po and ^{210}Pb in the Terrestrial Environment

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***Abstract*- The natural sources of ^{210}Po and ^{210}Pb in the terrestrial environment are from atmospheric deposition, soil and ground water. The uptake of radionuclides from soil to plant given as the soil transfer factor, varies widely between various types of crops with an average about 0.056±0.003.**

The atmospheric deposition of ^{210}Pb and ^{210}Po also affect the activity concentrations in leafy plants with a deposition transfer factor for ^{210}Pb is in the order of 0.1-1 ($m^2.Bq^{-1}$) plants and for root fruits it is < 0.003, Corresponding values for ^{210}Po are about a factor 3 higher.

The activity concentration ratios between milk and various types of forage for ^{210}Pb were estimated to 1.4±0.7 and for ^{210}Po to 0.41±0.09. By a daily food intake of 16 kg dry matter per day the transfer coefficient F_m. for ^{210}Pb was estimated to 0.01±0.008 $d.l^{-1}$ and for ^{210}Po 0.003 ± 0.0007 $d.l^{-1}$.

The high accumulation of ^{210}Po in the food chain Lichens (Cladonia alpestris)-Reindeer was used as a model for quantifying it´s transfer to man.

Keywords- ^{210}Po; ^{210}Pb; Terrestrial Environment; Soil; Water; Plants; Lichen; Milk; Reindeer; Man

I. INTRODUCTION

Marie and Pierre Curie in 1898 found a new radioactive element after removal of uranium and thorium from about 1000 kg of pitchblende [1]. The element was named Polonium after Marie Curie's native country of Poland.

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 polonium 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 in 1943 at the top-secret Manhattan Project site established at the Bone brake Theological Seminary in Dayton, Ohio. The polonium was to be used in a polonium–beryllium neutron source whose purpose was to ignite the plutonium atomic-bombs [2]. 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 [3, 4]. Together with fallout from the nuclear weapons tests, 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 [4].

During the 1960th century the presence of ^{210}Pb and ^{210}Po was extensively studied in human tissues and particularly in Arctic food chains [4-20].

In December of 2006, former Russian intelligence operative Alexander Litvinenko died from ingestion of a few μg of ^{210}Po. This incident demonstrated the high toxicity of ^{210}Po and resulted in a renaissance for research of bio-kinetics and biological effects of ^{210}Po. Already in 2009 there was an international conference on polonium (Po) and it´s 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 [21, 22]. The present article is an updated review and analysis of the transfer of ^{210}Po and lead (^{210}Pb) in the terrestrial environment.

I. 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.

$$^{238}\mathbf{U} >^{234}\mathbf{Th} >^{234}\mathbf{Pa} >^{234}\mathbf{U} >^{230}\mathbf{Th} >^{226}\mathbf{Ra} >^{222}\mathbf{Rn}$$

After the first 5 decays Radon-222 (3.82 days) is formed which is a noble-gas diffusing out from ground into the atmosphere where it decays to the following short lived products which attach to airborne small particles:

$$^{218}\mathbf{Po\ (RaA\ 3.10\ min)} >^{214}\mathbf{Pb\ (RaB\ 26.8\ min)} >$$

$$>^{214}\mathbf{Bi\ (RaC\ 19.9\ min)} >^{214}\mathbf{Po (RaC´ 164.3\ \mu s)}$$

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

$$^{210}\mathbf{Pb\ (\ RaD\ 22.20\ a)} > ^{210}\mathbf{Bi\ (RaE\ 5.01\ d)} >$$

$$>^{210}\mathbf{Po (RaF\ 138.4\ d)} > ^{206}\mathbf{Po (stable).}$$

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

II. ANALYSIS OF ^{210}PO AND ^{210}PB IN ENVIRONMENTAL SAMPLES

The volatility of ^{210}Po was recognised early as a problem in sample preparation, where losses begin at temperatures

above 100 °C, with 90% loss by 300 °C. This problem necessitates wet-ashing techniques wherever possible in sample preparation [23]. For many years, no radiochemical yield determinant was used, and alpha-particle counting was often done using Zink-sulphide (ZnS) scintillation counter coupled to a photomultiplier tube. But, the use of the yield determinants ^{208}Po and ^{209}Po and the development of alpha spectrometry showed that the yield was lower than expected because significant amounts of Po can be lost during wet-ashing especially when using normal open beakers. Closed systems such as microwave digestion or using e.g. Kjeldahl flasks, might reduce losses of some less volatile species of Po, but the more volatile ones are lost in most types of digestion systems [24]. Thus radiochemical yield tracers, ^{208}Po or ^{209}Po, would be employed to allow correction for losses.

Soils, sediments and other solid samples such as filtered materials are usually prepared by wet ashing, using HCl, HF, HNO_3 and $HClO_4$ in open vessels or in pressure vessels and microwave digestion systems. Biological samples are generally treated by first drying thoroughly at temperatures up to 80 °C for up to 48 h, followed by wet ashing treatment with various combinations of HNO_3, HCl, $HClO_4$ and H_2O_2 to eliminate organic matter.

Polonium is pre-concentrated from water samples by a wide variety of techniques, with the most common involving one of the following procedures:

a. Evaporation,
b. Co-precipitation typically on $Fe(OH)_3$ or MnO_2 [25],
c. Chelating with ammonium-pyrrolidine- dithiocarbamate (APDC) and methyl-isobutyl-ketone (MIBK) [26].

Solutions from the final preparatory steps are evaporated almost dry and the residue is dissolved in a small volume of dilute HCl. The interference of iron is suppressed by addition of ascorbic acid or hydroxylamine hydrochloride. Spontaneous auto-deposition onto a Silver or Nickel disc is then achieved through immersion of the disc, most commonly in 0.5M HCl [24].

The final alpha-spectrometric determination is most commonly performed using "Passivated Implanted Planar Silicon" (PIPS) surface barrier detectors. The radiometric tracer ^{208}Po or ^{209}Po, and hence ^{210}Po, recovery is determined from the resulting alpha-spectrum.

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

The atmospheric residence time of ^{210}Po 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 $Bq.m^{-2}.a^{-1}$ over Scandinavia [27]. The atmospheric concentration of ^{210}Pb is generally higher over terrestrial areas than oceanic areas including islands. Permafrost, ice and snow covered surface reduce the atmospheric ^{210}Pb concentrations [27]. 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 [28]. 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 [29].

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 [30].

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±8, 197±35 and 79±8 $Bq.m^{-2}.a^{-1}$ respectively. Higher ^{210}Pb 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 ^{222}Rn-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 ^{210}Po deposition at Akajima during winter. Anomalous unsupported ^{210}Pb input was observed during summer 1997, suggesting unknown source of ^{210}Pb at this area [31].

The latitudinal distribution of annual ^{210}Pb deposition summarized from various authors is displayed in Figure 1 [32, 33].

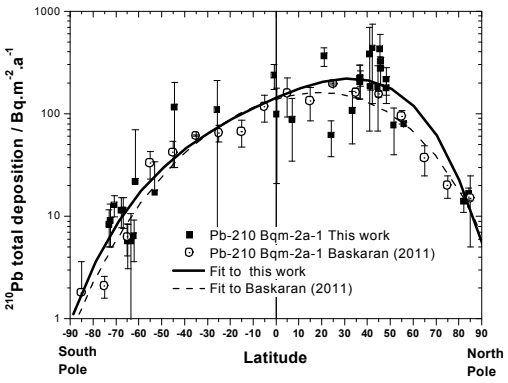

Fig. 1 Latitudinal distribution of all reported average values of deposition flux (Φ) of ^{210}Pb (Bq.m^{-2}.a^{-1}). The square dots are the data given in [33] and the open circles the data compilation of [32, 33]

The latitude distribution of ^{210}Po/^{210}Pb-activity ratio in the deposition was estimated from air filter studies during polar expeditions from the Arctic to Antarctic oceans [33]. 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.

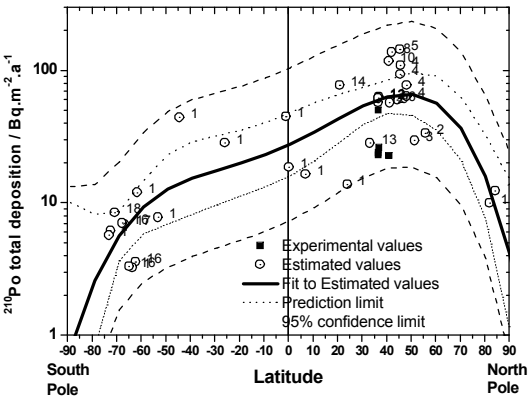

Fig. 2 Latitudinal distribution of air concentrations of ^{210}Po (μBq.m^{-3}) Estimated from: [Latitudinal distribution of ^{210}Pb]⊗ [^{210}Po/^{210}Pb-activity ratio] [33]

Mean annual ^{210}Pb concentrations (mBq.l^{-1}) in rainwater reported by various authors are displayed in Figure 3 [29-31]. The increasing trend up to a latitude of 60 ˚N agrees well the atmospheric deposition displayed in Figure 2.

