# ANALYSIS OF SELECTED BIOSPHERE PARAMETER CHANGES USING PROBABILISTIC METHODS

*DOROTA FLAMÍKOVÁ and VLADIMIR NEČAS*

Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information Technology, Institute of Nuclear and Physical Engineering, Bratislava, Slovakia
*e-mail: dorota.flamikova@stuba.sk*

*Abstract*

The impacts of planned discharges of radionuclides to the environment are assessed by means of models that approximate the transfer of radionuclides through the compartments of the environment. These models can be used as tools to evaluate the effectiveness of countermeasures applied to reduce the impacts of accidental releases of radionuclides and to predict the future impact of activity releases from deep geological repositories. For assessment of the long-term safety and potential radiological risk of the deep geological repository the model of the disposal system itself, geosphere and reference biosphere has been developed using the GoldSim simulation tool. The model of the biosphere considers the scenario of the agricultural habitat (normal evolutionary scenario) and it includes various biosphere components and multiple exposure pathways. This paper discusses the impact of selected parameter changes on annual individual effective dose for adult person form critical exposure group. Collected data changes are relevant to the transfer of radionuclides through food chains to humans (covers radionuclide transfer in the terrestrial environments) and results are compared to the reference case. A probabilistic analysis using the Monte Carlo method was performed to assess the impact of the changes. For all parameters log-normal distributions were applied with a geometric mean and geometric standard deviation values due to the widely varying yet for some cases lacking data.

***Keywords:*** *Deep geological repository, Long-term safety, GoldSim, Monte Carlo*

## Introduction

In the case of the use of nuclear energy, considerable attention must be paid to the safe disposal of radioactive waste and spent nuclear fuel, which aims at protecting the population and the environment at present and in the very distant future against undesirable radiological impacts. At present, in almost all countries with a developed nuclear program, when disposal of radioactive wastes containing long-lived radionuclides and spent nuclear fuel is considered, implementation of the concept of a deep geological repository is necessary. In order to assess the long-term safety of the deep repository, a comprehensive model of the reference biosphere, geosphere and disposal system should be created to obtain information on radionuclide migration in a given environment, radiation load, etc. The model serves as a calculation tool for the annual effective dose for the individual from the critical exposure group caused by radionuclides released into the environment.

This work focuses mainly on the creation of a reference biosphere model and parameters within the biosphere, which can influence the annual effective dose value for an individual from a critical exposure group. Received annual effective dose for an individual is calculated to assess the radiological risks and health damage caused by ionizing radiation.

For this purpose, a generally accepted method of calculating the radiation dose based on differential equation calculations is used, the results of which determine the concentrations of individual radionuclides in the environmental components (crops, animal products, etc.) based on known, respectively calculated values of individual radionuclide concentrations in water and agricultural components. These parameters are so-called translocation factors that determine the passage of contaminants from soil and water into plants, respectively from plants consumed by livestock to animal products.

## Creation of the model

The conceptual model of the reference biosphere was developed according to the BIOMASS methodology (IAEA, 1996). The role of the BIOMASS document is to provide a methodology in the process of creating practical examples demonstrating ways in which models of the biosphere for long-term safety assessment can be developed and appropriately assessed for the specific purposes. For the creation of our model, the methodology of Example 2B from the document was used. A relatively simple interface between the geosphere and the biosphere considers the natural flow of contaminated groundwater into the aquifer.

This water passes through other transport pathways and then it is discharged into the surface. The ultimate goal is to calculate the effective dose for the individual without considering the evolution of the biosphere system [1].

**Disposal system and geosphere**

The modelled disposal system is based on a multi-barrier concept, which consists of a combination of engineering and natural barriers providing sufficient protection for the environment and the population over a very long period. All individual elements of the multi-barrier protection system are interacting with each other in such a way to isolate radionuclides from the biosphere.

One of the barriers is the waste itself – very form of spent nuclear fuel. Another important barrier is disposal container inspired by Czech proposal, where spent fuel assemblies (from VVER-440 reactors) are considered to be disposed in. The disposal capacity of one container is 7 fuel assemblies. This container is constructed of stainless steel (inner part) and carbon steel (outer part) with an outer diameter of 650 mm and a length of 3670 mm. Fuel assemblies are inserted into the inner profiled pipes made of aluminium alloy [2].

