Radiologisk konsekvensanalyse ved utslipp av radionuklider fra IFE

Task 2: Impact Assessment to the public discharges - Agilera

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Index

List of Tables

List of Figures

1 Introduction

The Institute for Energy Technology (IFE) is an independent research foundation, established by the government of Norway in 1948, with approx. 1 billion NOK annual turnover and around 600 employees [1]. When founded, IFE's main goal was nuclear research, but currently IFE is one of the leaders in petroleum, environmental and nuclear technology as well as energy research and safety. Throughout the years IFE has been devoted to many projects aiming at the development of smart and environment-friendly industrial processes and transport solutions as well as the pharmaceutical and renewable energy sectors.

IFE is organized in three divisions, each of them further divided into sectors and departments.

- Nuclear Technology (NUK)
- Radiopharmacy (Agilera)
- Research and Development (R&D) (FoU)

As previously explained in Task 1, IFE holds a permit for liquid and atmospheric discharges from the facilities, issued pursuant to the Act of 13 March 1981 No.6 Protection Concerning Against Pollution and Waste [2]. This permit allows, among other things, for the receiving, treatment and intermediate storage of radioactive waste from the isotope production and provides authorisation for radioactive discharges to air and water from the reactor operations.

The split of IFE into three independent divisions requires a new regulatory permit for liquid and atmospheric discharges to the environment during normal operations for each of them. IFE has been required by the DSA (Norwegian Radiation and Nuclear Safety Authority) to perform a new environmental risk assessment including all relevant substances IFE has permission or requests permission to release.

1.1 Objectives

The objective of this project is to perform an environmental impact assessment of the discharge of radioactive substances from IFE Kjeller, both to human and non-human biota.

The environmental impact assessment will be conducted for each of the IFE divisions: NUK, Agilera and FoU, which are Nuclear Technology, Radiopharmacy and Research & Development respectively, following the same base conceptual model in all cases.

The project is divided into four tasks:

- Task 1: Preliminary model definition and parametrization
- Task 2: Impact assessment to the public
- Task 3: Impact assessment to non-human biota
- Task 4: Training of Ecolego and ERICA to IFE

Task 1 was delivered in November 2022 [3]. The task 1 report aimed at presenting and defining the model. Main compartments of the system were identified, as well as the main processes and transferences of radionuclides between compartments. It also included a description of the dose model by identifying the reference group and the main exposure pathways.

This document reports the work carried out in the frame of Task 2 for the Agilera division. The end goal of this task is to calculate the radiological impact to the public. After describing the methodology in the following section (Section 2), both the system and the conceptual model are presented (Section 3 and Section 4, respectively). Section 5 is focused on explaining the mathematical models where both the formulation and parametrization of all values are included. Lastly, the dose assessment results are presented in Section 6.

One report is prepared per division where Sections 1 to Section 5 and Appendix A are exactly the same and the information related with the results of the radiological impact assessment are specific of the division (Section 6, Section 7 and Appendix C).

It is worth mentioning that all information presented in Task 1 will not be repeated in the current report, but a summary will be provided. Some assumptions have changed from Task 1 report. In those cases, new information is included in this report. In case of discrepancies between Task 1 and Task 2 reports, note that the valid formulation, parametrization and assumptions are those in Task 2 report.

2 Methodology

The methodology that was followed to perform the dose assessment both to human and non-human biota is presented in Figure 2-1. The first step to estimate the dose is to prepare and develop the model, including the following activities:

(i) System definition: general description of the environment close to the IFE Facility, studied area, discharges to the environment and reference group to which the dose is assessed.

(ii) Conceptual model: description of the conceptual model which includes definition of the system compartments, processes affecting the transport of radionuclides in the environment and exposure pathways.

(iii) Mathematical model: formulation and parametrization of the compartments, processes, transferences, concentration in the environment, exposure pathways and dose. The mathematical model includes the definition of the radionuclide list and the release conditions that will be implemented in the model.

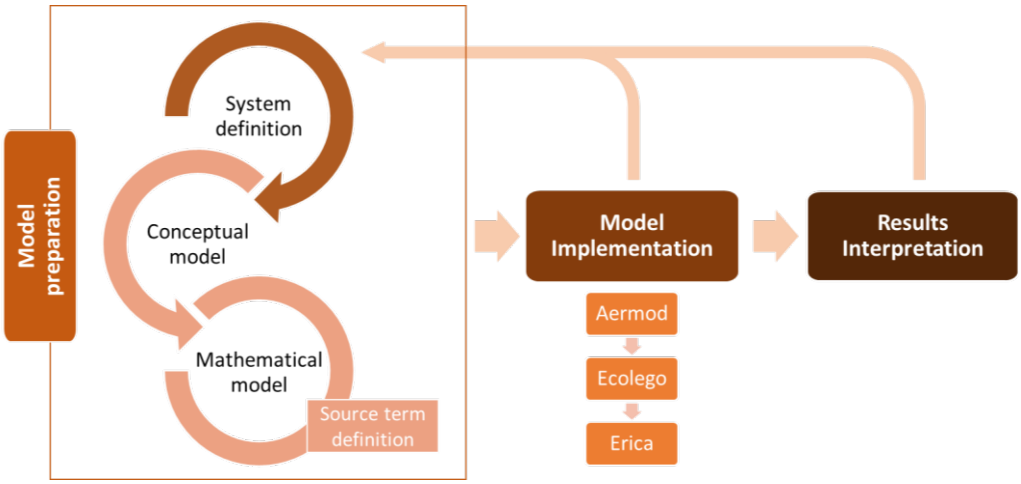

Figure 2-1. *Scheme of the project methodology.*

Once the model is conceptualized and mathematically described, the second step is to implement the model in the corresponding software. Different software is used to develop different types of calculations. In this work, the atmospheric concentration of each isotope due to atmospheric emissions is estimated using AERMOD. Both radionuclide transport and dose to humans are calculated with Ecolego, which is fed with the atmospheric radionuclide concentrations from AERMOD. Erica is used to calculate the dose to non-human biota taking into account the isotopic concentration in the environment provided by Ecolego.

This report is only focused on the dose assessment to humans, entailing that, neither information related to the conceptualization, mathematical formulation, or implementation of the non-human biota models nor the results obtained from Erica are provided in this document. See the report of Task 3 for all the details [4].

Finally, results obtained are treated and an evaluation on the main exposure pathways and isotopes contributing to the dose is discussed.

3 System Description

To evaluate the dose impact to humans due to the atmospheric and liquid discharges of IFE Kjeller facilities to the environment it is important to take into account the following:

- There are three different divisions: NUK, Agilera and FoU.
- The existence of two main sources of emission to the environment: the emission of gases to the atmosphere and the discharge of radionuclides in liquid form to the Nitelva river.

On one hand, each division requires its own dose assessment considering the radionuclides that are emitted from each division. The conceptual model will be the same but modifying the source term (radionuclides emitted and release rate).

On the other hand, each division is responsible for the release of radionuclides into the environment through either gas emissions to the atmosphere or liquid discharges to the Nitelva river. Each division contributes to the air emissions through the release of radionuclides in gas or aerosol form via chimneys located in different buildings at the IFE-Kjeller site (see Figure 5-1). Agilera and FoU do not discharge any radionuclides directly into the river but transfer their emissions to NUK, from where radionuclides are released to the Nitelva river via the NALFA pipeline (see Figure 5-6).

The studied system is defined considering the area close to the IFE-Kjeller facilities that could potentially be affected by the atmospheric and liquid discharges. In the case of atmospheric discharges, considering the orography and the meteorological conditions, the area close to the facilities could be affected, without reaching the area of the river. The liquid discharges to the Nitelva river through the pipeline will potentially affect the area downstream both in the rivers and the agricultural areas nearby. A detailed description of both systems was presented in Task 1 [3] and is summarized in Section 4 of this report.

The reference group selection is based on the behaviour of the population living in the area of Lillestrøm and is described in Section 4.2 and 5.2. Note that there are some changes in the assumptions with respect to Taks 1 report.

A radiological impact assessment is performed for each release pathway to the environment (atmospheric and liquid discharges) as there is no connection between the two physical systems (see next section for details). This means that there is no significant transport of radionuclides released to the atmosphere reaching the river nor the areas affected by the river, and vice versa, the radionuclides released to the river are not transported to the areas affected by the atmospheric emissions.

In addition, it should be noted that two different release scenarios are considered in the case of the atmospheric discharges: (i) continuous release and (ii) total acute release.

Therefore, three different dose assessments to the public are performed for each of the divisions (i.e., continuous atmospheric emissions, total acute atmospheric emissions and liquid discharges to the Nitelva river). As these assessments are conducted per division, 9 different environmental impact assessments based on the same conceptual models are developed in this project.

4 Conceptual model

The conceptual model has been described in detail in Task 1 of this project [3]. This section provides a summary of the conceptual model for better comprehension of the subsequent sections. Two different conceptual models have been described: one for the atmospheric emissions and one for the liquid discharge to the Nitelva river. No distinction on the conceptual model is made between the continuous and total acute release to the atmosphere apart from the release rate. In addition, a distinction has been made between the physical and the dose models.

The list of nuclides to be considered differs in each case and it depends on both the division and the type of release. For each case, a preliminary dose assessment was performed to estimate the main nuclides contributing to dose (using the 'Initial Radiological Assessment Tool', IRAT [5]). These isotopes are implemented in Ecolego, and their decay products were selected to be included in the dose assessment. A detailed explanation of the selected nuclides and the discharge rates considered is provided in Section 5.

4.1 Physical model

The physical model is the part of the model that describes the physical system, meaning that this is where the compartments of the environment and the radionuclide transport and processes are defined.

4.1.1 Atmospheric system

The atmospheric model considers that radionuclides released to the atmosphere are dispersed to agricultural and residential areas located a few hundred meters away from the IFE-Kjeller facilities (see selected area in Figure 4-1).

Figure 4-1. *Selected areas for the atmospheric model.*

As shown in Figure 4-2, radionuclides are then deposited onto the croplands area. The croplands are considered to consist of two layers: top soil and deep soil between which radionuclides can be transferred via different mechanisms:

- Bioturbation, which refers to the physical, chemical, and biological alteration of soil layers by living organisms.
- Advection, which refers to the transport of radionuclides by the flow of water.
- Diffusion, which refers to the movement of radionuclides from high concentration regions to lower ones.

Besides the abovementioned processes, the model also considers the decay of radionuclides and the sorption of radionuclides into the soil.

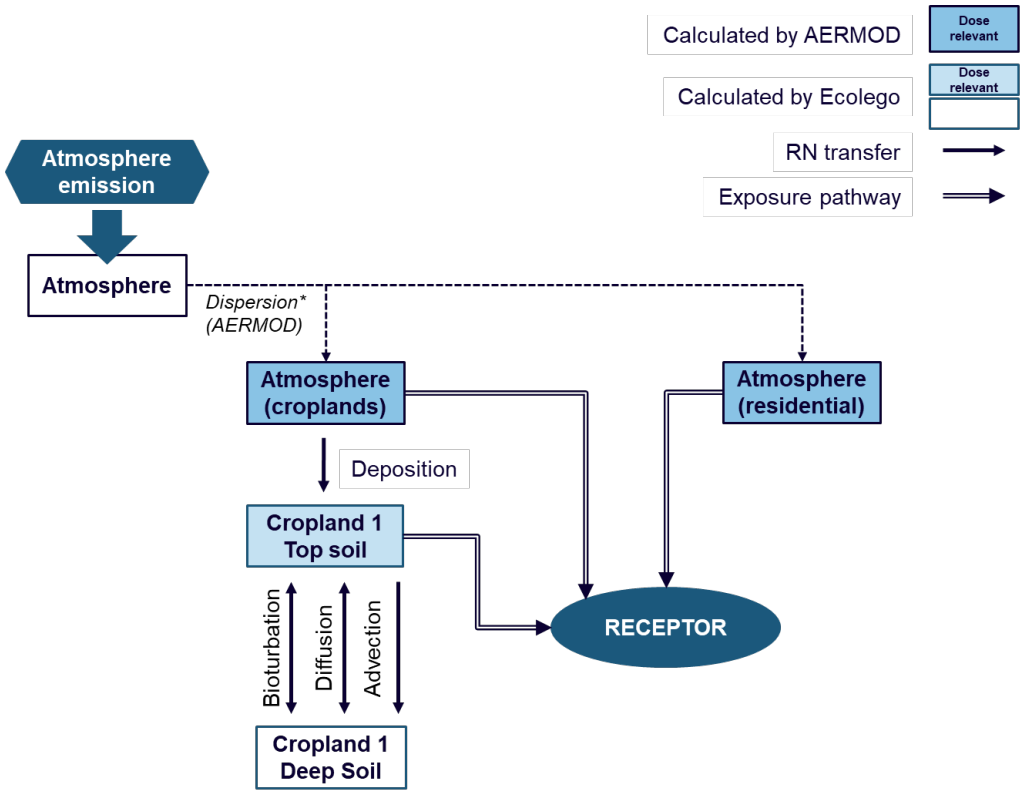

Figure 4-2. *Conceptual model for the atmospheric emissions.*

4.1.2 Surface water system

The surface water model considers the transport of radionuclides released to the environment via liquid discharges to the Nitelva river. The model includes the river shores and agricultural areas around the river, from which water is extracted to be used for the irrigation of the croplands. The section of the river modelled, and the selected cropland areas are presented in Figure 4-3.

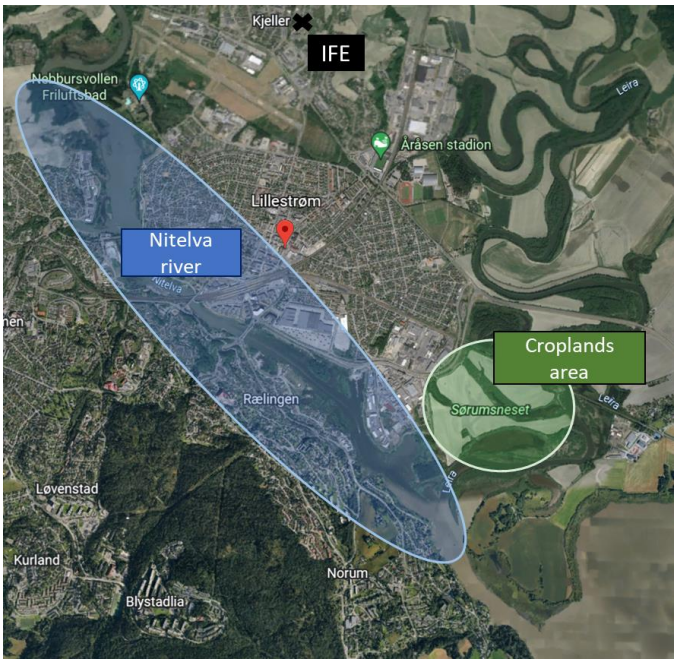

Figure 4-3. *Selected areas for the surface water model.*

As shown in Figure 4-4, the Nitelva river is divided into two compartments, which allows the model to calculate the decrease in radionuclide concentration in the areas further from the discharge point. A third river compartment, named “River downstream”, was added to account for the water flux leaving the studied system. The model considers the deposition of particulate matter on river sediments, which are divided into two compartments: top and deep sediment, due to the differing properties of the layers. Radionuclides can be transported between the river and the sediment compartments via the following mechanisms:

- Advection, accounting for the waterflow between river compartments.
- Sedimentation, considering the deposition of matter on sediments.
- Resuspension, taking into account the removal of the deposited matter from sediments.
- Diffusion, considering the effects of diffusivity due to the water content.

As mentioned before, the model considers irrigation of the croplands using water from Nitelva. Therefore, the croplands compartments were added to the surface water model, following the same reasoning as in the atmospheric model (see section 4.1.1).

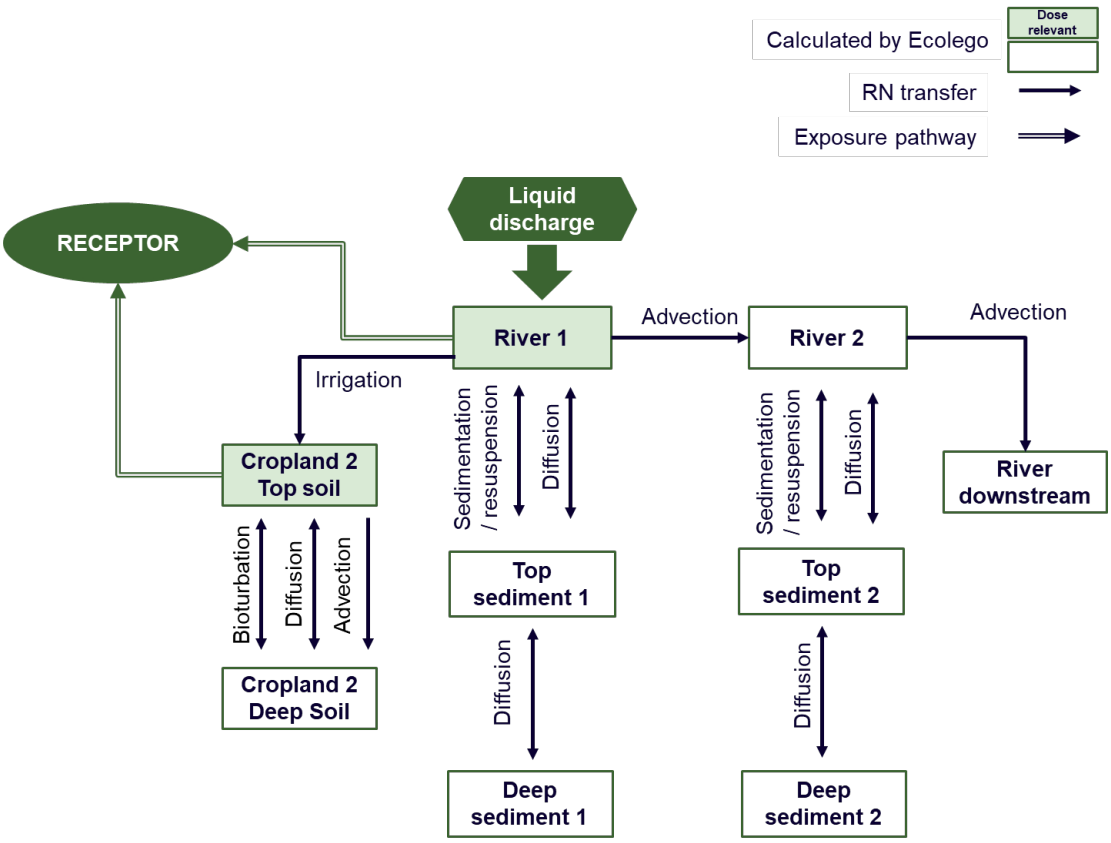

Figure 4-4. *Conceptual model of the radionuclide model for the liquid discharge.*

4.2 Dose model

The dose model is based on the potential behaviour of the most exposed group. Dose received by the reference group comes from their exposition to different pathways which differ as a function of the type of release (atmospheric emissions or liquid discharges).

The reference group is based on a farmer family living nearby the IFE-Kjeller plant. The dose is evaluated for three different age groups, which are 1 year old infants, 10-year-old children and adults. In the subsequent sections, the exposure pathways and the main assumptions considered for each age group are summarized.

4.2.1 Atmospheric system

The main exposure pathways considered in the atmospheric system are presented in Figure 4-5 and described below.

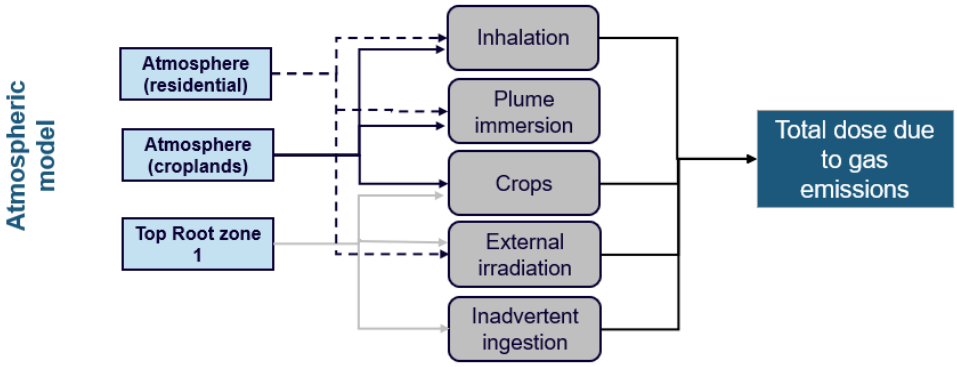

Figure 4-5. *Exposure pathway model showing the relationship between pathways and the relevant compartments for the estimation of the dose to public in the atmospheric system.*

Both the external irradiation due to the immersion in an atmospheric plume and the inhalation of radionuclides depend on the concentration of radionuclides in the air over the croplands and residential areas affected by the dispersion plume.

