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In memory of my fellow Elis Holm Ph.D. professor

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In memory of my fellow Elis Holm, Ph.D. professor

ANALYSIS AND MODELLING RADIOECOLOGICAL CONCENTRATION PROCESSES OF THE FOOD CHAIN LICHEN - REINDEER – MAN

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Abstract

At the first international radioecology conference 25-29 April 1966, in Stockholm, Sweden, I presented a study about the transfer of ^{55}Fe in the food chain lichen-reindeer-man. This present paper was presented on the 6th-9th, November, 2016 in Seville (Spain) for the 2nd INTERNATIONAL CONFERENCE ON RADIOECOLOGICAL CONCENTRATION PROCESSES (50 years later) which was organized by prof. Elis Holm, University of Gothenburg (Sweden) and prof. Rafael Garcia-Tenorio, University of Seville (Spain).

Analysis and modelling of the natural radioactive ^{210}Pb and ^{210}Po in the same food-chain was performed by using the methods of Partial Least Square regression (PLS-r) information about the atmospheric deposition of ^{210}Pb and ^{210}Po is derived from local precipitation data. The result of modelling the activity concentration in lichen is compared with experimental sample data collected during 1966-1971.

Data about reindeer lichen consumption, gastrointestinal absorption and organ distribution is derived from information in the literature. The results of modelling the transfer of ^{210}Pb and ^{210}Po to reindeer meat, liver and bone from lichen consumption is compared with measurements of samples collected in Sweden and Finland during 1966-1971.

Finally, the results of modelling ^{210}Pb and ^{210}Po activity concentration in various organs of man is compared with samples collected from reindeer breeders in Sweden and Finland during 1966-1971. The activity concentration of ^{210}Pb in the skeleton is modelled by using the results of studying the kinetics of lead in skeleton and blood in lead-workers after end of occupational exposure. The result of modelling ^{210}Pb and ^{210}Po activity in skeleton is compared with samples of teeth from reindeer-breeders and autopsy bone samples in Finland.

Keywords: Radioecology pathways, PCA, PLSr

I. Introduction

Radioecology is the study of the pathways of radionuclides released into the environment. The endpoint is the estimation of the radiation absorbed dose and the risk detrimental effects on various species including man. If the source is unknown the first step is usually to collect samples at different steps on the path in question. Usually aquatic and terrestrial pathways are separated and this presentation deals with terrestrial radioecology only.

Radio-ecological investigations usually study the radioactivity in various samples in relation to the latitude and longitude coordinates as well as and the time of sampling occasion. It is also important to record the fresh to dry weight ratio of the various samples and other parameters of important for analysing and modelling of the radio-ecological pathways.

The radio-ecological pathways considered in the present terrestrial model are the following:

A. Atmospheric deposition on the ground
B. Direct input to vegetation due to atmospheric deposition
C. Input to vegetation due to uptake from the ground
D. Intake rate of vegetation by animals or vegetables by man
E. Intake rate of full diet by animals and man
F. Activity concentration in diet
G. Gastrointestinal absorption of Activity in diet
H. Activity concentration in various organs and tissues

Definition of model parameters:

Rate of atmospheric radionuclide deposition

$DR(t)$ is the annual rate of radionuclide deposition ($Bq.m^{-2}.a^{-1}$);

Transfer to vegetation by deposition:

Input rate is equal to deposition and the deposited activity ($Bq.m^{-2}$) is converted to activity per unit of dry weight ($Bq.kg_{dw}^{-1}$).

P_{SB} is the standing biomass density i.e. ratio of vegetation surface standing above soil to dry mass of vegetation ($kg_{dw}\cdot m^{-2}$)

kV is the elimination rate due to various processes

Transfer to vegetation by uptake from soil:

Transfer factor, the ratio of activity-concentration in plant and activity concentration in soil

Rate of intake per body weight

The food intake varies due to the body mass of the subject (animal or man).

IR ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$) is the intake rate $kg_{dw}.a^{-1}$ by a subject of bodyweight kg_{bw}.

Gastrointestinal absorption (GIA)

The amount of activity absorbed by the body varies a lot with the type of radioactivity and diet.

Fraction of absorbed activity that goes to a specific organ.

In radio-ecological modelling one assume that a physiological equilibrium of input and output from the various organs and tissues is established. Thus the distribution of radioactivity is in steady state

ODF is the fraction of absorbed activity in the total body that is retained in the tissue or organ "O" (Bq_O/Bq_B)

Ratio of body mass kg_{bw} and mass of tissue or organ RBO

In order to convert to concentrations, it is necessary to establish the ratio of body mass to the weight of the organ ($kg_{bw}.kg_{fw}^{-1}$). This factor is usually given in dissection protocols.

Rate constant for the excretion of the radionuclide from the body.

By assuming physiological equilibrium, the excretion rate of the radioactivity from the total body is considered.

k_B is the elimination rate of the specific radionuclide from the body.

Rate constant for the physical decay of the radionuclide:

λ is the decay constant of radionuclide in question.

My first radio-ecological study was about iron-55 in the food chain lichen-reindeer-man, presented in 1966 at the first international radioecology conference (Persson, 1966).

Now 50 years later I will use the food chain lichen-reindeer and man as an example for dynamic modelling of radio-ecological concentration processes due to atmospheric fallout of ^{210}Pb and ^{210}Po.

The main structure of the "lichen-reindeer-man" food chain model is shown in **Figure 1-1**.

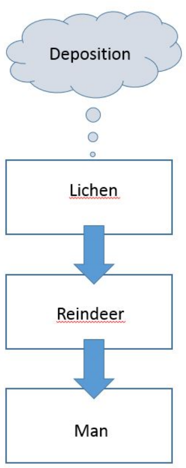

Figure 1-1

The food chain lichen reindeer man

The mathematical description of the Lichen-Reindeer-Man "L-Rd-M" pathway in this food chain is represented by a system of linear differential equations one for each step (i) in the food chain.

$$\frac{dA_i}{dt} = \mathcal{F}(A_{i-1})[input] - \mathcal{F}(A_i)[output]$$

Step 1

The first step is the atmospheric deposition of the radioactivity to the top layer of lichen at a rate DR $Bq.m^{-2}.a^{-1}$. The elimination of the activity from the top layer depend on the radioactivity decay constant of the radionuclide in question λ and the transfer rate to deeper layer kL. The activity concentration "ACL(t)" in the top-layer of lichen "L" that is grazed by the reindeer is described by the equation:

$$\frac{dACL(t)}{dt} = DR(t) \cdot P_{SB} \cdot IF - ACL(t) \cdot (kL + \lambda)\ ; \quad [Bq.\ kg_{dw}^{-1}.\ a^{-1}]$$

where

ACL(t)	is the radionuclide activity concentration in Lichen at time t after deposition ($Bq.kgdw^{-1}$);
$DR(t)$	is the annual rate of radionuclide deposition ($Bq.m^{-2}.a^{-1}$);
P_{SB}	is the standing biomass density i.e. ratio of vegetation surface standing above soil to dry mass of vegetation ($kg_{dw} \cdot m^{-2}$): P_{SB} = 0.63 for lichen
IF	is the *Interception fraction* . defined as the ratio of the activity retained by the vegetation A_R [$Bq.m^{-2}$] standing above soil, to the total activity deposited A_D [$Bq.m^{-2}$]: IF = 1 for lichen
k_L	is the elimination rate constant from Lichen
λ	is the decay constant of radionuclide in question

Step 2

The activity concentration in the tissue or organ in question is described by a model displayed in **Figure 1-2**.

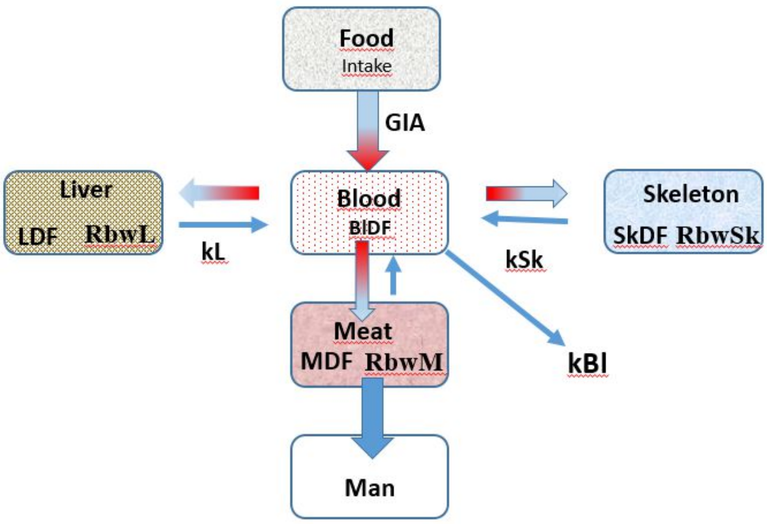

Figure 1-2
Model of the organ distribution of the radioactivity intake by reindeer

This simplified model of the organ and tissue distribution of the radioactivity consumed by reindeer is characterized of following parameters.

Body parameters
The intake rate of lichen per bodyweight of reindeer IRdL ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$) and the ratio of body mass kg_{bw} and mass of organ or tissue in question ($kg_{bw}.kg_{fw}^{-1}$) RbwO. These parameters are taken from reindeer research reports.