Within this assessment the calculations were performed for the spent fuel with an initial average enrichment in $U^{235}$ of 4.25 % and 60 MWd/kgU burnup. The spent fuel inventory calculation was performed for the radial profiled VVER-440 fuel assembly of the 2nd generation by using the depletion module TRITON included in SCALE 6.1.3 code system. The model is 2D assembly model developed in our institute [3]. The time of storage before the final disposal was set at 50 years. Disposal container is surrounded by a bentonite buffer with a wall thickness of 300 mm.

After the disposal container fails due to normal evolution processes (1 000 years) and water comes into contact with the source term (fuel and structural material), released radionuclides start to migrate through the bentonite buffer, excavation disturbed zone (EDZ) and crystalline host rock.

After the radionuclides penetrate all the barriers in the near field represented by the spent nuclear fuel matrix itself, the disposal container and the bentonite buffer, they reach the geosphere. In our model, the geosphere is represented by a crystalline host rock environment where radionuclides reach the geosphere through the fractures and faults. The connection of the geosphere with the biosphere is represented by an aquifer, from which the contaminated water flows through the surface flow into the water reservoir.

**Reference biosphere**

The biosphere in this model is represented by a set of interconnected biosphere objects. A biosphere object is defined as an area of the landscape that can receive radionuclides released, either through discharge of deep groundwater or in contaminated surface water, at any time. The identification of biosphere objects in the considered area is based on the modelling of flow paths from the repository to the ground surface.

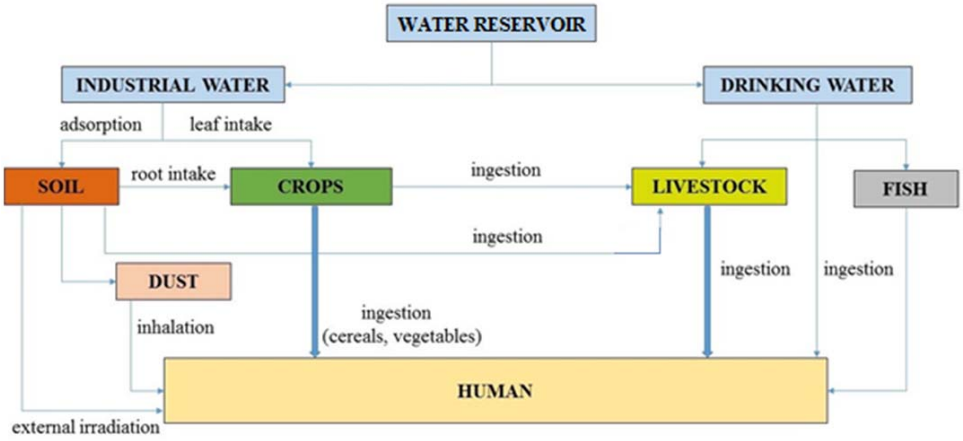



Fig.1. Scheme of the conceptual model of the reference biosphere

The primary medium through which radionuclides come into the biosphere is the water. Contaminated water from the considered water reservoir is used as drinking water for the population, water for livestock and also for irrigation of the agricultural land. In this water reservoir also fish are being farmed. On such land are cultivated cereals, vegetables, grassland and trees. Radionuclides are transported through the root or leaf system into the plants, hence either directly into the human organism, or into the animal organism from which the animal products enter the human body. Receiving of the radionuclides is also partially caused by the consumption of contaminated fish meat.

For livestock in our model, we consider bovine animals whose animal products - meat and milk, are consumed by residents from the critical exposure group. In the process of creating a reference biosphere, some input elements were selected, representing the constituent elements of the environment within the biosphere model. In the case of crops, cereals, grassland and trees are considered in the model. The schema of the conceptual model of biosphere and exposure pathways is shown in Fig. 1. Conservatively, it is assumed that all consumed environmental components are contaminated with radionuclides, with the primary exposure pathways such as ingestion, inhalation and external exposure.