The ingestion of crops cultivated in the contaminated agricultural areas is also considered. The received dose depends on the radionuclide concentration in the crops. Radionuclides are intercepted by crops via the deposition from the atmosphere and via the uptake from the soil through roots.

Humans can also receive dose while spending time in the croplands area due to the external exposition to the contaminated soil and the inadvertent (i.e., accidental) ingestion of soil.

The dose will also depend on assumptions considered for the reference group:

- Adults spend 4 hours per day working in the cropland area, while infants and children spends 2 h per week playing in this area.
- Adults spend 6 hours per day in the residential area, while infants and children 8 hours per day.
- Crops consumed by the exposed groups, come solely from the affected cropland areas.

4.2.2 Surface water system

The exposure pathways considered in the surface water system are presented in Figure 4-6. It can be seen that some of the exposure pathways are the same as presented in the atmospheric model. These are the ones related with the exposure to the cropland area and the products cultivated there. Therefore, the same exposure pathways and assumptions are considered (see previous section). Only one difference exists between both cases:

radionuclides are intercepted by crops from the soil and from the irrigation with the contaminated water from the river (instead of from atmospheric deposition).

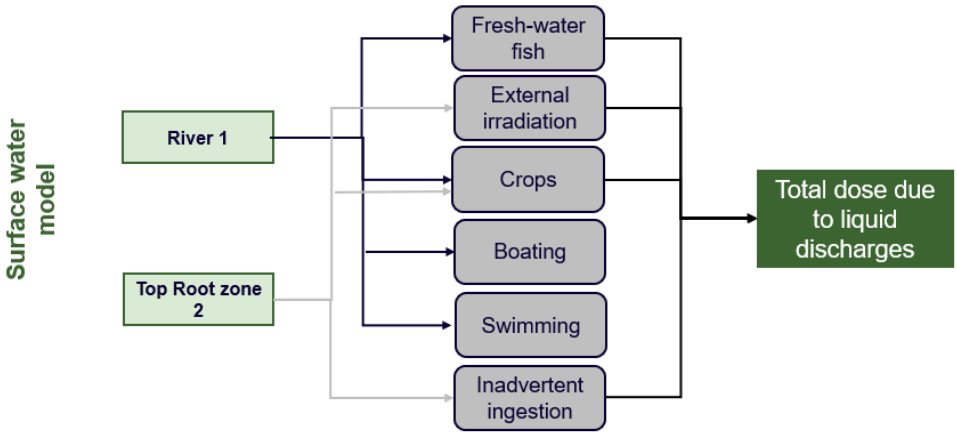

Figure 4-6. *Exposure pathway model showing the relationship between pathways and the relevant compartments for the estimation of the dose to public in the surface water system.*

In addition, humans can receive dose due to activities related with the river as the consumption of fresh fish, the external irradiation from boating in Niteva river and the external irradiation due to the swimming in Nitelva river. These last three pathways depend on the radionuclide concentration levels in the river water and the following assumptions.

- 1/10 of the fresh-fish consumption comes from Nitelva river.
- Adults spend 1 hour per month swimming in Nitelva river, while children and infants are considered not to swim.
- Adults, children and infants spend 2 hours per week doing boating activities in Nitelva river.

Note that the ingestion of radionuclides due to the inadvertent ingestion of water while swimming is considered negligible, and it is not implemented in the model.

5 Mathematical Model

This section describes the mathematical model, i.e., formulation and parametrization, implemented for the calculation of the concentration of radionuclides in the environment and the dose estimation to the public. The transport of radionuclides from source term, through the biosphere, to the final recipient has been implemented in the software Ecolego. Each model has been developed considering the following aspects:

- Radionuclides are assumed to be uniformly mixed in each compartment.
- A compartment is any specific part of the system being modelled (e.g., river).
- Each transfer is 'donor controlled', depending directly on the radionuclide amount present in the compartment from which RN is leaving.
- Radionuclide decay.

5.1 Physical Model

The physical model includes the characterization of the transport of all radionuclides emitted by IFE´s facilities to the environment. That includes definition of the source term, characteristics of the defined compartments, description of the transferences between compartments and the radionuclides' concentrations in the environment.

5.1.1 Source Term

Two main source terms are identified: (i) the emission of gases to the atmosphere and (ii) the discharge of radionuclides in liquid form to the Nitelva river through the NALFA pipeline. In addition, two different scenarios have been considered in the atmospheric releases, one of them being a continuous release to the atmosphere and the second one assuming a total acute release.

5.1.1.1 Atmospheric emissions

Atmospheric emissions include all radionuclides emitted to the atmosphere in gas or aerosol form through chimneys located in different buildings on the IFE-Kjeller site. Each IFE division has different emission points (Figure 5-1), and radionuclides released. Table 5-1 shows the list of the radionuclides emitted to the atmosphere by each of IFE´s division.

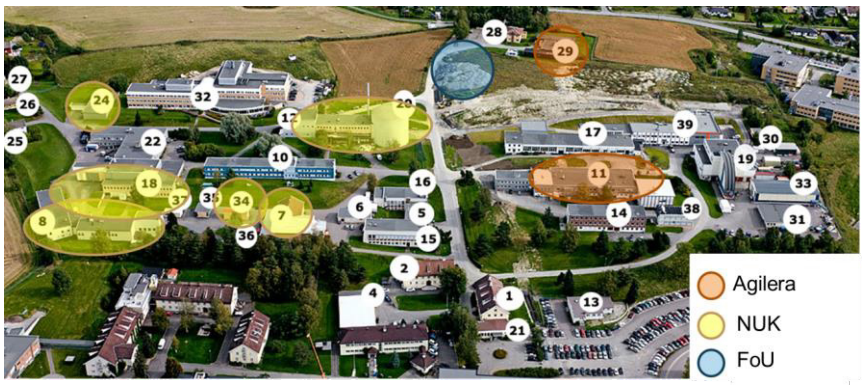

Figure 5-1. *Gas emission point locations per each division.*

Table 5-1. *List of radionuclides emitted to the atmosphere by each division.*

Radionuclide	NUK	Agilera	FoU	Radionuclide	NUK	Agilera	FoU
H-3	x		x	Eu-152	x		
C-14	x		x	Eu-154	x		
F-18		x		Eu-155	x		
Na-22	x		x	Gd-153	x		
Sc-46			x	Tb-160	x		
Co-60	x		x	Tb-161	x		x
Ni-59				Lu-177		x	
Ni-63	x			Hg-203	x		
Ni-69				At-211		x	
Zn-65	x		x	Pb-210	x		
Br-82	x			Pb-212		x	x
Kr-85	x			Rn-219		x	
Zr-89		x		Rn-220	x	x	x
Y-90		x		Rn-222	x		x
Sr-90	x			Ra-223		x	
Tc-99	x			Ra-224	x	x	x
Ru-106	x			Ra-226	x		
Ag-108m	x			Ra-228	x		x
Sn-113			x	Ac-225		x	
I-125		x		Ac-227	x	x	
I-129	x			Th-227		x	
I-131	x	x	x	Th-228	x	x	x
Ba-133	x		x	Th-230	x		
Cs-134	x		x	Th-232	x		x
Cs-135	x			U-234			x
Cs-137	x		x	U-235			x
Ce-144	x			U-238			x

It is expected that most of the isotopes have a minor contribution to the dose; in order to not implement all isotopes and decay products in the Ecolego model, a preliminary dose assessment was performed to select a list of radionuclides contributing more to the total dose.

The preliminary assessment was done with the IRAT tool ('Initial Radiological Assessment Tool') for each of the divisions. IRAT is a MS Excel tool developed and maintained by the Environment Agency of England for preliminary assessment of radioactive discharges to the environment from nuclear facilities, hospitals, laboratories, and radiopharmaceutical activities. The tool is based on discharge data with simple annually averaged assumptions and a few user-defined parameters (e.g., river flow for aqueous emissions and stack height for gaseous emissions).

Due to its simplicity, IRAT has some limitations i.e., not all the emitted radionuclides are available in the tool. For that reason, a few of the nuclides have been assessed as other beta/gamma-emitting radionuclides (Cs-137) or using surrogates.

After result evaluation (results shown in Appendix C.1), the list of radionuclides to evaluate using Ecolego is set as those that contributes more to the total dose as well as the ones evaluated as surrogates or as other beta/gamma nuclides which could not be properly evaluated with the IRAT tool (see the list of selected isotopes in Table 5-2). Note that decay products from all these isotopes are also introduced in the model.

Table 5-2. *Radionuclides selected for the atmospheric emission dose assessment and the discharge rate to be assessed (Bq/y).*

Radionuclide	NUK	Agilera	FoU	Radionuclide	NUK	Agilera	FoU
H-3	2.0E+12			Rn-219		1.0E+10	
Na-22			1.0E+05	Rn-220		8.0E+10	1.0E+06
Sc-46			1.0E+06	Rn-222	1.0E+09		1.0E+07
Sr-90	3.0E+07			Ra-223		1.0E+08	
Sn-113			1.0E+06	Ra-224	1.0E+06	1.0E+05	1.0E+03
I-131		2.0E+09	1.0E+05	Ra-228	1.0E+03		1.0E+03
Ba-133			1.0E+03	Br-82	1.0E+09		
Cs-134	1.0E+07			Ac-227	1.0E+06	5.0E+06	
Cs-135	1.0E+06			Th-227		5.0E+06	
Cs-137	3.0E+07			Th-228	5.0E+05	1.0E+06	1.0E+03
Gd-153	1.0E+06			Th-232			1.0E+03
Tb-160	1.0E+06			Tc-99	1.0E+06		
Tb-161	1.0E+06		1.0E+04	Eu-152	5.0E+06		
Hg-203	1.0E+04			Eu-154	1.0E+07		

The release of most of the radionuclides is not continuous and usually cannot be detected in the monitoring samples collected as part of the environmental monitoring program. To verify to the authorities that the emission limit does not have any significant effect to the public, two different scenarios were taken into account:

1. Continuous release (annual limit equally distributed along the year)
2. Total acute release (annual limit released in 1 day)

In order to know the atmospheric concentration in the areas of interest, an atmospheric dispersion plume is simulated with AERMOD.

The following steps and assumptions have been done:

- The studied area of 7x7 km was selected to study the development of the plume from the source in IFE-Kjeller's facilities to nearby areas including Lillestrøm and Rælingen. The model extent can be seen on Figure 5-2.

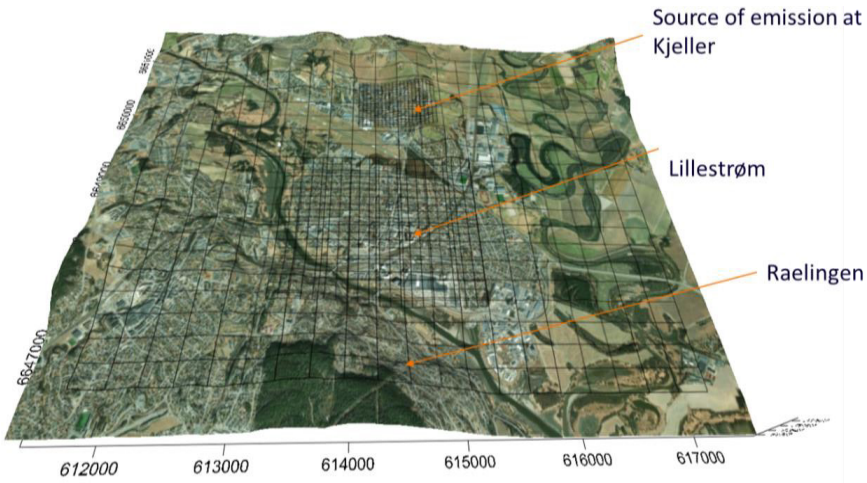

Figure 5-2. *AERMOD model domain.*

- Meteorological data (e.g., relative humidity, solar irradiance, precipitation, wind speed, etc.) used for the prediction of the radioactive plume movement were obtained from the closest weather station: Kjeller SN4200 [6] for 2021. The wind rose for 2021 is presented in Figure 5-3, showing that the major wind directions are from NE-SW and NW-SE directions.

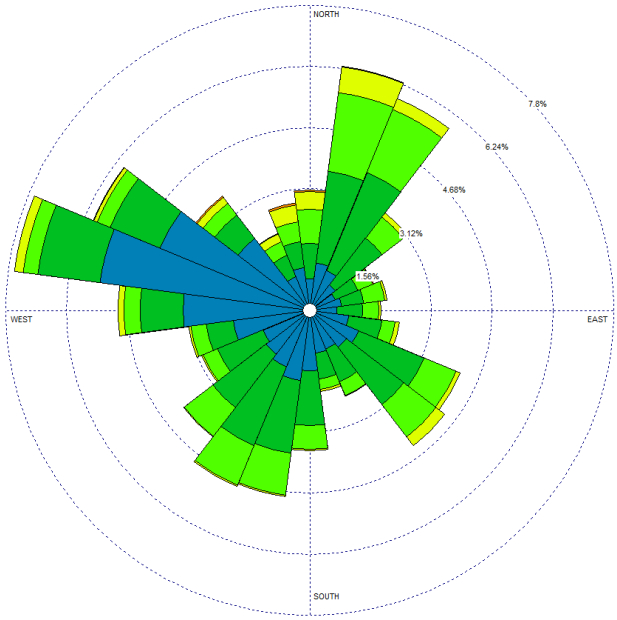

Figure 5-3. *Wind rose for 2021 (data processed from Kjeller SN4200 [6]).*

- After general scoping calculations of the effect of simulating a multiple source release or a single point release, it was decided that a single source is a bit more conservative. Therefore, one source term has been set for each division (Figure 5-4). The chosen emission points are characterized with a discharge point at a relatively low height and high emission rate, according to the conservative approach. In case one of the emission points changes, no need to re-evaluate the calculations will be needed unless the amount of any isotope changes or the stack heigh and gas flow decreases in comparison with the selected emission point.

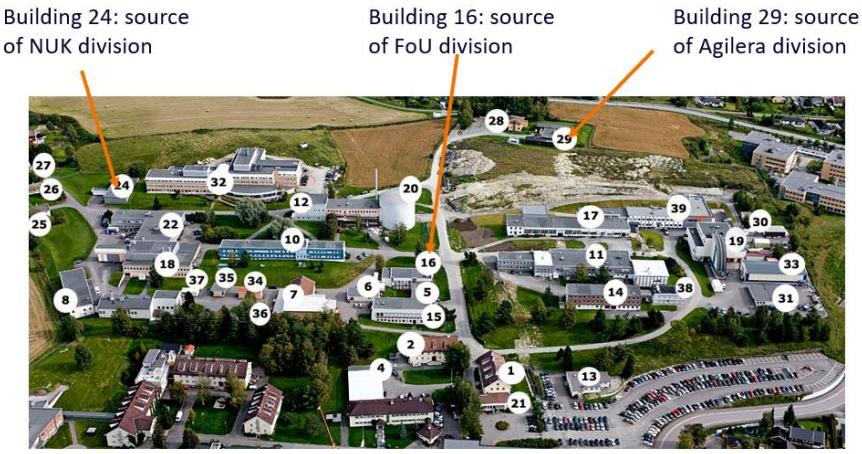

Figure 5-4. *Selected sources of emission introduced into AERMOD.*

- Two end-points have been selected as receptors to study the temporal evolution of concentration of radionuclides, one representing the concentration in the croplands and the other one, the concentration in the residential area (Figure 5-5).

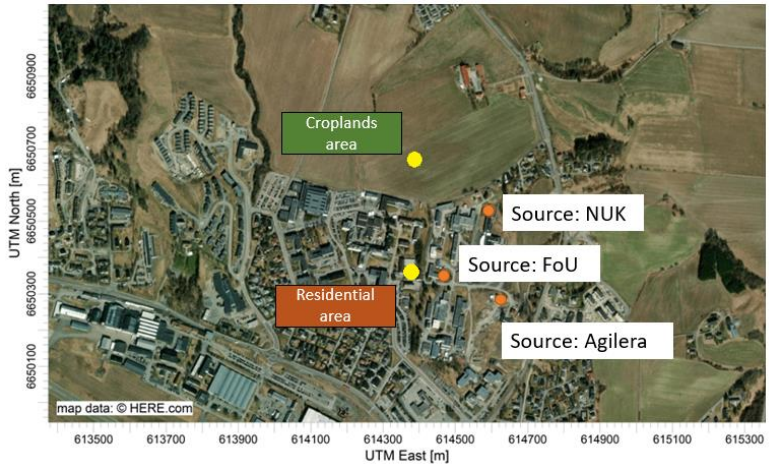

Figure 5-5. *Receptor points and emission sources of each division introduced into AERMOD.*

- The input data for the total acute release model were chosen based on the unique meteorological conditions at a given day of the year which led to the highest atmospheric concentration at the receptor points, therefore, representing the worst-case scenario.

The concentration values obtained from AERMOD are implemented in the Ecolego model. In the case of the continuous release, a monthly concentration is obtained for one year (see Table C. 4 and Table C. 5 in Appendix C.2). These data are repeated for each of the 60 operational years. On the other hand, in the total acute case, an average concentration along the release day is provided (see Appendix C.3.1 and C.3.2). Note that after the day of the total acute release it is considered that the concentration of radionuclides in the atmosphere is too low. Thus, it can be assumed that the radionuclide concentration is close to zero which means that no impact will reach the population due to inhalation or external irradiation due to immersion in the plume.

5.1.1.2 Liquid discharges

Radionuclides released in liquid form originated in each division are discharged together from Building nº 8 (see Figure 5-4) via the NALFA pipeline to the Nitelva river (see Figure 5-6). The release occurs three times per year, and it is assumed that 1/3 of the annual limit is released at every discharge during a period of 28.6 hours.

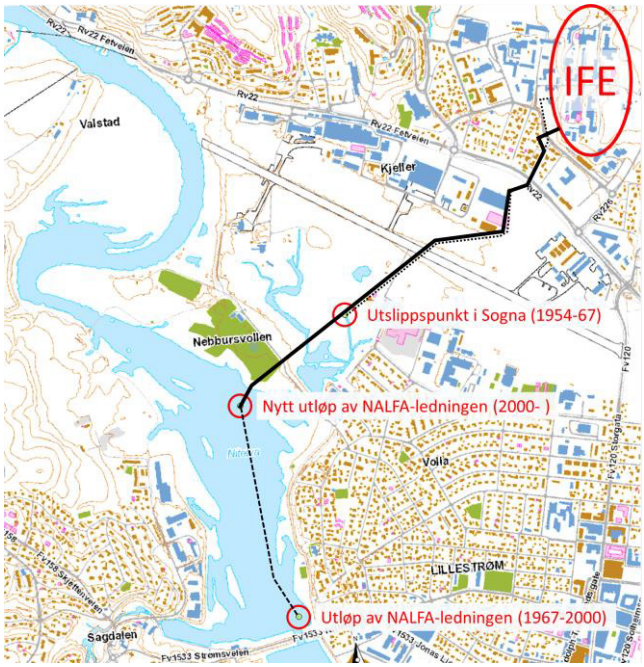

Figure 5-6. *Location of the NALFA pipeline, discharge point of the liquid wastes from the IFE-Kjeller facilities.*

Although all radionuclides are released from the same release point, each division should be authorised for a series of radionuclides. Therefore, the environmental assessment has been done for each division considering a list of radionuclides and annual limits specific for each division. The list of radionuclides discharged to the river Nitelva from each division is shown in Table 5-3.

Table 5-3. *List of radionuclides discharged to the Nitelva river by each division.*

Radionuclide	NUK	Agilera	FoU	Radionuclide	NUK	Agilera	FoU
H-3	x		x	Ce-141	x		
C-14			x	Ce-144	x		
Na-22			x	Gd-153	x		
Sc-46	x	x		Tb-160	x		
Cr-51	x			Tb-161	x		x
Mn-54	x			Lu-177	x	x	
Fe-59	x			Lu-177m	x	x	
Co-57	x			Pb-212	x	x	
Co-58	x			Ra-223	x	x	
Co-60	x		x	Ra-224	x	x	x

Radionuclide	NUK	Agilera	FoU	Radionuclide	NUK	Agilera	FoU
Ni-63	x			Ra-228	x		x
Zn-65	x			Ac-225	x	x	
Sr-90	x			Ac-227	x	x	
Y-90	x	x		Th-227	x	x	
Zr-95	x			Th-228	x	x	x
Nb-95	x			Th-230	x		x
Tc-99	x	x		Th-232	x		x
Ru-103	x			U-234	x		x
Ru-106	x			U-235	x		x
Ag-108m	x			U-236	x		
Ag-110m	x			U-238	x		x
Cd-109	x			Np-237	x		
Sn-113	x			Pu-238	x		
Sb-122	x			Pu-239	x		
Sb-124	x			Pu-240	x		
Sb-125	x			Pu-241	x		
I-125	x	x		Pu-242	x		
I-131	x	x		Am-241	x		
Ba-133	x		x	Am-242m	x		
Ba-140	x			Am-243	x		
Cs-134	x		x	Cm-242	x		
Cs-137	x		x	Cm-243	x		
La-140	x			Cm-244	x		

As explained before, a preliminary assessment was conducted using the IRAT tool. Table 5-4 presents the final list of nuclides included in the Ecolego model, which includes the isotopes contributing more to the total dose and those isotopes evaluated as surrogates or other beta/gamma emitters.