Model parameters
The fraction of consumed radioactivity, $\mathrm{IRdL} \cdot \mathrm{ACL}(t)$, that is absorbed by the body is the gastrointestinal absorption GIA. This parameter is taken from scientific reports as well as the fraction of absorbed activity that goes to the tissue or organ ODF. The factor BO (kg_{bw} kg_{fw}^{-1}) convert to activity concentration in the organ in question. The elimination of the activity from the organ depend on the radioactivity decay constant of the radionuclide in question λ and the elimination rate kO.

$$\frac{d\mathrm{ACO(t)}}{dt} = \mathrm{IRdL} \cdot \mathrm{ACL}(t) \cdot GIA \cdot \mathrm{ODF} \cdot B\mathrm{O} - \mathrm{ACO}(t) \cdot (kO + \lambda);$$

$$(kg_{dw}.a^{-1}.kg_{bw}^{-1})\ (Bq.kg_{dw}^{-1})\ (kg_{bw}\ kg_{fw}^{-1}) = [Bq.kg_{fw}^{-1}\cdot a^{-1}]$$

where

- IRdL is the lichen intake (kg_{dw}) rate by reindeer per kg of bodyweight ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$)
- ACL is the radionuclide activity concentration in lichen at time t after deposition ($Bq.kgdw^{-1}$);
- GIA Gastrointestinal absorption or the radionuclide
- ODF is the fraction of absorbed activity that goes to the tissue or organ in question
- BO is the ratio of body mass kg_{bw} and mass of tissue or organ ($kg_{bw}.kg_{fw}^{-1}$)
- ACO is the radionuclide activity concentration in The tissue or organ in question ($Bq.kg_{fw}^{-1}$);
- λ is the decay constant of radionuclide (a^{-1});
- kO is the elimination rate constant from the body (a^{-1})

This model is used for fitting the analytical results of samples taken from lichen and various organs and tissues from reindeer and man that will be exemplified in the following presentation.

II. Atmospheric Deposition input to Lichen

II.1 Atmospheric Deposition of ^{210}Pb and ^{210}Po

In the effort of modelling the global distribution ^{210}Pb and ^{210}Po in surface air, the results from exploration of radioactivity exploration from the Arctic to the Antarctic during 1980 to 1996 are compiled with the results reported by other authors (Persson and Holm, 2014, Persson, 2015). Partial least square regression modelling PLS-regression, predict missing ^{210}Pb and ^{210}Po values of air concentration or annual deposition.

The ^{210}Pb deposition rate was estimated to 12.5 ± 0.7 mm.s^{-1} with no significant variation with latitude, height, or average of interval of sampling date. With longitude, however, the ^{210}Pb deposition rate varied significantly (linear k=0.02) R=0.99.

In order to find an equation to predict the deposition of ^{210}Pb from rainfall reported data of correlated annual rainfall and deposition of ^{210}Pb was modelled with *Projection to Latent Structures*, PLS-regression (Persson, 2016). This resulted in the following equation:

$$^{210}\mathbf{Pb_{dep.}} = \mathbf{70.703 + 0.032{\times}Height + 0.205{\times}Lat. + 0{,}601{\times}Long. + 0.0829{\times}Rain}\ (\mathrm{Bq.m^{-2}.a^{-1}})$$

Reported values of ^{210}Pb deposition (in black dots) and the predicted values of equation above ((in red dots) and lineat fit with 95% prediction and concidence limis are given in the **Figures 2-1** versus longitude.

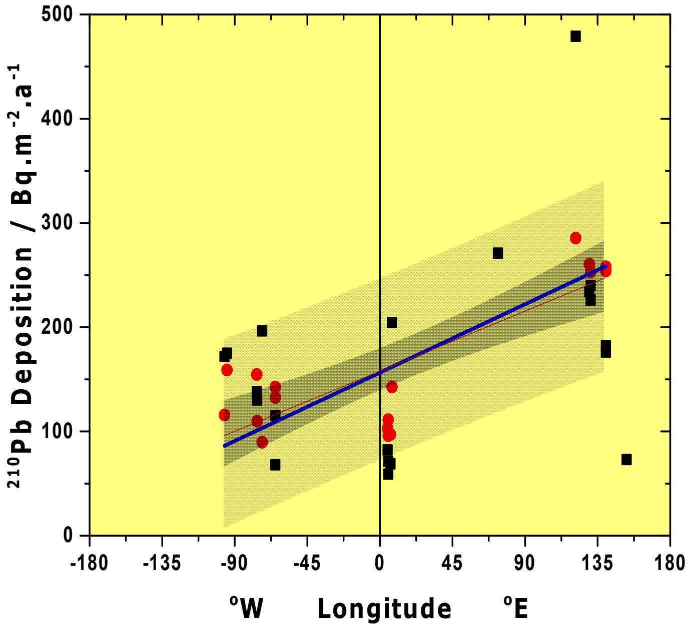

Figure 2-1

Reported values of ^{210}Pb deposition (in black dots) and the predicted values of equation above ((in red dots) and linear fit with 95% prediction and coincidence limis are displayed vesus longitude.

This equation was used to predict the deposition of ^{210}Pb at the sampling station Lake Rogen (62.3 °N,12.4 °E, height 758 m a.s.l.), from reported annual precipitation data at Myskelåsen 12 km NE of the sampling station and the results are displayed in **Figure 2-2** and **Table 2-1**.

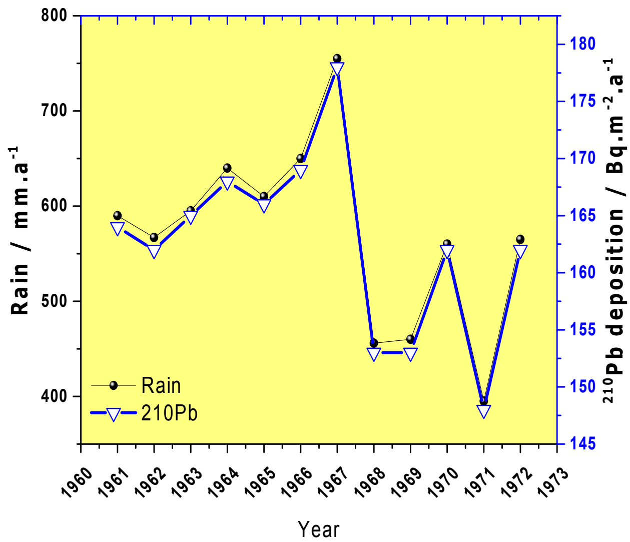

Figure 2-2

Annual precipitation data and predicted value of annual ^{210}Pb deposition-rate "DR(t) at the sampling station Lake Rogen

Table 2-1

Annual precipitation data and predicted value of annual ^{210}Pb deposition-rate "DR(t) at at the sampling stationLake Rogen

Year	Rain	^{210}Pb
	mm	Bq.m^{-2}.a^{-1}
1961	590	164
1962	567	162
1963	595	165
1964	640	168
1965	610	166
1966	650	169
1967	755	178
1968	456	153
1969	460	153
1970	560	162
1971	395	148
1972	565	162

The latitudinal and longitudinal distribution of the ^{210}Po/^{210}Pb activity ratio was modelled by PLS regression analysis of the values recorded at the Swedish Polar Research expeditions (Persson and Holm, 2014). The PLS regression modelling of the ^{210}Po/^{210}Pb activity ratio with latitudes and longitudes resulted in following equation:

$$\mathbf{{}^{210}Po/{}^{210}Pb = 0.542 + 1.13 \cdot 10^{-3} \times (Lat.) + 2.85 \cdot 10^{-3} \times (Long.)}$$

By using this equation, the air concentrations and deposition values are estimated from reported ^{210}Pb values of either air concentration or annual deposition. The ^{210}Po/^{210}Pb activity ration of the atmospheric deposition for the Rogen area (62.3°N, 12.4°E) estimated by this equation is about 0.7.

II.2 Activity concentration of ^{210}Pb and ^{210}Po in lichen "L":

The activity concentration "ACL(t)" in the top-layer of lichen "L" that is grazed by the reindeer is described by the equation:

$$\frac{dACL(t)}{dt} = fmaL \cdot DR(t) - ACL(t) \cdot (kL + \lambda) \; ; \quad [\text{Bq. kgdw}^{-1}.\ \text{a}^{-1}]$$

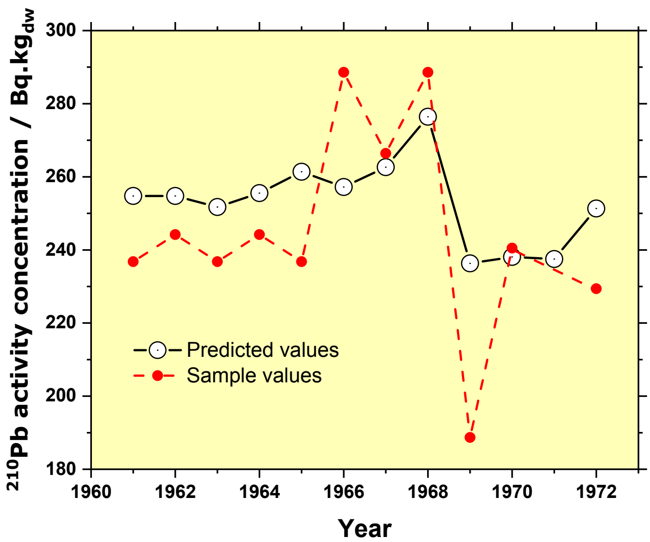

Figure 2-3

Modelled activity concentration of ^{210}Pb in lichen "A(Bq.kg$_{dw}$) (in open circles as well as experimental sample values in red dots (Persson et al., 1974, Persson, 1974).

These values agree quite well with the ^{210}Pb average activity concentration of 263 ± 42 Bq.kg$_{dw}^{-1}$ of lichen samples collected in Finland (Kauranen and Miettinen, 1969).

The $^{210}Po/^{210}Pb$ activity ratio in lichens is typically close one 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$_{d.w.}$ The average $^{210}Po/^{210}Pb$-activity ratio recorded is about 0.9, in agreement with the value in **Table 2-1** for an annual cycle of ^{210}Pb deposition.