The contaminated soil was considered as the source of an external exposure. On the surface of the soil, farmers are moved carrying out, for example, agricultural work. The value of the effective dose from external exposure is therefore dependent on the time spent on the contaminated soil. The exposure pathway of external exposure also includes external irradiation of the person's skin from the dust that is deposited on it.

The effective dose caused by inhalation depends, inter alia, on the amount of inhaled dust arising from the contaminated soil and the respiration rate of the exposed object, assuming a constant content of soil particles in the air. The exposure is caused by inhalation of particles of contaminated dust.

The effective dose caused by ingestion depends on the amount of ingested contaminated water and contaminated food. The model for long-term safety assessment of the deep geological repository was developed using the GoldSim simulation tool [4].

**Environmental uptake of radionuclides in agricultural ecosystems**

To assess radiological risks, the annual individual effective dose for an individual from a critical exposure group has been calculated. This value can be related to the risk of damage to health caused by ionizing radiation. For this purpose, a generally accepted method of calculating the radiation dose based on differential equation is used, the results of which determine the concentrations of individual radionuclides in the environmental components (crops, animal products, etc.) based on known, respectively calculated values of individual radionuclide concentrations in water and agricultural soil. Within these calculations so-called concentration and translocation factors are used. These factors determine the transport of contaminants from soil and water into plants, respectively from plants consumed by livestock to animal products. For the purpose of calculation of the radiation dose it is also necessary to know the characteristics of the assessed environment, as well as the habits of the assessed population, such as: annual consumption of water and individual foods for each age group, different types and energies of ionizing radiation, whether the biological half-life of radionuclides are taken into account using dose conversion factors that are specific for each radionuclide and for each assessed age category. Considered exposure pathways are ingestion, inhalation and external exposure.

**Annual effective dose calculation**

Total annual individual effective dose should be calculated according to the following equation, which taking into account the contributions of individual exposure pathways (ingestion, inhalation, external exposure) [5]:

$$E = E_{ing} + E_{inh} + E_{ext} \quad (1)$$

where: $E_{ing}$ [Sv/year] is the annual individual effective dose caused by ingestion,

$E_{inh}$ [Sv/year] is the annual individual effective dose caused by inhalation,

$E_{ext}$ [Sv/year] is the annual individual effective dose caused by external exposure.

**Dose caused by ingestion**

The effective dose caused by ingestion of radionuclides depends on the contamination of consumed food and the intake of contaminated water by humans per year. The dose caused by ingestion is determined as the sum of the partial doses caused by the ingestion of different types of food and water intake. The formula for calculation [5] is given below:

$$E_{ing} = DF_{ing} * C_{food} * Q_{food} \quad (2)$$

where: $E_{ing}$ [Sv/year] is the annual individual effective dose caused by ingestion,

$DF_{ing}$ [Sv/Bq] is the conversion factor for ingestion (specific for each radionuclide),

$C_{food}$ [Bq/kg] or [Bq/m$^3$] is the concentration of radionuclides in 1 kg of the food,

$Q_{food}$ [kg/year] or [m$^3$/year] is food consumption.

Radionuclide concentration in vegetables and cereals is calculated as follows [5]:

$$C_{food} = \left(CF_{food} + \left(1 - f_{prep}\right) * s_{food}\right) * C_{soil} + \\ + \mu_{food} * q_{irr} * C_{water} \frac{1 - f_{prep} + f_{trans}}{Y_{food} * \lambda_{weather}} \quad (3)$$

where: $CF_{food}$ [-] is a concentration factor for vegetables and cereals,

$f_{prep}$ [-] is an external contamination loss due to processing,

$S_{food}$ [kg/kg] is crop contamination by soil,

$C_{soil}$ [Bq/m$^3$] or [Bq/kg] is soil concentration of radionuclide in soil,

$\mu_{food}$ [-] is fraction of contamination caused by irrigation,

$q_{irr}$ [mm/year] is amount of irrigation water,

$C_{water}$ [Bq/kg] concentration of radionuclides in kilogram, resp. litters of water,

$f_{trans}$ [-] is fraction of activity passing from the surface to the interior of the plant,

$Y_{food}$ [kg/m$^2$] is crop yield,

$\lambda_{weather}$ [d/kg] is contamination loss coefficient due to weathering.