Table 5-4. *Radionuclides selected for the liquid discharge dose assessment and the discharge rate to be assessed (Bq/y).*

Radionuclide	NUK	Agilera	FoU	Radionuclide	NUK	Agilera	FoU
H-3	5.0E+12			Tb-161			1.0E+04
Sc-46	1.0E+04	1.0E+04		Lu-177	5.0E+08	5.0E+08	
Co-60	2.7E+08			Lu-177m	1.0E+04	1.0E+04	
Ru-106	1.0E+07			Ra-223	2.0E+08	2.0E+08	
Ag-108m	5.0E+06			Ra-224	1.0E+06	1.0E+06	1.0E+04
Cd-109	3.0E+07			Ra-228	1.0E+07		1.0E+04
Ag-110m	1.0E+06			Ac-227		2.5E+04	
Sn-113	1.0E+06			Th-227		1.0E+06	
I-125	5.0E+07	5.0E+07		Th-228		2.0E+06	
I-131	5.0E+08	5.0E+08		Th-232	1.0E+06		1.0E+04
Ba-133			1.0E+04	Pu-239	1.5E+07		
Cs-134	2.5E+07		1.0E+07	Pu-240	1.5E+06		
Cs-137	1.5E+08			Pu-242	1.0E+05		

5.1.2 Transferences

This section includes all the transferences of radionuclides released to the environment. Each transfer is characterised by an expression which has been introduced into Ecolego to obtain the concentration of each isotope in each compartment.

As some of the transferences are the same for both systems, they are not classified per system.

The values of parameters used in this project are not presented in this section. All of them are included in Appendix A to avoid a huge number of tables within the section. Note that some of the parameters such as the sorption coefficient depends on the element and the environment media that the radionuclide is sorbed onto, hence an extended number of values should be presented.

Liquid discharge

Liquid discharge refers to the release of radionuclides into the river via the pipeline during the three pulses made each year $\left(Disch, \frac{Bq}{s}\right)$. It can be calculated with Eq. 1.

$$Disch = Disch_r \cdot Pulse \qquad \textbf{Eq. 1}$$

where

$Disch_r$ is the discharge rate $\left(\frac{Bq}{y}\right)$,

$Pulse$ is a pulse lasting 28.6h, three times a year $(-)$. The value is set to 1 during the pulse and 0 when there is no discharge.

Deposition

Deposition is a process by which particles or gases in the atmosphere are transferred to a surface. The amount of radionuclides transferred from the air compartment *i* to the soil compartment *j* by deposition $\left(Dep_{rate,ij}, \frac{\mathrm{Bq}}{s}\right)$ can be calculated using Eq. 2.

$$Dep_{rate,ij} = Conc_{AtmC} \cdot Area_j \cdot V_{dep} \qquad \textbf{Eq. 2}$$

where

$Conc_{AtmC}$ is the ground level air concentration calculated by AERMOD $\left(\frac{Bq}{m^3}\right)$,

$Area_j$ is the area of compartment *j* (m^2),

V_{dep} is the dry deposition velocity $\left(\frac{m}{s}\right)$.

Sedimentation

Sedimentation refers to the transfer of radionuclides due to deposition of the particulate matter on the river bottom (sediments). The transfer rate of radionuclides from the river compartment *i* to the sediments compartment *j* due to sedimentation ($\lambda_{sed,ij}, y^{-1}$) is calculated using Eq. 3.

$$\lambda_{sed,ij} = \frac{r_{sed} \cdot {Kd_{SS}}^n}{h_i \cdot {R_i}^n} \qquad \textbf{Eq. 3}$$

where

r_{sed} is the sedimentation rate $\left(\frac{kg}{m^2 \cdot y}\right)$,

${Kd_{SS}}^n$ is the distribution coefficients for radionuclide *n* in suspended solids $\left(\frac{m^3}{kg}\right)$,

h_i is the depth or thickness of compartment *i* (m),

${R_i}^n$ is the retardation factor for radionuclide *n* in compartment *i* $(-)$.

The retardation factor for the radionuclide ${R_{Riv,i}}^n$, can be described using Eq. 4 where S_s is the concentration of suspended solids in the river $\left(\frac{kg}{m^3}\right)$.

$$ {R_{Riv,i}}^n = 1.0 + {Kd_{ss}}^n \cdot S_s \qquad \textbf{Eq. 4} $$

Resuspension

Resuspension stands for the removal of deposited material from the sediment back into the river. The transfer rate of radionuclides from source compartment *i* to target compartment *j* due to resuspension ($\lambda_{res,ij}, y^{-1}$) is described by Eq. 5

$$ \lambda_{res,ij} = \frac{r_{res} \cdot {Kd_i}^n}{h_i \cdot por_i \cdot {R_i}^n} \qquad \textbf{Eq. 5} $$

where

r_{res} is a resuspension rate $\left(\frac{kg}{m^2 \cdot y}\right)$.

For the sediment and soil compartments, the retardation factor for the radionuclide R_i^n is calculated using Eq. 6.

$$ {R_i}^n = 1.0 + \frac{{Kd_i}^n \cdot \rho_i}{por_i} \qquad \textbf{Eq. 6} $$

where

${Kd_i}^n$ is the distribution coefficients for radionuclide *n* in compartment *i* $\left(\frac{m^3}{kg}\right)$,

ρ_i is the density of compartment *i* $\left(\frac{kg}{m^3}\right)$,

por_i is the porosity of compartment *i* $\left(\frac{m^3}{m^3}\right)$.

Irrigation

Irrigation is the process of watering the crops. When water used for the irrigation is contaminated, the radionuclides are transported to the soils and can also contaminate the plants growing in the irrigated area. The transfer rate of radionuclides from source compartment *i* to target compartment *j* due to irrigation ($\lambda_{irr,ij}, y^{-1}$) is given by Eq. 7.

$$\lambda_{irr,ij} = \frac{Area_j \cdot r_{irr}}{V_j} \qquad \textit{Eq. 7}$$

where

r_{irr} is the irrigation rate $\left(\frac{m^3}{m^2 \cdot y}\right)$,

V_j is the volume of compartment *j* (m^3).

Advection in river

Advection in river refers to the transport of radionuclides by the bulk movement of the river water, i.e., the river flow. The transfer rate of radionuclides from river compartment *i* to river downstream compartment *j* due to advection ($\lambda_{adv,r,i\,j}, y^{-1}$) is given by Eq. 8.

$$\lambda_{adv,r} = \frac{Qv_i}{V_i} \qquad \textit{Eq. 8}$$

where

Qv_i is the water flux in the river compartment *i* $\left(\frac{m^3}{s}\right)$.

Bioturbation

Bioturbation is the physical rearrangement (reworking) of the upper part of the soil profile by actions of living organisms. This can include digging, burrowing, and other activities that change the structure of the soil or sediment, as well as the movement of nutrients and other materials within it. The transfer rate of radionuclides from source compartment *i* to target compartment *j* due to bioturbation ($\lambda_{B,ij}, y^{-1}$) is expressed in Eq. 9.

$$\lambda_{BT,ij} = \frac{BioT_i}{h_i \cdot \rho_i}\left(1 - \frac{1}{R_i{}^n}\right) \qquad \textit{Eq. 9}$$

where

$BioT_i$ is the amount of soil affected by bioturbation in compartment *i* $\left(\frac{kg}{m^2 \cdot y}\right)$.

Diffusion

Diffusion stands for the movement of particles from an area of high concentration to an area of low concentration. This process continues until the concentration of the particles is equalized. Diffusion can occur in liquids, gases, and solids, and therefore, it will affect radionuclides in both solid and aqueous phases of soil. The transfer rate of radionuclides

from source compartment *i* to target compartment *j* due to diffusion ($\lambda_{dif,ij}, y^{-1}$) is given by Eq. 10.

$$\lambda_{dif,ij} = \frac{2{D_i}^n}{{h_i}^2 \cdot {R_i}^n} \qquad \textit{Eq. 10}$$

where

${D_i}^n$ is the diffusion coefficient for radionuclide *n* in compartment *i* $\left(\frac{m^2}{y}\right)$.

And depending on whether the source compartment is a river or soil/sediment, $R^n_{Riv,i}$ or R^n_i is used respectively.

Advection

Advection in soils refers to the transport of solutes by the bulk movement of soil water due to pressure gradients. The transfer rate of radionuclides from source soil compartment *i* to target soil compartment *j* due to advection ($\lambda_{adv,s,i\ j}, y^{-1}$) is expressed by Eq. 11.

$$\lambda_{adv,s,i\ j} = \frac{Wf_i}{h_i \cdot por_i \cdot {R_i}^n} \qquad \textit{Eq. 11}$$

where

Wf_i is the water flux in the soil compartment *i* $\left(\frac{m}{\text{year}}\right)$.

5.1.3 Compartment concentration

The total concentration of the radionuclide *n* in compartment *i* is given by Eq. 12.

$${Conc_T}_i{}^n = \frac{{A_i}^n}{V_i} \qquad \textit{Eq. 12}$$

where

${A_i}^n$ is the total activity of radionuclide *n* in the compartment *i* (Bq).

The calculated concentrations of radionuclides in each soil or sediment compartment include both the aqueous and sorbed phases. The concentration of the radionuclide *n* in compartment *i* in the aqueous phase $\left({Conc_{aq}}_i{}^n, \frac{Bq}{m^3\ water}\right)$ was calculated using Eq. 13, while

the concentration of the radionuclide *n* in the compartment *i* in the solid phase $\left({Conc_{sorb}}_i{}^n, \frac{Bq}{kg\ soil}\right)$ is expressed by Eq. 14.

$$ {Conc_{aq}}_i{}^n = \frac{{A_i}^n}{V_i \cdot por_i + V_i \cdot {Kd_i}^n \cdot \rho_i (1 - por_i)} \qquad \textbf{Eq. 13} $$

$$ {Conc_{sorb}}_i{}^n = \frac{{A_i}^n \cdot {Kd_i}^n}{V_i \cdot por_i + V_i \cdot {Kd_i}^n \cdot \rho_i (1 - por_i)} \qquad \textbf{Eq. 14} $$

5.2 Dose Model

The dose model has been developed considering every possible exposure pathway. Both external and internal irradiation sources have been taken into consideration e.g., external dose received by immersion in plume and being near the contaminated water/soil or internal dose from eating contaminated foodstuff or inadvertent consumption of soil.

Total dose is calculated as the sum of the dose received by each radionuclide via each exposure pathway, as represented in Eq. 15.

$$ E_T = \sum_{n,path} {E_{path}}^n \qquad \textbf{Eq. 15} $$

External dose - Immersion in atmospheric plume

Radionuclides emitted into the air are transported within the plume based on the atmospheric conditions. Immersion in such an atmospheric plume can contribute to the received dose through an external irradiation. The annual effective dose received due to the submersion in air $\left(E_{im,a}, \frac{\mathrm{Sv}}{\mathrm{y}}\right)$ is expressed with the Eq. 16.

$$ E_{im,a} = Conc_{AtmC} \cdot {DC_{im,atm,m}}^n \cdot O_{fC,m} + Conc_{AtmR} \cdot {DC_{im,atm,m}}^n \cdot O_{fR,m} \qquad \textbf{Eq. 16} $$

where

$Conc_{AtmC}$ is the radionuclide concentration in air in cropland area $\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right)$,

${DC_{im,atm,m}}^n$ is the dose coefficient for air submersion for radionuclide *n* and age group *m* $\left(\frac{Sv/s}{Bq/m^3}\right)$,

$O_{fC,m}$ is the occupancy rate (time spent in the croplands area) for age group *m* $\left(\frac{\mathrm{y}}{\mathrm{y}}\right)$,

$Conc_{AtmR}$ is the radionuclide concentration in air in residential area $\left(\frac{\text{Bq}}{\text{m}^3}\right)$,

$O_{fR,m}$ is the occupancy rate (time spent in the residential area) for age group *m* $\left(\frac{\text{y}}{\text{y}}\right)$.

External dose - Irradiation from soil

Dose due to irradiation from soil refers to the amount of radiation that an individual is exposed to as a result of the radiation emitted from the soil. Annual effective dose received due to exposure to ground deposition $\left(E_{ext}, \frac{\text{Sv}}{\text{y}}\right)$ can be calculated with Eq. 17.

$$E_{ext} = Conc_{T_{TSo,i}} \cdot {DC_{ext,m}}^{n} \cdot O_{fC,m} \qquad \textbf{Eq. 17}$$

where

$Conc_{T_{TSo,i}}$ is the total radionuclide concentration in the top-soil compartment *i* $\left(\frac{\text{Bq}}{\text{m}^3}\right)$,

${DC_{ext,m}}^{n}$ is the dose coefficient for exposure to ground deposits for radionuclide *n* and age group *m* $\left(\frac{\text{Sv/s}}{\text{Bq/m}^3}\right)$.

External dose – Swimming in the river

Swimming in the contaminated river is contributing to the total dose due to the external irradiation. Annual effective dose received due to swimming in the contaminated river $\left(E_{im,w}, \frac{\text{Sv}}{\text{y}}\right)$ is expressed by Eq. 18.

$$E_{im,w} = Conc_{T_{Riv,i}} \cdot O_{fS,m} \cdot {DC_{im,w,m}}^{n} \qquad \textbf{Eq. 18}$$

where

$Conc_{T_{Riv,i}}$ is the radionuclide concentration in the river $\left(\frac{\text{Bq}}{\text{m}^3}\right)$,

$O_{fS,m}$ is the occupancy rate (time spent swimming in the river) for age group *m* $\left(\frac{\text{y}}{\text{y}}\right)$,

${DC_{im,w,m}}^{n}$ is the dose coefficient for water immersion for radionuclide *n* and age group *m* $\left(\frac{\text{Sv/y}}{\text{Bq/m}^3}\right)$.

External dose – Boating in the river

Boating in the contaminated river leads to the increase of the received dose via the external irradiation. Annual effective dose received due to boating in the contaminated river $\left(E_{ext,w}, \frac{\text{Sv}}{\text{y}}\right)$ can be calculated by Eq. 19.

$$E_{ext,\,w} = Conc_{T\,Riv,i} \cdot O_{fB,m} \cdot (0.5 \cdot DC_{im,w,m}{}^{n}) \qquad \textbf{Eq. 19}$$

where

$O_{fB,m}$ is the occupancy rate (time spent boating in the river) for age group *m* $\left(\frac{\mathrm{y}}{\mathrm{y}}\right)$.

Inhalation

Inhalation of the radioactive particles and/or gases is an important contribution to the total dose by internal irradiation. Since the radionuclides are transported into the organism, all types of radiation (alpha, beta and gamma) can cause harm to the organs and increase the dose. Annual effective dose received due to inhalation of radioactive particles and/or gases $\left(E_{inh}, \frac{\mathrm{Sv}}{\mathrm{y}}\right)$ is expressed by Eq. 20.

$$E_{inh} = Conc_{AtmC} \cdot R_{inhC,m} \cdot DC_{inh,m}{}^{n} \cdot O_{fC,m} + Conc_{AtmR} \cdot R_{inhR,m} \cdot DC_{inh,m}{}^{n} \cdot O_{fR,m} \qquad \textbf{Eq. 20}$$

where

$R_{inhC,m}$ is the inhalation rate in croplands for age group *m* $\left(\frac{\mathrm{m^3}}{\mathrm{h}}\right)$,

$DC_{inh,m}{}^{n}$ is the dose coefficient for inhalation for radionuclide *n* and age group *m* $\left(\frac{\mathrm{Sv}}{\mathrm{Bq}}\right)$,

$R_{inhR,m}$ is the inhalation rate in residential area for age group *m* $\left(\frac{\mathrm{m^3}}{\mathrm{h}}\right)$.

Ingestion of crops

Ingestion of contaminated crops can result in exposure to ionizing radiation if the crops have been contaminated with radioactive materials. The annual effective dose received due to consumption of contaminated crops $\left(E_{ing,c}, \frac{\mathrm{Sv}}{\mathrm{y}}\right)$ is described by Eq. 21.

$$E_{ing,c} = Conc_{crop} \cdot H_{c,m} \cdot DC_{ing,m}{}^{n} \qquad \textbf{Eq. 21}$$

where

$H_{c,m}$ is the consumption rate for crops for age group *m* $\left(\frac{\mathrm{kg}}{\mathrm{y}}\right)$,

$DC_{ing,m}{}^{n}$ is the dose coefficient for ingestion for radionuclide *n* and age group *n* $\left(\frac{\mathrm{Sv}}{\mathrm{Bq}}\right)$,

$Conc_{crop}$ is the radionuclide concentration in crops at the time of consumption $\left(\frac{\mathrm{Bq}}{\mathrm{kg}}\right)$ and is calculated following Eq. 22.

$$Conc_{crop} = (Conc_{crop,0})exp(-\lambda_i^n \cdot t_h) \quad \textbf{Eq. 22}$$

where

λ_i^n is the constant for radioactive decay of radionuclide *n* (y^{-1}),

t_h is the delay (hold-up) time which represents the time interval between harvest and consumption of the food (d),

$Conc_{crop,0}$ is the radionuclide concentration in crops at the time of harvesting $\left(\frac{\text{Bq}}{\text{kg}}\right)$.

Crops concentration, $Conc_{crop,0}$, depends on the source of emission. As explained in section 4.1, in both atmospheric and surface water models, radionuclides are considered to be intercepted by vegetation in three different ways: deposition for the atmospheric model, irrigation for the surface water model, and root uptake for both of them.

Taking this into account, radionuclide concentration in crops at the time of harvesting $\left(\boldsymbol{Conc_{crop,0}}, \frac{\boldsymbol{Bq}}{\boldsymbol{kg}}\right)$ for the atmospheric and for the surface water model are expressed in Eq. 23 and Eq. 24 respectively:

$$Conc_{crop,0} = Conc_{crop\_root} + Conc_{crop\_atm} \quad \textbf{Eq. 23}$$

$$Conc_{crop,0} = Conc_{crop\_root} + Conc_{crop\_irr} \quad \textbf{Eq. 24}$$

Radionuclide concentration in vegetation arising from root uptake from the soil and from soil adhering to the vegetation $\left(Conc_{crop\_root}, \frac{Bq}{\text{kg fresh matter}}\right)$ can be calculated using Eq. 25.

$$Conc_{crop\_root} = {F_v}^n \cdot Conc_{sorb\,TSo,i} \quad \textbf{Eq. 25}$$

where

${F_v}^n$ is the concentration factor for uptake of the radionuclide *n* from soil by edible parts of crops $\left(\frac{\text{Bq/kg plant tissue}}{\text{Bq/kg dry soil}}\right)$,

$Conc_{sorb\,TSo,i}$ is the sorbed radionuclide concentration in the top soil compartment *i* $\left(\frac{\text{Bq}}{kg}\right)$.

Radionuclide concentration due to direct deposition onto crops $\left(Conc_{crop\_atm}, \frac{Bq}{\text{kg fresh matter}}\right)$ is described in Eq. 26.

$$Conc_{crop\_atm} = \frac{\dot{d}_{atm}{}^{n} \cdot \alpha\left[1 - exp\left(-\lambda_E{}^{n} \cdot t_{e,crops}\right)\right]}{\lambda_E{}^{n}} \quad \textit{Eq. 26}$$

where

$\dot{d}_{atm}{}^{n}$ is the deposition rate of radionuclide *n* on to the ground $\left(\frac{\text{Bq}}{m^2 s}\right)$, calculated as $\dot{d}_{atm}{}^{n} = Conc_{AtmC} \cdot V_{dep}$,

α is the fraction of deposited activity intercepted by the edible portion of vegetation per unit mass $\left(\frac{\text{m}^2}{\text{kg}}\right)$,

$t_{e,crops}$ is the time period that crops are exposed to contamination during the growing season (d),

$\lambda_E{}^{n}$ is the effective rate constant for reduction of the activity concentration of radionuclide *n* from crops (y^{-1}) and is computed following Eq. 27.

$$\lambda_E{}^{n} = \lambda_i^n + \lambda_w \quad \textit{Eq. 27}$$

where

λ_w is the rate constant for reduction of the concentration of material deposited on the plant surfaces owing to processes other than radioactive decay (y^{-1}).