III. Modelling ^{210}Pb and ^{210}Po in Reindeer

3.1 The model for ^{210}Pb and ^{210}Po in Reindeer meat

The model for predicting the activity concentration "ACRM(t)" in the fresh reindeer meat "O=RM" is described by the equation:

$$\frac{d\text{ACRM(t)}}{dt} = \text{IRL} \cdot \text{ACL}(t) \cdot GIA \cdot \text{RMDF} \cdot BRM - \text{ACRM}(t) \cdot (kRM + \lambda);$$

$$(\text{kg}_{\text{dw}}.\text{a}^{-1}.\text{kg}_{\text{bw}}^{-1})\ (\text{Bq.kg}_{\text{dw}}^{-1})\ (\text{kg}_{\text{bw}}\ \text{kg}_{\text{fw}}^{-1}) = [\text{Bq.kg}_{\text{fw}}^{-1}\cdot\text{a}^{-1}]$$

The average value of ^{210}Pb in fresh reindeer meat in central Sweden and northern Scandinavia varies between 250 and 600 mBq/$\text{kg}_{\text{f.w.}}$ with an average of 360±50mBq/$\text{kg}_{\text{f.w.}}$(Persson, 1970a, Persson, 1972, Persson, 1974, Kauranen and Miettinen, 1969, Kauranen et al., 1971, Skuterud et al., 2005).

The average value of ^{210}Po in fresh reindeer meat in central Sweden and northern Scandinavia varies between 2.8 and 13.3 Bq/$\text{kg}_{\text{f.w.}}$ with an average of about 9 Bq/$\text{kg}_{\text{f.w.}}$(Persson, 1970a, Persson, 1972, Persson, 1974, Kauranen and Miettinen, 1969, Kauranen et al., 1971, Skuterud et al., 2005).

3.1.1 Modelling of ^{210}Pb and ^{210}Po in Reindeer meat in Rogen area (Persson 1972)

Modelling parameters for intake of ^{210}Pb:

Activity concentration "ACRM(t)" of ^{210}Pb in the fresh reindeer meat "RM" that is consumed man is modelled with the parameters in **Table 3-1**. The mean consumption rate of lichen for 11 reindeer was estimated to be 1.42 ± 0.08 kg/day of dry lichen or 16.4 ± 0.55 g/day per kg body weight (Holleman et al., 1979). Assuming lichen feeding only half of the year and a body weight of 80 kg, the annual consumption is estimated to 3 $\text{kg}_{\text{dw}}.\text{a}^{-1}\cdot\text{kg}_{\text{bw}}$.

Table 3-1 Modelling parameters of ^{210}Pb in Reindeer meat in Rogen area

Reindeer	IRL	GIA	RMDF	BRM	kRM	^{210}Pb	^{210}Po
ACRM(t) Bq.$\text{kg}_{\text{fw}}^{-1}$	$\text{kg}_{\text{dw}}.\text{a}^{-1}.\text{kg}_{\text{bw}}^{-1}$			$\text{kg}_{\text{bw}}\ \text{kg}_{\text{fw}}^{-1}$	a^{-1}	a^{-1}	a^{-1}
Meat	3	0,01	0.01	2,4	0,66	0.0311	1,828

Table 3-2
Activity concentration ACL of ^{210}Pb and ^{210}Po
in lichen used in reindeer meet model at Rogen

Year	^{210}Pb Bq.kgdw^{-1}	^{210}Po Bq.kgdw^{-1}
1961	255	230
1962	255	230
1963	252	227
1964	256	230
1965	261	235
1966	257	231
1967	263	237
1968	276	248
1969	236	212
1970	238	214
1971	238	214
1972	252	226

The result of activity concentration in reindeer meat modelled by using values of the various parameters in **Table 3-1** and the annual activity concentration of lichen varying between 242 and 264. The results of about 0.8 $Bq.kg_{fw}^{-1}$ agree pretty well with the few experimental data reported in the literature (Ramzaev et al., 1969, Persson, 1972, Persson, 1974, Kauranen and Miettinen, 1969, Kauranen et al., 1971, Skuterud et al., 2005).

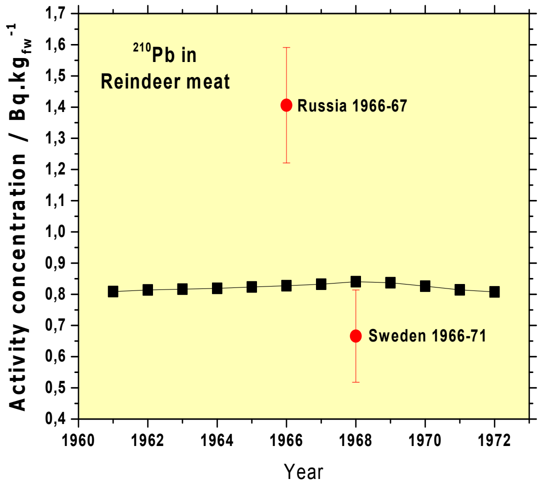

Figure 3-1

Result of modelling activity concentration in reindeer meat and experimental values from Russia and Sweden (Ramzaev et al., 1969, Persson, 1972, Persson, 1974).

Modelling parameters for intake of ^{210}Po:

Activity concentration "ACRM(t)" of ^{210}Po in the fresh reindeer meat "RM" that is consumed man is modelled with the parameters in **Table 3-3**.

Table 3-3 modelling parameters of ^{210}Po in Reindeer meat in Rogen area

Reindeer	IRL	GIA	RMDF	BRM	kRM	^{210}Pb	^{210}Po
ACRM(t) $Bq.kg_{fw}^{-1}$	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	a^{-1}	a^{-1}	a^{-1}
Meat ^{210}Po	3	0,4	0.084	2,4	6,2	0.0311	1,828

A GIA value of 0.4 for reindeer consuming lichen is considered here. Data from humans consuming reindeer meat containing ^{210}Po indicated absorption of about 0.3–0.7 (Hill, 1965, Kauranen and Miettinen, 1967, Ladinska. et al., 1973, Thomas et al., 2001b). The value of 0.5 is recommended to Po in foodstuffs (ICRP, 1993).

The fraction of ^{210}Po activity that goes to the meat RMDF is estimated to 0.084 (Henricsson and Persson, 2012). Ratio of reindeer body mass and mass of muscle tissue BRM = 2,4 (kg_{bw} kg_{fw}^{-1}).

The elimination rate constant of ^{210}Po ($T_{½}$=50 d) from muscle tissue in reindeer is kM = 6.2 (a^{-1}) (Henricsson and Persson, 2012).

The ingrowth of ^{210}Po from ^{210}Pb as a function of time T is estimated by the equation:

$$[ACPo_T] = [ACPb_{To}] \cdot 1.017 \cdot [e^{-0,03 \cdot T} - 0,0363 \cdot e^{-50,5 \cdot T} - e^{-1,83 \cdot T}]$$

As seen in **Figure 3-2** the ingrowth of ^{210}Po from ^{210}Pb present in reindeer meat quite low compared to the ^{210}Po due to intake.

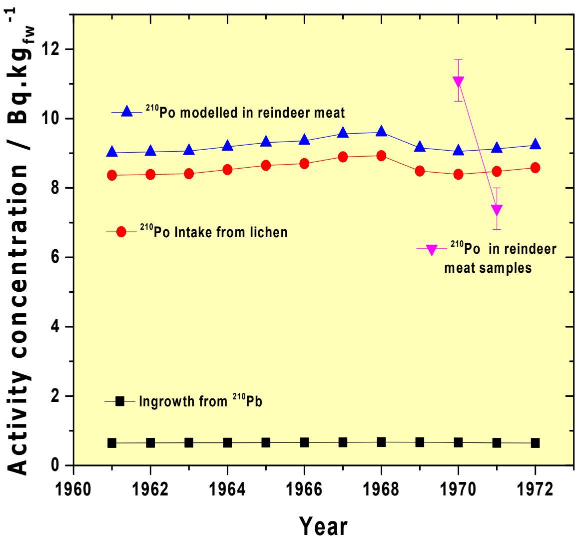

Figure 3-2

Activity concentration of ^{210}Po in reindeer meat in Funäsdalen, Sweden.

3.1.2 Modelling Reindeer meat in Inari area (Kauranen and Miettinen, 1969)

^{210}Pb and ^{210}Po activity concentration in Reindeer meat collected at various moths during the period 1964-67 from Inari are given in **Table 3-4** (Kauranen and Miettinen, 1969).

Table 3-4
Sample measurements of ^{210}Pb and ^{210}Po in fresh reindeer meat from Inari (Kauranen and Miettinen, 1969).

Sampling Year	Month	Bq/kg$_{fw}$ ^{210}Po	Bq/kg$_{fw}$ ^{210}Pb
1966	8	3,2	0,12
1967	10	3,0	0,27
1964	12	4,8	
1965	12	5,4	0,17
1967	3	12,4	0,30
Average	10	6,4	0,25
SD		3,6	0,05

Modelling parameters for intake of ^{210}Pb:

The activity concentration in Lichen was simulated randomly around the average 263 ± 42 Bq.kg$_{dw}^{-1}$ (Kauranen and Miettinen, 1969).
The annual variation of **^{210}Pb** activity concentration in reindeer meat in Inari is modelled by using values of the various parameters in **Table 3-5**.

