210Po and 210Pb in the Terrestrial Environment

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Abstract- The natural sources of 210Po and 210Pb 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 210Pb and 210Po also affect the activity concentrations in leafy plants with a deposition transfer factor for 210Pb is in the order of 0.1-1 (m.Bq-i) plants and for root fruits it is < 0.003. Corresponding values for 210Po are about a factor 3 higher.

The activity concentration ratios between milk and various types of forage for 210Pb were estimated to 1.4±0.7 and for 210Po to 0.4±0.09. By a daily food intake of 16 kg dry matter per day the transfer coefficient Fm. for 210Pb was estimated to 0.01±0.008 d.l-1 and for 210Po 0.003 ± 0.0007 d.l-1.

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

Keywords- 210Po; 210Pb; 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 210Po with a half-life of 138.376 days. Long lived artificial isotopes 209Po (half-life 103 a) and 208Po (half-life 2.9 a) can be made by accelerator proton bombardment of lead or bismuth. Although the melting point of polonium is 254 °C and its boiling point is 962 °C, about 50% of polonium is vaporized at 50 °C 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 210Po atmospheric fallout, and its potential health effect on mankind [3, 4]. Together with fallout from the nuclear weapons tests, high activity concentrations of 210Po were found in reindeer and caribou meat at high northern latitudes. This was, however, of natural origin and no evidence of significant contributions of 210Po 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 137Cs and 90Sr [4].

During the 1960th century the presence of 210Po and 210Po 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 210Po. This incident demonstrated the high toxicity of 210Po and resulted in a renaissance for research of bio-kinetics and biological effects of 210Po. Already in 2009 there was an international conference on polonium (Po) and its radioactive isotopes held in Seville, Spain, which was attended by 138 scientists from 38 different countries. The sessions covered all aspects on 210Po and lead (210Pb) 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 210Po and lead (210Pb) in the terrestrial environment.

I. ORIGIN OF 210Po IN THE TERRESTRIAL ENVIRONMENT

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

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

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:

$$^{218}Po (RaA 3.10 \text{ min}) > ^{214}Pb (RaB 26.8 \text{ min}) > ^{214}Bi (RaC 19.9 \text{ min}) > ^{214}Po (RaC 164.3 \text{ ms})$$

The decay products following 214Po are longer lived

$$^{218}Pb (RaD 22.20 \text{ a}) > ^{218}Bi (RaE 5.01 \text{ d}) > ^{218}Po (RaF 138.4 \text{ d}) > ^{206}Po (\text{stable})$$

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

II. ANALYSIS OF 210Po AND 210Pb IN ENVIRONMENTAL SAMPLES

The volatility of 210Po was recognised early as a problem in sample preparation, where losses begin at temperatures...
The atmospheric deposition of 210Po and 210Pb is generally higher over terrestrial areas than oceanic areas including islands. Permafrost, ice and snow covered Pb is commonly performed using “Passivated Implanted Planar Silicon” (PIPS) surface barrier detectors. The radionuclide tracer 208Po or 209Po, and hence 210Po, is recoverable from the resulting alpha-spectrum.

III. ATMOSPHERIC DEPOSITION OF 210Po AND 210Pb

The atmospheric residence time of 210Po varies between 15-75 days with a mean value in the order of 26±3 days. 210Pb 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 210Pb is generally higher over terrestrial areas than oceanic areas including islands. Permafrost, ice and snow covered surface reduce the atmospheric 210Pb concentrations [27]. Atmospheric fallout of 210Po is normally assumed to be constant at any given site, measured on timescales of a year or more. The 210Po 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 210Po fallout on both short and long timescales, and by developing mathematical models of 210Po in the atmosphere [28].

Bulk atmospheric deposition fluxes of 210Po and 210Pb 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 210Pb deposition fluxes at Odawa Bay, Tsuyazaki and Akajima were 73±8, 197±35 and 79±8 Bq.m⁻².a⁻¹ respectively. Higher 210Pb deposition was observed at the Chinese continental side of Japanese coast than at the Pacific Ocean coastal site. The high 210Pb atmospheric flux at the Chinese continental side coast was thought to be attributable to 222Rn-rich air-mass transport from the Chinese continent during the winter monsoon. In contrast, the annual 210Pb 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 210Po deposition at Akajima during winter. Anomalous unsupported 210Pb input was observed during summer 1997, suggesting unknown source of 210Pb at this area [31].