**Methods for selecting values for concentration ratios**

In the model of the reference biosphere, radionuclide concentrations in biota are calculated using several types of equilibrium concentration ratios (CR), which are generally defined as the ratio between the contaminant (element) concentration in the biota to its concentration in different environmental media such as soil, water and animal feeds.

In general, all isotopes of an element are assumed to have the same CR values, since uptake by biota and other relevant processes involved are generally very weakly affected by differences in isotopic mass or nuclear emissions.

There could be situations, where different isotopes of the same element may exhibit different bioavailability in soil, sediments and other environmental media. This could be the case, when the isotopes found in these media have different origins. However, in situations where constant radionuclide releases occur during very long periods, it is reasonable to expect, that radionuclides will be in equilibrium with their stable isotopes and that all isotopes of the same element will behave similarly.

This paper provides an analysis focused on the parameters ensuring the radionuclides transfer from the considered environmental media to the individual environmental compartments.

Selected parameters are so-called concentration (translocation) factors for leafy vegetables and plant roots. The analysis considers the scenario of agricultural habitat, mild climate zone and loamy soil.

The data contained here are generally presented as ranges of observed values, where the available data permit, mean values determined by statistical methods are also included. The data can be used for various purposes, in particular:

- to derive transfer parameters for screening purposes, that is, to evaluate, in a preliminary and approximate way, the radiological significance of a planned environmental release. For this purpose, modelling assumptions and data are chosen conservatively so that there is only a small probability to underestimate the detrimental environmental effects;
- to obtain realistic estimates of the radiation dose to humans by using the mean of the observed values and realistic modelling assumptions. However, it must be noted that generic data sets are no substitute for site specific data needed to obtain realistic estimates of the radiation dose.

Theoretical analyses have shown, that concentrations of elements in the environment will tend to follow lognormal distributions [6], which are supported by empirical observations of element concentrations in the environment that have been used here to calculate the CR values. At the same time, lognormal distributions are self-replicating under multiplication and division, i.e. products and quotients of lognormal variables are themselves lognormal distributions. Hence, lognormal distributions have been assumed for all CRs studied here.

The distributions have been parameterized using Geometric Means (GM) and Geometric Standard Deviations (GSD). For the purposes of the assessments, these distributions should be representative for the spatial and temporal variations considered. However, the variation observed in the available site-specific data was in most cases too narrow to be representative for the variation that can be expected within the long term period modelled within this paper. The values for selected parameters are shown in Table 1.

Table 1. Selected soil to plant transfer factors [6]

