Comparison of RESRAD-OFFSITE and NORMALYSA software tools for the Tessenderlo test case

MODARIA WG3 model inter-comparison exercise

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EXECUTIVE SUMMARY

This report documents a 'model-model' inter-comparison exercise for two computer codes for radiological assessment of contaminated land: RESRAD-OFFSITE and NORMALYSA.

The reported inter-comparison exercise was carried out in the frame of activities of Work Group 3 'NORM and Legacy Sites' of the IAEA MODARIA project ('Modeling and Data for Radiological Assessment'; 2012-2015) (https://www-ns.iaea.org/projects/modaria/).

The inter-comparison exercise uses radiological data set inspired from a real-world contaminated site - Tessenderlo site in Belgium – that is contaminated by NORM industry discharges. The radiation data set from this site was complemented (where needed) with literature parameters for radionuclide transfers in environment and agricultural systems.

The modelled scenario assumes that a land area contaminated by Ra-226 and its progeny (Po-210 and Pb-210) is used by the reference person (farmer) for agricultural activities (raising of corn and pastureland for cattle). The analyzed exposure pathways include external exposure, inhalation of aerosols and inadvertent ingestion of soil by farmer during agricultural activities, as well as ingestion of locally produced radioactively contaminated corn, meat and milk.

Inter-comparison of NORMALYSA and RESRAD-OFFSITE for the Tessenderlo test case described in this report shows that both codes provide generally (qualitatively and quantitatively) similar results.

In particular, both codes have shown good agreement (of an order of several percent) in radionuclide concentrations in contaminated topsoil layer (representing the main source of radioactivity and secondary contamination of agricultural foodstuffs). The time frame of modeling predictions is 500 years.

The estimated total dose to the reference person through various pathways (external exposure, inhalation, inadvertent ingestion of soil, ingestion of crops, meat and milk) differs for both codes not more than of 7-8%. Good agreement in dose results is observed also for most individual exposure pathways.

The only calculation end-point where code predictions differ significantly (by a factor of ≈8) is radionuclide concentrations in agricultural crops (and respectively doses to reference person from ingestion of crops). This can be explained by the fact that RESRAD-OFFSITE uses more sophisticated plant root uptake model compared to NORMALYSA. In RESRAD-OFFSITE root uptake model, radionuclide uptake by crops is proportional to the ratio of root length in contaminated topsoil layer (in the considered case it is 0.15 m) to the total root depths (the RESRAD-OFFSITE default value for this parameter is 1.2 m). On the contrary, NORMALYSA assumes that all plant roots in cropland area are situated in contaminated topsoil (root zone) layer, which resulted in higher predicted radionuclide uptake by crops compared to RESRAD.

Relatively small differences in dose results by RESRAD-OFFSITE and NORMALYSA of an order of 10-20%, maximum, for other individual exposure pathways (external exposure, inhalation, inadvertent ingestion of soil) can be explained by different values of some default parameters (e.g., inadvertent soil ingestion rate by adult) and different schematizations of radioactivity source geometry used by RESRAD-OFFSITE and NORMALYSA in the considered modeling case (see Section 5.3 for more detail).

CONTENTS

1. INTRODUCTION

1.1. OBJECTIVES AND SCOPE OF THIS REPORT

This report documents a 'model-model' inter-comparison exercise for two computer codes for radiological assessment of contaminated land: RESRAD-OFFSITE and NORMALYSA.

The inter-comparison exercise uses radiological data set inspired from a real-world contaminated site - Tessenderlo site in Belgium – that is contaminated by NORM industry discharges. The radiation data from this site were complemented (where needed) with literature parameters for radionuclide transfers in environment and agricultural systems.

This report compares performance of the mentioned above computer codes and discusses possible reasons for discrepancies in modeling results (when such discrepancies are observed).

The reported inter-comparison exercise was carried out in the frame of activities of Work Group 3 'NORM and Legacy Sites' of the IAEA MODARIA project ('Modeling and Data for Radiological Assessment'; 2012-2015) (https://www-ns.iaea.org/projects/modaria/).

1.2. SOFTWARE CODES USED

1.2.1. RESRAD-OFFSITE code

The RESRAD family of computer codes was developed by Argonne National Laboratory (USA) for radiological assessment purposes (http://resrad.evs.anl.gov/). These codes allow modeling the transport of radionuclides in the environment and calculating the intake by human and biota. Then the doses and risks from radiation exposure are estimated.

The RESRAD-OFFSITE computer code evaluates the radiological dose and excess cancer risk to an individual who is exposed while located within or outside the area of initial (primary) contamination. The primary contamination, which is the source of all the releases modeled by the code, is assumed to be a layer of soil. The releases of contaminants from the primary contamination to the atmosphere, to surface runoff, and to groundwater are considered. It also models the accumulation and redistribution of radioactive contaminants at off-site locations, and estimates resulting doses to humans [Yu et al., 2007].

RESRAD-OFFSITE considers nine exposure pathways: direct exposure from contamination in soil, inhalation of radioactive aerosols and radon, ingestion of contaminated agricultural crops, ingestion of meat, ingestion of milk, ingestion of aquatic foods, ingestion of water, and incidental ingestion of soil. By selecting different pathways, RESRAD-OFFSITE can be used to simulate various exposure scenarios, including Rural Resident Farmer, Urban Resident, Worker, and Recreationist.

1.2.2. NORMALYSA software tool

The NORMALYSA (NORM And LegacY Site Assessment) software tool is designed to simulate radionuclide transport in the environment from the source term (e.g., radioactively contaminated land) to the relevant receptors (e.g., residential areas, agricultural areas, water bodies, etc.), and to estimate resulting radiation exposure doses to humans [Avila et al., 2018].

The NORMALYSA software was developed by Facilia AB (Bromma, Sweden) with the support of the International Atomic Energy Agency (IAEA). The NORMALYSA software tool was further tested in 2012-2015 in the frame of IAEA MODARIA project Work Group 3.

The NORMALYSA software tool is based on the Ecolego 6 (http://ecolego.facilia.se/ecolego/) software [Avila et al., 2005]. Ecolego is a software package developed by Facilia AB for implementing deterministic and stochastic dynamic models described by first order ordinary differential equations (i.e., compartmental models).

The NORMALYSA tool consists of a Simulator program engine, which is integrated with a set of program modules organized in five main libraries: 'Sources', 'Cover Layers', 'Transports', 'Receptors' and 'Doses'. Specific modelling cases can be constructed by selecting needed modules and setting up data exchanges between these modules [Avila et al., 2018].

1.3. STRUCTURE OF THE REPORT

This report consists of six parts. It includes the following information:

- Presentation of test modeling case and input data set (Section 2);

- Brief description of schematizations and input data for NORMALYSA and RESRAD-OFFSITE codes (Sections 3 and 4);

- Comparison and discussion of results by both program codes (Section 5, which is the key section of the report), and

- Conclusions (Section 6).

Report also includes a list of references and appendices describing in detailed table format input data set and calculation results.

2. SITE AND SCENARIO DESCRIPTION

2.1. TESSENDERLO SITE DESCRIPTION

Tessenderlo is a town located in North-East Belgium. The chemical company Tessenderlo Chemie processed in this area phosphate ore for the production of dicalcium-phosphate (DCP) since the 1920-s. Waste water containing enhanced concentration in radium-226 was discharged into two small streams, Winterbeek and Grote Laak. To regulate the debit of the effluents, waste water retention basins were engineered and used as buffer.

For the development of the exposure scenarios for the model inter-comparison test discussed in this report, the MODARIA WG3 focused on the issue of the contamination by NORM discharges of the Winterbeek stream bed and banks.

The Winterbeek stream is 17 km long; the surface of its floodplain area is 721 ha. The dredging of sediments and the flooding of the stream has led to the contamination of large areas with Ra-226. The processes leading to contamination are illustrated on FIG. 1.

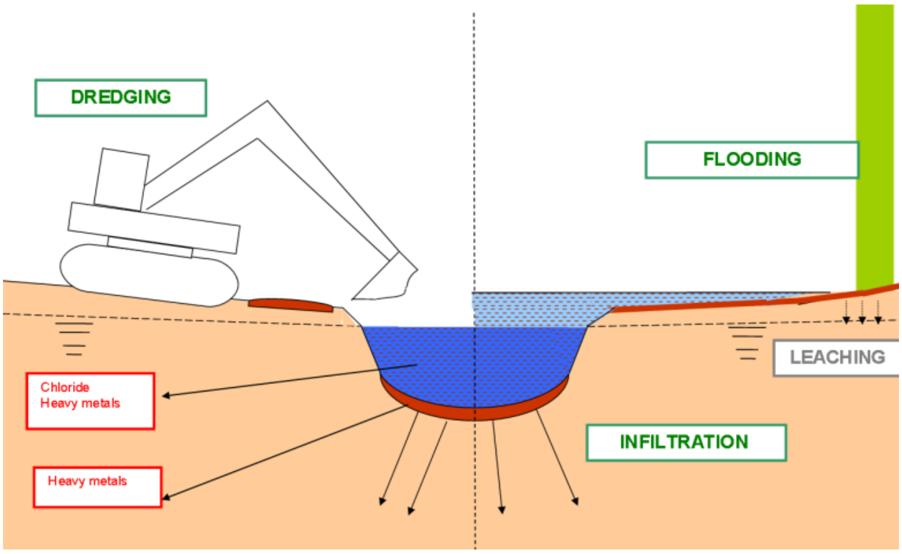


FIG. 1. Illustration[1] of the processes leading to contamination of the Winterbeek stream bed and banks at Tessenderlo Site in Belgium.