Finally, radionuclide concentration due to due to irrigation of cultivated areas for nuclide *n* $\left(Conc_{crop\_irr}, \frac{Bq}{\text{kg fresh matter}}\right)$ is expressed in Eq. 28.

$$Conc_{crop\_irr} = \frac{\dot{d}_{irr} \cdot \alpha\left[1 - exp\left(-\lambda_E{}^{n} \cdot t_{e,crops}\right)\right]}{\lambda_E{}^{n}} \quad \textit{Eq. 28}$$

where

$\dot{d}_{irr}$ is the deposition rate for irrigation of cultivated areas $\left(\frac{\text{Bq}}{m^2 y}\right)$, calculated as $\dot{d}_{irr} = r_{irr} \cdot Conc_{T_{Riv,i}}$.

Ingestion of fish

Ingestion of contaminated fish can result in exposure to ionizing radiation if the fish have been contaminated with radioactive materials. Annual effective dose received due to consumption of fish $\left(E_{ing,f}, \frac{\text{Sv}}{\text{y}}\right)$ is described by Eq. 29.

$$E_{ing,f} = Conc_{fish}{}^{n} \cdot H_{fish} \cdot DC_{ing,m}{}^{n} \quad \textit{Eq. 29}$$

where

H_{fish} is the consumption rate for fish $\left(\frac{\text{kg}}{\text{y}}\right)$.

$Conc_{fish}{}^{n}$ is the concentration of radionuclide *n* in fish at the time of consumption $\left(\frac{\text{Bq}}{\text{kg}}\right)$ is and is expressed in Eq. 30.

$$Conc_{fish}{}^{n} = Conc_{T_{Riv,i}} B_{fish}{}^{n} \qquad \textbf{Eq. 30}$$

where

$B_{fish}{}^{n}$ is the equilibrium ratio of the concentration of radionuclide *n* in fish to its dissolved concentration in water, known as the bioaccumulation factor $\left(\frac{\text{Bq/kg}}{\text{Bq/L}}\right)$.

Inadvertent ingestion of soil

Contaminated soil can be ingested unintentionally and increase the dose from internal irradiation. Annual effective dose received due to inadvertent consumption of soil $\left(E_{ing,in}, \frac{\text{Sv}}{\text{y}}\right)$ can be calculated with the Eq. 31.

$$E_{ing,in} = Conc_{sorb_{TSo,i}} \cdot Q_{soil,m} \cdot DC_{ing,m}{}^{n} \qquad \textbf{Eq. 31}$$

where

$Q_{soil,m}$ is the amount of soil ingested by inadvertence for age group *m* $\left(\frac{\text{mg}}{\text{d}}\right)$.

6 Results

This section presents the results obtained from the dose impact estimation to the public due to atmospheric and liquid discharges from IFE-Kjeller Agilera facilities. Results are presented per each discharge type and both the dose rate and the annual dose during the operational period is presented. An extended list of results is also included in Appendix C.3, where a summary of the obtained results for the last year of the operation of the facilities is presented in terms of environment concentration and the dose of each isotope via each pathway.

Results of the radionuclides concentration in the environment are not presented in this section but a summary is provided in Appendix B.

6.1 Continuous atmospheric emission

The continuous atmospheric emission scenario considers that the maximum amount of radionuclide that can be released along a year is continuously emitted to the atmosphere at a constant rate. As mentioned in Section 5.1.1.1, the atmospheric dispersion model has been implemented in AERMOD, providing monthly radionuclide concentration both in the croplands and residential areas. This has been the input data for the Ecolego model, which simulates the same annually evolution of radionuclides concentration in these areas along the whole operational period (60 years).

Figure 6-1 presents the evolution of the dose rate in μSv/h during the first and last year of the operational period for each of the studied age groups (infant, child and adult). In all cases the dose rate is lower than 0.002 μSv/h.

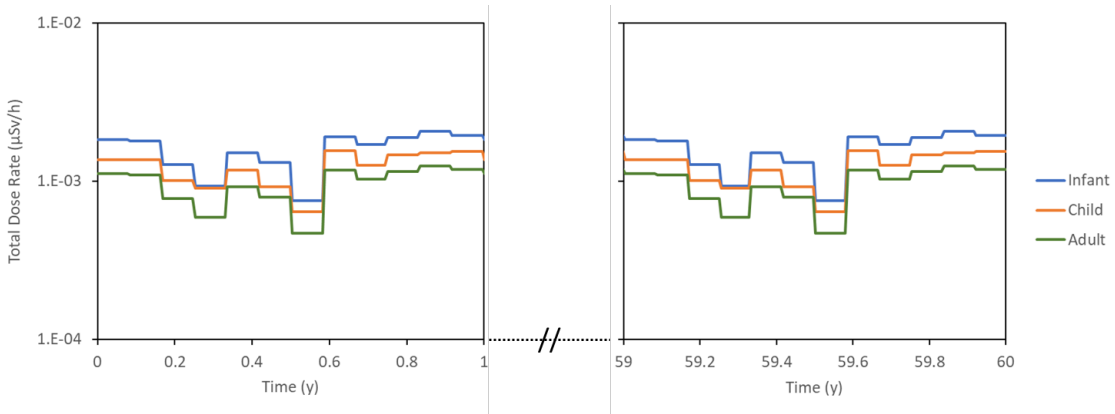

Figure 6-1. *Evolution of total dose rate with time for each exposed age group under the continuous atmospheric emission scenario.*

As the reference group is exposed to different dose rate along the year, Figure 6-2 presents the estimated annual dose each exposed group would receive every operational year, that remains lower than 15 µSv.

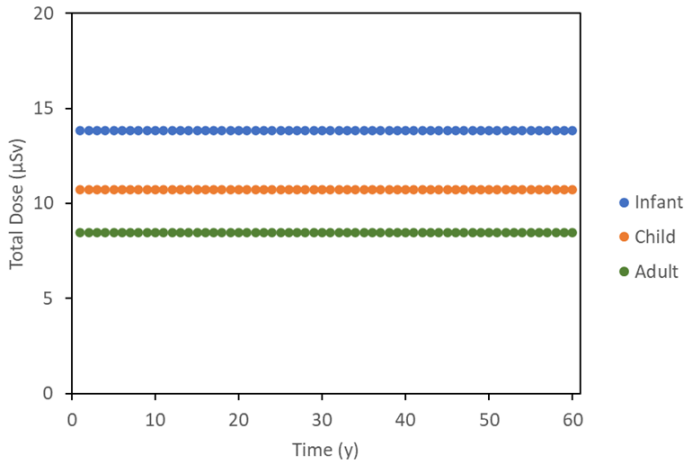

Figure 6-2. *Evolution of the total annual dose with time for each exposed age group under the continuous atmospheric emission scenario.*

Both inhalation and the consumption of crops cultivated in the croplands affected by the atmospheric plume are the exposure pathways that contributes more to the total dose (see left graph in Figure 6-3). The right graph in Figure 6-3 shows that I-131 ingested via crops contributes about 40% of the total dose. The inhalation of Ac-227 and Ra-223 are also contributing significantly to the total dose.

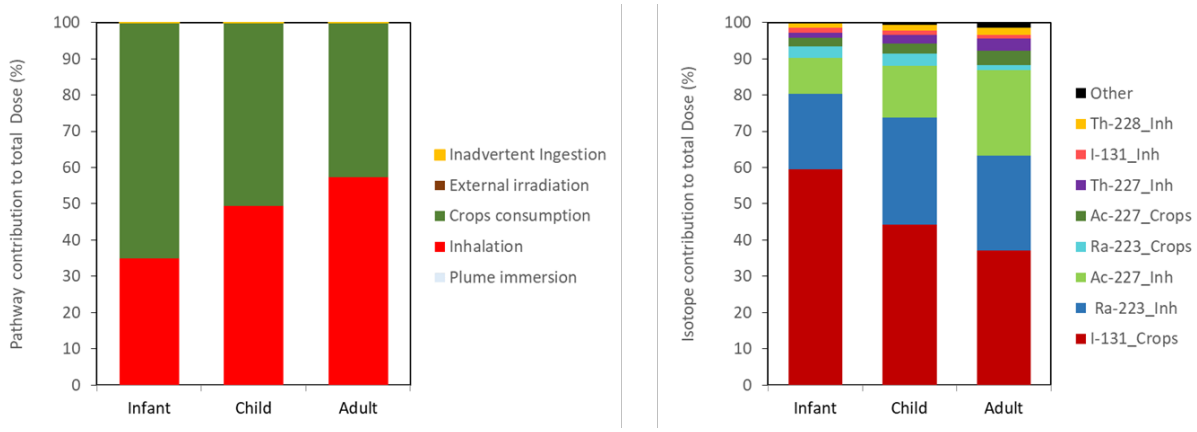

Figure 6-3. *Contribution of exposure pathways (left) and isotope (right) contribution to the total annual dose under the continuous atmospheric emission scenario.*

As observed in Figure 6-2, the annual dose received by the selected reference groups during the operational period of Kjeller-Agilera facilities is constant. The reason is that dose mainly comes from the inhalation of the emitted gases, which are not accumulated in the atmosphere and from the consumption of crops. Crops are contaminated via direct deposition from the environment and due to the absorption of isotopes from the soil via the plant roots. Although the concentration of al isotopes in the soil increases with time, the concentration in the plants is dominated by the deposition from the atmosphere (it contributes in a 99.9%).

An extended presentation of results is presented in Appendix C.3.1, where it is included:

- The mean concentration of each isotope during the last year of operation in the soil of the cropland area.
- Total annual dose received by each age group for each isotope via each exposure pathway.

6.2 Total acute atmospheric emission

This scenario aims on evaluating the impact to the population in case of a total acute release. It is assumed that the maximum amount that could be released in one year is released in one day. The output data from AERMOD can be found in the Appendix C.2. The mean concentration of each isotope during the release day, both in the croplands and the residential area, is implemented in Ecolego and the dose is estimated for the whole operational period assuming one total acute release per year.

The dose rate evolution is presented in Figure 6-4 where the first and last 4 years are shown. A similar evolution is observed every year, during the day of the total acute release, the population is exposed to the highest dose rate which rapidly decreases along the year.

With the years, the dose rate during the days after the total acute release increases due to the accumulation of radioactivity in the environment. This differs on the behaviour observed in the continuous scenario where the dose rate does not increase during the operational period. This is because in the continuous scenario, radionuclides are emitted without interruptions along the simulated period. However, in the case of the total acute release, when the emission stops, the isotopes contributing more to the dose (i.e. iodine-131, $T_{1/2}$ = 8 days) disappear by decay before the next release occurs. Then, the main contributor to the dose during the rest of the year is the ingestion of Ra-223 via crops (see Figure 6-5, left graph to see the main exposure pathway and right graph to identify the main isotope contribution). Ra-223 is accumulated in soils causing the slight increase observed in the dose rate during the time there is no acute release.

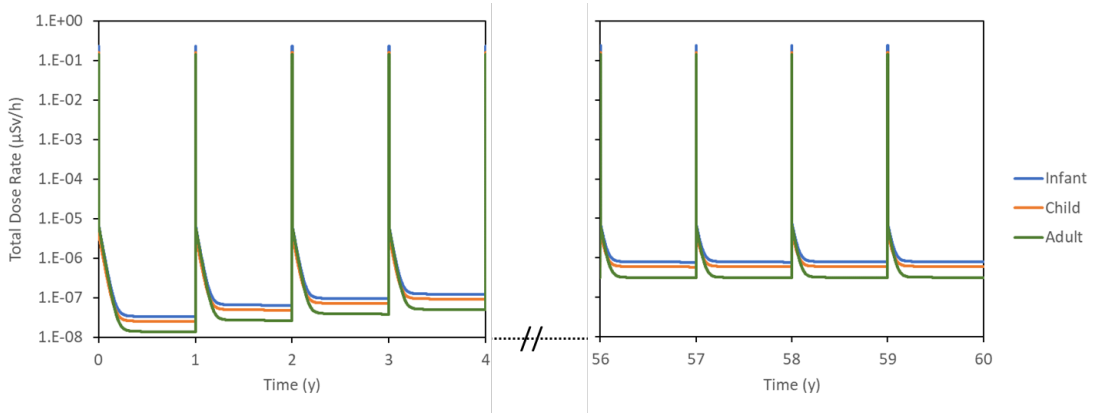

Figure 6-4. *Evolution of total dose rate with time for each exposed age group under the total acute atmospheric emission scenario.*

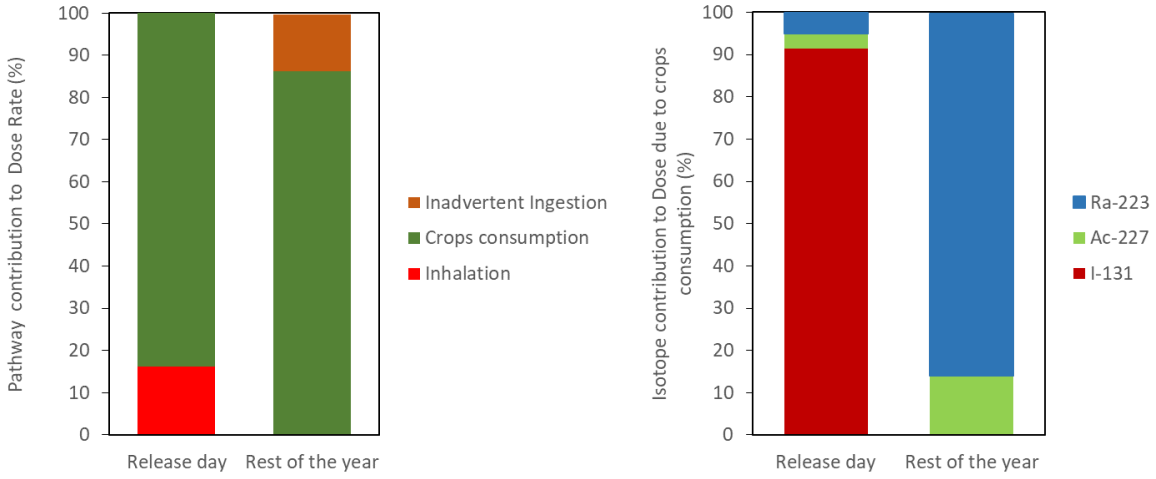

Figure 6-5. *Pathway contribution to the dose rate the day of the total acute release and the rest of the year (left) and the contribution of the main isotopes to the exposure via crops consumption (right).*

Although the dose rate during the release day is quite high in comparison with the rest of the year, it is worth mentioning that population is exposed to this dose only for 1 day. This means that the dose received by the population during the whole year is not high. The annual dose received by the exposed groups is lower than 10 µSv (see Figure 6-6). Note that, the 99.9% of the dose received along the year comes from the exposure to the radioactivity during the day of the total acute release.

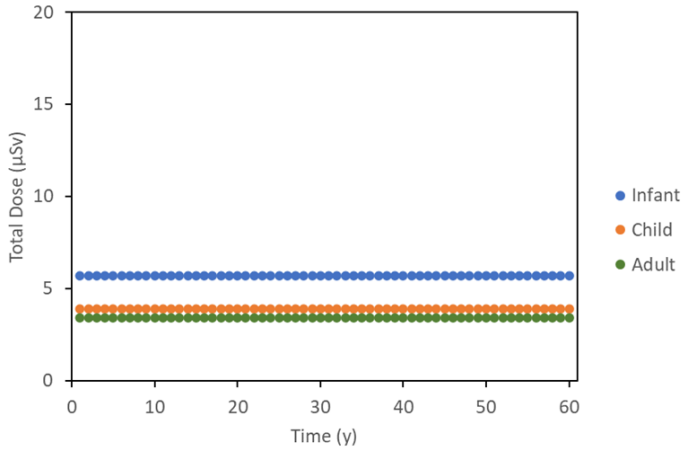

Figure 6-6. *Evolution of the total annual dose with time for each exposed age group under the total acute atmospheric emission scenario.*

Studied reference groups are mainly exposed to iodine-131 ingested via crops (see Figure 6-7). Note that this is a very conservative assumption as, dose is calculated from the concentration in the atmosphere that is deposited both to the crops and to the soil and Ecolego assumes an instantaneous and homogeneous distribution of the radionuclides in the compartments.

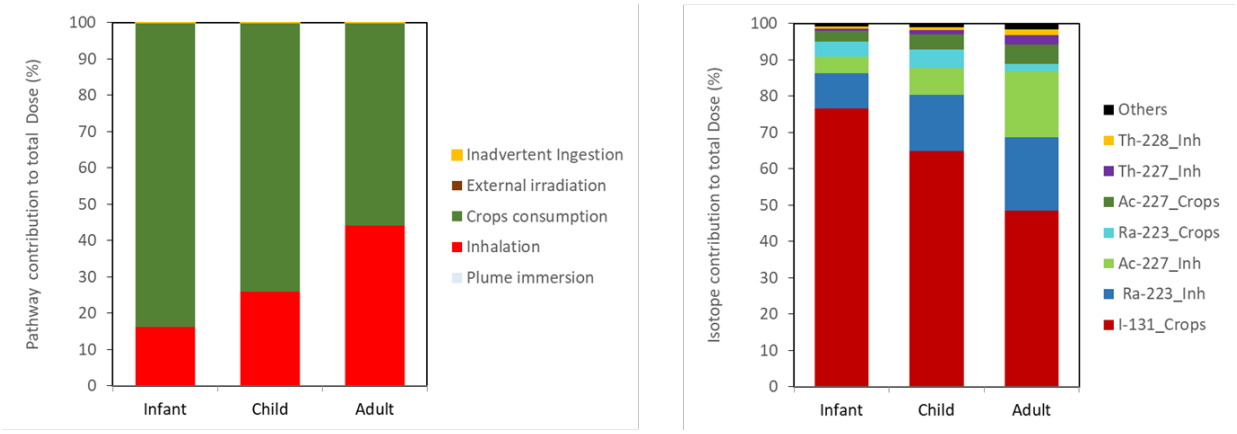

Figure 6-7. *Contribution of exposure pathways (left) and isotope (right) contribution to the total annual dose under the total acute atmospheric emission scenario.*

The following results can be found in Appendix C.3.2 for more details:

- The mean concentration of each isotope during the last year of operation in the soil of the cropland area.

- Total annual dose received by each age group for each isotope via each exposure pathway.

6.3 Liquid discharges

Liquid discharges are released to the Nitelva river three times per year through the NALFA pipeline. The activity of radionuclides released every time is 1/3 of the annual release to the river. The maximum dose rate is received every time a discharge to the river occurs, being always below 10^{-2} µSv/h (see Figure 6-8).

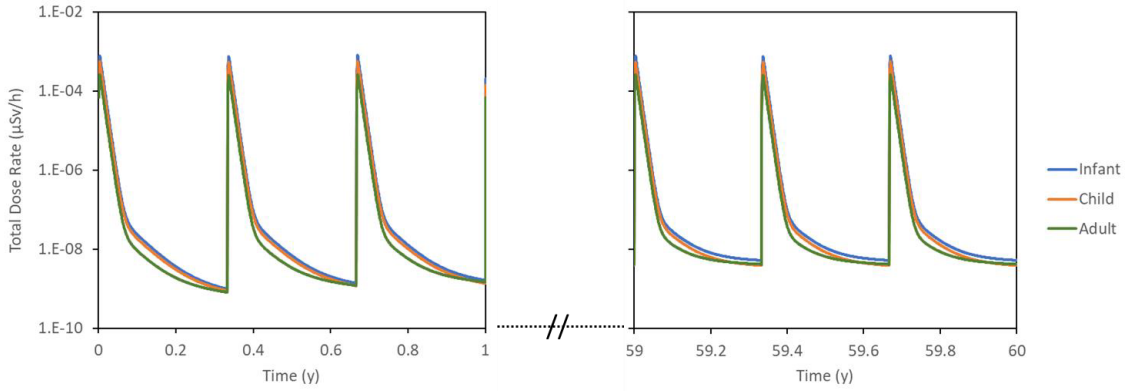

Figure 6-8. *Evolution of the total annual dose with time for each exposed age group under the liquid discharges scenario.*

As observed in the total acute release, the dose rate between release events slightly increases. But the accumulation in the environment it is not relevant. More information on the evolution of radionuclides in the environment is presented in Appendix B.

The annual exposure of the population along a year remains constant during the operational period and it is lower than 1 µSv for all the age group under the studied conditions. As shown in Figure 6-10, almost 90% of the dose comes from the consumption of fish coming from the Nitelva river affected by radioactive liquid discharges. Iodine-131 and radium-223 are the isotopes dominating the dose exposure via the fish consumption (Figure 6-10).

Fish consumption is the main exposure pathway contributing to the total dose, dose due to fish consumption depends on the radionuclides´ concentration in the river and the concentration in the river along the year is similar during the whole operational period. Those facts explain why the total dose received by the exposed groups is the same at the beginning and the end of the simulation period.