The latitudinal distribution of annual 210Pb deposition summarized from various authors is displayed in Figure 1 [32, 33].
The latitude distribution of annual $^{210}\text{Po}$ deposition was estimated from air filter studies during polar expeditions from the Arctic to Antarctic oceans [33]. The Latitude distribution of annual $^{210}\text{Po}$ deposition shown in Figure 2 was estimated by applying this relation to the $^{210}\text{Pb}$ data displayed in Figure 1.

![Figure 2: Latitudinal distribution of air concentrations of $^{210}\text{Po}$ (µBq.m$^{-2}$). Estimated from: [Latitudinal distribution of $^{210}\text{Pb}$]@ $^{210}\text{Po}$/ $^{210}\text{Pb}$-activity ratio [33]. Mean annual $^{210}\text{Pb}$ 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.

IV. LEVELS OF $^{210}\text{Po}$ AND $^{210}\text{Pb}$ IN THE GROUND

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

The levels of $^{210}\text{Po}$ and $^{210}\text{Pb}$ contained in the top layer of soil can be correlated with the amount of atmospheric precipitation. But the ingrowth from $^{238}\text{U}$ series present in the soil i.e. supported $^{210}\text{Po}$ is the main source of $^{210}\text{Po}$ 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 $^{210}\text{Po}$ content varies with soil type [34].

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

The depth distributions of $^{210}\text{Po}$ 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 $^{210}\text{Po}$ 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,
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].

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

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

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 $^{210}$Pb 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$^{-1}$).

Table 1: Estimates of the $^{210}$Po Activity Concentrations in Ground Water and Drinking Water at Different Locations Around the World [62]

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

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$_{\text{plant}}$) and soil (AC$_{\text{soil}}$) respectively. This activity ratio is called the “Soil Tranfer Factor” (STF):

$$\text{STF} = \frac{\text{AC}_{\text{plant}}}{\text{AC}_{\text{soil}}}$$

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 between various types of crops with an average about 0.056 excluding deposition and 0.074 including deposition.

Table 2: Concentrations in Ground Water and Drinking Water at Different Locations Around the World [62]
TABLE 2 AVERAGE POLONIUM SOIL-TO-PLANT TRANSFER FACTOR FOR CROP GROUPS, CROP COMPARTMENTS AND CROPS/SOIL COMBINATIONS [58, 59].

<table>
<thead>
<tr>
<th>Plant group</th>
<th>min.</th>
<th>Max.</th>
<th>Average STF x 1000</th>
<th>Rel. SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat grain-grain</td>
<td></td>
<td></td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td></td>
<td></td>
<td>7.00</td>
<td></td>
</tr>
<tr>
<td>Vegetables</td>
<td></td>
<td></td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>Grasses</td>
<td></td>
<td></td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Cereals-Grain</td>
<td>0.224</td>
<td>0.26</td>
<td>0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Maize-Grain</td>
<td>0.018</td>
<td>0.466</td>
<td>0.24</td>
<td>1.31</td>
</tr>
<tr>
<td>Rice-Grain</td>
<td></td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Leafy vegetables</td>
<td>0.016</td>
<td>0.37</td>
<td>0.19</td>
<td>1.30</td>
</tr>
<tr>
<td>Non-leafy vegetables</td>
<td>0.06</td>
<td>1.02</td>
<td>0.48</td>
<td>0.96</td>
</tr>
<tr>
<td>Root crops-roots</td>
<td>0.24</td>
<td>49</td>
<td>12</td>
<td>1.38</td>
</tr>
<tr>
<td>Root crops-shoots</td>
<td>58</td>
<td>97</td>
<td>77</td>
<td>0.35</td>
</tr>
<tr>
<td>Tubers</td>
<td>0.143</td>
<td>34</td>
<td>8.0</td>
<td>1.44</td>
</tr>
<tr>
<td>Natural pastures</td>
<td>22</td>
<td>1020</td>
<td>259</td>
<td>1.25</td>
</tr>
<tr>
<td>All cereals</td>
<td>0.018</td>
<td>16.8</td>
<td>3.6</td>
<td>2.09</td>
</tr>
<tr>
<td>Pastures/grasses</td>
<td>18</td>
<td>1020</td>
<td>259</td>
<td>1.25</td>
</tr>
<tr>
<td>Fodder</td>
<td>0.016</td>
<td>97</td>
<td>25</td>
<td>1.40</td>
</tr>
<tr>
<td>All excluding deposition</td>
<td>0.016</td>
<td>1020</td>
<td>56</td>
<td>2.86</td>
</tr>
<tr>
<td>All including deposition</td>
<td>0.016</td>
<td>1020</td>
<td>74</td>
<td>2.16</td>
</tr>
</tbody>
</table>

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 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.