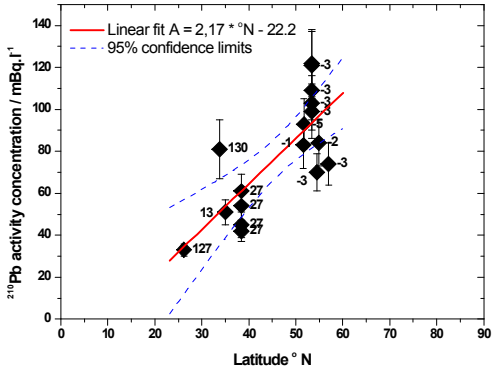

Fig. 3 Mean annual ^{210}Pb concentrations (mBq.l^{-1}) in rainwater at various latitudes (˚N) with longitudes (:W. E) as labels. Equation of fitted line: A(^{210}Pb) = -22.2 + 2.17 × (˚N)

IV. Levels of ^{210}Po and ^{210}Pb in the Ground

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 i.e. supported ^{210}Pb is the main source of ^{210}Po in soil and establish an equilibrium with a ratio close to one. Due to the different amount of clay and organic colloids in various soils the ^{210}Po content varies with soil type [34].

The activity concentrations of ^{210}Po in soils from various locations in the world are displayed in Figure 4 [35-53]. The world average of the activity concentrations of ^{210}Po in soil is 60±13 (SE) Bq/kg$_{d.w.}$, and the median value is 44 Bq/kg$_{d.w.}$.

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 and yearly tillage activities an almost uniform distribution of ^{210}Pb is found throughout the plough layer (12 - 14 cm) [54].

A. Fertilizers

About 85% of the phosphate rock used for fertilizers is formed mainly from organic residues which contain 50–200 ppm uranium and 2–20 ppm thorium. A minor fraction,

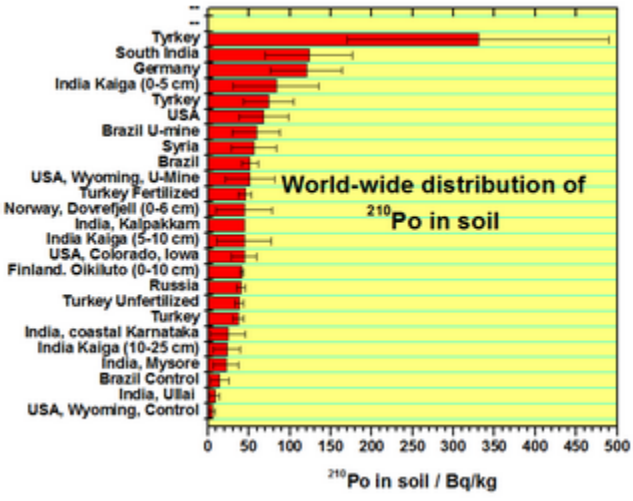

Fig. 4 Distribution of the activity concentrations of ^{210}Po in soils from various locations im the world [35-53].

15 % of the phosphate rock used for fertilizer is igneous phosphates of volcanic origin containing less than 10 ppm uranium, and 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 [55].

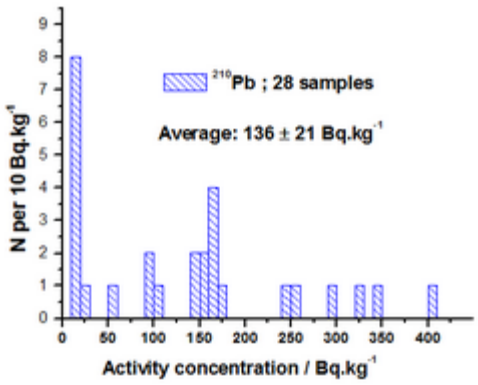

Fig. 5a ^{210}Pb concentration in phosphate fertilizers (Bq.kg^{-1}) [55]

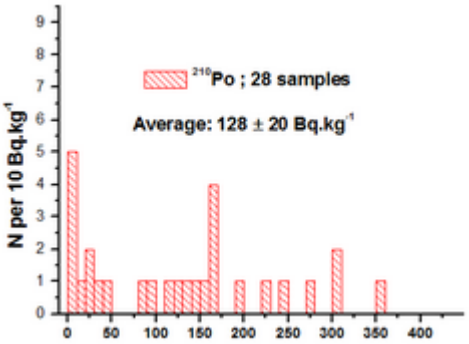

Fig. 5b ^{210}Po concentration in phosphate fertilizers (Bq.kg^{-1}) [55].

In 1999 dihydrate-phosphor-gypsum samples were collected from two important Brazilian phosphoric acid producers. For each company a stack was chosen, recorded as A and B. The activity concentration of ^{210}Po in the phosphor-gypsum ranged from 364±47 to 900±28 Bq.kg^{-1} (mean value of 581±97 Bq.kg^{-1}), within 1 m from stack A and 149±15 to 803±21 Bq.kg^{-1} (mean value of 325±114 Bq.kg^{-1}) within 1 m from stack B [56].

Continued application of phosphate fertilizers to soil over a period of many years could eventually increase the soil content of ^{210}Pb and ^{210}Po, 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} [57].

B. Concentrations of ^{210}Po in ground water

The average activity concentrations of ^{210}Po in water sources are given in Table 1. ^{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, however, the ^{210}Po concentrations 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}).

V. Levels of ^{210}Po and ^{210}Pb in Vegetation

A. Soil to Plant Transfer

Uptake of radionuclides from soil to plant is characterized by the ratio of radionuclide activity concentration per unit dry mass concentrations (Bq/kg$_{d.w.}$) of plant (AC_{plant}) and soil (AC_{soil}) respectively. This activity ratio is called the "Soil Tranfer Factor"(STF):

$$STF = \frac{AC_{plant}\ [Bq/kgd.w.]}{AC_{soil}\ [Bq/kgd.w.]}$$

In Table 2 is given estimated average values of soil transfer factors for ^{210}Po for various crop groups, crop compartments and crop/soil combinations. The upper part of Table 2 shows the current established values [58]. The lower data are compiled from an extensive compilation of recent published data on transfer factors [59].

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 2 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 transfer factor for ^{210}Po in vegetables and fruit are 1 and for grain 2 with corresponding values 0.1 and 5 for ^{210}Pb [60]. But in soils with high content of ^{226}Ra and its daughters ^{210}Pb and ^{210}Po the transfer factors can be much higher [42, 61].

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

TABLE 1 ESTIMATES OF THE ^{210}Po ACTIVITY CONCENTRATIONS IN GROUND WATER AND DRINKING WATER AT DIFFERENT LOCATIONS AROUND THE WORLD [62]

Type of plant	Location	^{210}Po min mBq/l	^{210}Po max mBq/l	^{210}Po average mBq/l	Ref.
Reference value	World wide			5	[63]
Recommendation	EU			100	[64]
Surface water	Finland	1.6	2.0	1.9	[65]
Lake water	Finland	1.0	6.5		[65]
Drilled wells	Finland			48	[65]
Water works	Finland			3	[65]
Ground water	Brazil			3	[66]
Mineral Water	Italy	<0.04	21	1.8	[67]
Ground water	California USA	0.25	555	< 26	[68]
Drilled wells	Nevada USA	0.4	6500	107	[69]
Mineral water	Italy	0.12	11.3	3	[70]
Mineral water	Austria	0.4	6.1	1.9	[71]

The activity concentration ratio between water and soil varies widely depending on the treatment of the water.

TABLE 2 AVERAGE POLONIUM SOIL-TO-PLANT TRANSFER FACTOR FOR CROP GROUPS, CROP COMPARTMENTS AND CROP/SOIL COMBINATIONS [58, 59].

Plantgroup	min.	Max.	Average STF×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
Fodder	0.016	97	25	1.40
All excluding deposition	0.016	1020	56	2.86
All including deposition	0.016	1020	74	2.16

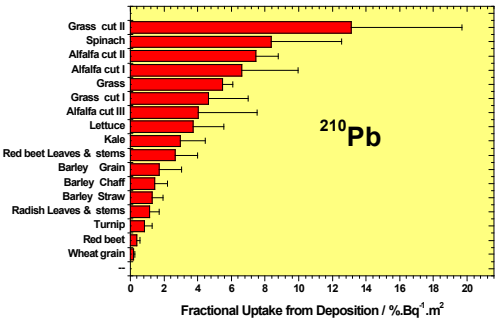

Fig. 6a The fractional uptake of ^{210}Pb for various corps from deposition calculated by dividing the difference with the local deposition of ^{210}Pb (Bq.m^{-2}) throughout the vegetative period.

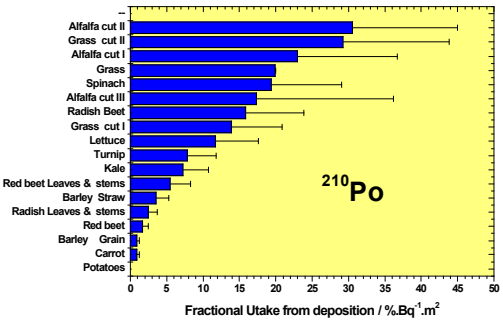

Fig. 6b The fractional uptake of ^{210}Po for various corps from deposition calculated by dividing the difference with the local deposition of ^{210}Po (Bq.m-2) throughout the vegetative period.