Table 3-5 modelling parameters of ^{210}Pb in Reindeer meat in Inari area

Reindeer	IRL	GIA	RMDF	BRM	kRM	^{210}Pb	^{210}Po
ACRM(t) Bq.kg$_{fw}^{-1}$	kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$			kg$_{bw}$ kg$_{fw}^{-1}$	a^{-1}	a^{-1}	a^{-1}
Meat ^{210}Pb	3	0,01	0.01	2,4	0,66	0.0311	1,828

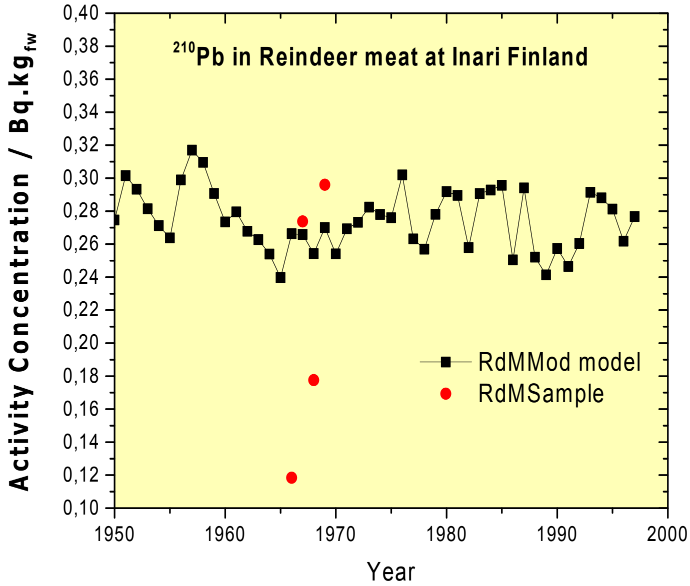

Figure 3-3

Result of modelling the ^{210}Pb activity concentration in reindeer meat at Inari the red dots are sample data from Inari (Kauranen and Miettinen, 1969)

Modelling parameters for intake of ^{210}Po:

Due to the short halftime of ^{210}Po compared to ^{210}Pb the timescale for modelling of ^{210}Po is taken to months instead of years. The ^{210}Po activity in green food intake during the summer period April-September is also considerd.

The monthly intake rate of lichen by reindeer per kg of body weight (80 kg_{bw}) during Oct-March "ILR" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$). The activity concentration of ^{210}Po in Lichen PoACL during this period is estimated to 270 ($Bq.kg_{dw}^{-1}$).

The monthly intake rate of green food "G" by reindeer per kg of body weight (80 kg_{bw}) during April –Sept "IRG" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$). The activity concentration of ^{210}Po in green food PoACG during this period is estimated to = 6,5 ($Bq.kg_{dw}^{-1}$).

Data from humans consuming reindeer meat containing ^{210}Po indicated a fraction of GI-absorption of about 0.3 – 0.7 (Hill, 1965, Kauranen and Miettinen, 1967, Ladinska. et al., 1973, Thomas et al., 2001b). The value of 0.5 is recommended to Po in foodstuffs (ICRP, 1993). For modelling the intake of ^{210}Po in reindeer GIA = 0.2 is considered.

The fraction absorbed ^{210}Po activity that goes to the meat is estimated to RMDF = 0.09 and the elimination rate kM = 0.53 ($month^{-1}$) (Henricsson and Persson, 2012).

The activity of ingrown ^{210}Po:

The model for predicting the activity concentration of ^{210}Po in reindeer organs O "ACOPo(t)" in the fresh reindeer organ take into account the ingrowth of ^{210}Po from ^{210}Pb also present in the organ:

Activity of Polonium

$$[APo(t)] = [Po] \cdot \lambda_{Po} = \frac{\lambda_{Po}}{(\lambda_{Po} - \lambda_{Pb})} [APb_0] \cdot (e^{-\lambda_{Pb} * t}) = 1{,}01731[APb(t)]$$

$$\frac{dACOPo(t)}{dt} = \mathrm{IRL} \cdot \mathrm{ACL}(t) \cdot GIA \cdot \mathrm{ODF} \cdot BO + \lambda_{Po} \cdot 1.02 \cdot ACOPb(t) - (kO + \lambda_{Po}) \cdot [ACOPo(t)]$$

ACOPo(t) is the ^{210}Po activity concentration in organ O at time t (Bq.kgdw^{-1})
ACOPb(t) is the ^{210}Pb activity concentration in organ O at time t (Bq.kgdw^{-1})

The activity of ingrown ^{210}Po in reindeer meat:
The model for predicting the activity concentration of ^{210}Po in reindeer meat "ACRMPo(t)" in the fresh reindeer meat take into account the ingrowth of ^{210}Po from ^{210}Pb:

Activity of Polonium

$$[APo(t)] = [Po] \cdot \lambda_{Po} = \frac{\lambda_{Po}}{(\lambda_{Po}-\lambda_{Pb})}[APb_0] \cdot (e^{-\lambda_{Pb}*t}) = 1{,}01731[APb(t)]$$

$$\frac{dACRMPo(t)}{dt} = \mathrm{IRL} \cdot \mathrm{ACL}(t) \cdot GIA \cdot \mathrm{RMDF} \cdot BRM + \lambda_{Po} \cdot 1.02 \cdot ACRMPb(t) - (kRM + \lambda_{Po}) \cdot [ACRMPo(t)]$$

ACRMPo(t) is the ^{210}Po activity concentration in meat at time t (Bq.kgdw^{-1})
ACRMPb(t) is the ^{210}Pb activity concentration in meat at time t (Bq.kgdw^{-1})

Table 3-6 modelling parameters of ^{210}Po in Reindeer meat in Inari area

Reindeer	IRL IRG	GIA	RMDF	BRM	kRM	^{210}Pb	^{210}Po
ACRdm(t)	$kg_{dw}.month^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	month^{-1}	month^{-1}	month^{-1}
^{210}Po intake	0,4	0,2	0,09	2,4	0,53	0,0026	0,15

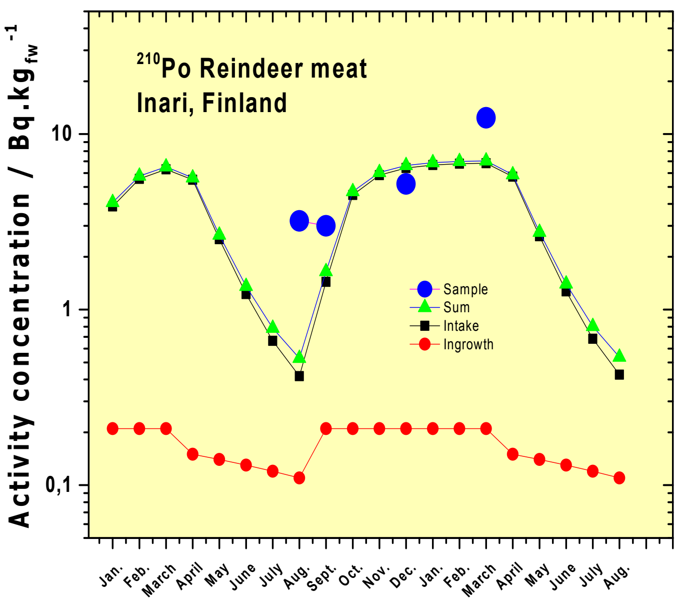

Figure 3-4

^{210}Po in reindeer meat from Inari Finland (Kauranen and Miettinen, 1969).

3.1.3 Modelling Reindeer liver in Inari area (Kauranen 1969)

Experimental sample measurements of reindeer liver

^{210}Pb and ^{210}Po activity concentration in Reindeer liver collected at various years from Inari are given in Table 3-7 (Kauranen and Miettinen, 1969).

Table 3-7
Sample measurements of ^{210}Pb and ^{210}Po in fresh reindeer liver from Inari (Kauranen and Miettinen, 1969).

Sampling Year	Month	Bq/kg_{fw} ^{210}Po	Bq/kg_{fw} ^{210}Pb
1966	8	38	11
1967	10	45	10
1964	12	122	24
1965	12	136	23
1967	3	174	56
Average	Winter	144	34
Average	Summer	41	11

Modelling parameters for intake of ^{210}Pb:

The result of activity concentration in reindeer liver "L" in Inari modelled by using following values of the various parameters. The fraction of absorbed ^{210}Pb activity that goes to the liver RLDF is 0,01 (Lloyd et al., 1975). Ratio of body mass kg_{bw} and mass of liver kg_{fw} BRL = 120(Krog et al., 1976). The activity concentration in Lichen was simulated randomly around the average 263 ± 42 $Bq.kg_{dw}^{-1}$ (Kauranen and Miettinen, 1969)

Table 3-8 Modelling parameters of ^{210}Pb in Reindeer liver in Inari area

Reindeer Liver	IRL IRG	GIA	RLDF	BRL	kRL	^{210}Pb	^{210}Po
ACRL(t) $Bq.kg_{fw}^{-1}$	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			kg_{bw} kg_{fw}^{-1}	a^{-1}	a^{-1}	a^{-1}
^{210}Pb intake	IRL = 3	0,01	0,01	120	0,3	0.0311	1,828

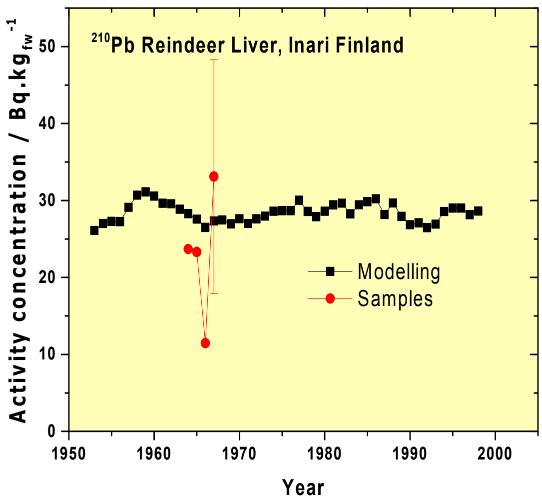

Figure 3-5

Result of modelling the ^{210}Pb activity concentration in reindeer liver at Inari the red dots are sample data from Inari (Kauranen and Miettinen, 1969)

Modelling parameters for intake of ^{210}Po:

Due to the short halftime of ^{210}Po compared to ^{210}Pb the timescale for modelling of ^{210}Po is taken to months instead of years. We also have to consider the ^{210}Po activity in green food intake during the summer period April-September.