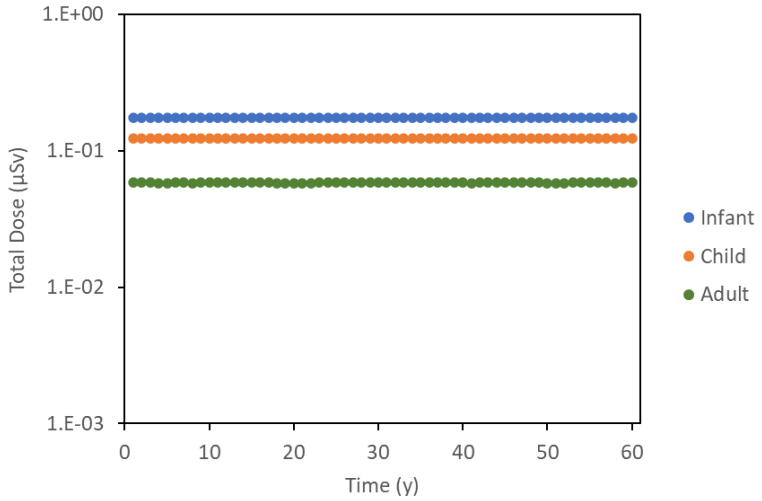

Figure 6-9. *Evolution of the total annual dose with time for each exposed age group under the liquid discharges scenario.*

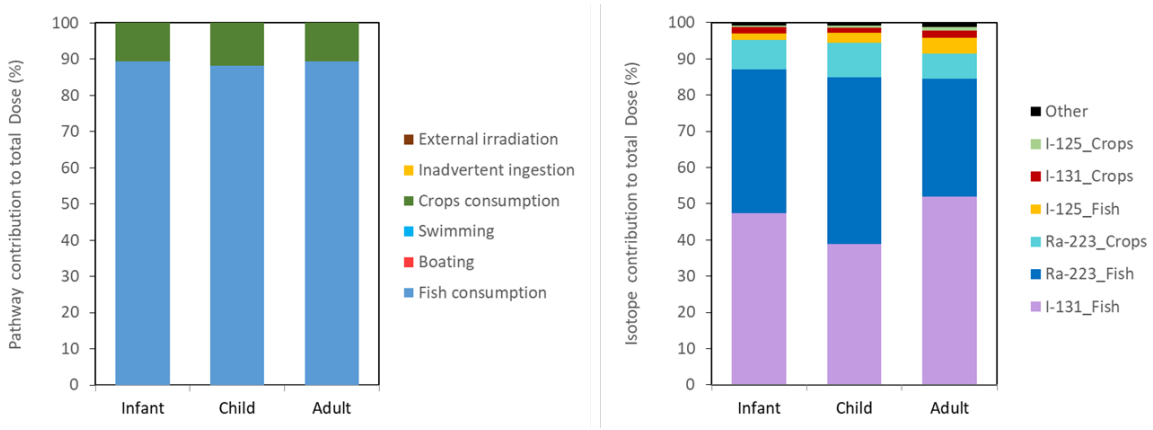

Figure 6-10. *Contribution of exposure pathways (left) and isotope (right) contribution to the total annual dose under the liquid discharges scenario.*

A detailed set of results obtained from the surface water model are presented in Appendix C.3.3. The results included are the following:

- The mean concentration of each isotope during the last year of operation in the soil of the cropland area, the river and sediments.
- Total annual dose received by each age group for each isotope via each exposure pathway.

7 Conclusions

A radiological dose assessment is conducted for three different discharge types for the IFE division Agilera: continuous atmospheric release, total acute atmospheric release and liquid discharge to the Nitelva river.

To perform the dose assessment the system was characterized, and the conceptual model described. After the mathematical model and parametrization of all required parameters, the model has been implemented in Ecolego to obtain the annual dose received to the three age scenarios of the reference group. Several exposition pathways have been considered including both internal and external radiation exposures.

The annual dose to the studied reference group under the three discharge scenarios (continuous atmospheric emission, total acute atmospheric emission and liquid discharges to the Nitelva river) is estimated to be below 15 μSv (see Figure 7-1). In all cases, the dose received by infants is slightly higher than for adults as dose coefficients are generally higher as age decreases.

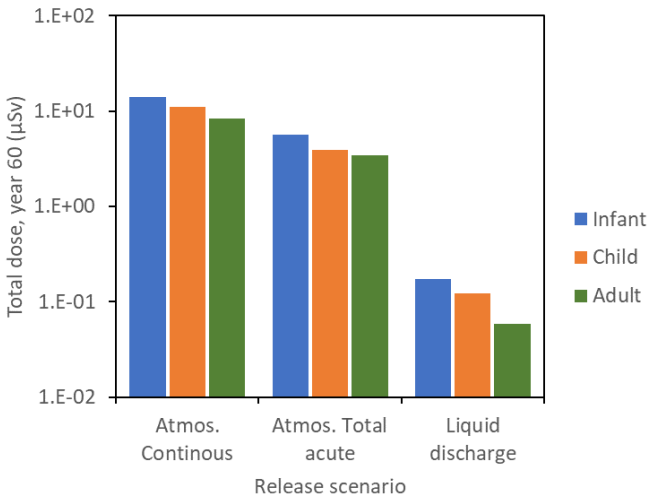

Figure 7-1. *Dose received during the last year of operation (year 60) as a function of the reference group and the discharge scenario.*

The dose does not increase during the operational period although there is accumulation in the environment. Accumulation is observed both in the soils and in the river sediments but there is not a significant impact on the dose, as the exposure pathways that depend on the concentration in these media are not highly contributing to the total dose and they are not producing a significant impact to the environment. Appendix B provides the evolution of the concentration of radionuclides in the different compartments of the system. It is worth

mentioning that this model has not been built to study in detail the behaviour and transport of radionuclides in the environment. In order to have a more detailed calculation on the transport of radionuclides in the media, more complex models, such as reactive transport models, should be applied. Those models not only consider decay and main physical processes like sorption via the Kd but also chemistry evolution or changes in physical properties of the media.

Finally, it can be concluded that the emissions/discharges to the environment from the IFE-Kjeller Agilera division are not producing a significant radiological impact to humans nor to the environment under the studied conditions.

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Appendix

A. Parameters

Appendix A includes the parametrization of both the physical and the dose model.

A.1 Physical model

This appendix includes the list of parameters and the corresponding values selected for the definition of the physical system. Firstly, those parameters that are not radionuclide specific are presented, either those that have a specific value and the ones that only depend on the compartment. The second part of this appendix is focused on the parameters that are radionuclide or element specific.

A.1.1 Non-radionuclide dependent data

Table A. 1. *Non-radionuclide nor compartment dependent data for physical model.*

Parameter	Unit	Value	Ref.
$DepT^{a,b}$	m/s	0.001	[7]
BioT	kg/(m²·year)	2	[8]
r_{Sed}	kg/(m²·year)	0.072	[9]
S_s	kg/m³	0.017	[8]
r_{Res}	kg/(m²·year)	0.047	[9]
r_{irr}	m³/(m²·year)	0.15	[10]

[a] *This value is 0.01 for iodine.*

[b] *Noble gases, such as radon, krypton, or xenon, do not interact with other substances or surfaces, therefore their deposition value is set to zero.*

Table A. 2. *Compartment dependent data for physical model.*

Compartment	Parameter	Unit	Value compartment #1	Value compartment #2	Ref.
River	Area	km²	1.1	1.6	[3]
	h	m	2.0	1.25	[3]
	Q_v	m³/s	9	9	[11]
Top soil	Area	km²	0.38	0.48	[3]
	h	m	0.3	0.3	[8]

Compartment	Parameter	Unit	Value compartment #1	Value compartment #2	Ref.
	ρ	kg/m^3	1626	1626	[12]
	por	-	0.36	0.36	[12]
	Wf	m/year	0.3	0.3	[8]
Deep soil	Area	km^2	0.38	0.48	[3]
	h	m	1	1	[a]
	ρ	kg/m^3	2115	2115	[12]
	por	-	0.21	0.21	[12]
Top sediment	Area	km^2	1.1	1.6	[3]
	h	m	0.05	0.05	[12]
	ρ	kg/m^3	1587	1587	[8]
	por	-	0.42	0.42	[8]
Deep sediment	Area	km^2	1.1	1.6	[3]
	h	m	0.73	0.73	[9]
	ρ	kg/m^3	1390	1390	[8]
	por	-	0.41	0.41	[8]

[a] *Default value.*

A.1.2 Radionuclide dependent data

Table A. 3. *Diffusion coefficient for radionuclide i in free solution (D_i, m^2/s).*

Element	D_i (m^2/s)	Ref.	Element	D_i (m^2/s)	Ref.
Ac	1.0E-09	[8]	Po	1.0E-09	[13]
Ag	1.7E-09	[8]	Pu	1.0E-09	[8]
Ba	1.0E-09	[13]	Ra	8.9E-10	[8]
Bi	1.0E-09	[13]	Rh	1.0E-09	[13]
Cd	7.2E-10	[13]	Rn	1.0E-09	[13]
Co	7.0E-10	[8]	Ru	1.0E-09	[13]
Cs	2.1E-09	[8]	Sc	1.0E-09	[13]
Gd	1.0E-09	[13]	Sn	1.0E-09	[8]
H	1.0E-09	[13]	Sr	7.9E-10	[8]
Hg	1.0E-09	[13]	Tb	1.0E-09	[13]

Element	D_i (m^2/s)	Ref.	Element	D_i (m^2/s)	Ref.
I	2.0E-09	[8]	Th	1.5E-10	[8]
Lu	1.0E-09	[13]	Tl	1.0E-09	[13]
Na	1.3E-09	[13]	Y	1.0E-9	[13]
Pb	1.0E-09	[13]			

Table A. 4. *Distribution coefficient for radionuclide i in suspended solids (Kd_{Ss}, m^3/kg_{DW}).*

Elements	K_{dSs} (m^3/kg_{DW})	Ref.	Elements	K_{dSs} (m^3/kg_{DW})	Ref.
Ac	15.6	[8]	Po	0.84	[8]
Ag	2.04	[8]	Pu	11.7	[8]
Ba	2.01	[8]	Ra	2.01	[8]
Bi	0.84	[8]	Rh	2.82	[8]
Cd	1.94	[8]	Rn	[a]	
Co	1.94	[8]	Ru	2.82	[8]
Cs	27.7	[8]	Sc	8.93	[8]
H	[a]		Sn	9.91	[8]
I	0.28	[8]	Tb	8.93	[8]
Lu	8.93	[8]	Th	25.4	[8]
Na	27.7	[8]	Tl	9.91	[8]
Pb	9.91	[8]			

[a] *Element not sorbed*

Table A. 5. *Distribution coefficients for radionuclide i in soils and sediments (Kd, m^3/kg_{DW}).*

Elements	Kd (m^3/kg_{DW})			
	Top Soil	Deep Soil	Top Sed.	Deep Sed.
Ac	1.7E+00 [14]	1.7E+00 [14]	8.8E+01 [12]	7.2E+00 [8]
Ag	1.9E+00 [15]	4.7 E-01 [15]	2.8E+01 [12]	2.8E-01 [8]
Ba	9.6E-01 [15]	3.1E+00 [15]	3.2E+00 [12]	3.2E+00 [8]
Bi	7.6E+00 [15]	1.3E+02 [15]	5.0E+00 [14]	5.0E+00 [14]
Cd	2.0E+00 [15]	1.7E+00 [15]	6.6E+01 [12]	6.6E+01 [8]
Co	4.2E+00 [15]	6.5E+01 [15]	1.6E+01 [12]	6.0E-01 [8]

Elements	Kd (m^3/kg_{DW})			
Cs	9.7E+01 [15]	3.7E+02 [15]	4.6E+01 [12]	1.2E+01 [8]
H	a	a	a	a
I	1.1E-01 [15]	0.24E-01 [15]	3.5E-01 [12]	7.8E-02 [8]
Lu	4.2E+00 [15]	5.0E+01 [15]	8.8E+01 [12]	2.5E+00 [8]
Na	2.0E-02 [15]	4.0E-02 [15]	4.6E+01 [12]	1.2E+01 [8]
Pb	1.1E+01 [15]	2.2E+02 [15]	1.5E+02 [12]	1.5E+02 [8]
Po	6.6E+00 [16]	1.5E+01 [12]	5.6E+01 [12]	5.6E+01 [12]
Pu	7.4E-01 [14]	7.4E-01 [14]	4.5E+00 [12]	3.6E+00 [8]
Ra	3.0E+00 [15]	1.1E+01 [15]	3.2E+00 [12]	1.1E+01 [8]
Rh	1.2E+00 [15]	3.1E+00 [15]	3.2E+01 [12]	3.2E+01 [8]
Rn	a	a	a	a
Ru	1.2E+00 [15]	3.1E+00 [15]	3.2E+01 [12]	3.2E+01 [8]
Sc	9.6E+00 [15]	1.0E+02 [15]	2.2E+02 [12]	2.2E+02 [8]
Sn	1.0E+01 [15]	1.1E+01 [15]	9.6E+00 [12]	9.6E+00 [8]
Tb	5.6E+00 [15]	9.8E+01 [15]	8.8E+00 [12]	2.5E+00 [8]
Th	6.1E+00 [15]	9.1E+01 [15]	2.1E+02 [12]	1.6E+01 [8]
Tl	9.4E+00 [15]	3.7E+01 [15]	1.5E+02 [12]	1.5E+02 [8]
Y	4.4E+00 [15]	5.8E+01 [15]	b	b
Gd	6.0E+00 [15]	9.6E+01 [15]	b	b
Hg	3.0E+00 [15]	1.7E+00 [15]	b	b
Sr	1.0E-01 [15]	5.1E-01 [15]	b	b

[a] *Element not sorbed*

[b] *Element not studied in the surface water model*

A.2 Dose Model

The parameters used to calculate the dose due to the exposure of population to radionuclides via different pathway are presented in the following tables. As in the case of the parameters defining the physical system, parameters are classified as non-radionuclide dependents and parameters that depend on either the radionuclide or the element.

A.2.1 Non-radionuclide dependent data

Table A. 6. *General, non-radionuclide dependent data for the dose model.*

Parameter	Unit	Value	Ref.
t_h	d	14	[17]
α	m2/kg	0.3	[17]
λ_w	d-1	0.05	[17]
$t_{e,crops}$	d	60	[17]

Table A. 7. *Age-group dependent data for dose model.*

Parameter	Unit	Infant	Child	Adult	Ref.
Of_C	-	1.0E-02	1.0E-02	1.7E-01	[a]
Of_R	-	3.3E-01	3.3E-01	2.5E-01	[a]
Of_S	-	0.0E+00	0.0E+00	1.4E-03	[a]
Of_B	-	6.0E-03	6.0E-03	6.0E-03	[a]
R_{inhC}	m_3/h	2.2E-01	3.8E-01	1.5E+00	[18]
R_{inhR}	m^3/h	2.9E-01	7.5E-01	1.0E+00	[18]
H_c	kg/y	4.5E+01	9.0E+01	1.4E+02	[19]
H_{fish}	kg/y	5.0E-01	1.0E+00	1.5E+00	[a]
Q_{sol}	mg/d	1.0E+02	5.0E+01	4.0E+01	[20]

[a] *Internal Assumption*

A.2.2 Radionuclide dependent data

Table A. 8. *Dose coefficient for inhalation for radionuclide i for each age group (DC_{inh}, Sv/Bq).*

Isotope	DC_{inh} (Sv/Bq)			Ref.
	Infant[a]	Child[b]	Adult	
Ac-227	2.0E-04	8.7E-05	7.2E-05	[21]
Bi-210	3.0E-07	1.3E-07	9.3E-08	[21]
Bi-211	4.6E-09	1.6E-09	1.1E-09	[22]
Bi-212	1.1E-07	4.4E-08	3.1E-08	[21]
Bi-214	6.1E-08	2.2E-08	1.4E-08	[21]
Cs-135	9.9E-10	6.1E-10	6.9E-10	[21]
Cs-137	5.4E-09	3.7E-09	4.6E-09	[21]
Gd-153	1.2E-08	3.9E-09	2.1E-09	[21]

Isotope	DC_{inh} (Sv/Bq)			Ref.
	Infant[a]	Child[b]	Adult	
H-3	2.7E-10	8.2E-11	4.5E-11	[21]
Hg-203	7.9E-09	3.4E-09	2.4E-09	[21]
I-131	7.2E-08	1.9E-08	7.4E-09	[21]
Pb-210	3.7E-06	1.5E-06	1.1E-06	[21]
Pb-211	4.5E-08	1.9E-08	1.1E-08	[21]
Pb-212	4.6E-07	2.2E-07	1.7E-07	[21]
Pb-214	4.6E-08	1.9E-08	1.4E-08	[21]
Po-210	4.8E-06	1.3E-06	6.1E-07	[21]
Po-212	0.0E+00	0.0E+00	0.0E+00	[23]
Po-214	1.5E-14	5.2E-15	3.1E-15	[24]
Po-215	0.0E+00	0.0E+00	0.0E+00	[23]
Po-216	0.0E+00	0.0E+00	0.0E+00	[23]
Po-218	1.6E-08	5.6E-09	3.5E-09	[24]
Ra-223	2.4E-05	1.1E-05	8.7E-06	[21]
Ra-224	9.2E-06	4.4E-06	3.4E-06	[21]
Rn-219	4.4E-10	4.4E-10	4.4E-10	[25]
Rn-220	1.8E-10	1.8E-10	1.8E-10	[25]
Rn-222	4.8E-11	4.8E-11	4.8E-11	[25]
Sr-90	4.0E-07	1.8E-07	1.6E-07	[21]
Tb-160	2.5E-08	1.0E-08	7.0E-09	[21]
Tb-161	4.7E-09	1.9E-09	1.3E-09	[21]
Th-227	2.5E-05	1.1E-05	8.5E-06	[21]
Th-228	1.1E-04	4.6E-05	3.2E-05	[21]
Tl-207	2.1E-11	6.0E-12	3.4E-12	[22]
Tl-208	2.8E-11	8.6E-12	4.5E-12	[22]
Y-90	8.8E-09	2.7E-09	1.5E-09	[21]

[a] *Values for one year old infants are selected.*

[b] *Values for ten years old children are selected.*

Table A. 9. *Dose coefficient for ingestion for radionuclide i for each age group (DC_{ing}, Sv/Bq).*

Isotope	DC_{ing} (Sv/Bq)			Ref.
	Infant[a]	Child[b]	Adult	
Ac-227	3.1E-06	1.5E-06	1.1E-06	[21]
Ac-228	2.8E-09	8.7E-10	4.3E-10	[21]
Ag-108	3.2E-11	8.6E-12	4.6E-12	[21]
Ag-108m	1.1E-08	4.3E-09	2.3E-09	[21]
Ag-110	1.4E-08	5.2E-09	2.8E-09	[21]
Ag-110m	1.4E-08	5.2E-09	2.8E-09	[21]
Ba-133	6.2E-09	4.6E-09	1.5E-09	[21]
Bi-210	9.7E-09	2.9E-09	1.3E-09	[21]
Bi-211	8.3E-11	2.3E-11	1.2E-11	[22]
Bi-212	1.8E-09	5.0E-10	2.6E-10	[21]
Bi-214	7.4E-10	2.1E-10	1.1E-10	[21]
Cd-109	9.5E-09	3.5E-09	2.0E-09	[21]
Co-60	2.7E-08	1.1E-08	3.4E-09	[21]
Cs-134	1.6E-08	1.4E-08	1.9E-08	[21]
Cs-135	2.3E-09	1.7E-09	2.0E-09	[21]
Cs-137	1.2E-08	1.0E-08	1.3E-08	[21]
Gd-153	1.8E-09	5.8E-10	2.7E-10	[21]
H-3	4.8E-11	2.3E-11	1.8E-11	[21]
I-125	5.7E-08	3.1E-08	1.5E-08	[21]
I-131	1.8E-07	5.2E-08	2.2E-08	[21]
Lu-177	3.9E-09	1.2E-09	5.3E-10	[21]
Lu-177m	1.1E-08	3.6E-09	1.7E-09	[21]
Na-22	1.5E-08	5.5E-09	3.2E-09	[21]
Pb-210	3.6E-06	1.9E-06	6.9E-07	[21]
Pb-211	1.4E-09	4.1E-10	1.8E-10	[21]
Pb-212	6.3E-08	2.0E-08	6.0E-09	[21]
Pb-214	1.0E-09	3.1E-10	1.4E-10	[21]
Po-210	8.8E-06	2.6E-06	1.2E-06	[21]
Po-212	0.0E+00	0.0E+00	0.0E+00	[23]
Po-214	0.0E+00	0.0E+00	0.0E+00	[23]
Po-215	0.0E+00	0.0E+00	0.0E+00	[23]