| LEAFY PLANTS | | | | | |
|---|---|---|---|---|---|
| **Element** | **Reference value** | **Min** | **Max** | **GM** | **GSD** |
| *Ac* | 4.70E-02 | 6.70E-03 | 2.70E+00 | 1.30E-01 | 4.6 |
| *Am* | 4.70E-04 | 1.20E-04 | 4.40E-03 | 8.00E-04 | 3.3 |
| *C* | 7.00E-03 | 8.60E-04 | 8.60E-02 | 8.60E-03 | 4.2 |
| *Cl* | 7.00E+01 | 4.10E+01 | 1.40E+02 | 7.70E+01 | 1.7 |
| *Cm* | 7.70E-03 | 5.90E-04 | 2.40E-02 | 4.10E-03 | 4.5 |
| *Cs* | 4.60E-01 | 8.90E-04 | 2.90E+00 | 1.80E-01 | 6.0 |
| *I* | 4.00E-02 | 3.20E-03 | 3.00E-01 | 1.90E-02 | 3.7 |
| *Nb* | 2.50E-02 | 2.50E-03 | 5.10E+01 | 6.40E-03 | 3.5 |
| *Np* | 3.20E-02 | 1.50E-02 | 2.40E-01 | 8.00E-02 | 3.0 |
| *Pa* | 4.70E-02 | 1.00E-03 | 1.00E-01 | 1.00E-02 | 3.2 |
| *Pb* | 1.00E-02 | 9.40E-03 | 7.40E+01 | 8.30E-02 | 13.0 |
| *Pd* | 1.50E-01 | 6.70E-02 | 6.70E+00 | 6.70E-01 | 3.2 |
| *Pu* | 6.00E-04 | 3.00E-05 | 8.60E-04 | 2.40E-04 | 2.7 |
| *Ra* | 4.90E-02 | 5.30E-03 | 3.80E+02 | 2.70E-01 | 6.7 |
| *Se* | 2.50E-01 | 2.90E-01 | 2.40E+00 | 5.10E-01 | 1.7 |
| *Sm* | 2.00E-01 | 1.00E-02 | 1.00E+00 | 1.00E-01 | 3.2 |
| *Sn* | 3.00E+00 | 3.30E-01 | 3.30E+01 | 3.30E+00 | 3.2 |
| *Tc* | 2.10E+02 | 1.10E-02 | 4.80E+00 | 5.30E+02 | 14.0 |
| *Th* | 1.80E-03 | 2.80E-04 | 6.20E-01 | 3.50E-03 | 6.0 |
| *U* | 8.00E-02 | 4.41E-03 | 2.60E+01 | 5.00E-01 | 15.0 |
| *Zr* | 1.00E-02 | 1.20E-03 | 1.20E-01 | 1.20E-02 | 14.0 |

**Evaluation of the long-term safety**

First of all, in order to evaluate the long-term safety of the disposal system of spent nuclear fuel, our aim was to determine the values of the annual effective doses for individuals from the critical exposure group for considered deep geological repository in Slovakia. The representative individual from a critical exposure group is considered to be an adult over the age of 17 years.

The geosphere and the disposal system, which includes disposal containers for spent nuclear fuel and sealing material (bentonite), are modelled conservatively. The scenario is based on the National Program for Spent Nuclear Fuel and Radioactive Waste Management in Slovak Republic [7], which requires the allocation of 32658 spent nuclear fuel assemblies, produced from the 60-year operation of Slovak nuclear power plants, in the repository. Since it is assumed that the capacity of one disposal container is 7 fuel assemblies, we assume that approximately 4 665 containers will be disposed in the deep geological repository. The conservative scenario further assumes that each disposal container will fail after 1000 years due to degradation of the materials used in the repository.

It is assumed that the main transport pathway of radionuclide migration is groundwater, which passes through fractures and faults in the geosphere and then into the aquifer. From there contaminants are transferred into the environmental media. It is considered that the use of the environmental components associated with the agricultural activity and other activities is identical throughout the evaluated period to the current habits.

The total calculated annual effective dose caused by ingestion, inhalation and external exposure for an adult from the critical exposure group is presented in Fig. 2.

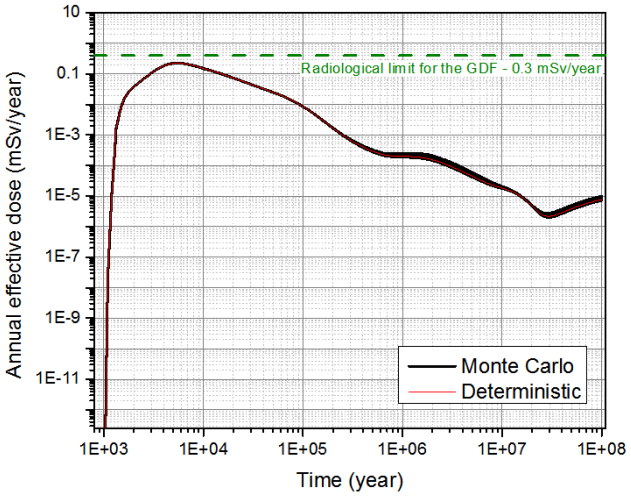



Fig. 2. Total annual effective dose for an adult individual (reference case)

From the figure, it can be seen that the maximum of obtained dose has a value of 0.2226 mSv/year. This value was compared to the radiological limit for the long-term assessment of the safety of a waste disposal facility recommended by ICRP. This limit is set to an annual dose constraint for the population of 0.3 mSv/year [8]. In all considered cases, the same radionuclides affect total annual effective dose. Contribution of selected radionuclides for an adult representative is given in Fig. 3.