The monthly intake rate of lichen by reindeer per kg of body weight (80 kg_{bw}) during Oct-March "ILRd" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$).

The activity concentration of ^{210}Po in Lichen PoACL during this period is estimated to = 270 ($Bq.kg_{dw}^{-1}$).

The monthly intake rate of green food "G" by reindeer per kg of body weight (80 kg_{bw}) during April –Sept "IGRd" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$). The activity concentration of ^{210}Po in green food PoACG during this period is estimated to = 9 ($Bq.kg_{dw}^{-1}$).

Data from humans consuming reindeer meat containing ^{210}Po indicated a fraction of GI-absorption of about 0.3 – 0.7 (Hill, 1965, Kauranen and Miettinen, 1967, Ladinska. et al., 1973, Thomas et al., 2001b). The value of 0.5 is recommended to Po in foodstuffs (ICRP, 1993). For modelling the intake of ^{210}Po in reindeer GIA = 0.4 is considered here.

The fraction of GI-absorbed ^{210}Po activity that goes to the sliver is estimated to SkDF = 0.022 and the elimination rate kRLi = 0.53 ($month^{-1}$) (Fellman et al., 1994, Henricsson and Persson, 2012).

Table 3-9 Modelling parameters of ^{210}Po in Reindeer liver in Inari area

Reindeer Liver	IRL IRG	GIA	RLDF	BRL	kRL	^{210}Pb	^{210}Po
ACRL(t) $Bq.kg_{fw}^{-1}$	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	$month^{-1}$	$month^{-1}$	$month^{-1}$
^{210}Po intake	0,4	0,4	0,022	120	0,53	0,0026	0,15

Ingrowth of ^{210}Po activity:

Due to the high accumulation of ^{210}Pb in the liver to about 28 $Bq.kg_{fw}$ the ingrowth of ^{210}Po become quite high. Due to the faster kinetics of ^{210}Po the activity level of the ingrown ^{210}Po become about 6,2 $Bq.kg_{fw}$.

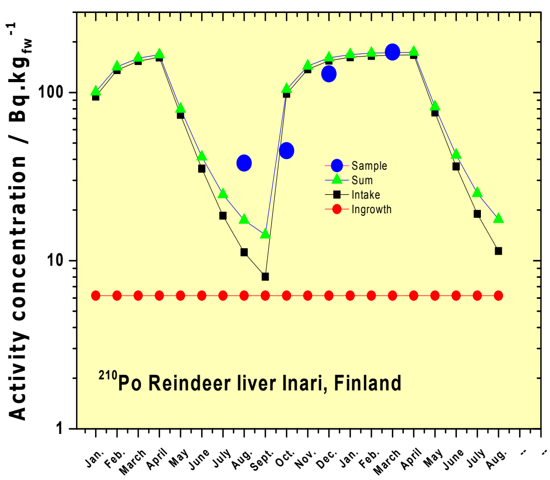

Figure 3-6

^{210}Po in reindeer livert from Inari Finland (Kauranen and Miettinen, 1969)

3.1.4 Modelling Reindeer bone in Inari area (Kauranen 1969)

Experimental sample measurements of reindeer bone

^{210}Pb and ^{210}Po activity concentration in Reindeer liver collected at various years from Inari are given in **Table 3-10** (Kauranen and Miettinen, 1969).

Table 3-10
Sample measurements of ^{210}Pb and ^{210}Po in fresh reindeer bone from Inari (Kauranen and Miettinen, 1969).

Year	Skeleton: Month	^{210}Po Bq/kg$_{fw}$	210Pb Bq/kg$_{fw}$
1966	8	73.3	173
1967	10		
1964	12	78.3	138
1965	12	76.2	196
1967	3		
Average		77.1	167
SD		0.9	29

Modelling parameters for intake of ^{210}Pb:

The result of activity concentration of ^{210}Pb in reindeer bone "B" in Inari modelled by using following values of the various parameters. The fraction of GI-absorbed ^{210}Pb activity that goes to the bone is estimated to 0,5 (Lloyd et al., 1975). Ratio of body mass kg$_{bw}$ and mass of liver kg$_{fw}$ bwRdL is 20 (SILVA et al., 2009). The activity concentration in Lichen was simulated randomly around the average 263 ± 42 Bq.kg$_{dw}^{-1}$ (Kauranen and Miettinen, 1969)

Table 3-11 modelling parameters of ^{210}Pb in Reindeer bone in Inari area

Reindeer bone	IRL	GIA	RBDF	BRB	kRL	^{210}Pb λ	^{210}Po λ
ACRB(t) Bq.kg$_{fw}^{-1}$	kg$_{dw}$.a^{-1}. kg$_{bw}^{-1}$			kg$_{bw}$ kg$_{fw}^{-1}$	a^{-1}	a^{-1}	a^{-1}
^{210}Pb intake	3	0.01	0.5	20	0.4	0.0311	1.828

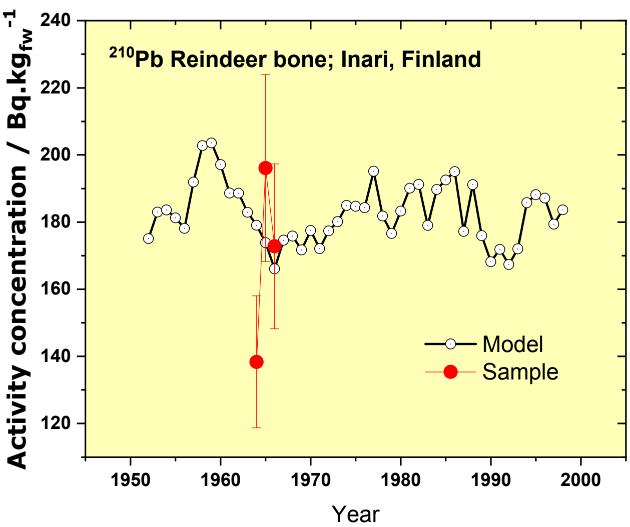

Figure 3-7

Result of modelling the ^{210}Pb activity-concentration in reindeerbone at Inari the red dots are sample data from Inari (Kauranen and Miettinen, 1969)

Modelling parameters for intake of ^{210}Po:

Due to the short halftime of ^{210}Po compared to ^{210}Pb the timescale for modelling of ^{210}Po is taken to months instead of years. We also have to consider the ^{210}Po activity in green food intake during the summer period April-September.

The monthly intake rate of lichen by reindeer per kg of body weight (80 kg_{bw}) during Oct-March "ILRd" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$). The activity concentration of ^{210}Po in Lichen PoACL during this period is estimated to = 270 ($Bq.kg_{dw}^{-1}$).

The monthly intake rate of green food "G" by reindeer per kg of body weight (80 kg_{bw}) during April –Sept "IGRd" is estimated to 0,4 ($kg_{dw}.a^{-1}.kg_{bw}^{-1}$). The activity concentration of ^{210}Po in green food PoACG during this period is estimated to = 9 ($Bq.kg_{dw}^{-1}$).

Data from humans consuming reindeer meat containing ^{210}Po indicated a fraction of GI-absorption of about 0.3 – 0.7 (Hill, 1965, Kauranen and Miettinen, 1967, Ladinska. et al., 1973, Thomas et al., 2001b). The value of 0.5 is recommended to Po in foodstuffs (ICRP, 1993). For modelling the intake of ^{210}Po in reindeer GIA = 0.4 is considered here.

The fraction of absorbed ^{210}Po activity that goes to the skeleton is estimated to RBDF = 0.09 and the elimination rate kRB= 0,53 ($month^{-1}$) (Fellman et al., 1994, Henricsson and Persson, 2012).

Table 3-12 modelling parameters of ^{210}Po in Reindeer bone in Inari area

Reindeer bone	IRL IRG	GIA	RBDF	BRB	kRB	^{210}Pb λ	^{210}Po λ
ACRdb(t)	$kg_{dw}.month^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	$month^{-1}$	$month^{-1}$	$month^{-1}$
^{210}Po intake	0.4	0.2	0.09	20	0.53	0.0026	0.15

Ingrowth of ^{210}Po activity:

Due to the high accumulation of ^{210}Pb in the skeleton to about 170 $Bq.kg_{fw}$ the ingrowth of ^{210}Po become quiet high. But due to the more rapid kinetics of ^{210}Po the activity of the ingrown ^{210}Po become about 40 $Bq.kg_{fw}$.

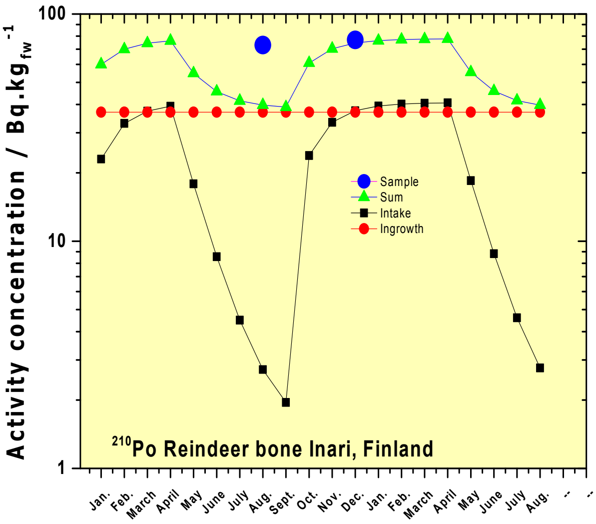

Figure 3-8

^{210}Po in reindeer bone from Inari Finland (Kauranen and Miettinen, 1969).