Isotope	DC_{ing} (Sv/Bq)			Ref.
Po-216	0.0E+00	0.0E+00	0.0E+00	[23]
Pu-238	4.0E-07	2.4E-07	2.3E-07	[21]
Pu-239	4.2E-07	2.7E-07	2.5E-07	[21]
Pu-240	4.2E-07	2.7E-07	2.5E-07	[21]
Pu-242	4.0E-07	2.6E-07	2.4E-07	[21]
Ra-223	1.1E-06	4.5E-07	1.0E-07	[21]
Ra-224	6.6E-07	2.6E-07	6.5E-08	[21]
Ra-228	5.7E-06	3.9E-06	6.9E-07	[21]
Rh-106	9.7E-10	3.3E-10	1.6E-10	[21]
Rn-222	6.9E-10	6.9E-10	6.9E-10	[25]
Ru-106	4.9E-08	1.5E-08	7.0E-09	[21]
Sc-46	7.9E-09	2.9E-09	1.5E-09	[21]
Sn-113	5.0E-09	1.6E-09	7.3E-10	[21]
Sr-90	7.30E-08	6.0E-08	2.8E-08	[21]
Tb-161	5.3E-09	1.6E-09	7.2E-10	[21]
Th-227	7E-08	2.3E-08	8.8E-09	[21]
Th-228	3.7E-07	1.4E-07	7.2E-08	[21]
Th-232	4.5E-07	2.9E-07	2.3E-07	[21]
Tl-207	4.9E-11	1.3E-11	7.1E-12	[22]
Tl-208	5.2E-11	1.5E-11	8.6E-12	[22]
Y-90	2.0E-08	5.9E-09	2.7E-09	[21]

[a] *Values for one year old infants are selected.*

[b] *Values for ten years old children are selected.*

Table A. 10. *Dose coefficient for air submersion for radionuclide i for each age group ($DC_{im,a}$, Sv/s per Bq/m³).*

Isotope	$DC_{im,a}$ ((Sv/s)/(Bq/m³))			Ref.
	Infant[a]	Child[b]	Adult	
Ac-227	6.8E-18	5.6E-18	4.2E-18	[26]
Bi-210	1.2E-15	1.1E-15	1.0E-15	[26]
Bi-211	2.6E-15	2.3E-15	2.0E-15	[26]
Bi-212	7.8E-15	7.1E-15	6.3E-15	[26]
Bi-214	8.8E-14	8.0E-14	7.2E-14	[26]
Cs-135	1.4E-16	1.3E-16	1.2E-16	[26]

Isotope	$DC_{im,a}$ ((Sv/s)/(Bq/m^3))			Ref.
Cs-137	4.6E-16	4.3E-16	3.9E-16	[26]
Gd-153	4.1E-15	3.4E-15	2.8E-15	[26]
H-3	4.7E-20	4.3E-20	3.8E-20	[26]
Hg-203	1.3E-14	1.2E-14	1.0E-14	[26]
I-125	5.7E-16	4.4E-16	2.8E-16	[26]
I-131	2.2E-14	1.9E-14	1.7E-14	[26]
Pb-210	7.0E-17	5.3E-17	3.8E-17	[26]
Pb-211	5.1E-15	4.6E-15	4.1E-15	[26]
Pb-212	7.8E-15	6.8E-15	5.9E-15	[26]
Pb-214	1.4E-14	1.3E-14	1.1E-14	[26]
Po-210	5.5E-19	5.0E-19	4.4E-19	[26]
Po-212	0.0E+00	0.0E+00	0.0E+00	[26]
Po-214	4.7E-18	4.3E-18	3.8E-18	[26]
Po-215	9.7E-18	8.8E-18	7.7E-18	[26]
Po-216	8.7E-19	7.8E-19	6.9E-19	[26]
Ra-223	7.3E-15	6.4E-15	5.4E-15	[26]
Ra-224	5.7E-16	5.0E-16	4.4E-16	[26]
Rn-219	3.2E-15	2.9E-15	2.5E-15	[26]
Rn-220	3.5E-17	3.2E-17	2.8E-17	[26]
Rn-222	2.2E-17	2.0E-17	1.7E-17	[26]
Sr-90	1.7E-19	1.6E-19	1.4E-19	[26]
Tb-160	6.5E-14	5.8E-14	5.2E-14	[26]
Tb-161	1.5E-15	1.2E-15	9.5E-16	[26]
Th-227	6.6E-15	5.8E-15	5.0E-15	[26]
Th-228	1.1E-16	9.2E-17	7.5E-17	[26]
Tl-207	1.8E-15	1.7E-15	1.5E-15	[26]
Tl-208	2.0E-13	1.8E-13	1.7E-13	[26]
Y-90	1.5E-18	1.4E-18	1.2E-18	[26]

[a] *Values for one year old infants are selected.*

[b] *Values for ten years old children are selected.*

Table A. 11. *Dose coefficient for water immersion for radionuclide i for each age group ($DC_{im,w}$, Sv/s per Bq/m³).*

Isotope	$DC_{im,w}$ ((Sv/s)/(Bq/m³))			Ref.
	Infant[a]	Child[b]	Adult	
Ac-227	1.2E-20	9.7E-21	6.9E-21	[26]
Ac-228	1.0E-16	9.4E-17	8.4E-17	[26]
Ag-108	2.7E-18	2.4E-18	2.2E-18	[26]
Ag-108m	1.9E-16	1.7E-16	1.5E-16	[26]
Ag-110	5.1E-18	4.6E-18	4.2E-18	[26]
Ag-110m	3.3E-16	3.0E-16	2.7E-16	[26]
Ba-133	4.2E-17	3.6E-17	3.2E-17	[26]
Bi-211	5.3E-18	4.6E-18	4.1E-18	[26]
Bi-212	1.3E-17	1.2E-17	1.1E-17	[26]
Cd-109	7.0E-19	5.5E-19	4.1E-19	[26]
Co-60	3.1E-16	2.8E-16	2.5E-16	[26]
Cs-134	1.8E-16	1.7E-16	1.5E-16	[26]
Cs-137	1.1E-19	1.1E-19	1.0E-19	[26]
H-3	2.8E-26	2.0E-26	6.2E-27	[26]
I-125	1.3E-18	9.4E-19	6.8E-19	[26]
I-131	4.4E-17	3.8E-17	3.4E-17	[26]
Lu-177	3.8E-18	3.2E-18	2.8E-18	[26]
Lu-177m	1.1E-16	9.4E-17	8.2E-17	[26]
Na-22	2.6E-16	2.4E-16	2.1E-16	[26]
Pb-211	7.9E-18	7.1E-18	6.3E-18	[26]
Pb-212	1.6E-17	1.3E-17	1.2E-17	[26]
Po-212	0.0E+00	0.0E+00	0.0E+00	[26]
Po-215	2.0E-20	1.8E-20	1.6E-20	[26]
Po-216	1.8E-21	1.7E-21	1.5E-21	[26]
Pu-238	1.6E-20	1.4E-20	6.6E-21	[26]
Pu-239	1.3E-20	1.1E-20	7.3E-21	[26]
Pu-240	1.6E-20	1.3E-20	6.5E-21	[26]
Pu-242	2.3E-20	2.0E-20	1.3E-20	[26]
Ra-223	1.5E-17	1.2E-17	1.1E-17	[26]
Ra-224	1.2E-18	9.9E-19	8.6E-19	[26]

Isotope	$DC_{im,w}$ ((Sv/s)/(Bq/m³))			Ref.
Ra-228	1.8E-20	1.5E-20	6.1E-21	[26]
Rh-106	2.6E-17	2.3E-17	2.1E-17	[26]
Rn-119	6.6E-18	5.7E-18	5.0E-18	[26]
Rn-220	7.3E-20	6.5E-20	5.7E-20	[26]
Ru-106	1.6E-24	1.3E-24	5.7E-25	[26]
Sc-46	2.4E-16	2.2E-16	2.0E-16	[26]
Sn-113	9.8E-19	8.2E-19	6.5E-19	[26]
Tb-161	2.5E-18	2.0E-18	1.6E-18	[26]
Th-227	1.3E-17	1.2E-17	1.0E-17	[26]
Th-228	2.2E-19	1.8E-19	1.5E-19	[26]
Th-230	4.5E-20	3.7E-20	2.8E-20	[26]
Th-232	2.6E-20	2.1E-20	1.5E-20	[26]
Tl-207	7.2E-19	6.7E-19	6.3E-19	[26]
Tl-208	4.3E-16	3.9E-16	3.6E-16	[26]

[a] *Values for one year old infants are selected.*

[b] *Values for ten years old children are selected.*

Table A. 12. *Dose coefficient for exposure to ground deposits for radionuclide i for each age group (DC_{Ext}, Sv/s per Bq/m³).*

Isotope	DC_{Ext} ((Sv/s)/(Bq/m³))			Ref.
	Infant[a]	Child[b]	Adult	
Ac-227	2.2E-21	1.9E-21	1.6E-21	[26]
Ac-228	1.8E-17	1.7E-17	1.5E-17	[26]
Ag-108	1.2E-18	1.1E-18	1.0E-18	[26]
Ag-108m	3.4E-17	3.1E-17	2.8E-17	[26]
Ag-110	2.7E-18	2.4E-18	2.2E-18	[26]
Ag-110m	5.8E-17	5.2E-17	4.8E-17	[26]
Ba-133	7.7E-18	6.9E-18	6.2E-18	[26]
Bi-210	4.5E-19	4.1E-19	3.7E-19	[26]
Bi-211	9.9E-19	8.9E-19	8.0E-19	[26]
Bi-212	2.9E-18	2.6E-18	2.4E-18	[26]
Bi-214	3.1E-17	2.8E-17	2.6E-17	[26]
Co-60	5.1E-17	4.7E-17	4.3E-17	[26]
Cd-109	8.3E-20	6.9E-20	5.4E-20	[26]

Isotope	DC_{Ext} ((Sv/s)/(Bq/m^3))			Ref.
Cs-134	3.3E-17	3.0E-17	2.7E-17	[26]
Cs-135	5.5E-20	5.0E-20	4.5E-20	[26]
Cs-137	1.7E-19	1.5E-19	1.4E-19	[26]
Gd-153	1.4E-18	1.1E-18	9.8E-19	[26]
H-3	2.2E-23	2.0E-23	1.9E-23	[26]
Hg-203	5.0E-18	4.5E-18	4.0E-18	[26]
I-125	1.1E-19	7.7E-20	5.4E-20	[26]
I-131	8.3E-18	7.4E-18	6.7E-18	[26]
Lu-177	7.9E-19	7.0E-19	6.3E-19	[26]
Lu-177m	2.0E-17	1.8E-17	1.6E-17	[26]
Na-22	4.6E-17	4.2E-17	3.8E-17	[26]
Pb-210	2.0E-20	1.5E-20	1.2E-20	[26]
Pb-211	1.9E-18	1.7E-18	1.6E-18	[26]
Pb-212	2.9E-18	2.6E-18	2.3E-18	[26]
Pb-214	5.4E-18	4.9E-18	4.4E-18	[26]
Po-210	2.1E-22	1.9E-22	1.7E-22	[26]
Po-212	0.0E+00	0.0E+00	0.0E+00	[26]
Po-214	1.8E-21	1.6E-21	1.4E-21	[26]
Po-215	3.8E-21	3.4E-21	3.0E-21	[26]
Po-216	3.2E-22	2.9E-22	2.7E-22	[26]
Pu-238	1.1E-21	8.8E-22	4.9E-22	[26]
Pu-239	1.6E-21	1.3E-21	1.1E-21	[26]
Pu-240	1.1E-21	8.7E-22	5.0E-22	[26]
Pu-242	2.5E-21	2.2E-21	1.7E-21	[26]
Ra-223	2.7E-18	2.4E-18	2.1E-18	[26]
Ra-224	2.2E-19	1.9E-19	1.7E-19	[26]
Ra-228	1.3E-21	1.0E-21	5.3E-22	[26]
Rh-106	6.9E-18	6.3E-18	5.7E-18	[26]
Rn-219	1.2E-18	1.1E-18	9.9E-19	[26]
Rn-220	1.3E-20	1.2E-20	1.1E-20	[26]
Rn-222	8.3E-21	7.4E-21	6.7E-21	[26]
Ru-106	5.6E-22	5.1E-22	4.7E-22	[26]
Sc-46	4.2E-17	3.8E-17	3.5E-17	[26]

Isotope	DC_{Ext} ((Sv/s)/(Bq/m^3))			Ref.
Sn-113	1.4E-19	1.2E-19	1.1E-19	[26]
Sr-90	1.7E-19	1.6E-19	1.4E-19	[26]
Tb-160	2.3E-17	2.1E-17	1.9E-17	[26]
Tb-161	4.8E-19	4.1E-19	3.5E-19	[26]
Th-227	2.5E-18	2.2E-18	2.0E-18	[26]
Th-228	3.8E-20	3.4E-20	3.0E-20	[26]
Th-232	3.4E-21	2.9E-21	2.3E-21	[26]
Tl-207	6.7E-19	6.1E-19	5.6E-19	[26]
Tl-208	6.6E-17	6.1E-17	5.6E-17	[26]
Y-90	1.5E-18	1.4E-18	1.2E-18	[26]

[a] *Values for one year old infants are selected.*

[b] *Values for ten years old children are selected.*

Table A. 13. *Concentration factor for uptake of the radionuclide from soil by edible parts of crops for radionuclide i (F_v, Bq/kg plant tissue per Bq/kg dry soil) and equilibrium ratio of the concentration of radionuclide i in fish to its dissolved concentration in water, known as the bioaccumulation factor (B_{fish}, (Bq/kg)/(Bq/L)).*

Elements	F_v (Bq/kg)	Ref.	B_{fish} ((Bq/kg)/(Bq/L))	Ref.
Ac	1.0E-03	[17]	1.5E+02	[27]
Ag	1.0E-02	[17]	1.1E+02	[27]
Ba	5.0E-02	[17]	4.7E+01	[27]
Bi	1.0E-01	[17]	1.0E+01	[16]
Cd	5.0E-01	[17]	4.0E+02	[27]
Co	8.0E-02	[17]	4.0E+02	[27]
Cs	4.0E-02	[17]	3.0E+03	[27]
Gd	2.0E-03	[17]	a	
H	0.0E+00	[14]	1.0E+00	[28]
Hg	3.0E-01	[17]	a	
I	2.0E-02	[17]	6.5E+02	[27]
Lu	2.0E-03	[17]	1.6E+01	[27]
Na	5.0E-02	[17]	1.4E+02	[27]
Pb	2.0E-02	[17]	3.7E+02	[27]
Po	2.0E-03	[17]	3.6E+01	[27]
Pu	1.0E-03	[17]	2.4E+00	[27]

Elements	F_v (Bq/kg)	Ref.	B_{fish} ((Bq/kg)/(Bq/L))	Ref.
Ra	4.0E-02	[17]	2.1E+02	[27]
Rh	5.0E-02	[17]	1.4E+02	[27]
Ru	5.0E-02	[17]	1.4E+02	[27]
Sc	3.0E-03	[17]	9.3E+02	[27]
Sn	3.0E-01	[17]	3.7E+02	[27]
Sr	3.0E-01	[17]	[a]	
Tb	2.0E-03	[17]	7.5E+02	[27]
Th	1.0E-03	[17]	1.9E+02	[27]
Tl	2.0E+00	[17]	5.8E+02	[27]
Y	3.0E-03	[17]	[a]	

[a] *Isotope not used in surface water model, hence no value needed.*

B. Environmental Results Data

This appendix is focused on presenting the radionuclide behaviour in the environment. In the following sections the evolution of the isotopic concentration in the different compartments of the studied system are presented.

It is worth mentioning that this model has not been built to study in detail the behaviour and transport of radionuclides in the environment. In order to have a more detailed calculation on the transport of radionuclides in the media, more complex models, such as reactive transport models, should be applied. Those models not only consider decay and main physical processes like sorption via the Kd but also chemistry evolution or changes in physical properties of the media.

B.1 Continuous atmospheric emission

The concentration of all isotopes in the aqueous phase and sorbed into the soils in the first and the last year of the operational period is presented in Table B. 1. To better show the evolution of the concentration of these isotopes in the media, the evolution of the sorbed concentration of the main isotopes contributing to the dose during the operational period are represented in Figure B. 1. It can be observed that the concentration of all isotopes increases along the period, but this has not a significant impact to the environment. The differences observed in the evolution of each isotope is the results of the mix between all processes included in the model such as the transferences, sorption, decay, etc.

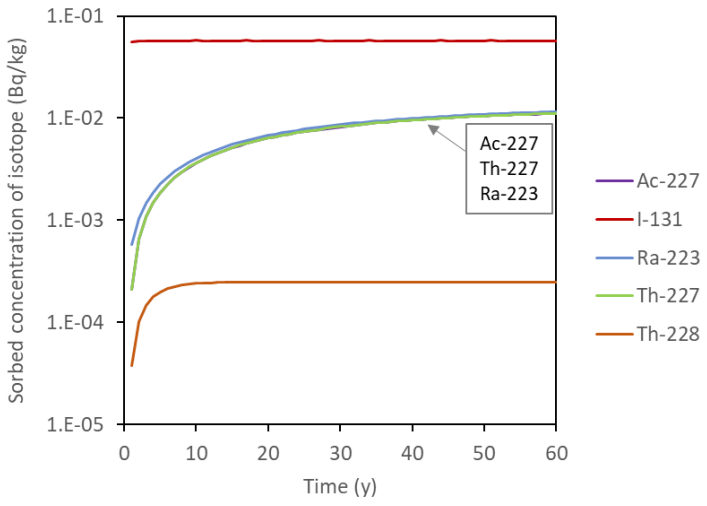

Figure B. 1. *Evolution of the concentration sorbed in the soils during the operational period under the continuous atmospheric emission scenario.*

Table B. 1 *Mean concentration values in top soil compartment for the first and last simulation year.*

Isotope	Top Soil 1			
	Aqueous concentration (Bq/m^3)		Sorbed concentration (Bq/kg)	
	Year 1	Year 60	Year 1	Year 60
Ac-227	1.2E-04	6.5E-03	2.1E-04	1.1E-02
Bi-211	7.6E-05	1.5E-03	5.8E-04	1.2E-02
Bi-212	4.8E-06	3.3E-05	3.7E-05	2.5E-04
I-131	5.0E-01	5.2E-01	5.5E-02	5.7E-02
Pb-211	5.2E-05	1.0E-03	5.8E-04	1.2E-02
Pb-212	3.3E-06	2.3E-05	3.7E-05	2.5E-04
Po-212	3.6E-06	2.4E-05	2.3E-05	1.6E-04
Po-215	8.7E-05	1.7E-03	5.8E-04	1.2E-02
Po-216	5.6E-06	3.8E-05	3.7E-05	2.5E-04
Ra-223	1.9E-04	3.8E-03	5.8E-04	1.2E-02
Ra-224	1.2E-05	8.3E-05	3.7E-05	2.5E-04
Rn-219	1.7E+00	3.3E+01	0.0E+00	0.0E+00
Rn-220	1.1E-01	7.2E-01	0.0E+00	0.0E+00
Th-227	3.4E-05	1.8E-03	2.1E-04	1.1E-02
Th-228	6.2E-06	4.1E-05	3.8E-05	2.5E-04
Tl-207	6.1E-05	1.2E-03	5.8E-04	1.2E-02
Tl-208	1.4E-06	9.5E-06	1.3E-05	8.9E-05

B.2 Total acute atmospheric emission

The concentration of all isotopes in the aqueous phase and sorbed into the soils in the first and the last year of the operational period is presented in Table B. 2. To better show the evolution of the concentration of these isotopes in the media, the sorbed concentration of the main isotopes contributing to the dose are represented in Figure B. 2. It can be observed that the concentration of all isotopes increases along the period, but this has not a significant impact to the environment. The evolution of each isotope is the mix between al processes included in the model such as the transferences, sorption, decay, etc.

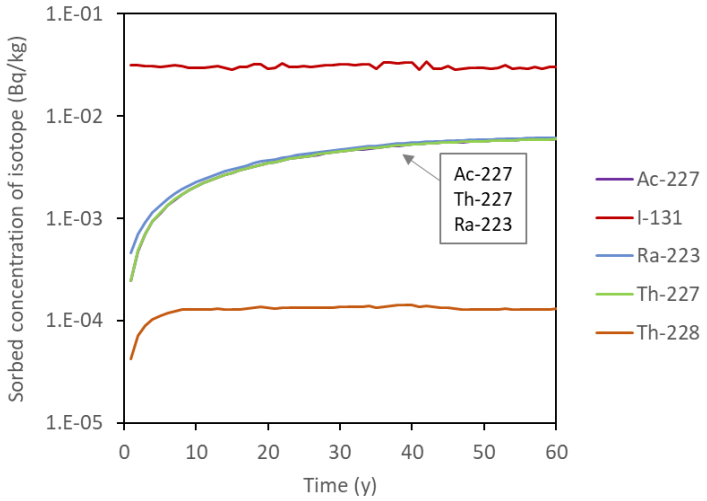

Figure B. 2. *Evolution of the concentration sorbed in the soils during the operational period under the continuous atmospheric emission scenario.*

Note that in the case of iodine, small differences are observed between years. This is the result of the data treatment. This graph presents the mean annual concentration of each isotope, but iodine has a short half live and the concentration decreases rapidly after the release day (see Figure B. 3). The same happens for Th-228 but the effect is lower.