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.

$$DTF = \frac{AP_{DS} - AP_{S}}{AD}$$

The deposition transfer factor DTF for various types of plants was calculated from the published data and is displayed in Figures 7 and 8.
reference value of 60 mBq/kg dw. 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].

### VII. LEVELS OF \(^{210}\)Po AND \(^{210}\)Pb IN FOOD CHAIN GRASS-CATTLE-MILK

#### A. ACTIVITY CONCENTRATIONS OF \(^{210}\)Pb AND \(^{210}\)Po

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

### TABLE 3 ACTIVITY CONCENTRATION OF \(^{210}\)Pb AND \(^{210}\)Po IN VARIOUS MILK AND MEAT PRODUCTS mBq/kg f.w.

<table>
<thead>
<tr>
<th>Country</th>
<th>(^{210})Pb ave mBq/kg f.w.</th>
<th>SD</th>
<th>(^{210})Po ave mBq/kg f.w.</th>
<th>SD</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World wide</td>
<td>25</td>
<td>10</td>
<td>23</td>
<td>10</td>
<td>[63]</td>
</tr>
<tr>
<td>Syria</td>
<td>22.5</td>
<td>194</td>
<td></td>
<td></td>
<td>[76]</td>
</tr>
<tr>
<td>India, Kalpakam</td>
<td>24.6</td>
<td>6</td>
<td>20</td>
<td>4</td>
<td>[77]</td>
</tr>
<tr>
<td>Poland</td>
<td>34</td>
<td>6</td>
<td>48</td>
<td>16</td>
<td>[79]</td>
</tr>
<tr>
<td>UK</td>
<td>35</td>
<td>1</td>
<td></td>
<td></td>
<td>[80]</td>
</tr>
<tr>
<td>Average</td>
<td>32</td>
<td>13</td>
<td>59</td>
<td>77</td>
<td>This work</td>
</tr>
<tr>
<td>Reference value</td>
<td>15</td>
<td>15</td>
<td></td>
<td></td>
<td>[63]</td>
</tr>
<tr>
<td>Meat products</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World wide</td>
<td>67</td>
<td>17</td>
<td>81</td>
<td>13</td>
<td>[63]</td>
</tr>
<tr>
<td>India, Kalpakam</td>
<td>28</td>
<td>6</td>
<td></td>
<td></td>
<td>[77]</td>
</tr>
<tr>
<td>Poland</td>
<td>102</td>
<td>15</td>
<td>101</td>
<td>15</td>
<td>[78]</td>
</tr>
<tr>
<td>UK</td>
<td>34</td>
<td>1</td>
<td></td>
<td></td>
<td>[80]</td>
</tr>
<tr>
<td>Average</td>
<td>81</td>
<td>19</td>
<td>70</td>
<td>38</td>
<td>This work</td>
</tr>
<tr>
<td>Reference value</td>
<td>80</td>
<td>60</td>
<td></td>
<td></td>
<td>[63]</td>
</tr>
</tbody>
</table>

### TABLE 4 THE AVERAGE CONCENTRATIONS (Bq/kg d.m.) 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].

<table>
<thead>
<tr>
<th>Fodder</th>
<th>(^{210})Pb Bq/kg d.m.</th>
<th>SD</th>
<th>(^{210})Po Bq/kg d.m.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.52</td>
<td>0.22</td>
<td>1.26</td>
<td>0.13</td>
</tr>
<tr>
<td>Corn Silage</td>
<td>0.63</td>
<td>0.23</td>
<td>0.59</td>
<td>0.14</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>1.04</td>
<td>0.22</td>
<td>1.59</td>
<td>0.18</td>
</tr>
<tr>
<td>Milk</td>
<td>(^{210})Pb</td>
<td></td>
<td>(^{210})Po</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.92</td>
<td>0.19</td>
<td>0.45</td>
<td>0.07</td>
</tr>
<tr>
<td>Corn Silage</td>
<td>1.38</td>
<td>0.19</td>
<td>0.53</td>
<td>0.03</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.94</td>
<td>0.19</td>
<td>0.58</td>
<td>0.07</td>
</tr>
<tr>
<td>Activity Concentration ratios (^{210})Pb (^{210})Po</td>
<td>(^{210})Pb Bq/kg d.m. (^{210})Po Bq/kg d.m.</td>
<td>ACR</td>
<td>SD</td>
<td>ACR</td>
</tr>
<tr>
<td>Control</td>
<td>1.77</td>
<td>0.83</td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Corn Silage</td>
<td>2.19</td>
<td>0.82</td>
<td>0.51</td>
<td>0.15</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.90</td>
<td>0.26</td>
<td>0.36</td>
<td>0.06</td>
</tr>
</tbody>
</table>

#### 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.
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 (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 \(F_{m}\) 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].