An aerial gamma-spectrometry performed in 2004 [Poffijn et al., 2005] allowed to identify the contour of contamination around the stream (FIG. 2). Data on average levels of contamination of stream banks with Ra-226 are shown in Table 1 [Poffijn et al., 2003].Table 1. Data on contamination by Ra-226 of Winterbeek stream banks.

	Left bank (Bq/kg)	Right bank (Bq/kg)
Soil content of Ra-226 average on whole study area	1330	810

[1] With courtesy of OVAM, public waste agency of Flanders.

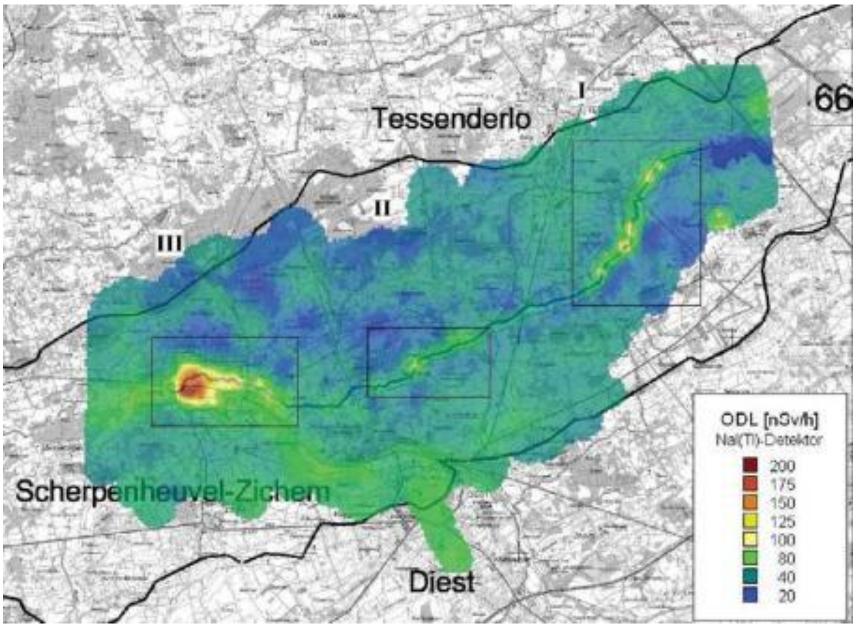


FIG. 2. Aerial gamma spectrometry of the zone around Winterbeek stream.

2.2. SCENARIO AND INPUT DATA DESCRIPTION

2.2.1. Scenario

Below is given scenario description, which is provided in the format developed for model inter-comparison exercises in the MODARIA WG3. This scenario was developed for the sake of the inter-comparison exercise only. It does not necessarily reflect the real exposure circumstances of individuals living in the area and the results of the present calculations should not be considered as a risk-assessment study.

Source: Wastewater from the phosphate processing facility was discharged to the Winterbeek stream. The dredging of sediments and the flooding of the stream has led to the contamination with Ra-226 of a large stream watershed area, which can be potentially used for agricultural activity.

Radionuclides included to simulation are: Ra-226, Pb-210 and Po-210. It is assumed that activity concentrations of Pb-210 and Po-210 in watershed soil are in equilibrium with Ra-226.

Exposure pathways:

- Food ingestion pathway via ingestion of maize (corn) grown on the contaminated area plus ingestion of meat and milk of cows pasturing on the contaminated area;

- External irradiation from material on the ground (agricultural worker on the field);

- Inhalation of suspended aerosol particles and inadvertent ingestion of soil during agricultural works.

Receptor environment: Although there are in practice restrictions on raising crops, we assume for this exercise that these restrictions are lifted. The main crop in the area is maize (corn) and also the area can be used for grazing by cows.

Exposed person:

The exposed person is an agricultural worker - farmer (adult). He works on a contaminated area but his home is not located in the contaminated area. It is assumed that around 10% of his diet is made from food grown on the contaminated area.

Occupancy:

Average annual time spent on fields = 1500 h.

Description of calculation endpoints:

- Activity concentration in soil and in crops (corn) grown on the contaminated area, and in meat (beef) and milk from the contaminated area;

- Annual committed effective dose to the exposed agricultural worker (total and by outlined above exposure pathways) on a time-frame of 500 years.

2.2.2. Input parameters

Input parameters for the Tessenderlo test case are listed in Appendix I to this report in Table 9 - Table 12.

The list of parameters include meteorological parameters (precipitation and evapotranspiration rates), contaminated source geometry and physical properties of soil (thickness of contaminated layer, density, porosity), radionuclides Kd-s for soil, and initial contamination of topsoil layer by radionuclides (Table 9).

Table 10 - Table 11 list parameters describing radionuclide uptake by agricultural plants and cattle, in particular radionuclide transfer factors to crops, pasture, meat and milk, ingestion rates of cattle etc.

Parameters defining data needed for calculation of radiation exposure doses for reference person (agricultural worker) such as time spent on contaminated land, inhalation rate, ingestion rates of agricultural products etc. are listed in Table 12.

A number of site-specific parameters listed in cited above tables were taken from BIOMASS project report [IAEA, 2004]. Soil radionuclide distribution coefficients and radionuclide transfer factors to plants and cattle were taken from the IAEA TRS no.472 report [IAEA, 2010].

3. CALCULATIONS USING NORMALYSA

3.1. SCHEMATIZATION OF CALCULATIONS IN NORMALYSA

To carry out simulation for Tessenderlo Scenario, a model was composed in NORMALYSA that included relevant set of Receptor modules and Dose modules from libraries.

Receptor Modules include modules to simulate radionuclide transfers in soil and uptake by agricultural products and cattle in two radioactively contaminated receptor environments: 'Pastureland' and 'Cropland'.

Calculated in receptor modules radionuclide concentrations in top soil layer, agricultural products (corn) and cattle (meat and milk) are passed as input parameters to Dose Modules for dose calculations.

Dose Modules include (in accordance with the exposure pathways modeled): 'Dose from occupancy outdoors' (doses from external exposure in agricultural land, inhalation and inadvertent ingestion of soil), 'Dose from ingestion of meat and milk', 'Dose from ingestion of crops' and 'Total Dose' (summing doses by individual pathways).

The calculations proceed as follows (FIG. 3):

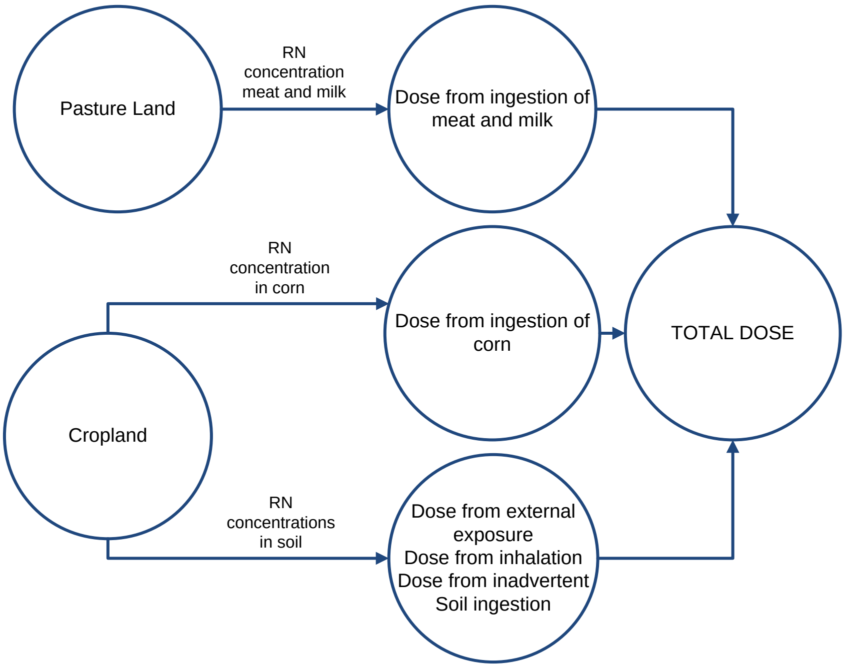


FIG. 3 Schematization of dose calculations for Tessenderlo exposure scenario.

Model realization in NORMALYSA using interaction matrix format is shown below (FIG. 4). Here diagonal elements of matrix represent individual Receptor and Dose modules. The off-diagonal elements show data exchanges between different modules.