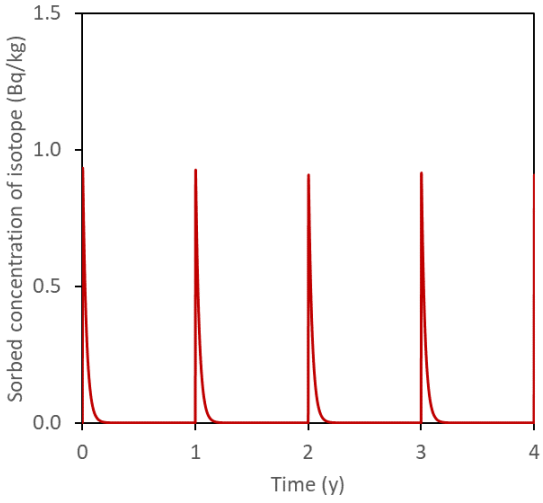

Figure B. 3. *Evolution of the I-131 concentration sorbed in the soils during the first 4 years of the operational period under the continuous atmospheric emission scenario.*

Table B. 2 *Mean concentration values in top soil compartment for the first and last simulation year.*

Isotope	Top Soil 1			
	Aqueous concentration (Bq/m^3)		Sorbed concentration (Bq/kg)	
	Year 1	Year 60	Year 1	Year 60
Ac-227	1.5E-04	3.5E-03	2.5E-04	6.0E-03
Bi-211	6.1E-05	8.1E-04	4.7E-04	6.2E-03
Bi-212	5.5E-06	1.7E-05	4.2E-05	1.3E-04
I-131	2.9E-01	2.8E-01	3.2E-02	3.0E-02
Pb-211	4.2E-05	5.6E-04	4.7E-04	6.2E-03
Pb-212	3.8E-06	1.2E-05	4.2E-05	1.3E-04
Po-212	4.0E-06	1.3E-05	2.7E-05	8.3E-05
Po-215	7.1E-05	9.4E-04	4.7E-04	6.2E-03
Po-216	6.3E-06	2.0E-05	4.2E-05	1.3E-04
Ra-223	1.6E-04	2.1E-03	4.7E-04	6.2E-03
Ra-224	1.4E-05	4.3E-05	4.2E-05	1.3E-04
Rn-219	1.3E+00	1.8E+01	0.0E+00	0.0E+00
Rn-220	1.2E-01	3.8E-01	0.0E+00	0.0E+00
Th-227	4.1E-05	9.8E-04	2.5E-04	6.0E-03
Th-228	6.9E-06	2.1E-05	4.2E-05	1.3E-04
Tl-207	5.0E-05	6.6E-04	4.7E-04	6.2E-03
Tl-208	1.6E-06	5.0E-06	1.5E-05	4.7E-05

B.3 Liquid discharges

The concentrations of all isotopes in the aqueous phase and sorbed into the soils the sediments as well as the concentration in the river in the first and the last year of the operational period are presented in several tables: Table B. 3 to Table B. 5. To better show the evolution of the concentration of these isotopes in the media, the sorbed concentration of the main isotopes contributing to the dose into soils and sediments are represented in Figure B. 4. It can be observed that the mean annual concentration of all isotopes are almost constant during the whole period. A slightly increase with no impact to the environment is observed in the case of Ra-223 in the bed sediments. The evolution of each isotope is the mix between all processes included in the model such as the transferences, sorption, decay, etc.

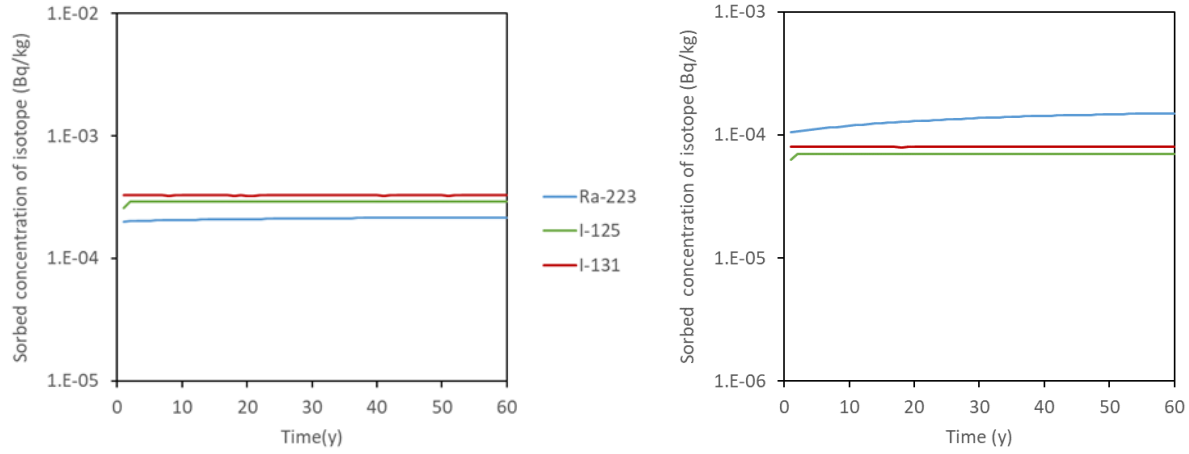

Figure B. 4. *Evolution of the concentration sorbed in the soils (left) and sediments (right) during the operational period under the continuous atmospheric emission scenario.*

Table B. 3 *Mean aqueous concentration (Bq/m^3) values in different compartments for the first and last simulation year.*

Isotope	Aqueous concentration (Bq/m^3)					
	Top Sediment 1		Top Sediment 2		Top Soil 2	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Ac-227	1.3E-08	5.2E-07	1.3E-08	5.2E-07	2.4E-07	9.2E-06
Bi-211	2.1E-05	3.0E-05	2.0E-05	2.9E-05	2.6E-05	2.9E-05
Bi-212	2.2E-05	1.1E-04	2.1E-05	1.1E-04	3.8E-06	1.8E-05
I-125	1.8E-04	2.0E-04	2.5E-04	2.8E-04	2.4E-03	2.6E-03
I-131	2.3E-04	2.3E-04	2.7E-04	2.7E-04	3.0E-03	3.0E-03
Lu-177	5.2E-06	5.2E-06	4.2E-06	4.2E-06	6.3E-05	6.3E-05
Lu-177m	1.9E-09	3.2E-09	2.0E-09	3.2E-09	2.3E-08	3.8E-08
Pb-211	7.1E-07	1.0E-06	6.7E-07	9.7E-07	1.8E-05	2.0E-05
Pb-212	7.3E-07	3.6E-06	7.1E-07	3.5E-06	2.7E-06	1.3E-05
Po-212	1.2E-06	6.1E-06	1.2E-06	6.1E-06	8.9E-05	4.3E-04
Po-215	1.9E-06	2.7E-06	1.8E-06	2.6E-06	9.5E-04	1.0E-03
Po-216	2.0E-06	9.5E-06	1.9E-06	9.5E-06	1.4E-04	6.6E-04
Ra-223	3.3E-05	4.7E-05	3.1E-05	4.5E-05	6.7E-05	7.2E-05
Ra-224	3.4E-05	1.7E-04	3.4E-05	1.7E-04	9.7E-06	4.7E-05
Rn-219	2.3E-01	3.3E-01	2.2E-01	3.2E-01	5.8E-01	6.3E-01

Isotope	Aqueous concentration (Bq/m³)					
	Top Sediment 1		Top Sediment 2		Top Soil 2	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Rn-220	2.4E-01	1.2E+00	2.4E-01	1.2E+00	8.4E-02	4.0E-01
Sc-46	5.3E-10	6.6E-10	5.3E-10	6.6E-10	7.0E-09	8.7E-09
Th-227	3.6E-08	2.5E-07	3.3E-08	2.5E-07	3.4E-07	2.8E-06
Th-228	5.3E-07	2.5E-06	5.2E-07	2.5E-06	4.8E-06	2.3E-05
Tl-207	7.1E-07	1.0E-06	6.7E-07	9.7E-07	2.1E-05	2.3E-05
Tl-208	2.6E-07	1.3E-06	2.6E-07	1.3E-06	1.1E-06	5.3E-06

Table B. 4 *Mean aqueous concentration (Bq/m³) in river compartments for the first and last simulation year.*

Isotope	Aqueous concentration (Bq/m³)			
	River 1		River 2	
	Year 1	Year 60	Year 1	Year 60
Ac-227	8.7E-05	8.8E-05	8.7E-05	8.7E-05
Bi-211	5.9E-01	5.9E-01	5.2E-01	5.2E-01
Bi-212	3.8E-03	3.8E-03	5.1E-03	5.1E-03
I-125	1.7E-01	1.7E-01	1.6E-01	1.7E-01
I-131	1.4E+00	1.4E+00	1.2E+00	1.2E+00
Lu-177	1.4E+00	1.4E+00	1.1E+00	1.1E+00
Lu-177m	3.5E-05	3.5E-05	3.4E-05	3.4E-05
Pb-211	5.9E-01	5.9E-01	5.2E-01	5.2E-01
Pb-212	3.8E-03	3.8E-03	5.1E-03	5.1E-03
Po-212	2.4E-03	2.4E-03	3.3E-03	3.3E-03
Po-215	6.0E-01	6.0E-01	5.2E-01	5.2E-01
Po-216	4.7E-03	4.7E-03	5.4E-03	5.4E-03
Ra-223	6.0E-01	6.0E-01	5.2E-01	5.2E-01
Ra-224	4.7E-03	4.7E-03	5.4E-03	5.4E-03
Rn-219	6.0E-01	6.0E-01	5.2E-01	5.2E-01
Rn-220	4.7E-03	4.7E-03	5.4E-03	5.4E-03
Sc-46	3.4E-05	3.4E-05	3.3E-05	3.3E-05
Th-227	3.2E-03	3.2E-03	2.9E-03	2.9E-03
Th-228	7.0E-03	7.0E-03	6.9E-03	6.9E-03

Isotope	Aqueous concentration (Bq/m³)			
	River 1		River 2	
	Year 1	Year 60	Year 1	Year 60
Tl-207	5.9E-01	5.9E-01	5.2E-01	5.2E-01
Tl-208	1.3E-03	1.3E-03	1.8E-03	1.8E-03

Table B. 5 *Mean sorbed concentration (Bq/kg) values in different compartments for the first and last simulation year.*

Isotope	Sorbed concentration (Bq/kg)					
	Top Sediment 1		Top Sediment 2		Top Soil 2	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Ac-227	1.1E-06	4.6E-05	1.1E-06	4.6E-05	4.2E-07	1.6E-05
Bi-211	1.1E-04	1.5E-04	1.0E-04	1.5E-04	2.0E-04	2.2E-04
Bi-212	1.1E-04	5.3E-04	1.1E-04	5.3E-04	2.9E-05	1.4E-04
I-125	6.3E-05	7.0E-05	8.8E-05	9.9E-05	2.6E-04	2.9E-04
I-131	8.0E-05	8.0E-05	9.5E-05	9.5E-05	3.3E-04	3.3E-04
Lu-177	4.6E-04	4.6E-04	3.7E-04	3.7E-04	2.6E-04	2.7E-04
Lu-177m	1.7E-07	2.8E-07	1.7E-07	2.8E-07	9.8E-08	1.6E-07
Pb-211	1.1E-04	1.5E-04	1.0E-04	1.5E-04	2.0E-04	2.2E-04
Pb-212	1.1E-04	5.3E-04	1.1E-04	5.3E-04	2.9E-05	1.4E-04
Po-212	7.0E-05	3.4E-04	6.9E-05	3.4E-04	1.9E-05	9.0E-05
Po-215	1.1E-04	1.5E-04	1.0E-04	1.5E-04	2.0E-04	2.2E-04
Po-216	1.1E-04	5.3E-04	1.1E-04	5.3E-04	2.9E-05	1.4E-04
Ra-223	1.1E-04	1.5E-04	1.0E-04	1.5E-04	2.0E-04	2.2E-04
Ra-224	1.1E-04	5.3E-04	1.1E-04	5.3E-04	2.9E-05	1.4E-04
Rn-219	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Rn-220	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Sc-46	1.2E-07	1.4E-07	1.2E-07	1.4E-07	6.7E-08	8.3E-08
Th-227	7.5E-06	5.2E-05	6.9E-06	5.2E-05	2.1E-06	1.7E-05
Th-228	1.1E-04	5.3E-04	1.1E-04	5.3E-04	2.9E-05	1.4E-04
Tl-207	1.1E-04	1.5E-04	1.0E-04	1.5E-04	2.0E-04	2.2E-04
Tl-208	3.9E-05	1.9E-04	3.8E-05	1.9E-04	1.0E-05	5.0E-05

C. Additional Results Data

This appendix is focused on presenting additional results than those presented in the report. It includes detailed results from the preliminary dose assessment carried out with the IRAT tool (see Appendix C.1), as well as the results from the AERMOD and Ecolego models (see Appendix C.2 and C.3, respectively).

Note that the isotopic concentration in different compartments of the environment obtained by Ecolego are presented in Appendix B.

C.1 Preliminary Dose Assessment

The following tables include the results from the preliminary dose assessment performed with the IRAT tool. Note that it is presented the contribution of each isotope in the selected exposure group scenario to the total dose. In each case, radionuclides selected for the detailed dose assessment in Ecolego are highlighted in bold.

Note that IRAT Tool has pre-defined scenarios that are not the same as those defined in this project, so that, slightly differences could be observed between the IRAT results and the results obtained with Ecolego.

Table C. 1. *IRAT results of isotope contribution to dose received from atmosphere. Isotopes highlighted in bold are those selected for the final assessment.*

Isotope	Contribution (%)	Isotope	Contribution (%)
I-131	**5.2E+01**	F-18	2.0E-02
Rn-222[a]	**3.1E+01**	Ac-225	2.0E-02
Ra-223[b]	**1.5E+01**	Lu-177	1.0E-02
Th-227[c]	**1.2E+00**	Pb-212	3.0E-04
Other alpha/gamma emitting nuclides[d]	**5.3E-01**	Zr-89	3.0E-06
Y-90	5.0E-02		

[a] *Rn-222 has been used to assess Rn-220 and Rn-219.*

[b] *Ra-223 has been used to assess Ra-223 and Ra-224.*

[c] *Other alpha/gamma emitting nuclides stands for Ac-227.*

[d] *Th-227 has been used to assess Th-227 and Th-228.*

Table C. 2. *IRAT results of isotope contribution to dose received from surface water based on angling family. Isotopes highlighted in bold are those selected for the final assessment.*

Isotope	Contribution (%)	Isotope	Contribution (%)
Ra-223[a]	**6.3E+01**	Other beta/gamma emitting nuclides[d]	2.0E-02
I-131	**3.1E+01**	Y-90	1.0E-02
Lu-177[b]	**3.7E+00**	Other alpha emitting nuclides[e]	1.0E-02
I-125	**1.1E+00**	Pb-212	1.0E-03
Th-227[c]	**2.6E-01**	Tc-99	4.0E-06
Ac-225	5.0E-02		

[a] *Ra-223 has been used to assess Ra-223 and Ra-224.*

[b] *Lu-177 has been used to assess Lu-177 and Lu-177m.*

[c] *Th-227 has been used to assess Th-227 and Th-228.*

[d] *Other beta/gamma emitting nuclides stands for Sc-46.*

[e] *Other alpha emitting nuclides stands for Ac-227.*

Table C. 3. *IRAT Results of isotope contribution to dose received from irrigated food. Isotopes highlighted in bold are those selected for the final assessment.*

Isotope	Contribution (%)	Isotope	Contribution (%)
Ra-223[a]	**6.7E+01**	Th-227[d]	1.0E-02
I-131	**3.1E+01**	Other alpha emitting nuclides[e]	5.0E-04
I-125	**1.4E+00**	Pb-212	2.0E-04
Lu-177[b]	9.0E-02	Tc-99	1.0E-04
Ac-225	2.0E-02	Y-90	0.0E+00
Other beta/gamma emitting nuclides[c]	1.0E-02		

[a] *Ra-223 has been used to assess Ra-223 and Ra-224.*

[b] *Lu-177 has been used to assess Lu-177 and Lu-177m.*

[c] *Other beta/gamma emitting nuclides stands for Sc-46.*

[d] *Th-227 has been used to assess Th-227 and Th-228.*

[e] *Other alpha emitting nuclides stands for Ac-227.*

C.2 Atmospheric dispersion model

This appendix provides the atmospheric concentration calculated with AERMOD. The maximum atmospheric concentration (Bq/m^3) on croplands and residential areas is presented.

For each location, values for the two different release scenarios are provided: a constant value for each month of the year in the case of a constant release, and a single value for the day of the release for the total acute release.

Table C. 4. *Maximum atmospheric concentration (Bq/m^3) over croplands area. A monthly value is provided for the continuous release, and a single value for the total acute release.*

Isotope	Maximum atmospheric concentration (Bq/m^3) - Croplands area Continuous release						
	Jan	Feb	Mar	Apr	May	Jun	July
Ac-227	5.7E-06	5.4E-06	3.5E-06	1.1E-06	4.3E-06	4.7E-06	1.7E-06
Th-227	5.7E-06	5.4E-06	3.5E-06	1.1E-06	4.3E-06	4.7E-06	1.7E-06
Ra-223	1.1E-04	1.1E-04	6.9E-05	2.2E-05	8.6E-05	9.3E-05	3.3E-05
I-131	2.3E-03	2.1E-03	1.4E-03	4.4E-04	1.7E-03	1.9E-03	6.7E-04
Th-228	1.1E-06	1.1E-06	6.9E-07	2.2E-07	8.6E-07	9.4E-07	3.4E-07
Ra-224	1.1E-07	1.1E-07	6.9E-08	2.2E-08	8.6E-08	9.4E-08	3.4E-08
Rn-220	9.1E-02	8.6E-02	5.5E-02	1.8E-02	6.9E-02	7.5E-02	2.7E-02
Rn-219	1.1E-02	1.1E-02	6.9E-03	2.2E-03	8.6E-03	9.4E-03	3.4E-03

Isotope	Continuous release					Total acute release
	Aug	Sept	Oct	Nov	Dec	
Ac-227	4.8E-06	5.4E-06	5.4E-06	6.8E-06	5.3E-06	8.8E-04
Th-227	4.8E-06	5.4E-06	5.4E-06	6.8E-06	5.3E-06	8.8E-04
Ra-223	9.6E-05	1.1E-04	1.1E-04	1.3E-04	1.0E-04	1.8E-02
I-131	1.9E-03	2.2E-03	2.2E-03	2.7E-03	2.1E-03	3.5E-01
Th-228	9.6E-07	1.1E-06	1.1E-06	1.4E-06	1.1E-06	1.8E-04
Ra-224	9.6E-08	1.1E-07	1.1E-07	1.4E-07	1.1E-07	1.8E-05
Rn-220	7.7E-02	8.7E-02	8.6E-02	1.1E-01	8.4E-02	8.8E+00
Rn-219	9.6E-03	1.1E-02	1.1E-02	1.4E-02	1.1E-02	1.1E+00

Table C. 5. *Maximum atmospheric concentration (Bq/m³) over residential area. A monthly value is provided for the continuous release, and a single value for the total acute release.*

Isotope	Maximum atmospheric concentration (Bq/m³) - Residential area Continuous release						
	Jan	Feb	Mar	Apr	May	Jun	July
Ac-227	7.7E-06	8.3E-06	7.1E-06	1.0E-05	7.8E-06	3.6E-06	5.4E-06
Th-227	7.7E-06	8.3E-06	7.1E-06	1.0E-05	7.8E-06	3.6E-06	5.4E-06
Ra-223	1.5E-04	1.7E-04	1.4E-04	2.0E-04	1.6E-04	7.2E-05	1.1E-04
I-131	3.1E-03	3.3E-03	2.8E-03	4.0E-03	3.1E-03	1.4E-03	2.2E-03
Th-228	1.5E-06	1.7E-06	1.4E-06	2.0E-06	1.6E-06	7.2E-07	1.1E-06
Ra-224	1.5E-07	1.7E-07	1.4E-07	2.0E-07	1.6E-07	7.2E-08	1.1E-07
Rn-220	1.2E-01	1.3E-01	1.1E-01	1.6E-01	1.2E-01	5.7E-02	8.7E-02
Rn-219	1.5E-02	1.7E-02	1.4E-02	2.0E-02	1.6E-02	7.2E-03	1.1E-02

Isotope	Continuous release					Total acute release
	Aug	Sept	Oct	Nov	Dec	
Ac-227	1.2E-05	6.8E-06	9.6E-06	7.5E-06	1.1E-05	5.5E-04
Th-227	1.2E-05	6.8E-06	9.6E-06	7.5E-06	1.1E-05	5.5E-04
Ra-223	2.4E-04	1.4E-04	1.9E-04	1.5E-04	2.2E-04	1.1E-02
I-131	4.7E-03	2.7E-03	3.8E-03	3.0E-03	4.3E-03	2.2E-01
Th-228	2.4E-06	1.4E-06	1.9E-06	1.5E-06	2.2E-06	1.1E-04
Ra-224	2.4E-07	1.4E-07	1.9E-07	1.5E-07	2.2E-07	1.1E-05
Rn-220	1.9E-01	1.1E-01	1.5E-01	1.2E-01	1.7E-01	8.8E+00
Rn-219	2.4E-02	1.4E-02	1.9E-02	1.5E-02	2.2E-02	1.1E+00

C.3 Dose Assessment

This section contains the detailed results of the three different radionuclide release scenarios. For each scenario and reference group, a table including the annual dose estimated for the last year of operation due to the exposure to each radionuclide and each exposure pathway is presented.