B. ATMOSPHERIC DEPOSITION TO PLANT

The atmospheric deposition transfer of ^{210}Pb and ^{210}Po to different types of plants used as food (potatoes, vegetables, cereals) or as fodder (grass, alfalfa) varies a lot. This effect 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 [72]. ^{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 taken as a 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 figures 6a and 6b 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 the deposition transfer factor "DTF" of ^{210}Pb and ^{210}Po were higher than in the grains, stems 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 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 in diet and a fodder.

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}).

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

The deposition transfer factor DTF for various types of plants was calculated from the published data and is displayed in Figures 7 and 8.

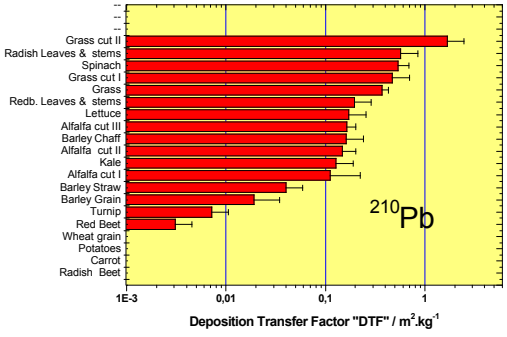

Fig. 7 Deposition transfer factor of ^{210}Pb

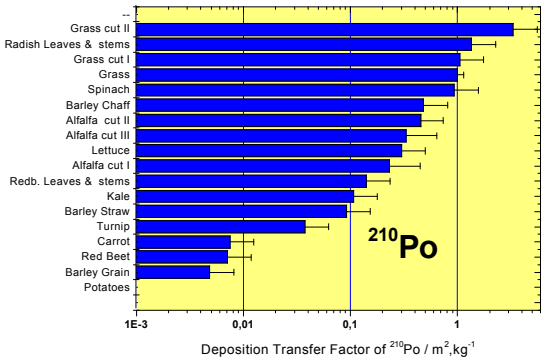

Fig. 8 Deposition transfer factor of ^{210}Po

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.

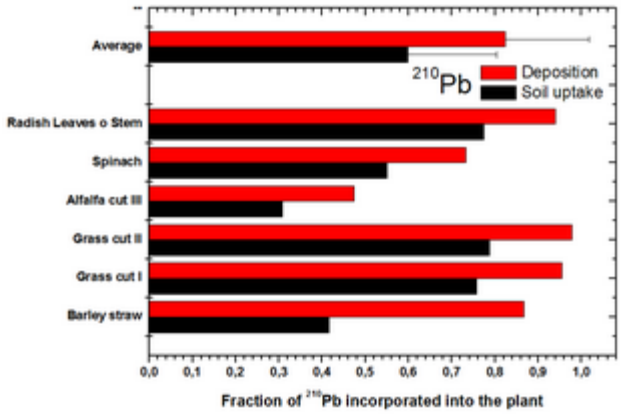

Fig. 9 The fractions of ^{210}Pb firmly incorporated into various corps from atmospheric deposition and up-take from soil.

VII. Levels of ^{210}Po and ^{210}Pb in Food Chain Grass-Cattle-Milk

A. *Activity Concentrations of ^{210}Pb and ^{210}Pb*

The fresh weight (f.w.) activity concentrations of ^{210}Pb and ^{210}Po in various types of milk and meat products mBq/kg$_{f.w.}$ are given in Table 3.

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

For ^{210}Pb in meat the minimum was 15 mBq/kg$_{f.w}$ and maximum 140 mBq/kg$_{f.w}$ and average of all reported values was 32±13 mBq/kg$_{f.w}$ which is the same as the UNSCEAR`s reference value of 80 mBq/kg$_{f.w}$. For ^{210}Po in meat the minimum was 21 mBq/kg$_{f.w}$ and maximum 120 mBq/kg$_{f.w}$ and average of all reported values was 70 ± 39 mBq/kg$_{f.w}$, which does not differ significantly from the UNSCEAR´s reference value of 60 mBq/kg$_{f.w}$. The dietary intake of milk and meat products is 170 kg.a^{-1} which is the highest of all food items of terrestrial origin [63].

A few studies have been performed to quantitatively study the transfer of the natural radionuclides ^{210}Pb and ^{210}Po from fodder to milk [73-75]. In Table 4 is given the average concentrations and activity-concentration ratios between fodder and milk. ^{210}Pb and ^{210}Po in fodder and milk was 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 [74].

TABLE 3 ACTIVITY CONCENTRATION OF ^{210}Pb AND ^{210}Po IN VARIOUS MILK AND MEAT PRODUCTS mBq/kg$_{f.w}$

Country	^{210}Pb ave mBq/kg$_{f.w}$	SD	^{210}Po ave mBq/kg$_{f.w}$	SD	Reference
Milk products					
World wide	25	10	23	10	[63]
Syria	22.5		194		[76]
India, Kalpakkam			10	1	[77]
Poland	24	6	20	4	[78]
Slovenia	54	6	48	16	[79]
UK	35	1			[80]
Average	32	13	59	77	This work
Reference value	15		15		[63]
Meat products					
World wide	67	17	81	13	[63]
India, Kalpakkam			28	6	[77]
Poland	102	15	101	15	[78]
UK	74	1			[80]
Average	81	19	70	38	This work
Reference value	80		60		[63]

TABLE 4 THE AVERAGE CONCENTRATIONS (Bq/kg$_{d.w.}$) 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 : ^{210}Pb AND ^{210}Po [74].

Fodder	^{210}Pb Bq/kg$_{d.w.}$	Sd.	^{210}Po Bq/kg$_{d.w}$	SD
Control	0.52	0.22	1.26	0.15
Corn Silage	0.63	0.22	0.59	0.11
Alfalfa	1.04	0.22	1.59	0.18
Milk	^{210}Pb		^{210}Po	
Control	0.92	0.19	0.45	0.07
Corn Silage	1.38	0.19	0.3	0.07
Alfalfa	0.94	0.19	0.58	0.07
Activity Concentration ratios	^{210}Pb		^{210}Po	
(Bq/kg $_{d.m.}$) /(Bq/kg $_{d.m.}$) Milk / fodder	ACR	SD	ACR	SD
Control	1.77	0.83	0.36	0.07
Corn Silage	2.19	0.82	0.51	0.15
Alfalfa	0.90	0.26	0.36	0.06

B. *Transfer of ^{210}Po and ^{210}Pb from Fodder to Milk*

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

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

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

TABLE 5. THE AVERAGE CONCENTRATIONS ($Bq/kg_{d.w.}$) IN SOIL, FORAGE AND MILK AND ACTIVITY-COCENTRATION RATIOS FODDER/MILK OF : ^{210}Pb [73].

	^{210}Pb $Bq/kg_{d.w.}$	SD	Min.	Max.
Soil	104	1.7	60	253
Forage (grass)	26	2	9.4	83
Milk (fresh)	0.016	3	5	60
Activity concentration ratios	^{210}Pb			
($Bq/kg_{d.w.}$/ $Bq/kg_{d.w.}$)	ACR	SD		
Forage (grass)/Soil	0.25	0.08		
Milk/forage	0.62	0.20		

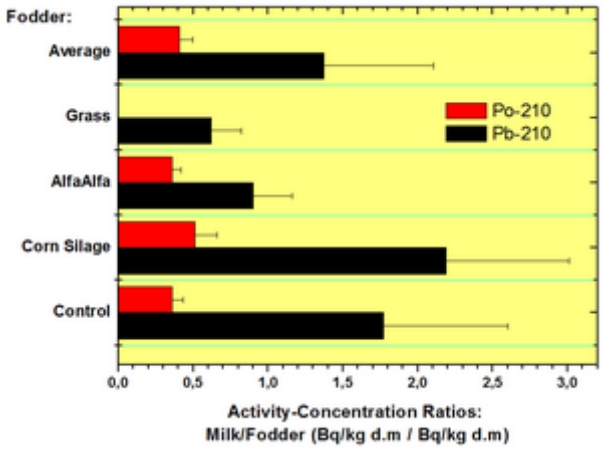

Fig. 10 Activity Concentration ratios ($Bq/kg_{d.w.}$)/ ($Bq/kg_{d.w.}$) between milk and different kinds of fodder [73-75]

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 (SD) has been calculated from literature data [81].

From these studies 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 by assuming a daily food intake of 16 kg dry matter per day.

A few studies have been performed to quantitatively study the transfer of the natural radionuclides ^{210}Pb and ^{210}Po from fodder to milk [73-75].

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 by assuming a daily food intake of 10 kg dry matter per day.

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 [82, 83].