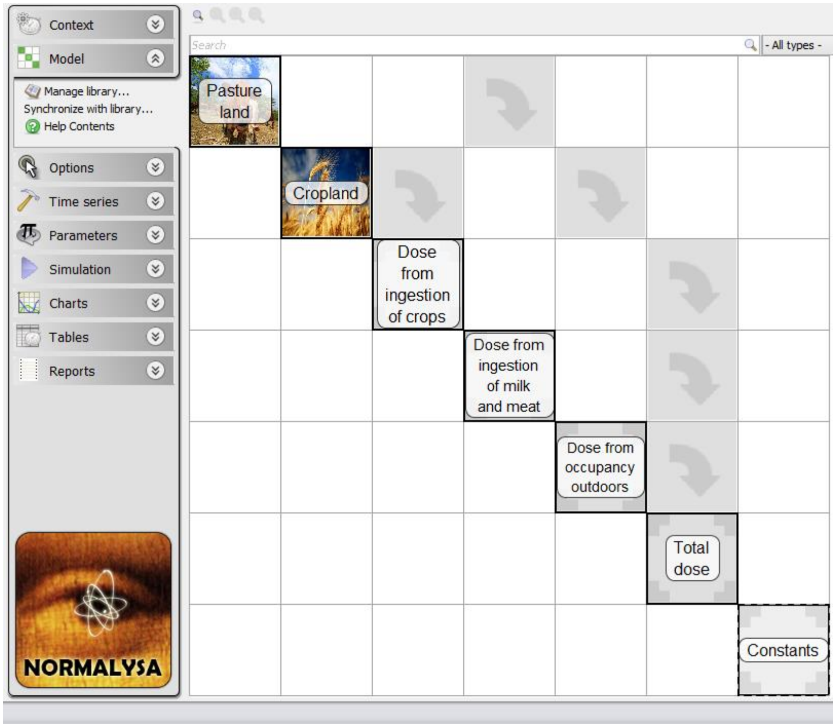


FIG. 4 Realization of the model for Tessenderlo Scenario in NORMALYSA.

3.2. INPUT PARAMETERS FOR NORMALYSA

Input parameter values for Tessenderlo test case that are similar for both codes are shown in Table 9 - Table 12 (Appendix I).

It was decided when planning the inter-comparison exercise that along with common list of parameters, codes will use specific for particular code default values for those parameters that are not included to the common list. This was done to explore possible effects of default code parameters on results of simulations.

In particular, for dose calculations NORMALYSA employs by default the following dose conversion coefficients. Dose coefficients for effective doses from external irradiation from surface deposition and immersion into radioactive cloud and water are based on [EPA, 1993]. Dose coefficients for internal exposure through inhalation and ingestion pathways are based on ICRP Publication no.72 [ICRP, 1995b].

Other various values of default parameters of NORMALYSA can be found in the software user manual [Avila et al., 2018].

4. CALCULATIONS USING RESRAD-OFFSITE

4.1. SCHEMATIZATION OF CALCULATIONS IN RESRAD-OFFSITE

The following exposure pathways were used in the RESRAD-OFFSITE to simulate the Tessenderlo scenario:

- Direct exposure to external radiation from the contaminated soil material;

- Internal exposure from inhalation of airborne radionuclides;

- Internal exposure from ingestion of plant foods grown in the contaminated soil;

- Internal exposure from ingestion of meat and milk from livestock fed with contaminated fodder;

- Ingestion of contaminated soil.

Model realization in RESRAD is shown below (FIG. 5).

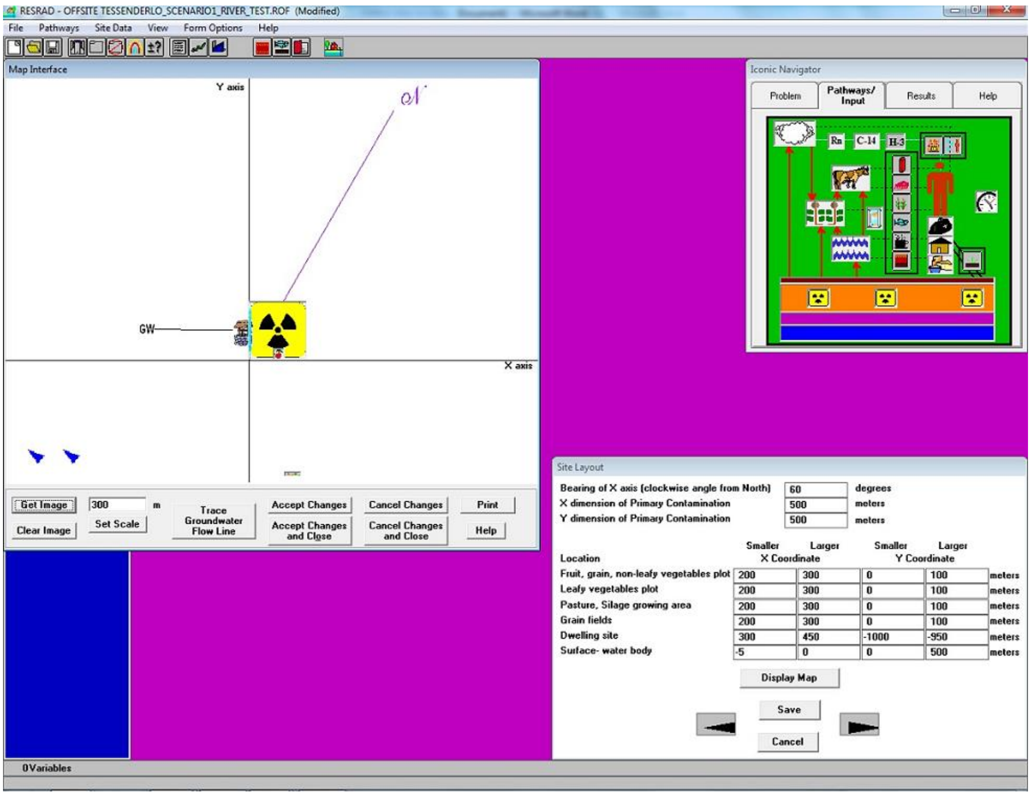


FIG. 5. Map interface of RESRAD-OFFSITE for the Tessenderlo Scenario.

4.2. INPUT PARAMETERS FOR RESRAD-OFFSITE

Input parameter values for Tessenderlo test case that are similar for both codes are shown in Table 9 - Table 12 (Appendix I).

In addition, RESRAD-OFFSITE simulation used a number of code-specific default parameter values. These parameters, for example, included “Plant Factors” such as crop yield, weathering (removal) constant, foliar interception factors, root depth etc. The impact of some of these parameters on calculation results will be discussed in Section 5.2.1.

For dose calculations RESRAD-OFFSITE employs by default the dose conversion coefficients for ingestion and inhalation pathway from the FGR no.11 [EPA, 1988] but allows using other sets of dose conversion factors. In the present calculations, ICRP Publication no.72 coefficients have also been used (similarly to NORMALYSA calculation case) for ingestion and inhalation exposure pathways.

Other values of various default parameters of RESRAD-OFFSITE can be found in the software user manual [Yu et al., 2007].

5. COMPARISON OF CODES: RESULTS AND DISCUSSION

Calculations of radionuclide concentrations in soil, agricultural products and resulting doses by various pathways were carried out using both codes for time points t=0, 100, 200, 300, 400, and 500 years.

5.1. RADIONUCLIDE CONCENTRATIONS IN SOIL

Simulated by RESRAD-OFFSITE and NORMALYSA radionuclide concentrations in soil are shown in Table 2.

Radionuclide concentrations in soil are governed by leaching by rainfall, erosion and radioactive decay. Under influence of these process radionuclide concentrations decrease in time over the simulated 500 years period by a factor of ≈7 (FIG. 3). Both codes show a good agreement in predicted radionuclide soil concentrations.

Table 2. Simulated radionuclide concentrations in soil.

Time, Years	**Radionuclide concentration in soil, Bq/kg.DW**					
	NORMALYSA			**RESRAD-OFFSITE**		
	Pb-210	**Po-210**	**Ra-226**	**Pb-210**	**Po-210**	**Ra-226**
0	1,30E+03	1,30E+03	1,30E+03	1,30E+03	1,30E+03	1,30E+03
100	8,17E+02	8,17E+02	8,80E+02	8,20E+02	8,20E+02	8,80E+02
200	5,52E+02	5,52E+02	5,96E+02	5,55E+02	5,55E+02	5,99E+02
300	3,74E+02	3,74E+02	4,04E+02	3,76E+02	3,76E+02	4,07E+02
400	2,53E+02	2,53E+02	2,74E+02	2,56E+02	2,56E+02	2,76E+02
500	1,72E+02	1,72E+02	1,85E+02	1,73E+02	1,73E+02	1,87E+02

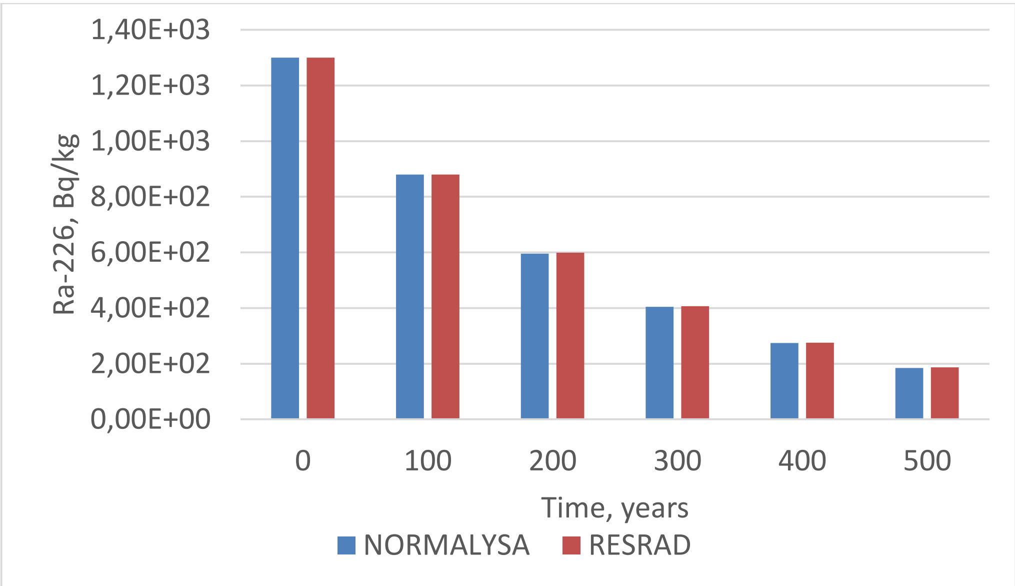


FIG. 6. Simulated Ra-226 activity in the top soil layer of contaminated site.