IV. Results of modelling ^{210}Pb and ^{210}Po in Reindeer breeders

4.1 Modelling ^{210}Pb and ^{210}Po in Reindeer breeder in Rogen area Sweden

The ^{210}Pb and ^{210}Po activity concentration in blood collected from reindeer breeders at Funäsdalen is given in the table 4-1 below (Persson, 1970b);(Persson, 1972)

Table 4-1
Activity concentration of ^{210}Po and ^{210}Pb
in samples of blood from reindeer breeders. (Bq.kg$_{fw}^{-1}$);

Year	^{210}Pb Bq.kg^{-1}	^{210}Po Bq.kg^{-1}
1968	0,159	0,39
1969	0,133	0,29
1970	0,122	0,28
1971	0,148	0,22
Average	0,141 ± 0,014	0,29 ± 0,07

^{210}Pb Modelling parameters:

The activity concentration of ^{210}Pb in Reindeer meat at time t after deposition ACRdm(t) (Bq.kgdw^{-1}) is from **Figure 3-3.** The annual intake of reindeer meat (kg$_{dw}$) by reindeer breeders per kg of bodyweight (80 kg) IMRdm. is estimated to 3.68 (kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$).

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 (ICRP, 1994, Thomas et al., 2001a).

Fractional Gastrointestinal absorption (GIA) of ^{210}Pb is 0.1 (Heard and Chamberlain, 1982, Leggett, 1993, Chamberlain et al., 1979). The fraction of GI-absorbed activity that stays the blood MDFbl is 0.1 (Kaushal et al., 1996). The ratio of body mass kg$_{bw}$ and mass of blood bwMbl is 12.25 (kg$_{bw}$ kg$_{fw}^{-1}$), derived from human blood volume of 77 ml/kg$_{bw}$. The geometric average of the elimination rate constant of ^{210}Pb from blood in Man kM is estimated to 0.6 (a^{-1}) (Nilsson et al., 1991).

Table 4-2 Modelling parameters of ^{210}Pb in Reindeer breeders in Rogen area

Man.blood	IMRdm	GIA	MDFbl	bwMbl	kRdm	^{210}Pb	^{210}Po
ACMbl(t) Bq.kg_{fw}^{-1}	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			kg_{bw} kg_{fw}^{-1}	a^{-1}	a^{-1}	a^{-1}
^{210}Pb intake	3.68	0.1	0.1	12.25	0.6	0.0311	1.828

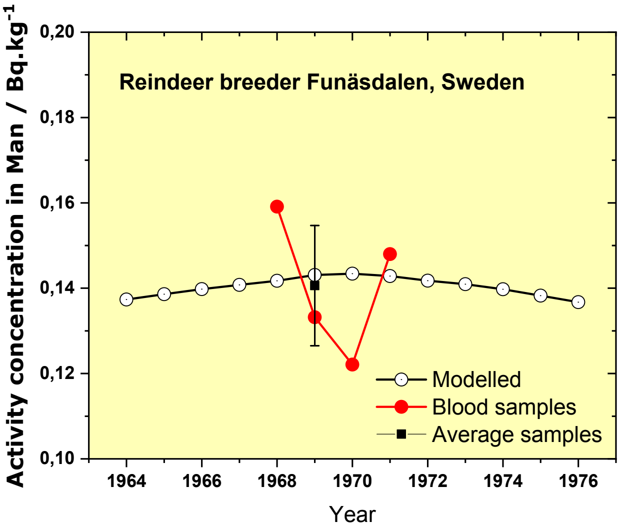

Figure 4-1

Modelled and sampled activity concentration of ^{210}Pb in blood of reindeer breeders at Funäsdalen Sweden.

^{210}Po Modelling parameters:

Table 4-3 Modelling parameters for intake of ^{210}Po

Blood Man	IMRd	GIA	MDF	bwMbl	kM	^{210}Pb	^{210}Po
ACRdm(t)	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			kg_{bw} kg_{fw}^{-1}	a^{-1}	a^{-1}	a^{-1}
^{210}Po intake	2.1	0.1	0.08	12.,25	2.5	0.0311	1.828

Ingrowth of ^{210}Po activity:

The ^{210}Po activity concentration in blood at time t PoACMbl (Bq.kg_{fw}^{-1}) due to ingrowth from ^{210}Pb is estimated to about 0.05 Bq.kg_{fw}^{-1}.

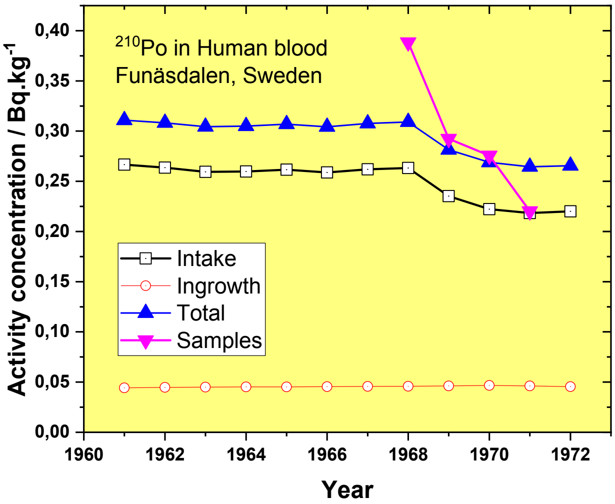

Figure 4-2

Activity concentration of ^{210}Po in human blood at Funäsdalen Sweden PoACMbl (Bq.kg$_{fw}^{-1}$)

4.2 Modelling activity of ^{210}Pb and ^{210}Po in Reindeer breeders from Inari area in Finland

^{210}Pb and ^{210}Po in blood

The ^{210}Pb and ^{210}Po activity concentration in blood collected from reindeer breeders at Inari area in Finland is given in **Table 4-4 (Kauranen and Miettinen, 1969)**

Table 4-4 Result of ^{210}Pb and ^{210}Po activity concentration in blood samples from Finland (Kauranen and Miettinen, 1969)

Blood	Year	Month	Bq/kg ^{210}Po	Bq/kg ^{210}Pb
Inari	1966	Mar-Apr	0,5	0,26
Helsinki	1966-67	Jan	0,026	0,10

^{210}Pb Modelling parameters:

The result of activity concentration of ^{210}Pb blood of reindeer breeders in Inari area modelled by using following values of the various parameters

Table 4-5 Modelling parameters of ^{210}Pb in blood of Reindeer breeders in Inari area

Reindeer breeder blood	IMRdm	GIA	MDFbl	bwMbl	kRdm	^{210}Pb	^{210}Po
ACMbl(t) Bq.kg$_{fw}^{-1}$	kg$_{dw}$.a^{-1}. kg$_{bw}^{-1}$			kg$_{bw}$ kg$_{fw}^{-1}$	a^{-1}	a^{-1}	a^{-1}
^{210}Pb intake	4.1	0.1	0.1	12.25	0.6	0.0311	1.828

ACMbl(t) Bq.kg$_{fw}^{-1}$	kg$_{dw}$.month^{-1}. kg$_{bw}^{-1}$			kg$_{bw}$ kg$_{fw}^{-1}$	month^{-1}	month^{-1}	month^{-1}
^{210}Po intake	0.27	0.26	0.13	12.25	0.15	0.0026	0.15

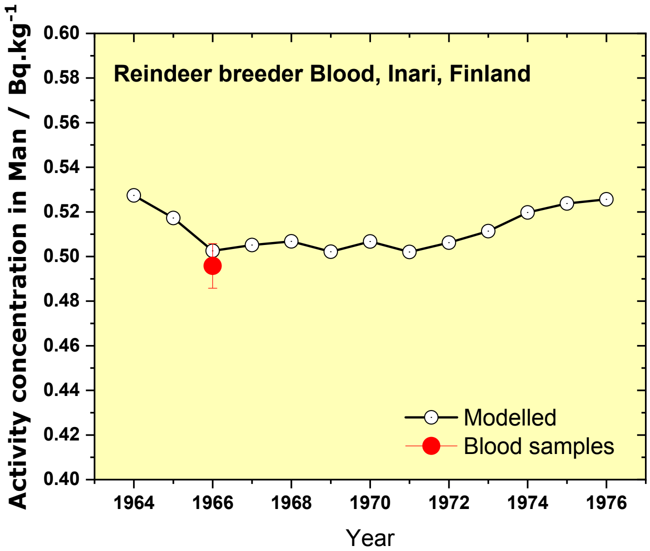

Figure 4-3

Modelled and sampled activity concentration of ^{210}Pb in blood of reindeer breeders at Inari Finland V1610-8

^{210}Po Modelling parameters

4.3 Modelling of ^{210}Po activity concentration in human blood (Kauranen 1969)

The activity concentration of ^{210}Po in human blood due to intake of reindeer meat with the ^{210}Po activity concentration ACRdm = 6.5 Bq.kgdw^{-1} assumed to be constant. The annual amount of reindeer meat intake by man per kg of bodyweight BW = 80 IMRd is assumed yo be 2.1 $kg_{dw}.kg_{bw}^{-1}.a^{-1}$. The adopted gastrointestinal absorption of ^{210}Po from reindeer meat GIA is 0.26, and the fraction of GI-absorbed activity that stays to the blood MDF = 0,13 (Henricsson and Persson, 2012). The ratio of body mass kg_{bw} and mass of blood (derived from human blood volume of 77 ml/kg_{bw}) bwMbl = 12.25 $kg_{bw}.kg_{fw}^{-1}$.
The elimination rate constant of ^{210}Po from blood in man kM = 0.15 month^{-1} (Henricsson and Persson, 2012).

Table 4-6 modelling parameters of ^{210}Po in blood of Reindeer breeders in Inari area

Blood man	IMRd	GIA	MDF	bwMbl	kM	^{210}Pb λ	^{210}Po λ
ACMbl(t) Bq.kg_{fw}^{-1}	kg_{dw}.month^{-1}. kg_{bw}^{-1}			kg_{bw} kg_{fw}^{-1}	month^{-1}	month^{-1}	month^{-1}
^{210}Po intake	0.27	0.26	0.13	12.25	0.15	0.0026	0.15

Ingrowth of ^{210}Po activity:

The ^{210}Po activity concentration in blood PoACMbl (Bq.kg_{fw}^{-1}) due to ingrowth from ^{210}Pb is estimated from the equation (?) to about 0.14 Bq.kg_{fw}^{-1}.