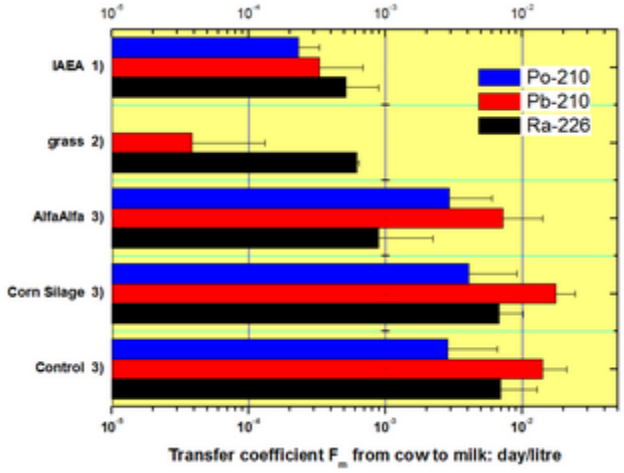

Fig. 11 The transfer coefficient F_m describes the fraction of the daily intake of radionuclides that is secreted per litre of milk.

C. *Transfer of ^{210}Po and ^{210}Pb from Fodder to Meat*

Activity concentrations of ^{210}Pb and ^{210}Po in meat products are given in Table 6

TABLE 6 ACTIVITY CONCENTRATION ($mBq/kg_{f.w}$) OF ^{210}Pb AND ^{210}Po IN MEAT PRODUCTS

Country	^{210}Pb ave $mBq/kg_{f.w}$	SD	^{210}Po ave $mBq/kg_{f.w}$	SD	Reference
Meat products					
World wide	67	17	81	13	[63]
India, Kalpakkam			28	6	[77]
Poland	102	15	101	15	[78]
UK	74	1			[80]
Average	81	19	70	38	This work
Reference value	80		60		[63]

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 ($Bq/kg_{f.w.}$) divided by the dry mass radionuclide activity concentration in the feedstuff ingested ($Bq/kg_{d.w.}$) [84].

$$ACR = \frac{\text{Activity concentration of fresh Meat}}{\text{Dry mass Activity concentration in food}} \quad \frac{[Bq/kg_{f.w.}]}{[Bq/kg_{d.m.}]}$$

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

$$F_{meat} = \frac{\text{Activity concentration of Meat}}{\text{Daily Radionuclide Intake}} \quad \frac{\left[Bq.kg^{-1}\right]}{\left[Bq.day^{-1}\right]} = \frac{day}{kg} = day.kg^{-1}$$

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

A compilation of ACR values and transfer coefficients for Pb and Po are given in Table 7 [85].

TABLE 7 A COMPILATION OF ACTIVITY CONCENTRATION RATIOS (ACR) AND TRANSFER COEFFICIENTS FOR ^{210}Pb AND ^{210}Po [85].

Transfer factor day.kg^{-1}	**^{210}Pb Average day.kg^{-1}**	**SD**	**^{210}Po Average day.kg^{-1}**	**SD**
Cow meat	0.0009	0.0006		
Sheep meat	0.0071			
Poultry meat			2.4	
Poultry Egg			2.1	
Activity Concentration Ratios (ACR)	**^{210}Pb Average**	**SD**	**^{210}Po Average**	**SD**
Beef	0.077	0.180	0.14	0.13
Sheep	0.012	0.004		
Pork	0.066			

VII. ^{210}Po and ^{210}Pb in Arctic food chain.

A. ^{210}Po and ^{210}Pb 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 $Bq/kg_{d.w.}$, Lichens 200 $Bq/kg_{d.w.}$, and in leafy plants 2-20 $Bq/kg_{d.w.}$.

Peat bogs are characterized of being covered by primitive plants that grows from the top while the dead bottom develops to peat, which 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 8**.**

A strategy to control the release of ^{210}Po and ^{210}Pb into the environment could be to establish regularly sampling of lichen, moss or peat profiles. Lichen and mosses review the short term history of strategy to control the release of these elements into the environment Such studies could be uses to study the impact on the surrounding environments of uranium mining [43, 86, 87], coal-fired power plants [88-90], and phosphate industry [91].

The profile of ^{210}Pb in peat cores reflects the long term atmospheric deposition history of these elements. Peat-bog profiles of ^{210}Po and ^{210}Pb could also serve as a monitor for the impact of climate changes on the environment to compare with simulation models [92-94].

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 $Bq/kg_{d.w.,}$ with an average of 243±11 $Bq/kg_{d.w.}$ [4, 22, 95, 96].

In a previous study the sorpition and retention of atmospheric deposition of ^{210}Pb in lichen was modelled [96].

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

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

*

TABLE 8 ESTIMATES OF THE ^{210}Po ACTIVITY CONCENTRATIONS IN MOSSES, LICHENS AND PEAT AT DIFFERENT LOCATIONS.

Type of plant	**Location**	**^{210}Po average** $Bq/kg_{d.w.}$	**SE**	**Ref.**
Mosses:				
Polytrichum	N. Sweden	630	330	[97]
Sphagnum	N. Sweden	443	258	[97]
Alectoria	N. Sweden	605	35	[97]
Pterobryopsis tumida.	S. India	2724	13	[45]
Grimmia pulvinata	W. Turkey.	1228		[98]
Lycopodium cernuum	Syria	1322		[99]
Funaria hygrometrica	Syria	2392		[99]
Lichens:				
Cladonia alpestris	Central. Sweden	250	30	[4]
				[96]
Cladonia arbuscula	Vågå Norway	140	27	[100]
Cladonia arbuscula	E Namdal Norway	141	11	[100]
Cladonia arbuscula	Dovrefjell Norway	138		[53]
Cladonia stellaris	Dovrefjell Norway	30		[53]
Peat:				
Sphagnum	N Sweden	192	37	[101]
Sphagnum	S Sweden	439	117	[101]

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}]

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.

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

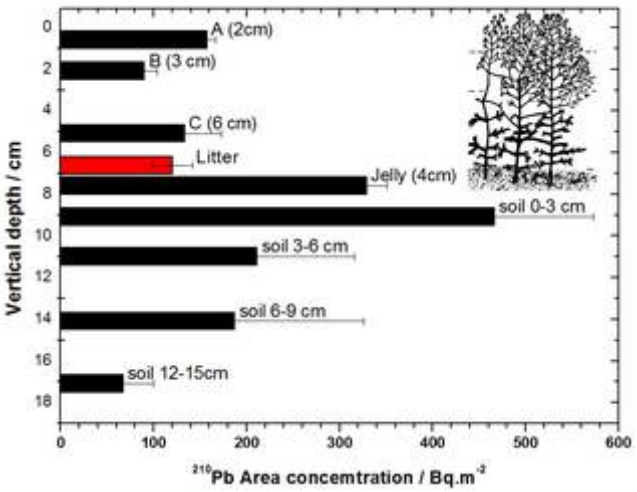

Fig 13 Distribution of ^{210}Pb in the lichen-Jelly-soil profile

B. ^{210}Po and ^{210}Pb in lichen-reindeer-man

The activity concentrations of ^{210}Pb in reindeer meet varies between 200 and 1200 mBq/kg$_{f.w.}$ with an average of 500±100 mBq/kg$_{f.w.}$. The activity concentrations of ^{210}Po in reindeer meet varies between 1700 and 13300 mBq/kg$_{f.w.}$ with an average of 7800±1300 mBq/kg$_{f.w.}$. This maintains about 10 times higher ^{210}Po concentration in soft tissues of residences regularly consuming caribou or reindeer meet. The level for the general population has been estimated to 80 mBq/ kg$_{f.w.}$ [20, 102] .

Results of ^{210}Pb and ^{210}Po activity concentrations in reindeer and caribou meet samples collected in various countries are summarized in Table 9 and displayed in Figures 14 and 15.

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

This maintains about 12 times higher ^{210}Po concentration in soft tissues of reindeer breeding Lapps than in southern Finns [19]. This was shown to be true also for Alaskan residents consuming caribou or reindeer meat [103]

^{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$_{f.w.}$ These animals, two years old, had grazed within the same reindeer breeding district where the lichen sampling area is situated [4, 95, 96, 104].

In bone of reindeer the concentrations of ^{210}Pb in varies between 111 to 481 Bq/kg$_{f.w.}$, with an average of 282±48 Bq/kg$_{f.w}$ [12, 19, 20, 95]. The ^{210}Pb in bone of caribou varies between 160 to 870 Bq/kg$_{f.w.}$, with an average of 450±80 Bq/kg$_{f.w.}$ [10, 12, 105, 106]. 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$_{f.w.}$) is similar to that which was in the teeth of reindeer a hundred years ago (650-750 Bq/kg$_{f.w.}$) and significantly higher than in the recent mainland reindeer from different regions (180-170 Bq/kg$_{f.w.}$) [107]. The ^{210}Pb in bone of caribou from 1989-74 varied between 490 and 800 Bq/kg$_{f.w.}$[106]. This compares well with the level of 170±190 Bq/kg$_{f.w.}$ found in Finnish reindeer during 1964-67 [19].