5.2. RADIONUCLIDE CONCENTRATIONS IN AGRICULTURAL PRODUCTS

5.2.1. Agricultural crops

Simulated by RESRAD-OFFSITE and NORMALYSA, radionuclide concentrations in agricultural crops (corn, pasture) are shown in Table 3. During 500-year simulation period concentrations of radionuclides in agricultural products decrease being dependent from decreasing soil concentrations (see previous paragraph). Graph for Ra-226 is shown in FIG. 7 (time dynamics of other radionuclides concentrations in crops simulated by RESRAD-OFFSITE and NORMALYSA is generally similar to Ra-226).

Table 3. Simulated radionuclide concentrations in crops.

Time, Years	Radionuclide concentration in crops, Bq/kg.FW					
	NORMALYSA			RESRAD-OFFSITE		
	Pb-210	Po-210	Ra-226	Pb-210	Po-210	Ra-226
0	8,58E-01	1,72E-01	1,72E+00	1,70E-01	2,20E-02	2,20E-01
100	5,39E-01	1,08E-01	1,16E+00	6,80E-02	1,30E-02	1,40E-01
200	3,64E-01	7,29E-02	7,87E-01	4,50E-02	9,00E-03	1,00E-01
300	2,47E-01	4,94E-02	5,33E-01	3,00E-02	6,00E-03	6,00E-02
400	1,67E-01	3,35E-02	3,61E-01	2,00E-02	4,00E-03	4,00E-02
500	1,13E-01	2,27E-02	2,45E-01	1,30E-02	3,00E-03	3,00E-02

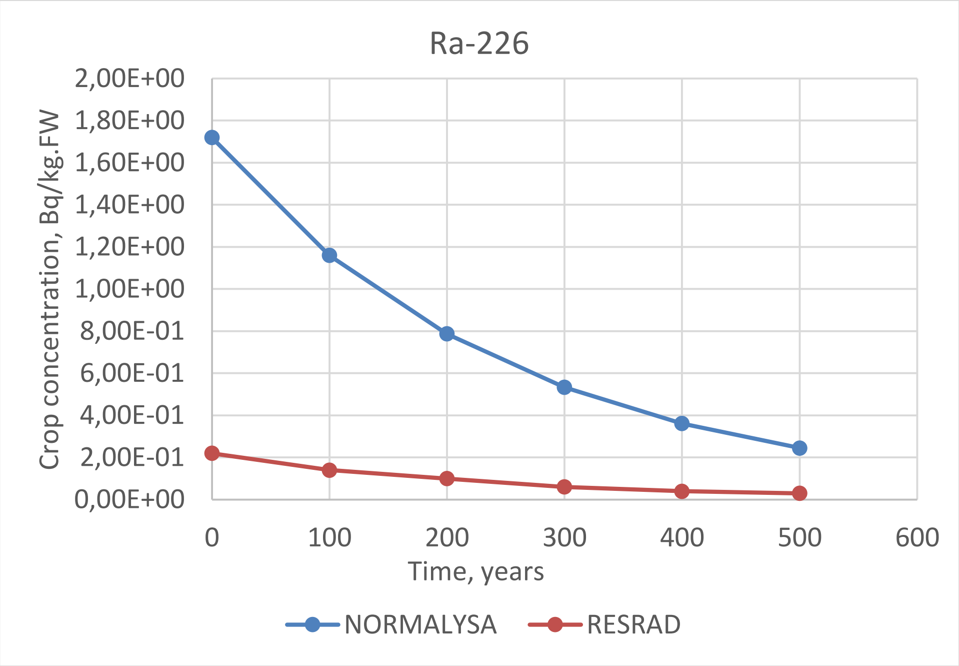


FIG. 7. Simulated dynamics of Ra-226 content in crops.

Somewhat unexpectedly, we found out significant differences in agricultural crops concentrations predicted by RESRAD-OFFSITE and NORMALYSA. Crop concentrations simulated by NORMALYSA are in agreement with the transfer factors listed in Table 10.

RESRAD-OFFSITE predicted by a factor of about ≈8 smaller crop concentrations than NORMALYSA. Analysis has shown that this is explained by the fact that the radionuclide crop uptake model used by RESRAD-OFFSITE [Yu et al., 2007] assumes that uptake is proportional to the ratio of crop root length in contaminated soil layer to the total root depths. In our case the thickness of contaminated layer is 0.15 m, while the default crop root depths in RESRAD-OFFSITE is 1.2 m (for fruit, grain and non-leafy vegetables)[2] [Yu et al., 2007]. On the contrary, NORMALYSA assumes by default that all plant roots are situated in top soil (root zone) layer, that have the same thickness as contaminated layer. This explains the smaller crop concentrations predicted by RESRAD-OFFSITE.

5.2.2. Meat and milk

Simulated by RESRAD-OFFSITE and NORMALYSA radionuclide concentrations in milk and meat are shown in Table 4 – Table 5. Example graph of Ra-226 activity in meat is shown at FIG. 8.

Table 4. Simulated radionuclide concentrations in meat.

Time, Years	Radionuclide concentration meat, Bq/kg.FW					
	NORMALYSA			RESRAD-OFFSITE		
	Pb-210	Po-210	Ra-226	Pb-210	Po-210	Ra-226
0	4,71E-01	3,27E+00	1,18E+00	4,50E-01	3,20E+00	1,10E+00
100	2,96E-01	2,06E+00	8,02E-01	2,70E-01	2,00E+00	7,50E-01
200	2,00E-01	1,39E+00	5,43E-01	2,00E-01	1,40E+00	5,00E-01
300	1,36E-01	9,42E-01	3,68E-01	1,20E-01	9,00E-01	3,50E-01
400	9,18E-02	6,38E-01	2,49E-01	9,00E-02	6,00E-01	2,00E-01
500	6,22E-02	4,32E-01	1,69E-01	5,00E-02	4,00E-01	1,60E-01

Table 5. Simulated radionuclide concentrations in milk.

Time, Years	Radionuclide concentration milk, Bq/L					
	NORMALYSA			RESRAD-OFFSITE		
	Pb-210	Po-210	Ra-226	Pb-210	Po-210	Ra-226
0	1,28E-01	1,37E-01	2,65E-01	1,20E-01	1,40E-02	2,50E-01
100	8,04E-02	8,65E-02	1,79E-01	8,00E-02	8,00E-03	1,60E-01
200	5,43E-02	5,84E-02	1,21E-01	5,00E-02	6,00E-03	1,10E-01
300	3,68E-02	3,96E-02	8,23E-02	3,50E-02	4,00E-03	8,00E-02
400	2,49E-02	2,68E-02	5,58E-02	2,10E-02	2,30E-03	5,00E-02
500	1,69E-02	1,82E-02	3,78E-02	1,70E-02	1,90E-03	3,00E-02

[2] In a realistic calculation however, this default value should have been substituted by the root depth of the crops which are actually raised on the contaminated land.

Radionuclide activity in meat and milk decrease with time, as they are related to radionuclide activity in soil and pasture. Despite the large difference in simulated activity of pasture by RESRAD-OFFSITE and NORMALYSA (see previous paragraph), simulated values of radionuclide activity in meat and milk by both codes differ on average by about ≈10% only. This is explained by relatively low radionuclide transfer factors to pasture, and relatively large assumed direct (inadvertent) ingestion of contaminated soil by cattle (0.5 kg.DW/d; see Table 11). As a result, the main simulated uptake of radioactivity by cattle occurs due to inadvertent ingestion of contaminated soil (rather than ingestion of pasture).

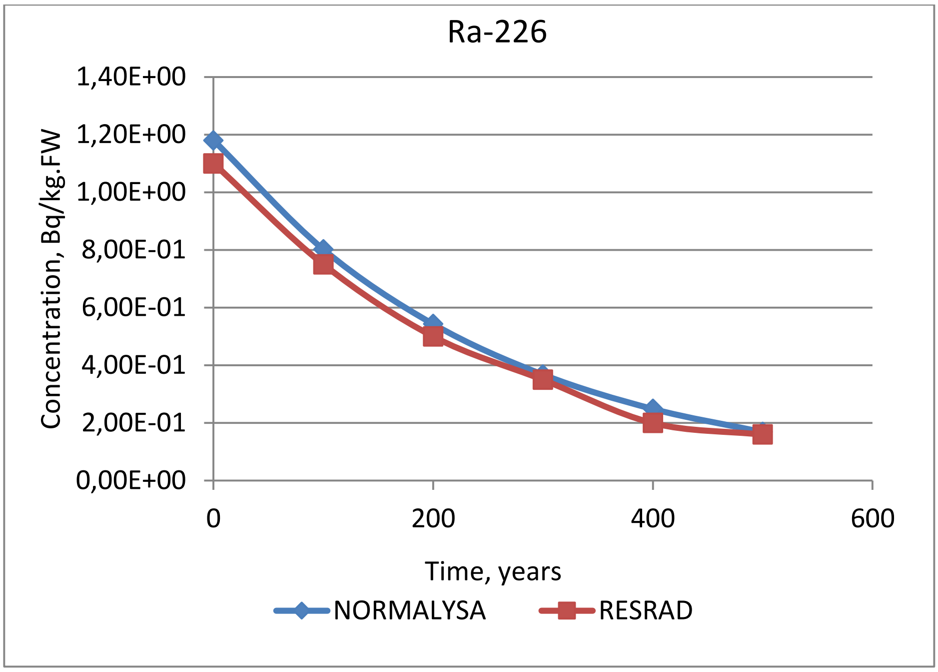


FIG. 8. Simulated Ra-226 concentration in meat of cattle.