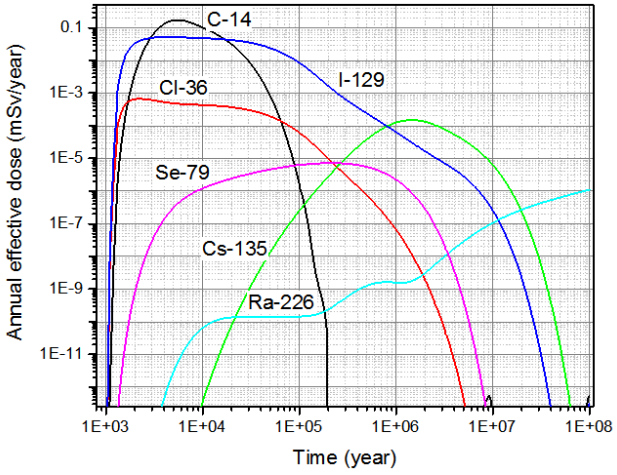



Fig. 3. Detailed contribution of individual radionuclides (reference case)

The release rate of many nuclides is reduced due to the transport of nuclides through the host rock and the major water-conducting fault. Actinides are relatively strongly sorbed on the bentonite as well as on the host rock matrix and therefore their release rates are very low. The largest contribution to total annual effective dose represent activation and fission products $C^{14}$, $Cl^{36}$, $I^{129}$, $Se^{79}$, $Cs^{135}$ and $Ra^{226}$.

$I^{129}$ and $Cl^{36}$ are assumed to have very poor retentive properties and that's why these nuclides dominate the total release rate for a long period of time. In the early years, the most significant nuclide dominating the total release rate is $C^{14}$. It is caused by its relatively high specific activity in comparison with long-lived radionuclides.

A simple probabilistic analysis was performed using the Monte Carlo method, which is directly implemented in the GoldSim simulation tool. Within the analysis, the transfer factors used to determine the rate of transport of contaminants from the soil to the leaves of plants grown in the considered farm were selected. Lognormal distribution was applied to the parameters and 50 system realizations were performed. The effect of parameter change on total annual effective dose value was investigated and results can be seen also in Fig. 2.

As Fig. 2 shows, the analysis performed has no significant effect on the total annual effective dose. The maximum value remains unchanged; a small variation of the values can be noticed in the last years of analysis. The effect of changing the selected parameters on the dose value is up to 8% in all significant time periods compared to the reference value.

This effect is due to the fact that specific radionuclides such as $Ra^{226}$, $Ra^{228}$, $Pb^{210}$, $Th^{230}$ contribute to the total dose value in the last years of analysis. The contribution of these radionuclides to the total dose in the last years of analysis generally increases with time until it reaches a saturated value (see in Figs 4, 5, 6).