By letting 14 volunteers consume 2.0 kg of caribou meat containing 9–40 Bq/kg$_{f.w.}$ while 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 [108, 109].

A study of concentrations of ^{210}Po and ^{210}Pb in Norwegian reindeer during 2000-2003 focused on differences in 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 tissues, collected in December 2000 at Vargå, were 23.7±3.7 Bq/ kg$_{d.w.}$ in calves and 35.5±9.2 Bq/ kg$_{d.w.}$ In females (7 years). These values correspond to 6±1 and 9.2±2.3 Bq/kg$_{f.w.}$ respectively and are not significantly different from those in 2002. This is in agreement with the values recorded in Sweden 1970-71 [4, 95, 96, 104, 108].

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 [16, 19, 95, 96, 100, 110, 111].

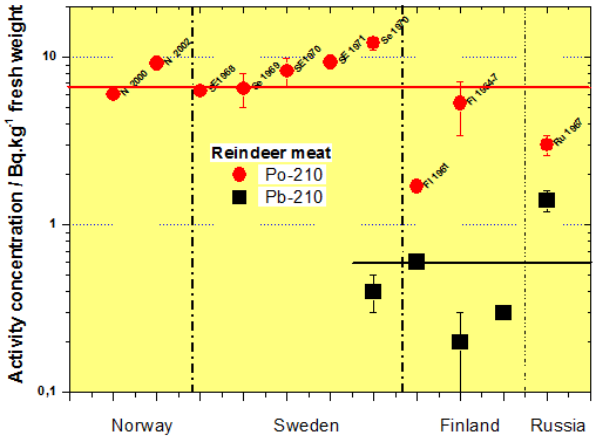

Fig. 14 ^{210}Pb and ^{210}Po activity concentrations in reindeer meet samples collected in various countries. The average activity concentration of ^{210}Pb is 0.6 ±0.2 Bq/kg$_{f.w.}$, and for ^{210}Po 6.8 ±1.0 Bq/kg$_{f.w.}$ [12, 19, 95, 100, 104, 112, 113].

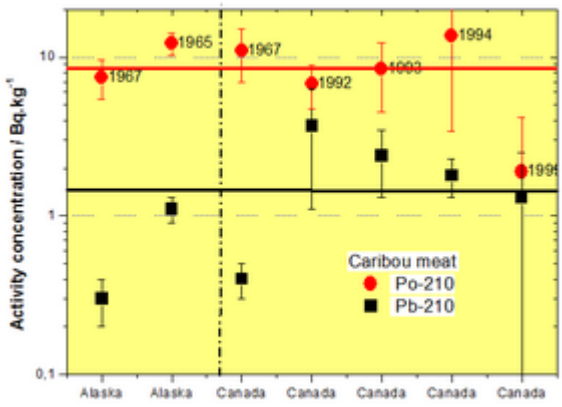

Fig. 15 ^{210}Pb and ^{210}Po activity concentrations in caribou meet samples collected in various countries. The average activity concentration of ^{210}Pb is 1.6 ±0.5 Bq/kg$_{f.w.}$ and for ^{210}Po 8.8 ± Bq/kg$_{f.w.}$ [10, 12, 106, 109, 114].

During winter the fraction of daily radionuclide intake of ^{210}Po from lichen that is transferred to reindeer meat varies between 0.04 and 0.06 day/kg [115].

Results of ^{210}Pb and ^{210}Po activity concentrations in reindeer meet samples collected in various countries are given in Figure 16 as well as the ^{210}Po activity transfer coefficient from lichen to caribou meet samples collected in various countries.

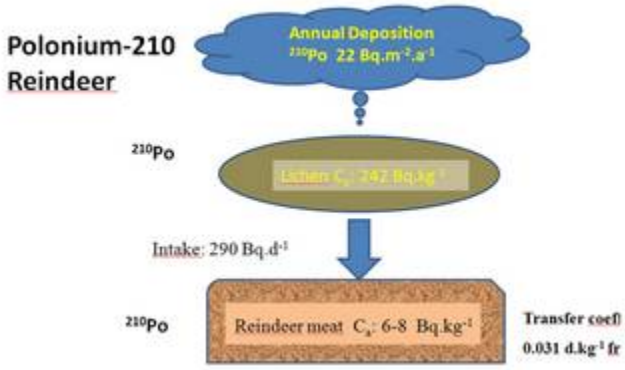

Fig. 16 Transfer of ^{210}Po from deposition to lichen and reindeer (Transfer coefficient 0.031±0.002 day.kg^{-1} fresh mass).

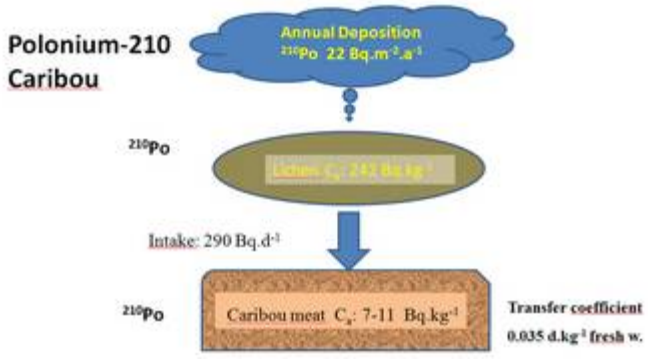

Fig. 17 Transfer of ^{210}Po from deposition to lichen and caribou meat (Transfer coefficient 0.035±0.008 day.kg^{-1} fresh mass)

Results of ^{210}Pb and ^{210}Po activity concentrations in caribou meet samples collected in various countries are given in Figure 17 as well as the ^{210}Po activity transfer coefficient from lichen to caribou meet samples collected in various countries. The caribou average values of the transfer coefficients (0.035) and activity concentration ratios (0.034) agree well with corresponding values for reindeer (0.031 and 0.037).

C. ^{210}Po and ^{210}Pb in Moose

^{210}Pb, and ^{210}Po has been studied by Thomas et al, (2005) in tissues from 45 moose and 4 cattle which were collected to assess the health of country foods near uranium mines in northern Saskatchewan [116]. Their results of ^{210}Pb and ^{210}Po activity concentration and the ratios between activity concentration in meat and rumen content of Moose and cattle are given in Table 9. 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 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 low human doses (0.0068 mSv.a^{-1}), a mere 0.3% of the dose from intake of caribou (2.4 mSv.a^{-1}), the dietary staple in the area [116].

TABLE 9 RESULTS OF ^{210}Pb AND ^{210}Po ACTIVITY-CONCENTRATION AND CONCENTATION RATIOS (CR) MEAT/ RUMEN-CONTENT IN MOOSE AND CATTLE [116].

	^{210}Pb meat Bq/kg$_{f.w.}$	SE ±	^{210}Po meat Bq/kg$_{f.w.}$	SE ±	^{210}Pb CR $_{f.w.}$	SD ±	^{210}Po CR $_{f.w.}$	SD ±
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

D. ^{210}Po and ^{210}Pb in Man

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 [95].

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

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"

$$\mathbf{\tau \approx f_a / k_a = (M_a \cdot C_a) / (R_i \cdot C_i) = A / I;}$$

$$\mathbf{(Bq/Bq.a^{-1}; Bq/Bq.d^{-1}); (a) \text{ or } (d)}$$

where

R_i = rate of mass transfer into the step i 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 i 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 i which is eliminated per unit of time (a^{-1}) or (d^{-1})

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 time of ^{210}Po is thus given by the expression:

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

where **g** is the fraction of ^{210}Po originating from decay of existing ^{210}Pb.

In lichen and reindeer bone, where the biological elimination of ^{210}Pb is relatively slow, the value of **g** is larger than $\mathbf{f_a}$. But due to the rapid elimination of ^{210}Pb from blood the value of **g** is much smaller than $\mathbf{f_a}$ in reindeer blood and flesh.

VIII. Radiation exposure of ^{210}Po intake.

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, and red bone marrow [117]. 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 [118, 119].

The committed effective dose by dietary intake of and ^{210}Po for adult members of the public recommended by ICRP is 1.2 $\mu Sv.Bq^{-1}$ respectively considering a transfer coefficient of 50% for ingestion of ^{210}Po [117, 120]. 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) [63].

In Table 11 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 11 [63].

TABLE 10 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, AND C_A=ACTIVITY CONCENTRATION [16, 19, 121-124].

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

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 $\mu Sv.a^{-1}$ 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 $\mu Sv.a^{-1}$ and 10 $\mu Sv.a^{-1}$ respectively [22].

TABLE 11 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[63].

	^{210}Po min $\mu Sv.a^{-1}$	**^{210}Po max $\mu Sv.a^{-1}$**	**^{210}Po Average $\mu Sv.a^{-1}$**	**SE**	**^{210}Po Reference level [63]**
Drinking water	0.02	3900	1113	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

For inhalation of ^{210}Po aerosols assuming 10% absorption to the blood the recommended effective dose

coefficient is 3.3 μSv.Bq^{-1} [119]. 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} [63].

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 [125, 126].