5.3. CALCULATED EXPOSURE DOSES

Detailed results of dose calculations using RESRAD-OFFSITE and NORMALYSA for different radionuclides and exposure pathways are summarized in Appendix II in Table 13 and Table 14. Below we carry out comparison and discussion of results by different codes for specific exposure pathways.

5.3.1. External exposure

Important exposure pathway is external exposure of reference person (farmer) during agricultural activities at contaminated cropland. RESRAD-OFFSITE and NORMALYSA estimate external exposure doses based on calculated radionuclide concentrations in soil using relevant dose conversion coefficients. External dose calculations were carried out using parameters listed in Table 12. The main radionuclide contributing to external exposure is Ra-226 (see Table 13). Comparison of external exposure doses calculated by RESRAD-OFFSITE and NORMALYSA is shown at FIG. 9. Results are generally in reasonable agreement. RESRAD-OFFSITE gives doses by ≈12-13% higher than NORMALYSA. The mentioned above differences in values can be explained by differences in assumptions about source geometry in compared software codes. NORMALYSA assumes simple plain source at air-ground interface. RESRAD-OFFISITE uses more complicated assessment procedure taking into account depth and shape factors accounting for specific geometry of contaminated soil area [Yu et al., 2007].

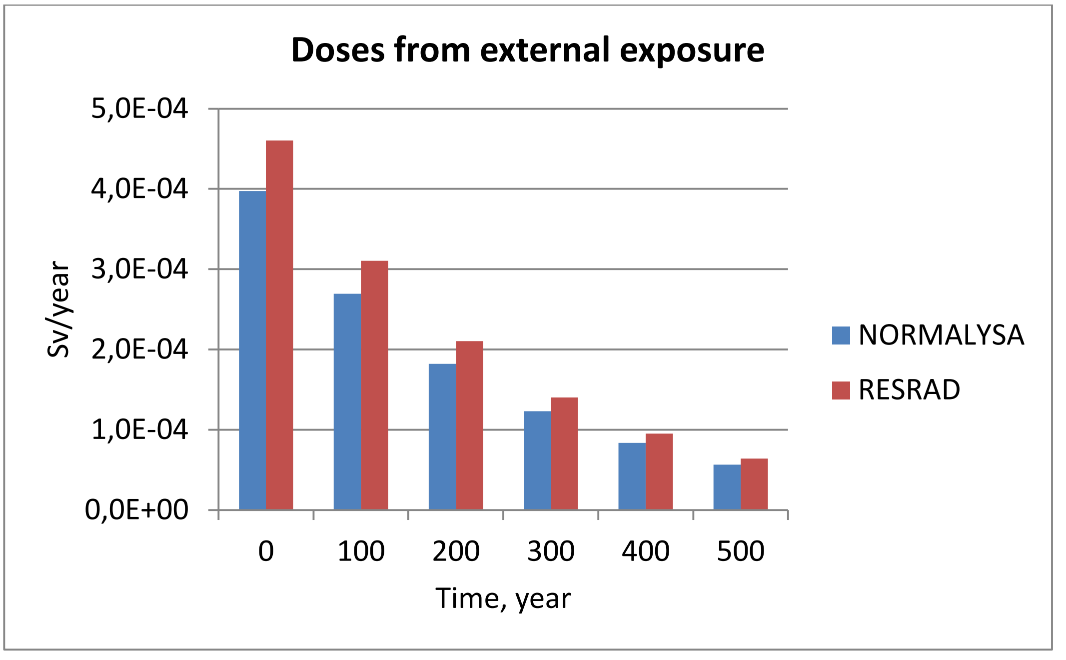


FIG. 9. Calculated external exposure doses by RESRAD-OFFSITE and NORMALYSA.

5.3.2. Inhalation pathway

Doses due to inhalation of dust by reference person (farmer) during agricultural works at contaminated cropland are calculated based on radionuclide concentration in soil and assumed resuspension of radioactivity to the air that is determined by dust load parameter (see Table 9). Comparison of doses due to inhalation of dust calculated by RESRAD-OFFSITE and NORMALYSA is shown at FIG. 10.

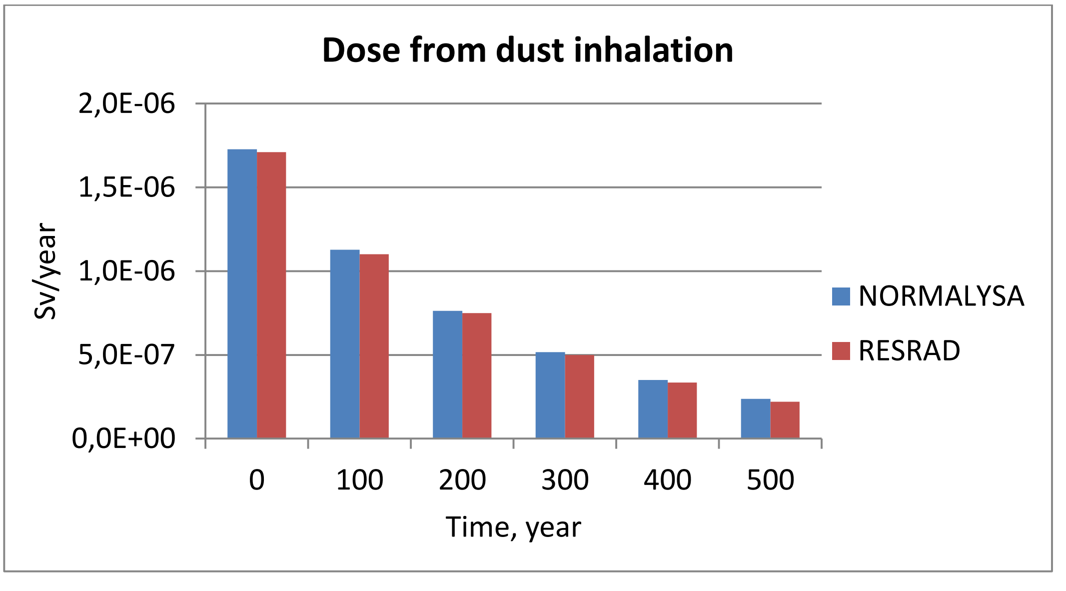


FIG. 10. Calculated doses due to inhalation of dust by RESRAD-OFFSITE and NORMALYSA.

The calculated values by both codes are in good agreement (they differ on average by several percent only reflecting small differences in predicted by both codes soil concentrations).

5.3.3. Inadvertent ingestion of soil

Doses due to inadvertent ingestion of soil by farmer in the course of agricultural activities are calculated based on radionuclide concentration in soil and assuming inadvertent intake rate of soil listed in Table 12.

The calculated values by RESRAD-OFFSITE and NORMALYSA are generally in reasonable agreement (difference of about ≈20%), which corresponds to a slight difference in the inadvertent soil ingestion rate: RESRAD-OFFSITE uses a default value of 36.5 g/y (or 4.2 mg/h) compared to 5 mg/h for NORMALYSA. When using the same value in both codes, the calculated doses are identical.

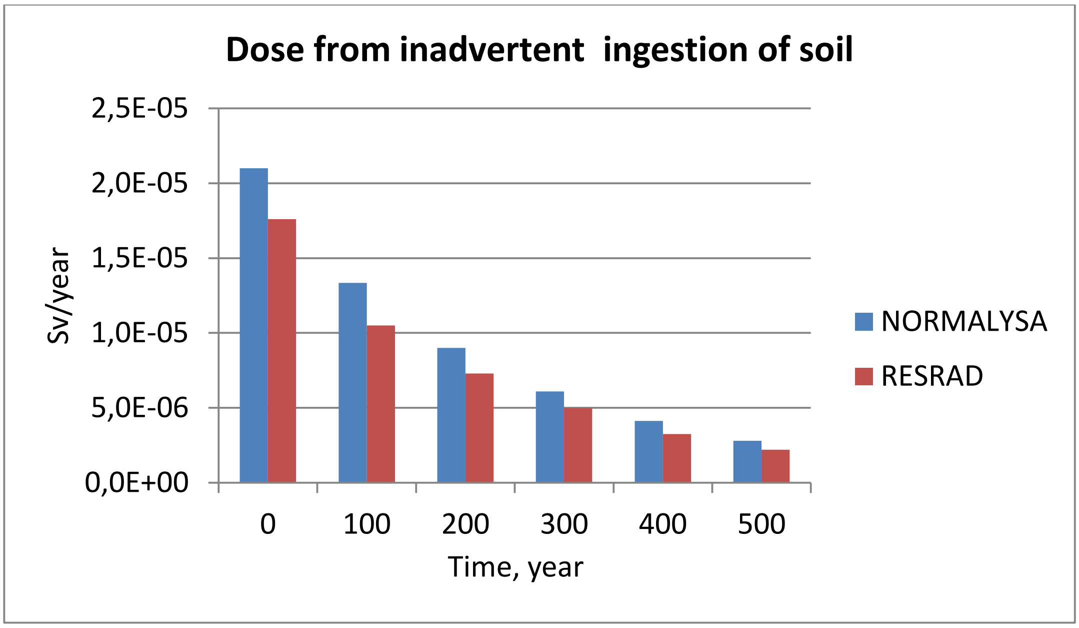


FIG. 11. Calculated doses due to inadvertent ingestion of soil by RESRAD-OFFSITE and NORMALYSA.