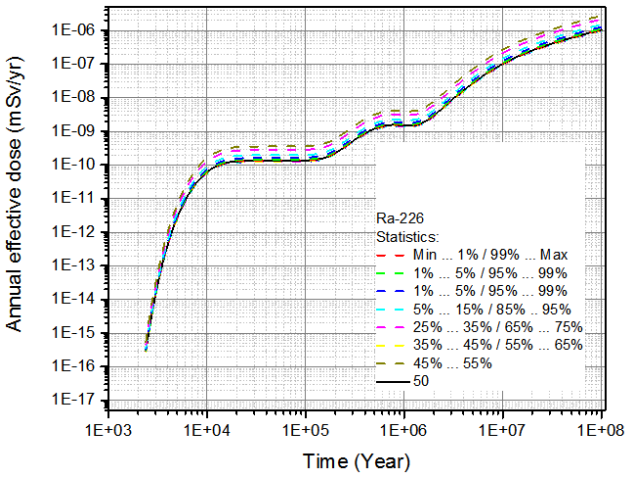



Fig. 4. Contribution of $Ra^{226}$ in last years of the analysis

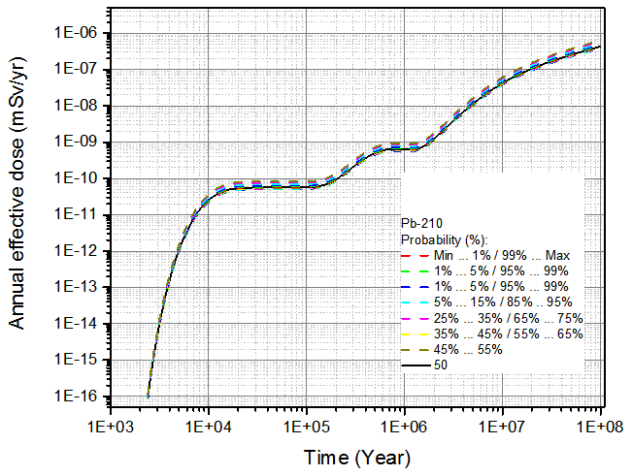



Fig. 5. Contribution of $Pb^{210}$ in last years of the analysis

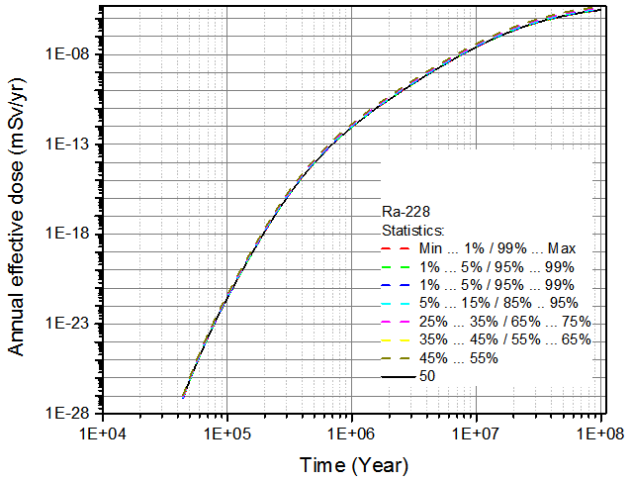



Fig. 6. Contribution of $Ra^{228}$ in last years of the analysis

The contribution from $Pb^{210}$ increases with increasing time. This radionuclide accumulates in the soil at a later time of the analysis and from there passes into the plant leaves. The maximum far field dose from $Ra^{226}$ increases because of the greater amount of uranium in spent fuel. Due to the fact, that uranium is solubility limited, $Ra^{226}$ migrates appreciably from the repository system only as a result of the $Th^{230}$ migration, which is not at a high enough concentration to be solubility limited. Consequently, the higher initial uranium concentration in spent fuel creates fourfold more $Th^{230}$ and fourfold greater concentration of $Ra^{226}$ within soil transport. The time dependence of these radionuclides has a very similar shape because they come from the same decay chain.

## Conclusions

For evaluation of the long-term safety of deep geological repository, a model of the disposal system, geosphere and the initial model of the reference biosphere have been developed.

Using the GoldSim simulation tool, the annual effective dose for adult individual from critical exposure group was calculated. Within simple probabilistic analysis, the influence of changes of selected parameters was evaluated - namely the transfer factors for leaf plants, which represent a rate of the contaminant transport from loamy soil to plants leaves.

The analysis was performed using the Monte Carlo method using the GoldSim simulation tool. The lognormal distribution with its respective parameters was used for the analysis.

As the results show, the analysis performed has no significant effect on the total annual effective dose value. The maximum value remains unchanged, a small variation of the values being noticed in last years of analysis, when specific radionuclides such as $Ra^{226}$, $Ra^{228}$, $Pb^{210}$ and $Th^{230}$ contribute to the total dose value. The effect of selected parameters changing on the dose value is up to 8 % in all significant time periods compared to the reference value.

## Acknowledgements

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