TABLE 12 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 intake (Bq.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

[1] P. Curie, and M. Curie, "Radiations from Compounds of Uranium and of Thorium," *Comptes Rendus*, vol *126*, 1898.

[2] K. Sopka, and E. Sopka, "The Bonebrake Theological Seminary: Top-Secret Manhattan Project Site," *Physics in Perspective (PIP)*, vol *12*, pp. 338-349, 3, 2010.

[3] Z. Jaworowski, "Radioactive lead in the environment and in the human body," *Atomic Energy Rev.* , vol *7*, pp. 3-45, 1, 1969.

[4] B.R. Persson, "Pb-210 atmospheric deposition in lichen-carpets in northern Sweden during 1961-1969," *Tellus*, vol *22*, pp. 564-571, 5, 1970.

[5] C.R. Hill, "Lead-210 and Polonium-210 in grass," *Nature*, vol *187*, pp. 211-212, 4733, 1960.

[6] R.B. Holtzman, "Measurement of the natural contents of RaD(Pb-210) and RaF(Po210) in human bone estimates of whole-body burdens," *Health Phys.*, vol *9*, pp. 385-400, 1963.

[7] R.V. Osborne, "Lead-210 and Polonium-210 in human tissues," *Nature*, vol *199*, pp. 295-296, 489, 1963.

[8] K.W. Skrable, F.J. Haughey, J.B. Little, V.R. Hunt, E.P. Radford, and Alexande.El, "Polonium-210 in cigarette smokers," *Science*, vol *146*, pp. 86-90, 364, 1964.

[9] C.R. Hill, "Polonium-210 in man," *Nature*, vol *208*, pp. 423-428, 5009, 1965.

[10] T.M. Beasley, and H.E. Palmer, "Lead-210 and Polonium-210 in Biological Samples from Alaska," *Science*, vol *152*, pp. 1062-1064, 3725, 1966.

[11] C.R. Hill, *Routes of uptake of 210Po into human tissues.*, in: Radioecological concentration processes. B. Åberg, and F.P.. Hungate, Ed. Stockholm: Academic Press.1966.

[12] R.B. Holtzman, "Natural levels of Lead-210 Polonium-210 and Radium-226 in humans and biota of Arctic," *Nature*, vol *210*, pp. 1094-1097, 5041, 1966.

[13] Kilibard.M, D. Petrovic, D. Panov, and D. Djuric, "Contamination with Polonium-210 Uranium and Radium-226 due to smoking," *Health Phys.*, vol *12*, pp. 1808-1814, 12, 1966.

[14] D.H. Peirson, R.S. Cambray, and G.S. Spicer, "Lead-210 and Polonium-210 in atmosphere," *Tellus*, vol *18*, pp. 427-431, 2-3, 1966.

[15] R.B. Holtzman, "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, 1, 1967.

[16] P. Kauranen, and J.K. Miettinen, *^{210}Po and ^{210}Pb in environmental samples in Finland*, in: Radioecological Concentration Processes, Proceedings of an International Symposium B. Åberg, and F.P. Hungate, Ed. Stockholm 25-29 April1966: Pergamon Press, Oxford.1967.

[17] T. Baltakmens, "Lead-210 in New Zealand milk.," *Aust. 5. Sci.*, vol *31*, pp. 111-114, 1969.

[18] Blanchar.R.l., and J.B. Moore, "210Pb and 210Po in tissues of Alaskan Eskimo," *Health Phys.*, vol *17*, pp. 387-394, 2, 1969.

[19] P. Kauranen, and J.K. Miettinen, "^{210}Po and ^{210}Pb in Artic Food Chain and Natural radiation exposure of Lapps," *Health Phys.*, vol *16*, pp. 287-295, 3, 1969.

[20] B.R.R. Persson, *^{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*, PhD thesis, Lund University, Lund Sweden 1970.

[21] E. Holm, and R. Garcia-Tenorio, "Journal of Environmental Radioactivity special issue: international topical conference on Po and radioactive Pb isotopes," *Journal of Environmental Radioactivity*, vol *102*, pp. 413-414, 5, 2011.

[22] B.R.R. Persson, and E. Holm, "Polonium-210 and lead-210 in the terrestrial environment: a historical review," *Journal of Environmental Radioactivity*, vol *102*, pp. 420-429, 5, 2011.

[23] K.M. Matthews, C.-K. Kim, and P. Martin, "Determination of Po-210 in environmental materials: A review of analytical methodology," *Appl. Radiat. Isot.*, vol *65*, pp. 267-279, 3, 2007.

[24] F. Henricsson, Y. Ranebo, E. Holm, and P. Roos, "Aspects on the analysis of Po-210," *Journal of Environmental Radioactivity*, vol *102*, pp. 415-419, 5, 2011.

[25] P. Vesterbacka, "Pilot study of radionuclide removal - Using conventional iron- and manganese-removal equipment," *Journal American Water Works Association*, vol *100*, pp. 24-26, 7, 2008.

[26] L.V. Shannon, and M.J. Orren, "A rapid method for determination of Po-210 and Pb-210 in sea water," *Analytica Chimica Acta*, vol *52*, pp. 166-171, 1, 1970.

[27] F. Eldaoushy, and R. Garciatenorio, "Speciation of Pb-210/Po-210 in aquatic systems and their " *Science of the Total Environment*, vol *69*, pp. 191-209, 1988.

[28] G.T. Piliposian, and P.G. Appleby, "A simple model of the origin and transport of Rn-222 and Pb-210 in the atmosphere," *Continuum Mech. Thermodyn.*, vol *15*, pp. 503-518, 5, 2003.

[29] P.G. Appleby, "Three decades of dating recent sediments by fallout radionuclides: a review," *Holocene*, vol *18*, pp. 83-93, 1, 2008.

[30] A. Ugur, B. Ozden, and I. Filizok, "Determination of (210)Po and (210)Pb concentrations in atmospheric deposition in Izmir (Aegean sea-Turkey)," *Atmos. Environ.*, vol *45*, pp. 4809-4813, 27, 2011.

[31] Y. Tateda, and K. Iwao, "High Po-210 atmospheric deposition flux in the subtropical coastal area of Japan,"

Journal of Environmental Radioactivity, vol *99*, pp. 98-108, 1, 2008.

[32] M. Baskaran, "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, 5, 2011.

[33] B.R.R. Persson, and E. Holm, "^{7}Be. ^{210}Pb. and ^{210}Po in the surface air from the Arctic to Antarctica," *INCOPoPb-2013 conference, Mangalore University*, vol *1*, Feb.12, 2013.

[34] Y.D. Parfenov, "Polonium-210 in Environment and in Human Organism.," *Atomic Energy Review*, vol *12*, pp. 75-143, 1, 1974.

[35] M. Dowdall, and J. O'Dea, "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, 1999.

[36] E. Hasanen, "Dating of sediments, based on ^{210}Po measurements," *Radiochem. Radianal. Lett.* , vol *31*, pp. 207, 4-5, 1977.

[37] T.E. Myrick, B.A. Berven, and F.F. Haywood, "Determination of concentrations of selected radionuclides in surface soil in the United States,," *Health Phys.*, vol *45* pp. 631–642, 1983.

[38] H. Schuttelkopf, and H. Kiefer, *The radium-226 and polonium-210 concentration of the Black Forest,* , in: Natural radiation environment (Proceedings of the second special symposium) K.G. Vohra, U.C. Mishra, K.C. Pillai, and S. Sadasivan, Ed. Bombay: Wiley Eastern, New Delhi, pp. 194-200.1982.

[39] R.C. Santos, I.R. Gouvea, V.A. Dutta, and R.C. Gouvea, "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, 1990.

[40] S. Akyil, M.A.A. Aslani, G. Gurboga, S. Aytas, and M. Eral, "Activity concentration of radium-226 in agricultural soils," *J. Radioanal. Nucl. Chem.*, vol *254*, pp. 9–14, 1, 2002.

[41] S. Akyil, G. Gurboga, M.A.A. Aslani, and S. Aytas, "Vertical distribution of Ra-226 and Po-210 in agricultural soils in Buyuk Menderes Basin, Turkey," *J. Hazard. Mater.*, vol *157*, pp. 328-334, 2-3, 2008.

[42] M.S. Al-Masri, B. Al-Akel, A. Nashawani, Y. Amin, K.H. Khalifa, and F. Al-Ain, "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, 2, 2008.

[43] P.L. Santos, R.C. Gouvea, and I.R. Dutra, "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, 1-3, 1993.

[44] E. Ekdal, I. Karali, and M.M. Sac, "Po-210 and Pb-210 in soils and vegetables in Kucuk Menderes basin of Turkey," *Radiat. Meas.*, vol *41*, pp. 72-77, 1, 2006.

[45] N. Karunakara, D.N. Avadhani, H.M. Mahesh, H.M. Somashekarappa, Y. Narayana, and K. Siddappa, "Distribution and enrichment of Po-210 in the environment of Kaiga in South India," *Journal of Environmental Radioactivity*, vol *51*, pp. 349-362, 3, 2000.