5.3.4. Ingestion of agricultural products

Calculated doses due to ingestion of agricultural products (crops, meat and milk) by reference person using RESRAD-OFFSITE and NORMALYSA are listed in Table 6.

Estimated doses due to ingestion of crops differ significantly (by a factor of ≈7). This is the consequence of significant differences in simulated radionuclide concentrations in crops by RESRAD-OFFSITE and NORMALYSA (see Section 5.2.1).

Smaller differences are observed in estimated doses due to ingestion of meat and milk (mostly less than 10%), as there is a better agreement in predicted by codes radionuclide concentrations in meat and milk (see Section 5.2.2).

Table 6. Calculated doses due to ingestion of agricultural products by reference person using RESRAD-OFFSITE and NORMALYSA.

	RESRAD-OFFSITE		**NORMALYSA**	
Time, years	**Ingestion of crops, Sv/year**	**Ingestion meat and milk, Sv/year**	**Ingestion of crops, Sv/year**	**Ingestion meat and milk, Sv/year**
0	2,4E-06	2,5E-05	1,6E-05	2,7E-05
100	1,6E-06	1,5E-05	1,0E-05	1,7E-05
200	1,0E-06	1,0E-05	7,1E-06	1,1E-05
300	6,9E-07	7,0E-06	4,8E-06	7,8E-06
400	4,7E-07	4,8E-06	3,2E-06	5,3E-06
500	3,2E-07	3,2E-06	2,2E-06	3,6E-06

5.3.5. Total dose

5.3.5.1. Dominant radionuclide

Doses formed by each radionuclide through all pathways are shown below in Table 7. Doses are dominated by Radium-226 (≈90%), as this radionuclide contributes mostly to external exposure, which is the dominant exposure pathway for the considered modeling case. Both codes provide qualitatively and quantitatively similar results.

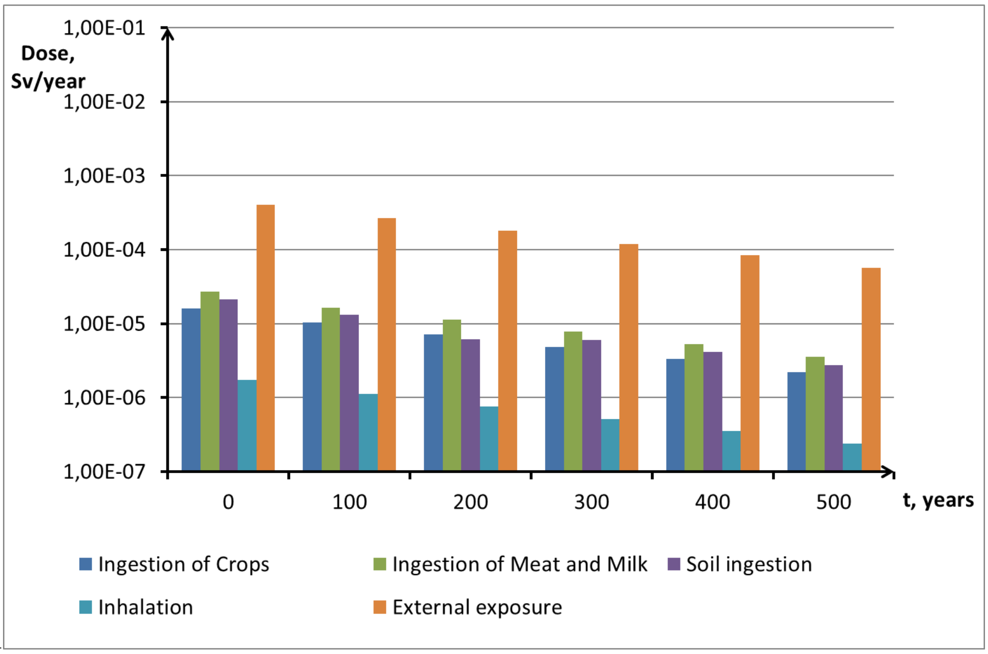
Table 7. Total dose from all pathways for each radionuclide.

Time, Years	**Total dose for all pathways each radionuclide, Sv/year**					
	NORMALYSA			**RESRAD-OFFSITE**		
	Pb-210	**Po-210**	**Ra-226**	**Pb-210**	**Po-210**	**Ra-226**
0	1,8E-05	3,6E-05	4,1E-04	1,0E-05	3,1E-05	4,7E-04
100	1,1E-05	2,3E-05	2,8E-04	3,9E-06	1,6E-05	3,2E-04
200	7,5E-06	1,5E-05	1,9E-04	4,2E-06	1,3E-05	2,1E-04
300	5,1E-06	1,0E-05	1,3E-04	2,9E-06	8,5E-06	1,4E-04
400	3,4E-06	7,1E-06	8,6E-05	1,9E-06	5,7E-06	9,6E-05
500	2,3E-06	4,8E-06	5,8E-05	1,3E-06	3,9E-06	6,5E-05

5.3.5.2. Dominant pathways

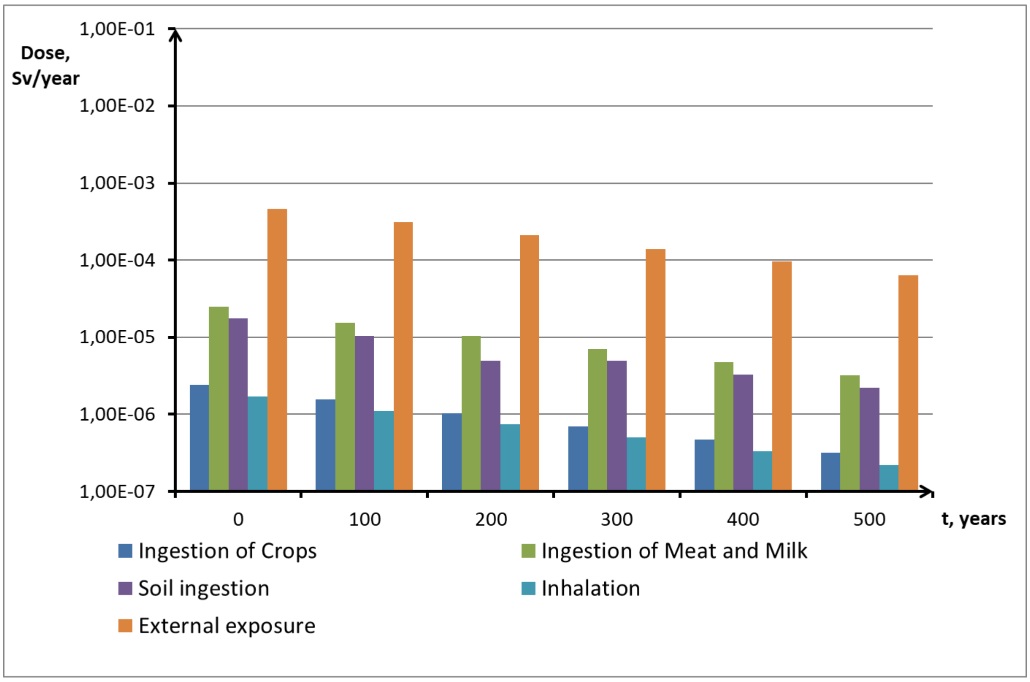
Data on contribution of various pathways to exposure of reference person based on calculations using the NORMALYSA and RESRAD-OFFSITE codes are shown in FIG. 12 - FIG. 13. It can be seen that based on simulation results of both codes the dominant exposure pathway is external exposure during agricultural works on contaminated cropland which contributes about 86% (as estimated by NORMALYSA) to 91% (as estimated by RESRAD) to the total dose. The inhalation pathway is of minor importance (0.3-0.4% contribution to total dose).

The only qualitative and quantitative difference in predictions of RESRAD-OFFSITE and NORMALYSA is that RESRAD-OFFSITE predicts smaller contribution to dose due to ingestion of crops (0.5%) compared to NORMALYSA (3.5%). The reason for this discrepancy between code results has been discussed above in sections 5.2.1 and 5.3.4.