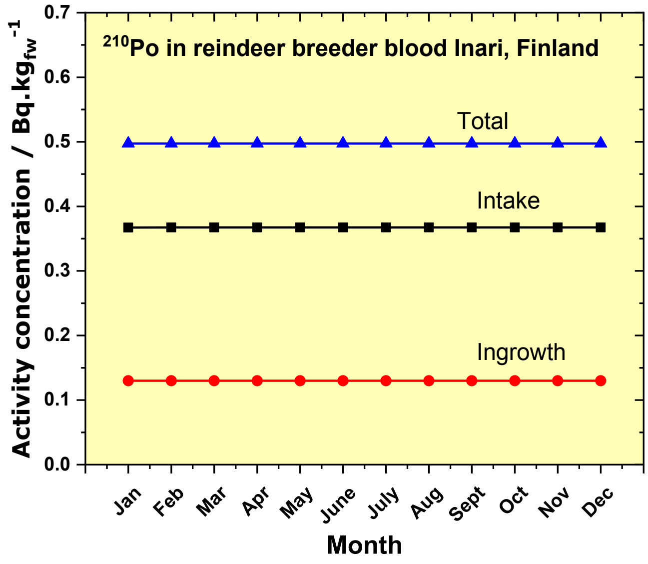

Figure 4-4

^{210}Po activity concentration in blood from reindeer breeders at Inari, Finland. Samples average 1966 = 0,5 bq.kg$_{fw}^{-1}$

4.5 ^{210}Pb and ^{210}Po in skeleton

The ^{210}Pb and ^{210}Po activity concentration in the skeleton from reindeer breeders at Inari area in Finland given in the **Table 4-7** was estimated from samples of teeth and autopsy (Kauranen and Miettinen, 1969)

Table 4-7 Activity concentration estimated from teeth and autopsy samples

Location	Year	Month	^{210}Po Bq/kg$_{fw}$	^{210}Pb Bq/kg$_{fw}$
Inari	1966	Mar-Apr	4,8	5,8
Helsinki	1966-67	Jan	2,0	2,1

^{210}Pb Modelling parameters:

The result of activity concentration of **^{210}Pb** in reindeer skeleton in Inari is modelled by using following values of the various parameters:

The ^{210}Pb activity concentration in Reindeer meat at time t after deposition ACRdm(t) (Bq.kgdw^{-1}) is taken from **Figure 3-4**. The annual amount of reindeer meat intake IMRd (kg$_{dw}$) by reindeer breeders per kg of bodyweight BW = 80 (kg$_{bw}$) is 4.1 (kg$_{dw}$.a^{-1}.kg$_{bw}^{-1}$).
Fractional Gastrointestinal absorption or ^{210}Pb GIA is taken to 0.1(Heard and Chamberlain, 1982, Leggett, 1993, Chamberlain et al., 1979). The fraction of GI-absorbed activity that stays to the skeleton MDF is 0.7 (Kaushal et al., 1996). The Ratio of body mass and mass of Skeleton Rbwsk = 20 kg$_{bw}$.kg$_{fw}^{-1}$(SILVA et al., 2009.The elimination rate constant of 210Pb from Skeleton in Man kMsk has been estimated to 0.231 a-1 by {McNeill, 1997 #2333),0,04 (a^{-1}) by (Nilsson et al., 1991) and 0,1 by (Christoffersson et al., 1986). In the present model kMsk a value of 0,4 a^{-1} was adopted.

Table 4-8 Modelling parameters of ^{210}Pb in skeleton of Reindeer breeders in Inari area

Man Skeleton Inari	IMRdm	GIA	MDsk	Rbwsk	kMsk	λ ^{210}Pb	λ ^{210}Po
ACMSk(t) $Bq.kg_{fw}^{-1}$	$kg_{dw}.a^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	a^{-1}	a^{-1}	a^{-1}
^{210}Pb Intake	4.1	0.1	0.7	20	0.4	0.0311	1.828

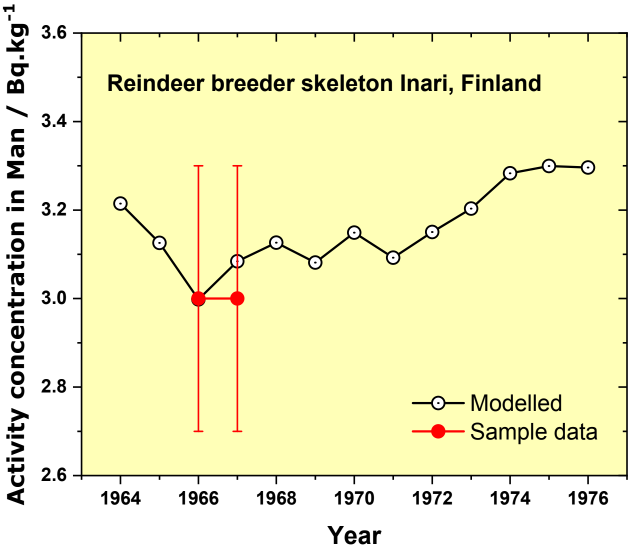

Figure 4-5

Modelled and sampled activity concentration of ^{210}Pb in skeleton of reindeer breeders at Inari Finland V1611-15

^{210}Po Modelling parameters:

The activity concentration of ^{210}Po in human estimated from samples of teeth and autopsy is given in **Table 4-7.**

The ^{210}Po activity concentration in skeleton of man PoACMsk in Inari after intake of reindeer meat is modelled on a monthly time scale by using following parameters.
The average ^{210}Po activity concentration in Reindeer meat during the year was assumed to be about 6,5 $Bq.kg_{dw}^{-1}$

The monthly amount of reindeer meat intake by reindeer breeders per kg of bodyweight IMRd = 0,22 $kg_{dw}.month^{-1}.kg_{bw}^{-1}$.

Th fractional Gastrointestinal absorption or ^{210}Po GIA = 0.26 (Heard and Chamberlain, 1982, Leggett, 1993, Chamberlain et al., 1979)

The fraction of GI-absorbed ^{210}Po activity that stays to the skeleton MDF = 0.13 (Kaushal et al., 1996).

The Ratio of body mass and mass of skeleton in man is Rbwsk 20 $kg_{bw}\ kg_{fw}^{-1}$ (SILVA et al., 2009). The elimination rate constant of ^{210}Po from skeleton in man kSk = 0,15 ($month^{-1}$) (Henricsson and Persson, 2012).

Table 4-9 Modelling parameters of ^{210}Po in skeleton of Reindeer breeders in Inari area

Man Skeleton Inari	IMRd	GIA	MDF	Rbwsk	kM	^{210}Pb λ	^{210}Po λ
ACMSk(t) $Bq.kg_{fw}^{-1}$	$kg_{dw}.month^{-1}.kg_{bw}^{-1}$			$kg_{bw}\ kg_{fw}^{-1}$	$month^{-1}$	$month^{-1}$	$month^{-1}$
Intake ^{210}Po	0.22	0,26	0.13	20	0.15	0.0026	0.15

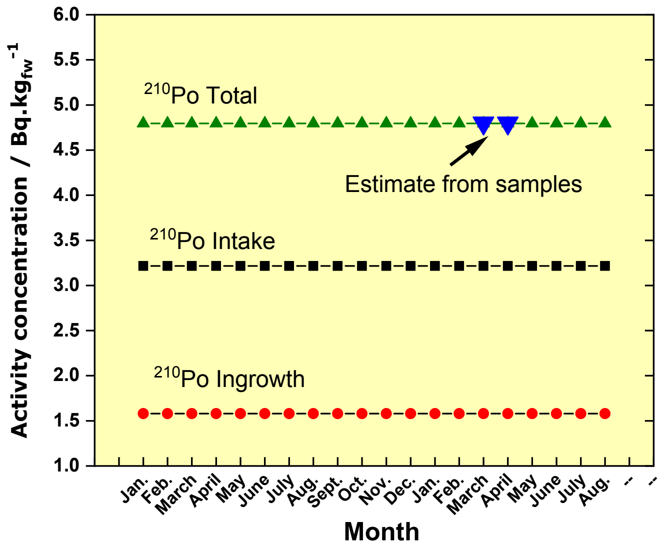

Figure 4-6

Modelled and sampled activity concentration of ^{210}Po in skeleton of reindeer breeders at Inari Finland

The ^{210}Po activity concentration in skeleton PoACMsk ($Bq.kg_{fw}^{-1}$) due to intake of ^{210}Po is modelled to 3,22 $Bq.kg_{fw}^{-1}$

Ingrowth of ^{210}Po activity:

The ^{210}Po activity concentration in skeleton PoACMsk ($Bq.kg_{fw}^{-1}$) due to ingrowth from ^{210}Pb is estimated from the equation (?) to about 1,6 $Bq.kg_{fw}^{-1}$.

The sum of intake and ingrowth activity is 4,8 $Bq.kg_{fw}^{-1}$ in agreement with the sample value in **Table 4-8**

V. Summary and Conclusions

^{210}Pb Summary

Figure 4-5 display the values of modelled and sampled activity concentration of ^{210}Pb in lichen, reindeer meat and in blood of reindeer breeders at Funäsdalen Sweden. There is at least 2 order of magnitude difference between the ^{210}Pb activity levels in lichen and reindeer meat and one decade further to man.