[46] M. Bolca, M.M. Sac, B. Cokuysal, T. Karali, and E. Ekdal, "Radioactivity in soils and various foodstuffs from the Gediz River Basin of Turkey," *Radiat. Meas.*, vol *42*, pp. 263-270, 2, 2007.

[47] M.A.R. Iyengar, M.P. Rajan, S. Ganapathy, and P.R. Kamath, *Sources of natural radiation exposure in a low monazite environment.*, in: Natural radiation environment III, Proceedings of international Conference, CONF-780422 T.F. Gesell, and W.M. Lowder, Ed. Houston, 1978,: Oak Ridge TN: Technical Information Centre, US Department of Energy., pp. 1106-1090.1980.

[48] N. Nagaiah, S. Malini, L. Paramesh, P. Venkataramaiah, and M. Raghavayya, *Dependence of Po-210 to Ra-226 ratio on soil characteristics.* , in: Fourth national symposium on environment A.R. Sundararajan, L.V. Kirshnan, D.S. Surya Narayana, V. Rajagopal, and R. Mathiyarasu, Ed. Chennai: Anna University, pp. 219-222.1995.

[49] A.P. Radhakrishna, H.M. Somashekarappa, Y. Narayana, and K. Siddappa, "A new natural background-radiation area on the southwest coast of India," *Health Phys.*, vol *65*, pp. 390-395, 4, 1993.

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

[51] USAEC, *Po-210 in soils and plants.*, Ed.: United States Atomic Energy Commission, Special Report vol 11, 1980.

[52] S.A. Ibrahim, and F.W. Whicker, "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, 1987.

[53] J.E. Brown, R. Gjelsvik, P. Roos, J.A. Kalas, I. Outola, and E. Holm, "Levels and transfer of (210)Po and (210)Pb in Nordic terrestrial ecosystems," *Journal of Environmental Radioactivity*, vol *102*, pp. 430-437, 5, 2011.

[54] M. Benmansour, L. Mabit, A. Nouira, R. Moussadek, H. Bouksirate, M. Duchemin, and A. Benkdad, "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, 2013.

[55] C. Roselli, D. Desideri, and M.A. Meli, "Radiological characteri-zation of phosphate fertilizers: Comparison between alpha and gamma spectrometry," *Microchem J.*, vol *91*, pp. 181-186, 2, 2009.

[56] M.H.T. Taddei, "The natural radioactivity of Brazilian phospho-gypsum," *J. Radioanal. Nucl. Chem.*, vol *249*, pp. 251-255, 1, 2001.

[57] C.H.R. Saueia, and B.P. Mazzilli, "Distribution of natural radio-nuclides in the production and use of phosphate fertilizers in Brazil," *Journal of Environmental Radioactivity*, vol *89*, pp. 229-239, 3, 2006.

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

[59] H. Vandenhove, G. Olyslaegers, N. Sanzharova, O. Shubina, E. Reed, Z. Shang, and H. Velasco, "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, 9, 2009.

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

[61] M.S. Al-Masri, A. Al-Hamwi, Z. Eadan, and Y. Amin, "Transfer factors of Polonium from soil to parsley and mint," *Journal of Environmental Radioactivity*, vol *101*, pp. 1038-1042, 12, 2010.

[62] P. Vesterbacka, I. Makelainen, and H. Arvela, "Natural radioactivity in drinking water in private wells in Finland," *Radiat. Prot. Dosim.*, vol *113*, pp. 223-232, 2, 2005.

[63] UNSCEAR, *United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risk of ionizing radiation*, New York: United Nation 2000.

[64] WHO, *Guidelines for drinking water quality: radiological aspects*, in: Water sanitation health, Geneva: World Health Organization.2004.

[65] P. Vesterbacka, "Natural radioactivity in drinking water in Finland," *Boreal Environ. Res.*, vol *12*, pp. 11-16, 1, 2007.

[66] D.M. Bonotto, and T.O. Bueno, "The natural radioactivity in Guarani aquifer groundwater, Brazil," *Appl. Radiat. Isot.*, vol *66*, pp. 1507-1522, 10, 2008.

[67] D. Desideri, M.A. Meli, L. Feduzi, and C. Roselli, "Po-210 and Pb-210 inhalation by cigarette smoking in Italy," *Health Phys.*, vol *92*, pp. 58-63, 1, 2007.

[68] S.R. Ruberu, Y.G. Liu, and S.K. Perera, "Occurrence and distribution of Pb-210 and Po-210 in selected California groundwater wells," *Health Phys.*, vol *92*, pp. 432-441, 5, 2007.

[69] R.L. Seiler, "Po-210 in Nevada Groundwater and Its Relation to Gross Alpha Radioactivity," *Ground Water*, vol *49*, pp. 160-171, 2, 2011.

[70] G. Jia, and G. Torri, "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," *Appl. Radiat. Isot.*, vol *65*, pp. 849–857, 2007.

[71] G. Wallner, R. Wagner, and C. Katzlberger, "Natural radionuclides in Austrian mineral water and their sequential measurement by fast methods," *Journal of Environmental Radioactivity*, vol *99*, pp. 1090-1094, 7, 2008.

[72] Z. Pietrzak-Flis, and M. Skowronskasmolak, "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, 2-3, 1995.

[73] E.C.S. Amaral, Z.L. Carvalho, and J.M. Godoy, "Transfer of Ra-226 and Pb-210 to forage and milk in a Brazilian high natural radioactivity region," *Radiat. Prot. Dosim.*, vol *24*, pp. 119-121, 1-4, 1988.

[74] C.R. Staples, R. Umana, J.A. Stricker, D. Shibles, M.J. Hayen, C.D. Hissem, D.S. Lough, and D.L. Demorest, " 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, 4, 1994.

[75] M. Strok, and B. Smodis, "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, 2012.

[76] M.S. Al-Masri, H. Mukallati, A. Al-Hamwi, H. Khalili, M. Hassan, H. Assaf, Y. Amin, and A. Nashawati, "Natural radionuclides in Syrian diet and their daily intake," *J. Radioanal. Nucl. Chem.*, vol *260*, pp. 405-412, 2, 2004.

[77] V. Kannan, M.A.R. Iyengar, and R. Ramesh, "Dose estimates to the public from 210Po ingestion via dietary sources at Kalpakkam (India)," *Appl. Radiat. Isot.*, vol *54*, pp. 663-674, 4, 2001.

[78] Z. Pietrzak-Flis, M.M. Suplinska, and L. Rosiak, "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," *J. Radioanal. Nucl. Chem.*, vol *222*, pp. 189-193, 1-2, 1997.

[79] M. Štrok, and B. Smodiš, "Natural radionuclides in milk from the vicinity of a former uranium mine," *Nuclear engineering and design*, vol *241*, pp. 1277-1281, 4, 2010.

[80] J.L. Smithbriggs, and E.J. Bradley, "Measurement of natural radionuclides in UK diet," *Science of the Total Environment*, vol *35*, pp. 431-440, 3, 1984.

[81] K. Yazgan, J. Makulska, A. Weglarz, E. Ptak, and M. Gierdziewicz, "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, 3, 2010.

[82] I.A.E.A., *Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, IAEA-TECDOC-1616*, International Atomic Energy Agency (IAEA), VIENNA, 2009.

[83] I.A.E.A., *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 2010.

[84] B.J. Howard, N.A. Beresford, C.L. Barnett, and S. Fesenko, "Quantifying the transfer of radionuclides to food products from domestic farm animals," *Journal of Environmental Radioactivity*, vol *100*, pp. 767-773, 9, 2009.

[85] B.J. Howard, N.A. Beresford, C.L. Barnett, and S. Fesenko, "Radionuclide transfer to animal products: revised recommended transfer coefficient values," *Journal of Environmental Radioactivity*, vol *100*, pp. 263-273, 3, 2009.

[86] M. Cerne, B. Smodis, M. Strok, and L. Benedik, "Radiation impact assessment on wildlife from an uranium mine area," *Nuclear engineering and design*, vol *246*, pp. 203-209, 2012.

[87] P.A. Thomas, and T.E. Gates, "Radionuclides in the lichen-caribou-human food chain near uranium mining operations in northern Saskatchewan, Canada," *Environ. Health Perspect.*, vol *107*, pp. 527-537, 7, 1999.

[88] A. Baeza, J.A. Corbacho, J. Guillen, A. Salas, J.C. Mora, B. Robles, and D. Cancio, "Enhancement of natural radionuclides in the surroundings of the four largest coal-fired power plants in Spain," *Journal of Environmental Monitoring*, vol *14*, pp. 1064-1072, 3, 2012.

[89] E. Sert, A. Ugur, B. Ozden, M.M. Sac, and B. Camgoz, "Biomonitoring of (210)Po and (210)Pb using lichens and mosses around coal-fired power plants in Western Turkey," *Journal of Environmental Radioactivity*, vol *102*, pp. 535-542, 6, 2011.