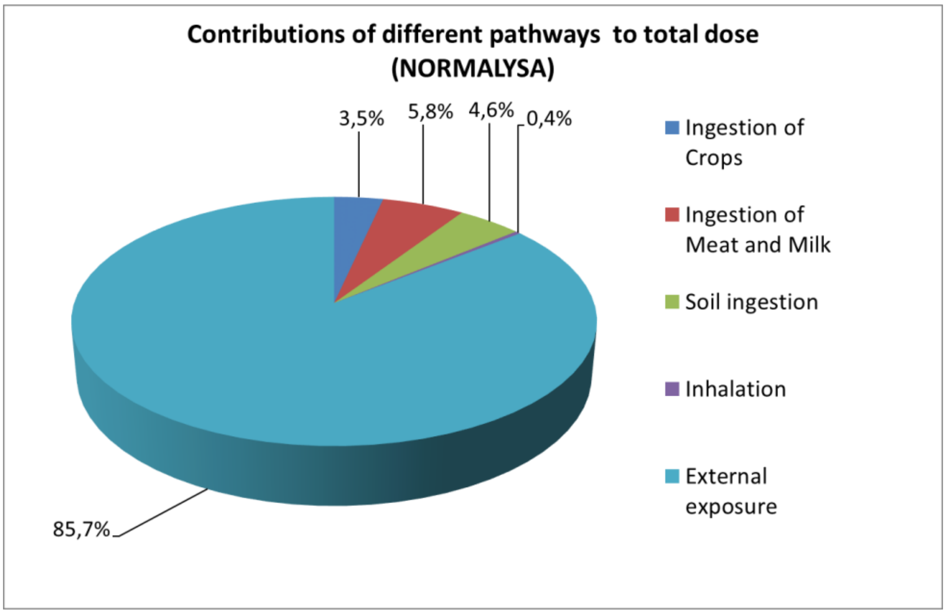
11

a) NORMALYSA

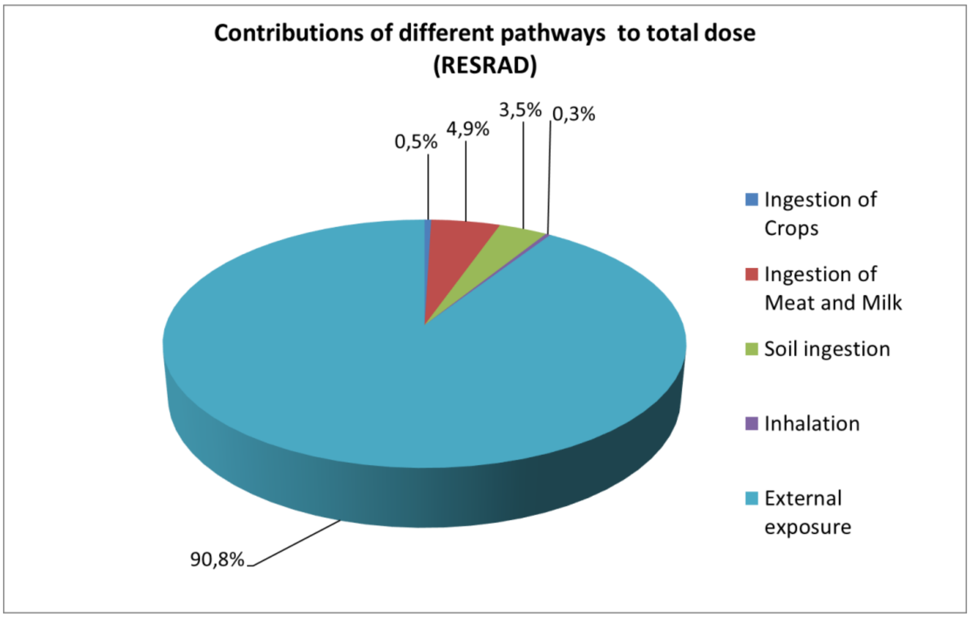


b) RESRAD-OFFSITE

FIG. 12. Contributions of different pathways to exposure of reference person for Tessenderlo Scenario: calculations using NORMALYSA and RESRAD-OFFSITE.



a) NORMALYSA



b) RESRAD-OFFSITE

FIG. 13. Contributions of different exposure pathway to the total dose (time t=0).

5.3.5.3. Total dose summed over all radionuclides and pathways

Results on calculated total dose for reference person (farmer) for Tessenderlo modeling case summed over all radionuclide and exposure pathways are summarized in Table 8.

Codes show a good agreement with regard to the estimated total dose (difference not more than of 7-8%). Reasons for the mentioned differences are explained in previous sections of this report, and these reasons steam mainly from different sets of some default parameters (such as inadvertent soil ingestion rate) and different schematizations of radioactivity source geometry used by RESRAD-OFFSITE and NORMALYSA. In addition, RESRAD-OFFSITE uses more sophisticated plant root uptake model compared to NORMALYSA, where radionuclide uptake is proportional to the ratio of root length in contaminated soil layer to the total root depths (see Section 5.2.1).

Table 8. Total dose from all pathways summed over all radionuclides.

Time, Years	Total Dose, Sv/year	
	NORMALYSA	**RESRAD-OFFSITE**
0	4,7E-04	5,1E-04
100	3,1E-04	3,4E-04
200	2,1E-04	2,3E-04
300	1,4E-04	1,5E-04
400	9,7E-05	1,0E-04
500	6,6E-05	7,0E-05

Total dose from all exposure pathways has maximum value at time point t=0 and constitutes 4.6E-04 Sv/y (by NORMALYSA) and 5.1E-04 Sv/y (by RESRAD-OFFSITE).

Doses decrease on a scale of 500 years by a factor of ≈7 due to decrease of radionuclide activity of topsoil layer (source of radiation exposure) as a consequence of leaching by rainfall, erosion and radioactive decay.

6. CONCLUSIONS

Inter-comparison of NORMALYSA and RESRAD-OFFSITE software codes for the Tessenderlo test case described in this report has shown that the both codes provide generally (qualitatively and quantitatively) similar results.

In particular, booth codes have shown good agreement (of an order of several percent) in simulated radionuclide concentrations in contaminated by Ra-226 and its progeny Po-210 and Pb-210 topsoil layer (representing the main source of radioactivity and secondary contamination of agricultural foodstuffs).

The estimated total dose to reference person through various pathways (external exposure, inhalation, inadvertent ingestion of soil, ingestion of crops, meat and milk) differs for both codes not more than of 7-8%. Good agreement in dose results was observed also for most individual exposure pathways.

The only calculation end-point where code predictions differ significantly (by a factor of $\approx$8) is radionuclide concentrations in agricultural crops (and respectively doses to reference person from ingestion of crops). This is because RESRAD-OFFSITE uses more sophisticated plant root uptake model compared to NORMALYSA. In RESRAD-OFFSITE root uptake model, radionuclide uptake by crops is proportional to the ratio of root length in contaminated topsoil layer (in the considered case it is 0.15 m) to the total root depths (the RESRAD-OFFSITE default value for this parameter is 1.2 m). On the contrary, NORMALYSA assumes that all plant roots in cropland area are situated in contaminated topsoil (root zone) layer, which resulted in higher predicted radionuclide uptake by crops compared to RESRAD-OFFSITE.

Relatively small differences in dose results by RESRAD-OFFSITE and NORMALYSA of and order of 10-20%, maximum, for other individual exposure pathways (external exposure, inhalation, inadvertent ingestion of soil) can be explained by different sets of some default parameters (e.g., inadvertent soil ingestion rate by adult) and different schematizations of radioactivity source geometry used by RESRAD-OFFSITE and NORMALYSA in the considered modeling case (see Section 5.3 for more detail).

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APPENDIX I. INPUT PARAMETERS FOR TESSENDERLO TEST CASE (SIMILAR FOR FOR BOTH CODES)

Table 9. Input parameters related to contaminated cropland and pastureland areas

Parameter	**Value**	**Unit**
Precipitation rate	0.76	m/year
Evapotranspiration rate	0.5	m/year
Irrigation rate	0	m/year
Thickness of contaminated topsoil layer	0.15	m
Total soil porosity	0.5	m
Dry bulk density of soil	1000	kg_{DW}/m^3
Concentration of dust in air (dust load)	5.0E-8	$kg.DW/m^3$
Radionuclide activity concentration in contaminated soil (at time t=0)		Bq/kg
Ra-226	1300	
Pb-210	1300	
Po-210	1300	
Distribution coefficient for the soil rooting zone		$m^3/kg.DW$
Ra-226	0.5	
Pb-210	0.27	
Po-210	0.6	

Table 10. Radionuclide transfer factors (TF) to agricultural plants and pasture *.

Radionuclide	**TF, kg_{FW}/kg_{DW}**	**TF, kg_{DW}/kg_{DW} ****
Ra-226	1.32E-3	2.4E-3
Pb-210	1.32E-4	2.4E-4
Po-210	6.6E-4	1.2E-3

Remarks: * - transfer factors are based on [IAEA, 2010]

** - Plant ‘fresh weight’ transfer factors calculated assuming plant fractional water content (by mass) F=0.45

Table 11. Input parameters related to radionuclide uptake by cattle.

Parameter	Value	Unit
Transfer factor to meat*		
Ra-226	1.7E-3	d/kg_{FW}
Pb-210	7E-4	d/kg_{FW}
Po-210	5E-3	d/kg_{FW}
Transfer factor to milk*		
Ra-226	3.8E-4	d/L
Pb-210	1.9E-4	d/L
Po-210	2.1E-4	d/L
Ingestion rates by cattle		
Ingestion rate of pasture by meat animals (cow)	15	kg_{DW}/d
Ingestion rate of pasture by milk animals (cow)	15	kg_{DW}/d
Ingestion rate of soil by meat animals (cow)	0.5	kg_{DW}/d
Ingestion rate of soil by milk animals (cow)	0.5	kg_{DW}/d
Water consumption by cattle	0	l/d

Remark: * Reference - IAEA, 2010

Table 12. Input parameters related to calculations of radiation exposure doses for reference person (agricultural worker).