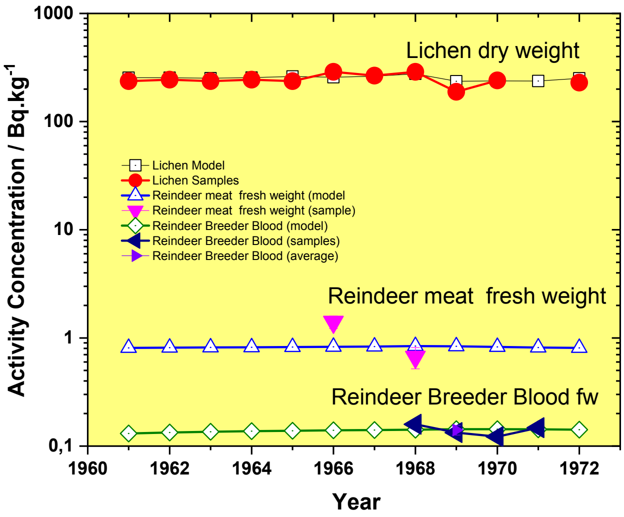

Figure 4-5

Modelled and sampled activity concentration of ^{210}Pb in lichen, reindeer meat and in blood of reindeer breeders at Funäsdalen Sweden,

Figure 4-6 display the values of modelled and sampled activity concentration of ^{210}Pb in reindeer meat liver and skeleton at Inari Finland. The activity concentration in Lichen was simulated randomly around the 1966-67 average of 263 ± 42 $Bq.kg_{dw}^{-1}$ (Kauranen and Miettinen, 1969).

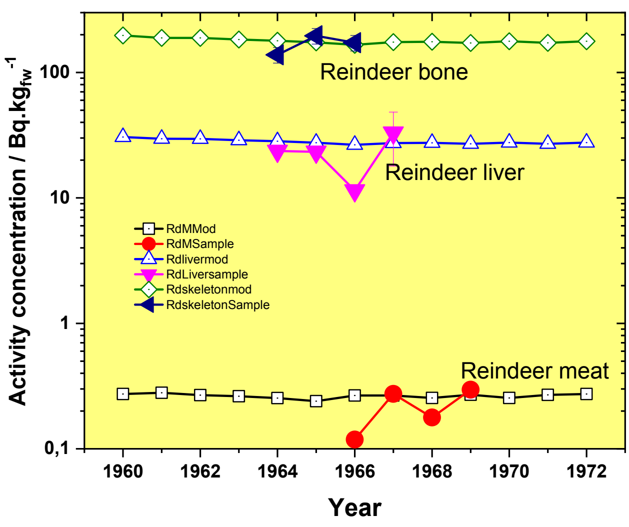

Figure 4-6

Modelled and sampled activity concentration of ^{210}Pb in reindeer meat liver and skeleton at Inari Finland. The activity concentration in Lichen was simulated randomly around the 1966-67 average of 263 ± 42 $Bq.kg_{dw}^{-1}$ (Kauranen and Miettinen, 1969).

The transfer of ^{210}Pb and ^{210}Po in the food chain lichen-reindeer-man is considered as an example of dynamic modelling of radio-ecological concentration processes. The model for deposition apply differential equations with various parameters such as *Interception fraction* “IF”, and bio-elimination rate constants. The *Standing biomass density* P_{Sb} = 0.63 ($kg_{dw}.m^{-2}$), *the Interception fraction IF=1, elimination rate constants kL = 0.3* a^{-1}, and $\lambda = 0.031\ a^{-1}$. The values for lichen were, P_{Sb} = 0.63, *IF*=1 and *kL* = *0.3* a^{-1}. With different values of these parameters, however, the equation can be applied to modelling of other radio-ecological vegetation pathways as well.

The Model equations for animals and man involves gastrointestinal absorption “GIA”, the distribution fraction “DF” of radionuclide that is distributed to the various organs, and the ratio of body mass versus mass of organ in question “BO “ ($kg_{bw}.kg_{fw}^{-1}$). With different values, these parameters can be applied for radio-ecological modelling of various subjects. Even if only a few samples are available, the dynamic modelling can be used to predict the temporal and seasonal variation of the activity concentration of various radio-ecological compartments.

The final message for researchers in radio-ecological concentration processes is to embrace, as many descriptor variables as possible in the sampling procedure. By both dynamic and PLSR modelling, it is then possible to predict both the most important variables in the process, and the progress of activity concentration in various radio-ecological compartment with time.

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Supplementary data:

The radioactive decay of ^{210}Pb and ingrowth of ^{210}Po

Table S-1 The radioactive decay-chain of ^{210}Pb

	^{210}Pb		^{210}Bi		^{210}Po		$^{210}Pb_{stable}$
T½ (a)	22.3		0.014		0.379		
λ = (a^{-1})	0.031		50.47		1.83		
T½ (month)	267.6		0.16		4.55		
λ ($month^{-1}$)	0.0026		4.21		0.15		
T½ (days)			5.013		138.4		
λ ($days^{-1}$)			0.138		0.005		

The equation for in-growth of number of nuclei ^{210}Po from ^{210}Pb is:

$$\frac{d[Pb]}{dt} = -\lambda_{Pb} \cdot [Pb] \qquad [Pb] = [Pb_o] \cdot e^{-\lambda_{Pb} \cdot t}$$

$$\frac{d[Bi]}{dt} = -\frac{d[Pb]}{dt} = \lambda_{Pb} \cdot [Pb] = \lambda_{Pb} \cdot [Pb_o] \cdot e^{-\lambda_{Pb} \cdot t}$$

$$[Bi] = \frac{\lambda_{Pb}}{(\lambda_{Bi} - \lambda_{Pb})} [Pb_o] \cdot (e^{-\lambda_{Pb} \cdot T} - e^{-\lambda_{Bi} \cdot T})$$

$$\frac{d[Po]}{dt} = -\frac{d[Bi]}{dt} = \lambda_{Bi} \cdot [Bi]$$

$$\frac{d[Po]}{dt} = \lambda_{Bi} \cdot \frac{\lambda_{Pb}}{(\lambda_{Bi} - \lambda_{Pb})}[Pb_o] \cdot (e^{-\lambda_{Pb} \cdot t} - e^{-\lambda_{Bi} \cdot t})$$

Since λ_{Pb} (0,03 a^{-1}) < λ_{Po} (1,83 a^{-1})< λ_{Bi} (50,5 a^{-1})

$$\frac{d[Po]}{dt} \approx \lambda_{Bi} \cdot \frac{\lambda_{Pb}}{(\lambda_{Bi} - \cancel{\lambda_{Pb}})}[Pb_o] \cdot (e^{-\lambda_{Pb} \cdot t} - \cancel{e^{-\lambda_{Bi} \cdot t}})$$

$$\frac{d[Po]}{dt} = \lambda_{Pb} \cdot [Pb_o] \cdot (e^{-\lambda_{Pb} \cdot t})$$

$$\frac{dPoAC(t)}{dt} = \lambda_{Po} \cdot PbAC(t)$$

The equation of ^{210}Po activity concentration $[ACPo_T]$ in a sample with ^{210}Pb present $[ACPo_o]$ is however given more exactly by the equation:

$$[ACPo_T] = [ACPo_o] \cdot e^{-\lambda_{Po} \cdot T} +$$

$$[ACPb_o] \cdot \left[\frac{\lambda_{Po} \cdot \lambda_{Bi} \cdot e^{-\lambda_{Pb} \cdot T}}{(\lambda_{Po} - \lambda_{Pb})(\lambda_{Bi} - \lambda_{Pb})} + \frac{\lambda_{Po} \cdot \lambda_{Bi} \cdot e^{-\lambda_{Bi} \cdot T}}{(\lambda_{Po} - \lambda_{Bi})(\lambda_{Pb} - \lambda_{Bi})} + \frac{\lambda_{Po} \cdot \lambda_{Bi} \cdot e^{-\lambda_{Po} \cdot T}}{(\lambda_{Bi} - \lambda_{Po})(\lambda_{Pb} - \lambda_{Po})}\right]$$

Since λ_{Pb} (0,03) < λ_{Po} (1,83)<< λ_{Bi} (50,5) this equation can be reduced to

$$[ACPo_T] = [ACPo_o] \cdot e^{-\lambda_{Po} \cdot T} + [ACPb_o] \cdot \frac{\lambda_{Po}}{\lambda_{Po} - \lambda_{Pb}} \cdot \left[e^{-\lambda_{Pb} \cdot T} + \frac{(\lambda_{Po} - \lambda_{Pb}) \cdot e^{-\lambda_{Bi} \cdot T}}{(\lambda_{Po} - \lambda_{Bi})} - e^{-\lambda_{Po} \cdot T}\right]$$

If $[ACPo_o] \cdot e^{-\lambda_{Po} \cdot T} = 0$

$$[ACPo_T] = [ACPb_o] \cdot \frac{\lambda_{Po}}{\lambda_{Po} - \lambda_{Pb}} \cdot \left[e^{-\lambda_{Pb} \cdot T} + \frac{(\lambda_{Po} - \lambda_{Pb}) \cdot e^{-\lambda_{Bi} \cdot T}}{(\lambda_{Po} - \lambda_{Bi})} - e^{-\lambda_{Po} \cdot T}\right]$$

$$[ACPo_T] = [ACPb_o] \cdot 1.017 \cdot [e^{-0,03 \cdot T} - 0,0363 \cdot e^{-50,5 \cdot T} - e^{-1,83 \cdot T}]$$

$$\frac{[ACPo_T]}{[ACPb_T]} = \cdot \frac{1.017}{e^{-0,03 \cdot T}} \cdot [e^{-0,03 \cdot T} - 0,0363 \cdot e^{-50,5 \cdot T} - e^{-1,83 \cdot T}]$$

Table S-2

The activity ratio of ^{210}Po and ^{210}Pb as a function of time.

Time/a	$\frac{[ACPo_T]}{[ACPb_T]}$
0	0
1	0,849
2	0,989
3	1,012
4	1,016
5	1,017