[90] A. Ugur, B. Ozden, M.M. Sac, G. Yener, U. Altinbas, Y. Kurucu, and M. Bolca, "Lichens and mosses for correlation between trace elements and Po-210 in the areas near coal-fired power plant at Yatagan, Turkey," *J. Radioanal. Nucl. Chem.*, vol *259*, pp. 87-92, 1, 2004.

[91] I. Othman, and M.S. Al-Masri, "Impact of phosphate industry on the environment: A case study," *Appl. Radiat. Isot.*, vol *65*, pp. 131-141, 1, 2007.

[92] M.J. Amesbury, K.E. Barber, and P.D.M. Hughes, "The relationship of fine-resolution, multi-proxy palaeoclimate records to meteorological data at Fagelmossen, Varmland, Sweden and the implications for the debate on climate drivers of the peat-based record," *Quaternary International*, vol *268*, pp. 77-86, 2012.

[93] M.J. Amesbury, K.E. Barber, and P.D.M. Hughes, "Can rapidly accumulating Holocene peat profiles provide sub-decadal resolution proxy climate data?," *Journal of Quaternary Science*, vol *27*, pp. 757-770, 8, 2012.

[94] K.E. Barber, R.W. Battarbee, S.J. Brooks, G. Eglinton, E.Y. Haworth, F. Oldfield, A.C. Stevenson, R. Thompson, P.G.

Appleby, W.E.N. Austin, et al., "Proxy records of climate change in the UK over the last two millennia: documented change and sedimentary records from lakes and bogs," *Journal of the Geological Society*, vol *156*, pp. 369-380, 2, 1999.

[95] B.R. Persson, *Lead-210, Polonium-210, and stable Lead in the Food-Chain lichen Reindeer and man*, in: The Natural Radiation Environment II J.A.S. Adms, Lowder W. M., and Gesell T. F., Ed. Rice University , Houston, Texas, USA, pp. 347-367.1972.

[96] B.R.R. Persson, E. Holm, and K. Lidén, "Radiolead (Pb-210) and stable lead in lichen Cladonia-alpestris," *Oikos*, vol *25*, pp. 140-147, 2, 1974.

[97] E. Holm, C. Samuelsson, and R.B.R. Persson, *Natural Radioactivity around a prospected Uranium mining site*, in: Natural radiation environment : proceedings of the Second Special Symposium on Natural Radiation Environment, held at Bhabha Atomic Research Centre, Bombay 400 085, India, during January 19-23, 1981 K.G. Vohra, Ed. Bhabha Atomic Research Centre, Bombay 400 085, India: A Halsted Press book.1982.

[98] A. Ugur, B. Ozden, M.M. Sac, and G. Yener, "Biomonitoring of Po-210 and Pb-210 using lichens and mosses around a uraniferous coal-fired power plant in western Turkey," *Atmos. Environ.*, vol *37*, pp. 2237-2245, 16, 2003.

[99] M.S. Al-Masri, S. Mamish, M.A. Al-Haleem, and K. Al-Shamali, "Lycopodium cernuum and Funaria hygrometrica as deposition indicators for radionuclides and trace metals," *J. Radioanal. Nucl. Chem.*, vol *266*, pp. 49-55, 1, 2005.

[100] L. Skuterud, J.P. Gwynn, E. Gaare, E. Steinnes, and K. Hove, "Sr-90, Po-210 and Pb-210 in lichen and reindeer in Norway," *Journal of Environmental Radioactivity*, vol *84*, pp. 441-456, 3, 2005.

[101] N. Malmer, and E. Holm, "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, 1984.

[102] C.R. Hill, "Polonium-210 Content of Human Tissues in Relation to Dietary Habit," *Science*, vol *152*, pp. 1261-1262, 3726, 1966.

[103] Blanchar.R.l., and J.B. Moore, "Body burden, distribution and internal dose of Pb-210 and Po-210 in a uranium miner population," *Health Phys.*, vol *21*, pp. 499-518, 1, 1971.

[104] S. Mattsson, and R.B.R. Persson, *Radioecology of ^{22}Na.^{210}Po and ^{210}Pb in the unique food-chain: Lichen-Reindeer-man*, in: Radioecology applied to the protection of man and his environment, Rome: EUR 4800 d-f-i-e.1971.

[105] R.l. Blanchar, and J.B. Moore, "Pb-210 and Po-210 in tissues of some alaskan residents as related to consumption of caribou or reindeer meat," *Health Phys.*, vol *18*, pp. 127-134, 2, 1970.

[106] C.R. Macdonald, L.L. Ewing, B.T. Elkin, and A.M. Wiewel, "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, 1-3, 1996.

[107] G.A. Klevezal, A.E. Bakhur, V.N. Kalyakin, and N.L. Krushinskaya, "Dynamics of radionuclide concentrations in calcified tissues of reindeer in the western Russian Arctic," *Chemosphere*, vol *42*, pp. 61-67, 1, 2001.

[108] ICRP, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 2. Ingestion Dose Coefficients* in: ICRP Publication, International Commission on Radiological Protection.1994.

[109] P.A. Thomas, I. Fisenne, D. Chorney, and A.S. Baweja, "Human absorption and retention of polonium-210 from caribou meat," *Radiat. Prot. Dosim.*, vol *97*, pp. 241-250, 3, 2001.

[110] J.P. Gwynn, J.E. Brown, K.M. Kovacs, and C. Lydersen, "The derivation of radionuclide transfer parameters for and dose-rates to an adult ringed seal (Phoca hispida) in an Arctic environment," *Journal of Environmental Radioactivity*, vol *90*, pp. 197-209, 3, 2006.

[111] B.L. Tracy, *Exposure of northern Canadians to natural and artificial radioactivity in caribou meat.*, in: Environmental Radioactivity in the Arctic and Antarctic P. Strand, and E. Holm, Ed. Österås, Norway: Norwegian Radiation Protection Authority, pp. 371-374.1993.

[112] P. Kauranen, J. Jaakola, and J.K. Miettinen, *Stable lead and radiolead(210Pb) in the Arctic food chain*, Helsinki, Finland: Dept. of Radiochemistry 1971.

[113] P.V. Ramzaev, M.A. Nevstueva, J.M. Dmitriev, M.S. Ibatullin, E.P. Lisachemko, B.Y. Litver, A.A. Moiseev, A.I. Nignikov, M.N. Troitskaja, and L.A. Harchenke, *Radioactivity in the lichen-reindeer-reindeer herding man food chain in the north of the USSR.*, in: Fifth Symposium on Radioactivity Investigation in Scandinavia J.K. Miettinen, Ed. Helsimki, Finland: Helsinki University.1969.

[114] R.B. Holtzman, and F.H. Ilcewicz, "Renal excretion rates of Pb-210 and Po-210 of northern Canadians," *Health Phys.*, vol *21*, pp. 61-69, 6, 1971.

[115] E. Gaare, and H. Staaland, *Pathways of fallout radiocaesium via reindeer to man*, in: Studies in Environmental Science; Nordic radioecology: The transfer of radionuclides through Nordic ecosystems to man, H. Dahlgaard, Ed., pp. 303-334.1994.

[116] P. Thomas, J. Irvine, J. Lyster, and R. Beaulieu, "Radionuclides and trace metals in Canadian moose near uranium mines: Comparison of radiation doses and food chain transfer with cattle and caribou," *Health Phys.*, vol *88*, pp. 423-438, 5, 2005.

[117] ICRP, "Age-dependent doses to members of the public from intake of radionuclides: Part 2 ingestion dose coefficients.," *Annals of ICRP* vol *23*, pp. 3/4, 1993.

[118] ICRP, *Limits for Intakes of Radionuclides by Workers*, International Commission on Radiological Protection. Protection, Oxford: Pergamon Press 1994.

[119] ICRP, "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*, pp. 1, 1996.

[120] G.J. Hunt, and H.S. Rumney, "The human alimentary tract transfer and body retention of environmental polonium-210," *J. Radiol. Prot.*, vol *27*, pp. 405-426, 4, 2007.

[121] W.M. Burton, and N.G. Stewart, "Use of long-lived natural radioactivity as an atmospheric tracer," *Nature*, vol *186*, pp. 584-589, 4725, 1960.

[122] K. Lidén, and M. Gustafsson, *Relationships and annual variation of 137Cs in lichen, reideer and man in northern Sweden 1961-1965.*, in: Radioecological Concentration Procesesses B. Åberg, and F.P. Hungate, Ed. Oxford: Pergamon Press, pp. 193-208.1967.

[123] A. Rühling, and G. Tyler, "Heavy metal pollution and decomposition of spruce needle litter.," *Oikos*, vol *24*, pp. 402-416, 1973.

[124] A. Rühling, and G. Tyler, *Fallout of heavy metals over Scandinavia (in Swedish)*, in: Dept of Ecological Botany Report. Lund, Sweden: Lund University, pp. 13-16.1972.

[125] F.P. Carvalho, "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 Phys.*, vol *69*, pp. 469-480, 4, 1995.

[126] H. Sugiyama, H. Terada, K. Isomura, I. Iijima, J. Kobayashi, and K. Kitamura, "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, 4, 2009.

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