Parameter	Unit	Value
Time spent on contaminated land	h/year	1500
Ingestion rate of corn	$kg_{FW}/year$	126.9
Fractional contribution of contaminate land to ingestion of corn	unitless	0.1
Ingestion rate of beef	$kg_{FW}/year$	50
Ingestion rate of milk	L/year	120
Fractional contribution of contaminated land to the ingestion of meat and milk	unitless	0.1
Ingestion rate of soil (inadvertent)	kg_{DW}/h	5.0E-6
Inhalation rate	m^3/h	0.92
Conversion factor from ambient to effective dose	unitless	0.6

APPENDIX II. CALCULATIONS RESULTS FOR RESRAD-OFFSITE AND NORMALYSA (DETAILED TABLE FORMAT)

Table 13. Doses to reference person for specific radionuclides for particular exposure pathway for both codes.

Time, Years	NORMALYSA				RESRAD-OFFSITE			
	Pb-210	Po-210	Ra-226	Total	Pb-210	Po-210	Ra-226	Total
	Dose from ingestion of crops, Sv/year							
0	7,5E-06	2,6E-06	6,1E-06	*1,6E-05*	1,1E-06	4,5E-07	8,7E-07	*2,4E-06*
100	4,7E-06	1,6E-06	4,1E-06	*1,0E-05*	6,7E-07	2,9E-07	5,9E-07	*1,6E-06*
200	3,2E-06	1,1E-06	2,8E-06	*7,1E-06*	4,5E-07	1,9E-07	3,9E-07	*1,0E-06*
300	2,2E-06	7,5E-07	1,9E-06	*4,8E-06*	3,0E-07	1,3E-07	2,6E-07	*6,9E-07*
400	1,5E-06	5,1E-07	1,3E-06	*3,2E-06*	2,0E-07	8,7E-08	1,8E-07	*4,7E-07*
500	9,9E-07	3,5E-07	8,7E-07	*2,2E-06*	1,4E-07	5,8E-08	1,2E-07	*3,2E-07*
	Dose from ingestion of meat, Sv/year							
0	1,6E-06	2,0E-05	1,7E-06	*2,3E-05*	1,6E-06	1,8E-05	1,6E-06	*2,1E-05*
100	1,0E-06	1,2E-05	1,1E-06	*1,5E-05*	9,8E-07	1,1E-05	1,0E-06	*1,3E-05*
200	6,9E-07	8,3E-06	7,6E-07	*9,8E-06*	6,6E-07	7,5E-06	7,0E-07	*8,9E-06*
300	4,7E-07	5,7E-06	5,2E-07	*6,6E-06*	4,4E-07	5,0E-06	4,7E-07	*5,9E-06*
400	3,2E-07	3,8E-06	3,5E-07	*4,5E-06*	3,0E-07	3,4E-06	3,2E-07	*4,0E-06*
500	2,2E-07	2,6E-06	2,4E-07	*3,0E-06*	2,0E-07	2,3E-06	2,1E-07	*2,7E-06*
	Dose from ingestion of milk, Sv/year							
0	1,1E-06	2,0E-06	8,9E-07	*3,9E-06*	1,0E-06	2,0E-06	8,3E-07	*3,8E-06*
100	6,7E-07	1,2E-06	6,0E-07	*2,5E-06*	6,4E-07	1,2E-06	5,6E-07	*2,4E-06*
200	4,5E-07	8,4E-07	4,1E-07	*1,7E-06*	4,3E-07	8,2E-07	3,8E-07	*1,6E-06*
300	3,1E-07	5,7E-07	2,8E-07	*1,2E-06*	2,9E-07	5,5E-07	2,5E-07	*1,1E-06*
400	2,1E-07	3,9E-07	1,9E-07	*7,8E-07*	1,9E-07	3,7E-07	1,7E-07	*7,3E-07*
500	1,4E-07	2,6E-07	1,3E-07	*5,3E-07*	1,3E-07	2,5E-07	1,1E-07	*4,9E-07*
	Dose from inadvertent ingestion of soil, Sv/year							
0	6,7E-06	1,2E-05	2,7E-06	*2,1E-05*	5,6E-06	9,7E-06	2,3E-06	*1,8E-05*
100	4,2E-06	7,3E-06	1,8E-06	*1,3E-05*	3,5E-06	6,0E-06	1,5E-06	*1,1E-05*
200	2,8E-06	4,9E-06	1,2E-06	*9,0E-06*	2,3E-06	4,0E-06	1,0E-06	*7,3E-06*
300	1,9E-06	3,3E-06	8,4E-07	*6,1E-06*	1,6E-06	2,7E-06	6,8E-07	*5,0E-06*
400	1,3E-06	2,3E-06	5,7E-07	*4,1E-06*	1,0E-06	1,8E-06	4,6E-07	*3,3E-06*
500	8,8E-07	1,5E-06	3,9E-07	*2,8E-06*	7,0E-07	1,2E-06	3,1E-07	*2,2E-06*
	External exposure dose from agricultural activity, Sv/year							
0	2,8E-07	1,8E-09	4,0E-04	*4,0E-04*	4,2E-07	2, 2E-09	4,6E-04	*4,6E-04*
100	1,7E-07	1,2E-09	2,7E-04	*2,7E-04*	2,6E-07	1, 4E-09	3,1E-04	*3,1E-04*
200	1,2E-07	7,8E-10	1,8E-04	*1,8E-04*	1,8E-07	9,3E-10	2,1E-04	*2,1E-04*
300	8,0E-08	5,3E-10	1,2E-04	*1,2E-04*	1,2E-07	6, 3E-10	1,4E-04	*1,4E-04*
400	5,4E-08	3,6E-10	8,4E-05	*8,4E-05*	8,2E-08	4,3E-10	9,5E-05	*9,5E-05*
500	3,7E-08	2,4E-10	5,7E-05	*5,7E-05*	5,6E-08	2,9E-10	6,4E-05	*6,4E-05*
	Dose from dust inhalation, Sv/year							
0	5,0E-07	3,8E-07	8,5E-07	*1,7E-06*	5,0E-07	3,8E-07	8,3E-07	*1,7E-06*

Time, Years	NORMALYSA				RESRAD-OFFSITE			
	Pb-210	**Po-210**	**Ra-226**	**Total**	**Pb-210**	**Po-210**	**Ra-226**	**Total**
100	3,1E-07	2,4E-07	5,7E-07	*1,1E-06*	3,1E-07	2,3E-07	5,6E-07	*1,1E-06*
200	2,1E-07	1,6E-07	3,9E-07	*7,6E-07*	2,1E-07	1,6E-07	3,8E-07	*7,5E-07*
300	1,4E-07	1,1E-07	2,6E-07	*5,2E-07*	1,4E-07	1,1E-07	2,5E-07	*5,0E-07*
400	9,7E-08	7,5E-08	1,8E-07	*3,5E-07*	9,4E-08	7,1E-08	1,7E-07	*3,4E-07*
500	6,6E-08	5,1E-08	1,2E-07	*2,4E-07*	6,3E-08	4,7E-08	1,1E-07	*2,2E-07*

Table 14. Doses to reference person for specific pathway summed over all radionuclides for both codes.

	RESRAD-OFFSITE						NORMALYSA					
Time, years	**External exposure, Sv/year**	**Inhalation, Sv/year**	**Soil ingestion, Sv/year**	**Ingestion of crops, Sv/year**	**Ingestion meat and milk, Sv/year**	**Total dose, Sv/year**	**External exposure, Sv/year**	**Inhalation, Sv/year**	**Soil ingestion, Sv/year**	**Ingestion of crops, Sv/year**	**Ingestion meat and milk, Sv/year**	**Total dose, Sv/year**
0	4,6E-04	1,7E-06	1,8E-05	2,4E-06	2,5E-05	5,1E-04	4,0E-04	1,7E-06	2,1E-05	1,6E-05	2,7E-05	4,7E-04
100	3,1E-04	1,1E-06	1,1E-05	1,6E-06	1,5E-05	3,4E-04	2,7E-04	1,1E-06	1,3E-05	1,0E-05	1,7E-05	3,1E-04
200	2,1E-04	7,5E-07	7,3E-06	1,0E-06	1,0E-05	2,3E-04	1,8E-04	7,6E-07	9,0E-06	7,1E-06	1,1E-05	2,1E-04
300	1,4E-04	5,0E-07	5,0E-06	6,9E-07	7,0E-06	1,5E-04	1,2E-04	5,2E-07	6,1E-06	4,8E-06	7,8E-06	1,4E-04
400	9,5E-05	3,4E-07	3,3E-06	4,7E-07	4,8E-06	1,0E-04	8,4E-05	3,5E-07	4,1E-06	3,2E-06	5,3E-06	9,7E-05
500	6,4E-05	2,2E-07	2,2E-06	3,2E-07	3,2E-06	7,0E-05	5,7E-05	2,4E-07	2,8E-06	2,2E-06	3,6E-06	6,6E-05