The transfer coefficient \(F_{m}\) for \(^{210}\)Pb and \(^{210}\)Po 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\(_{d.m.}\)) [84].

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

The transfer coefficient \(F_{m}\) describes the fraction of the daily intake of radionuclides that is secreted per litre of milk.
compare with simulation models [92-94].

The impact of climate changes on the environment to profiles of uranium mining [43, 86, 87], coal-fired power plants [88-90], and phosphate industry [91].

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

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

<table>
<thead>
<tr>
<th>Transfer factor</th>
<th>$^{210}\text{Pb}$ Average</th>
<th>SD</th>
<th>$^{210}\text{Po}$ Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow meat</td>
<td>0.0009</td>
<td></td>
<td>0.0006</td>
<td></td>
</tr>
<tr>
<td>Sheep meat</td>
<td>0.0071</td>
<td></td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Poultry meat</td>
<td></td>
<td></td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Poultry Egg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Activity Concentration Ratios (ACR) | $^{210}\text{Pb}$ Average | SD | $^{210}\text{Po}$ Average | SD |

Mosses and Lichens are slow growing perennials that have high interception potentials for aerosols in precipitation, and therefore contain significantly higher $^{210}\text{Po}$ and $^{210}\text{Pb}$ 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 $^{210}\text{Po}$ activity concentrations in Mosses, Lichens, and Peat at different locations are given in Table 8.

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

The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in lichens is typically equal to 1 as $^{210}\text{Po}$ approaches secular equilibrium with $^{210}\text{Pb}$. The activity concentrations in lichens of $^{210}\text{Pb}$ 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].

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

<table>
<thead>
<tr>
<th>Type of plant</th>
<th>Location</th>
<th>$^{210}\text{Po}$ average Bq/kg d.w.</th>
<th>SE</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mosses:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphagnum</td>
<td>N Sweden</td>
<td>443</td>
<td>258</td>
<td>[97]</td>
</tr>
<tr>
<td>Cladonia alpestris</td>
<td>Central. Sweden</td>
<td>250</td>
<td>30</td>
<td>[4]</td>
</tr>
<tr>
<td>Cladonia arbuscula</td>
<td>Vågå Norway</td>
<td>140</td>
<td>27</td>
<td>[100]</td>
</tr>
<tr>
<td>Cladonia arbuscula</td>
<td>E Namdal Norway</td>
<td>141</td>
<td>11</td>
<td>[100]</td>
</tr>
<tr>
<td>Cladonia arbuscula</td>
<td>Dovrejell Norway</td>
<td>138</td>
<td>35</td>
<td>[53]</td>
</tr>
<tr>
<td>Cladonia stellaris</td>
<td>Dovrejell Norway</td>
<td>30</td>
<td></td>
<td>[53]</td>
</tr>
<tr>
<td>Funaria hygrometrica</td>
<td>Sweden</td>
<td>2392</td>
<td></td>
<td>[99]</td>
</tr>
<tr>
<td>Peat:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphagnum</td>
<td>S Sweden</td>
<td>192</td>
<td>37</td>
<td>[101]</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>S Sweden</td>
<td>439</td>
<td>117</td>
<td>[101]</td>
</tr>
<tr>
<td>Polytrichum</td>
<td>N Sweden</td>
<td>630</td>
<td>330</td>
<td>[97]</td>
</tr>
<tr>
<td>Lycopodium cernuum</td>
<td>Syria</td>
<td>1322</td>
<td></td>
<td>[99]</td>
</tr>
</tbody>
</table>

Where
- $C(z)$ = the activity concentration at $z$ [Bq kg$^{-1}$]
- $z$ = the mass depth [kg m$^{-2}$]
- $K(z)$ = the diffusion coefficient, which varies with depth
- $I_o$ = 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 $dz$ at the mass depth $z$
- $\lambda$ = physical decay constant [a$^{-1}$]
- $\kappa$ = rate constant for chemical fixation [a$^{-1}$]
- $\theta$ = rate constant for biological degradation through growth and decomposition [a$^{-1}$]
- $k_{eff}$ = the effective rate-constant 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
between 111 to 481 Bq/kg. This was shown to be true also for reindeer from different regions [107]. The 210Pb in bone of reindeer from 1989–74 varied between 490 and 800 Bq/kg [106]. This compares well with the level of 170±190 Bq/kg found in Finnish reindeer during 1964-67 [19].

By letting 14 volunteers consume 2.0 kg of caribou meat containing 9–40 Bq/kg, 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 210Po and 210Pb in reindeer during 2000-2003 focused on differences in ages. Concentrations of 210Po and 210Pb in muscle and liver tissues were comparable to those reported for reindeer in other Nordic areas, with no significant difference in 210Po and 210Pb concentrations between adults and calves or between reindeer from the two different study areas. Mean 210Po activity concentrations in muscle tissues, collected in December 2000 at Vargå, were 23.7±3.7 Bq/kg f.w. in calves and 35.5±9.2 Bq/kg f.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 210Pb and 210Po activity concentrations determined in muscle and liver tissue from Norway were similar to values reported from other Nordic areas [16, 19, 95, 100, 110, 111].

B. 210Po and 210Pb in lichen-reindeer-man

The activity concentrations of 210Pb in reindeer meat varies between 200 and 1200 mBq/kg f.w. with an average of 500±100 mBq/kg f.w. The activity concentrations of 210Po in reindeer meat varies between 1700 and 13300 mBq/kg f.w. with an average of 7800±1300 mBq/kg f.w. This maintains about 12 times higher 210Po concentration in soft tissues of residences regularly consuming caribou or reindeer meat.

Results of 210Po and 210Pb activity concentrations in reindeer and caribou meat 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 210Pb the annual average activity concentrations in reindeer meat was ten times lower, 0.22±0.04 Bq/kg f.w., with less seasonal fluctuation. This maintains about 12 times higher 210Po 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].

210Po average activity concentrations in Swedish reindeer meat 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 210Pb 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 210Pb 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 210Po and 210Pb 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 210Pb 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, 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 210Po and 210Pb in reindeer during 2000-2003 focused on differences in ages. Concentrations of 210Po and 210Pb in muscle and liver tissues were comparable to those reported for reindeer in other Nordic areas, with no significant difference in 210Po and 210Pb concentrations between adults and calves or between reindeer from the two different study areas. Mean 210Po activity concentrations in muscle tissues, collected in December 2000 at Vargå, were 23.7±3.7 Bq/kg f.w. in calves and 35.5±9.2 Bq/kg f.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 210Pb and 210Po activity concentrations determined in muscle and liver tissue from Norway were similar to values reported from other Nordic areas [16, 19, 95, 100, 110, 111].

Po average activity concentrations in reindeer meat samples collected in various countries. The average activity concentration of 210Po is 0.6±0.2 Bq/kg f.w. and for 210Po 6.8±1.0 Bq/kg f.w. [12, 19, 95, 100, 104, 112, 113].
During winter the fraction of daily radionuclide intake of $^{210}\text{Po}$ from lichen that is transferred to reindeer meat varies between 0.04 and 0.06 day/kg [115].

Results of $^{210}\text{Po}$ and $^{210}\text{Pb}$ activity concentrations in reindeer meat samples collected in various countries are given in Figure 16 as well as the $^{210}\text{Po}$ activity transfer coefficient from lichen to reindeer meat 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, $^{210}\text{Po}$ and $^{210}\text{Pb}$ in Moose

$^{210}\text{Pb}$, and $^{210}\text{Po}$ 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 $^{210}\text{Pb}$ and $^{210}\text{Po}$ 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 $^{210}\text{Po}$ 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 $^{210}\text{Pb}$ and $^{210}\text{Po}$ 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 $^{210}\text{Po}$ in liver was similar to a second positive control area with mineral-rich shale hills. In cattle kidneys the activity concentration of $^{210}\text{Po}$ 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].

### D, $^{210}\text{Po}$ and $^{210}\text{Pb}$ in Man

A steady state model considering the fraction of annual or daily intake of $^{210}\text{Pb}$ or $^{210}\text{Po}$ 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].
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:

\[ R_i \cdot C_i \cdot f_i = M_i \cdot C_i \cdot k_a \quad \text{(Bq.a}^{-2}) \quad \text{or} \quad \text{(Bq.d}^{-2}) \]

The ratio \( f_i/k_a \) characterize the “metabolic” behaviour of the actual step in the chain is called “fractional residence time \( \tau \)"

\[ \tau \equiv f_i/k_a = (M_i \cdot C_i)/(R_i \cdot C_i) = A/I; \]

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

where

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

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

\[ \tau \equiv (f + g)/k_a = A_{ao}/I_{pc}; \text{ a} \text{ or d} \]

The average median daily intakes of \( ^{210}\text{Po} \) for the adult world population from terrestrial products is estimated to be in the range of \( 20-300 \text{ Bq.a}^{-1} \) with an average of \( 80-60 \text{ Bq.a}^{-1} \). That corresponds to a committed annual effective dose of \( 91 \pm 70 \mu\text{Sv.a}^{-1} \) for \( ^{210}\text{Po} \) from terrestrial products. The dietary intakes of \( ^{210}\text{Po} \) and \( ^{210}\text{Pb} \) from vegetarian food, however, was estimated to correspond to annual effective doses of only about \( 30 \mu\text{Sv.a}^{-1} \) and \( 10 \mu\text{Sv.a}^{-1} \) respectively [22].

VIII. RADIATION EXPOSURE OF \( ^{210}\text{PO} \) INTAKE.

According to the model recommended by the International Commission on Radiological Protection (ICRP) about 10–50% of ingested \( ^{210}\text{Po} \) 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 \( ^{210}\text{Po} \) material of workers was in a form with fast or moderate absorption to the blood. But for members of the public, 50% of ingested \( ^{210}\text{Po} \) 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 \( ^{210}\text{Po} \) for adult members of the public recommended by ICRP is 1.2 \( \mu\text{Sv.a}^{-1} \) respectively considering a transfer coefficient of 50% for ingestion of \( ^{210}\text{Po} \) [117, 120]. That is the highest value for any of the natural radionuclides \( ^{3}\text{H}, \text{Be}, ^{14}\text{C}, ^{23}\text{Na}, ^{40}\text{K}, ^{238}\text{U(series); } ^{232}\text{Th(series) or } ^{235}\text{U(series) [63].} \)

In Table 11 is given the minimum and maximum annual dose equivalent of \( ^{210}\text{Po} \) 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>
<thead>
<tr>
<th>TABLE 11 THE MINIMUM AND MAXIMUM ANNUAL DOSE EQUIVALENT OF ( ^{210}\text{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].</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food Product</strong></td>
</tr>
<tr>
<td>Drinking water</td>
</tr>
<tr>
<td>Cereals</td>
</tr>
<tr>
<td>Leafy vegetables</td>
</tr>
<tr>
<td>Root vegetables and fruit</td>
</tr>
<tr>
<td>Milk products</td>
</tr>
<tr>
<td>Meat products</td>
</tr>
<tr>
<td>Terrestrial Products</td>
</tr>
<tr>
<td>Marine products</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

For inhalation of \( ^{210}\text{Po} \) aerosols assuming 10% absorption to the blood the recommended effective dose...
coefficient is 3.3 $\mu$Sv·Bq$^{-1}$ [119]. The committed effective dose equivalent by breathing inhalation of natural $^{210}$Po aerosols (50 $\mu$Bq·m$^{-3}$) has been estimated to be about 1.2 $\mu$Sv·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 $\mu$Sv·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

<table>
<thead>
<tr>
<th>TYPE OF DIET</th>
<th>$^{210}$Pb</th>
<th>$^{210}$Po</th>
</tr>
</thead>
<tbody>
<tr>
<td>World average:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual intake (Bq·a$^{-1}$)</td>
<td>40</td>
<td>58</td>
</tr>
<tr>
<td>Annual DE ($\mu$Sv·a$^{-1}$)</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Vegetarians intake:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual intake (Bq·a$^{-1}$)</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>Annual DE ($\mu$Sv·a$^{-1}$)</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Marine Food Intake:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual intake (Bq·a$^{-1}$)</td>
<td>321</td>
<td>467</td>
</tr>
<tr>
<td>Annual DE ($\mu$Sv·a$^{-1}$)</td>
<td>222</td>
<td>561</td>
</tr>
<tr>
<td>Reindeer Meat Intake:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual intake (Bq·a$^{-1}$)</td>
<td>90</td>
<td>1700</td>
</tr>
<tr>
<td>Annual DE ($\mu$Sv·a$^{-1}$)</td>
<td>60</td>
<td>2000</td>
</tr>
</tbody>
</table>

REFERENCES


[109] F.P. Carvalho, "Po-210 and Pb-210 Intake by The Portuguese Population - The Contribution of Seafood in the Dietary-


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