Each table also provides the total dose received to the exposure of each nuclide through all pathways, the dose due to the exposure to each exposure pathway considering the contribution of all isotopes and the total dose received is also presented.

C.3.1 Continuous atmospheric emission

Table C. 6. *Total dose received per pathway and isotope during the last simulation year for infants.*

Isotope	Exposure pathway dose - Infants (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	4.7E-11	1.4E+00	3.1E-01	7.8E-09	1.3E-03	1.7E+00
Bi-211	0.0E+00	0.0E+00	0.0E+00	3.8E-06	3.5E-08	3.8E-06
Bi-212	0.0E+00	0.0E+00	0.0E+00	2.3E-07	1.6E-08	2.5E-07
I-131	7.3E-04	2.0E-01	8.2E+00	1.6E-04	3.8E-04	8.4E+00
Pb-211	0.0E+00	0.0E+00	0.0E+00	7.2E-06	5.9E-07	7.8E-06
Pb-212	0.0E+00	0.0E+00	4.3E-15	2.4E-07	5.7E-07	8.1E-07
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	0.0E+00	0.0E+00	1.4E-08	0.0E+00	1.4E-08
Po-216	0.0E+00	0.0E+00	0.0E+00	2.6E-11	0.0E+00	2.6E-11
Ra-223	1.2E-05	2.9E+00	4.5E-01	1.0E-05	4.6E-04	3.4E+00
Ra-224	9.7E-10	1.3E-03	4.1E-05	1.8E-08	6.0E-06	1.4E-03
Rn-219	5.5E-04	6.0E-03	0.0E+00	4.7E-06	0.0E+00	6.6E-03
Rn-220	4.8E-05	2.0E-02	0.0E+00	1.1E-09	0.0E+00	2.0E-02
Th-227	5.6E-07	2.1E-01	2.5E-03	9.1E-06	2.8E-05	2.1E-01
Th-228	1.8E-09	1.5E-01	7.2E-03	3.1E-09	3.4E-06	1.6E-01
Tl-207	0.0E+00	0.0E+00	0.0E+00	2.5E-06	2.1E-08	2.5E-06
Tl-208	0.0E+00	0.0E+00	0.0E+00	1.9E-06	1.7E-10	1.9E-06
Total dose per pathway	1.3E-03	4.8E+00	9.E+00	2.0E-04	2.1E-03	**1.4E+01**

Table C. 7. *Total dose received per pathway and isotope during the last simulation year for children.*

Isotope	Exposure pathway - Children (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	4.2E-11	1.5E+00	3.0E-01	6.8E-09	3.0E-04	1.8E+00
Bi-211	0.0E+00	0.0E+00	0.0E+00	3.4E-06	4.8E-09	3.4E-06
Bi-212	0.0E+00	0.0E+00	0.0E+00	2.1E-07	2.3E-09	2.1E-07
I-131	6.6E-04	1.3E-01	4.8E+00	1.4E-04	5.4E-05	4.9E+00

Isotope	Exposure pathway - Children (µSv/y)					
Pb-211	0.0E+00	0.0E+00	0.0E+00	6.5E-06	8.6E-08	6.6E-06
Pb-212	0.0E+00	0.0E+00	2.7E-15	2.1E-07	9.1E-08	3.0E-07
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	0.0E+00	0.0E+00	1.3E-08	0.0E+00	1.3E-08
Po-216	0.0E+00	0.0E+00	0.0E+00	2.4E-11	0.0E+00	2.4E-11
Ra-223	1.1E-05	3.2E+00	3.7E-01	9.1E-06	9.5E-05	3.6E+00
Ra-224	8.5E-10	1.5E-03	3.2E-05	1.6E-08	1.2E-06	1.5E-03
Rn-219	4.9E-04	1.5E-02	0.0E+00	4.2E-06	0.0E+00	1.5E-02
Rn-220	4.3E-05	5.1E-02	0.0E+00	9.8E-10	0.0E+00	5.1E-02
Th-227	4.9E-07	2.5E-01	1.7E-03	8.1E-06	4.7E-06	2.5E-01
Th-228	1.6E-09	1.6E-01	5.4E-03	2.8E-09	6.3E-07	1.7E-01
Tl-207	0.0E+00	0.0E+00	0.0E+00	2.3E-06	2.7E-09	2.3E-06
Tl-208	0.0E+00	0.0E+00	0.0E+00	1.8E-06	2.4E-11	1.8E-06
Total dose per pathway	1.2E-03	5.3E+00	5.4E+00	1.8E-04	4.6E-04	**1.1E+01**

Table C. 8. *Total dose received per pathway and isotope during the last simulation year for adults.*

Isotope	Exposure pathway dose - Adults (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	9.8E-08	2.0E+00	3.4E-01	9.8E-08	1.8E-04	2.3E+00
Bi-211	5.1E-05	0.0E+00	0.0E+00	5.1E-05	2.0E-09	1.0E-04
Bi-212	3.3E-06	0.0E+00	0.0E+00	3.3E-06	9.4E-10	6.6E-06
I-131	2.1E-03	8.2E-02	3.1E+00	2.1E-03	1.8E-05	3.2E+00
Pb-211	1.0E-04	0.0E+00	0.0E+00	1.0E-04	3.0E-08	2.0E-04
Pb-212	3.2E-06	0.0E+00	1.3E-15	3.2E-06	2.2E-08	6.4E-06
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	2.0E-07	0.0E+00	0.0E+00	2.0E-07	0.0E+00	4.0E-07
Po-216	3.7E-10	0.0E+00	0.0E+00	3.7E-10	0.0E+00	7.4E-10
Ra-223	1.4E-04	2.2E+00	1.3E-01	1.4E-04	1.7E-05	2.3E+00
Ra-224	2.4E-07	1.9E-03	1.3E-05	2.4E-07	2.4E-07	1.9E-03
Rn-219	6.4E-05	2.4E-02	0.0E+00	6.4E-05	0.0E+00	2.4E-02
Rn-220	1.5E-08	8.0E-02	0.0E+00	1.5E-08	0.0E+00	8.0E-02

Isotope	Exposure pathway dose - Adults (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Th-227	1.2E-04	2.8E-01	9.9E-04	1.2E-04	1.4E-06	2.8E-01
Th-228	4.1E-08	1.8E-01	4.3E-03	4.1E-08	2.6E-07	1.8E-01
Tl-207	3.6E-05	0.0E+00	0.0E+00	3.6E-05	1.2E-09	7.2E-05
Tl-208	2.8E-05	0.0E+00	0.0E+00	2.8E-05	1.1E-11	5.6E-05
Total dose per pathway	2.7E-03	4.8E+00	3.6E+00	2.7E-03	2.2E-04	**8.4E+00**

C.3.2 Total acute atmospheric emission

Table C. 9. *Total dose received per pathway and isotope during the last simulation year for infants.*

Isotope	Exposure pathway dose - Infants (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	9.1E-12	2.6E-01	1.7E-01	4.2E-09	6.7E-04	4.3E-01
Bi-211	0.0E+00	0.0E+00	0.0E+00	2.0E-06	1.9E-08	2.0E-06
Bi-212	0.0E+00	0.0E+00	0.0E+00	1.2E-07	8.6E-09	1.3E-07
I-131	1.4E-04	3.7E-02	4.4E+00	8.2E-05	2.0E-04	4.4E+00
Pb-211	0.0E+00	0.0E+00	0.0E+00	3.9E-06	3.2E-07	4.2E-06
Pb-212	0.0E+00	0.0E+00	2.3E-15	1.3E-07	3.0E-07	4.3E-07
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	0.0E+00	0.0E+00	7.6E-09	0.0E+00	7.6E-09
Po-216	0.0E+00	0.0E+00	0.0E+00	1.4E-11	0.0E+00	1.4E-11
Ra-223	2.4E-06	5.5E-01	2.4E-01	5.5E-06	2.5E-04	7.9E-01
Ra-224	1.9E-10	2.4E-04	2.2E-05	9.2E-09	3.1E-06	2.7E-04
Rn-219	1.0E-04	1.1E-03	0.0E+00	2.5E-06	0.0E+00	1.2E-03
Rn-220	9.0E-06	3.7E-03	0.0E+00	5.7E-10	0.0E+00	3.7E-03
Th-227	1.1E-07	3.9E-02	1.3E-03	4.9E-06	1.5E-05	4.0E-02
Th-228	3.5E-10	2.9E-02	3.8E-03	1.6E-09	1.8E-06	3.3E-02
Tl-207	0.0E+00	0.0E+00	0.0E+00	1.4E-06	1.1E-08	1.4E-06
Tl-208	0.0E+00	0.0E+00	0.0E+00	1.0E-06	8.9E-11	1.0E-06
Total dose per pathway	2.5E-04	9.2E-01	4.8E+00	1.0E-04	1.1E-03	**5.7E+00**

Table C. 10. *Total dose received per pathway and isotope during the last simulation year for children.*

Isotope	Exposure pathway dose - Children (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	8.2E-12	2.9E-01	1.6E-01	3.7E-09	1.6E-04	4.5E-01
Bi-211	0.0E+00	0.0E+00	0.0E+00	1.8E-06	2.6E-09	1.8E-06
Bi-212	0.0E+00	0.0E+00	0.0E+00	1.1E-07	1.2E-09	1.1E-07
I-131	1.2E-04	2.5E-02	2.5E+00	7.4E-05	2.9E-05	2.5E+00
Pb-211	0.0E+00	0.0E+00	0.0E+00	3.5E-06	4.6E-08	3.5E-06
Pb-212	0.0E+00	0.0E+00	1.4E-15	1.1E-07	4.8E-08	1.6E-07
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	0.0E+00	0.0E+00	6.8E-09	0.0E+00	6.8E-09
Po-216	0.0E+00	0.0E+00	0.0E+00	1.2E-11	0.0E+00	1.2E-11
Ra-223	2.1E-06	6.0E-01	2.0E-01	4.9E-06	5.1E-05	8.0E-01
Ra-224	1.6E-10	2.9E-04	1.7E-05	8.3E-09	6.2E-07	3.1E-04
Rn-219	9.2E-05	2.9E-03	0.0E+00	2.2E-06	0.0E+00	3.0E-03
Rn-220	8.1E-06	9.5E-03	0.0E+00	5.1E-10	0.0E+00	9.5E-03
Th-227	9.4E-08	4.7E-02	8.9E-04	4.4E-06	2.5E-06	4.8E-02
Th-228	3.0E-10	3.1E-02	2.9E-03	1.4E-09	3.3E-07	3.4E-02
Tl-207	0.0E+00	0.0E+00	0.0E+00	1.2E-06	1.5E-09	1.2E-06
Tl-208	0.0E+00	0.0E+00	0.0E+00	9.4E-07	1.3E-11	9.4E-07
Total dose per pathway	2.3E-04	1.0E+00	2.9E+00	9.3E-05	2.5E-04	**3.9E+00**

Table C. 11. *Total dose received per pathway and isotope during the last simulation year for adult.*

Isotope	Exposure pathway dose - Adult (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Ac-227	1.1E-11	6.2E-01	1.8E-01	5.3E-08	9.6E-05	8.0E-01
Bi-211	0.0E+00	0.0E+00	0.0E+00	2.8E-05	1.1E-09	2.8E-05
Bi-212	0.0E+00	0.0E+00	0.0E+00	1.7E-06	5.0E-10	1.7E-06
I-131	1.7E-04	2.5E-02	1.7E+00	1.1E-03	9.7E-06	1.7E+00
Pb-211	0.0E+00	0.0E+00	0.0E+00	5.4E-05	1.6E-08	5.4E-05
Pb-212	0.0E+00	0.0E+00	6.7E-16	1.7E-06	1.1E-08	1.7E-06

Isotope	Exposure pathway dose - Adult (µSv/y)					
	Plume immersion	Inhalation	Ing. Crops	Ext. irradiation	Inad. Ingestion	Total dose per isotope
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	0.0E+00	0.0E+00	1.0E-07	0.0E+00	1.0E-07
Po-216	0.0E+00	0.0E+00	0.0E+00	1.9E-10	0.0E+00	1.9E-10
Ra-223	2.7E-06	6.9E-01	6.9E-02	7.4E-05	9.0E-06	7.6E-01
Ra-224	2.2E-10	5.9E-04	6.7E-06	1.3E-07	1.2E-07	6.0E-04
Rn-219	9.9E-05	5.8E-03	0.0E+00	3.4E-05	0.0E+00	5.9E-03
Rn-220	8.8E-06	1.9E-02	0.0E+00	7.9E-09	0.0E+00	1.9E-02
Th-227	1.2E-07	8.7E-02	5.3E-04	6.6E-05	7.7E-07	8.8E-02
Th-228	3.7E-10	5.5E-02	2.3E-03	2.2E-08	1.4E-07	5.7E-02
Tl-207	0.0E+00	0.0E+00	0.0E+00	1.9E-05	6.4E-10	1.9E-05
Tl-208	0.0E+00	0.0E+00	0.0E+00	1.5E-05	5.9E-12	1.5E-05
Total dose per pathway	2.8E-04	1.5E+00	1.9E+00	1.4E-03	1.2E-04	**3.4E+00**

C.3.3 Liquid discharges

Table C. 12. *Total dose received per pathway and isotope during the last simulation year for infants.*

Isotope	Exposure pathway dose - Infants (µSv/y)					
	Fish ingestion	Boating	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Ac-227	2.0E-05	3.1E-21	3.1E-05	1.8E-06	1.1E-11	5.3E-05
Bi-211	2.5E-07	9.4E-15	0.0E+00	6.6E-10	7.1E-08	3.2E-07
Bi-212	3.4E-08	1.5E-16	5.8E-107	9.2E-09	1.3E-07	1.7E-07
I-125	3.1E-03	6.4E-16	7.3E-04	6.1E-07	1.1E-08	3.9E-03
I-131	8.3E-02	1.8E-13	3.1E-03	2.2E-06	8.9E-07	8.6E-02
Lu-177	4.2E-05	1.5E-14	4.5E-05	3.8E-08	6.9E-08	8.8E-05
Lu-177m	3.0E-09	1.1E-17	3.5E-08	6.4E-11	1.1E-09	4.0E-08
Pb-211	1.5E-04	1.4E-14	2.6E-175	1.1E-08	1.4E-07	1.5E-04
Pb-212	8.5E-05	1.8E-16	5.1E-15	6.1E-07	1.3E-07	8.6E-05
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	3.6E-17	0.0E+00	0.0E+00	2.7E-10	2.7E-10

Isotope	Exposure pathway dose - Infants (µSv/y)					
	Fish ingestion	Boating	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Po-216	0.0E+00	2.6E-20	0.0E+00	0.0E+00	1.5E-11	1.5E-11
Ra-223	6.9E-02	2.7E-14	1.4E-02	8.7E-06	1.9E-07	8.4E-02
Ra-224	3.3E-04	1.6E-17	1.7E-05	3.4E-06	9.9E-09	3.5E-04
Rn-219	0.0E+00	1.2E-14	0.0E+00	0.0E+00	8.7E-08	8.7E-08
Rn-220	0.0E+00	1.0E-18	0.0E+00	0.0E+00	6.2E-10	6.2E-10
Sc-46	1.3E-07	2.5E-17	2.2E-08	2.4E-11	1.1E-09	1.5E-07
Th-227	2.1E-05	1.3E-16	8.4E-06	4.4E-08	1.4E-08	3.0E-05
Th-228	2.5E-04	4.6E-18	2.7E-04	1.9E-06	1.7E-09	5.1E-04
Tl-207	8.4E-06	1.3E-15	0.0E+00	3.9E-10	4.8E-08	8.5E-06
Tl-208	2.0E-08	1.7E-15	0.0E+00	9.5E-11	1.1E-06	1.1E-06
Total dose per pathway	1.6E-01	2.7E-13	1.9E-02	1.9E-05	2.9E-06	**1.7E-01**

Table C. 13. *Total dose received per pathway and isotope during the last simulation year for children.*

Isotope	Exposure pathway dose - Children (µSv/y)					
	Fish ingestion	Boating	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Ac-227	2.0E-05	2.5E-21	3.0E-05	4.3E-07	9.6E-12	5.0E-05
Bi-211	1.4E-07	8.2E-15	0.0E+00	9.1E-11	6.3E-08	2.0E-07
Bi-212	1.9E-08	1.3E-16	3.2E-107	1.3E-09	1.2E-07	1.4E-07
I-125	3.4E-03	4.8E-16	8.0E-04	1.6E-07	7.3E-09	4.2E-03
I-131	4.8E-02	1.6E-13	1.8E-03	3.1E-07	8.0E-07	5.0E-02
Lu-177	2.6E-05	1.3E-14	2.8E-05	5.8E-09	6.1E-08	5.4E-05
Lu-177m	2.0E-09	9.7E-18	2.3E-08	1.1E-11	9.5E-10	2.6E-08
Pb-211	9.0E-05	1.3E-14	1.5E-175	1.6E-09	1.2E-07	9.0E-05
Pb-212	5.0E-05	1.5E-16	3.0E-15	8.9E-08	1.2E-07	5.0E-05
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	3.2E-17	0.0E+00	0.0E+00	2.4E-10	2.4E-10
Po-216	0.0E+00	2.3E-20	0.0E+00	0.0E+00	1.3E-11	1.3E-11
Ra-223	5.7E-02	2.2E-14	1.2E-02	1.8E-06	1.7E-07	6.8E-02
Ra-224	2.6E-04	1.4E-17	1.3E-05	6.6E-07	8.9E-09	2.7E-04

Isotope	Exposure pathway dose - Children (μSv/y)					
	Fish ingestion	Boating	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Rn-219	0.0E+00	1.0E-14	0.0E+00	0.0E+00	7.8E-08	7.8E-08
Rn-220	0.0E+00	9.2E-19	0.0E+00	0.0E+00	5.5E-10	5.5E-10
Sc-46	9.2E-08	2.3E-17	1.6E-08	4.4E-12	1.0E-09	1.1E-07
Th-227	1.4E-05	1.1E-16	5.5E-06	7.3E-09	1.3E-08	1.9E-05
Th-228	1.9E-04	3.7E-18	2.0E-04	3.6E-07	1.5E-09	3.9E-04
Tl-207	4.5E-06	1.2E-15	0.0E+00	5.1E-11	4.4E-08	4.5E-06
Tl-208	1.2E-08	1.6E-15	0.0E+00	1.4E-11	1.0E-06	1.0E-06
Total dose per pathway	1.1E-01	2.3E-13	1.5E-02	3.8E-06	2.6E-06	**1.2E-01**

Table C. 14. *Total dose received per pathway and isotope during the last simulation year for adults.*

Isotope	Exposure pathway dose -Adults (μSv/y)						
	Fish ingestion	Boating	Swimming	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Ac-227	2.2E-05	1.8E-21	8.3E-22	3.4E-05	2.5E-07	1.4E-10	5.6E-05
Bi-211	1.1E-07	7.2E-15	3.3E-15	0.0E+00	3.8E-11	9.7E-07	1.1E-06
Bi-212	1.5E-08	1.2E-16	5.4E-17	2.6E-107	5.3E-10	1.9E-06	1.9E-06
I-125	2.5E-03	3.5E-16	1.6E-16	6.1E-04	6.4E-08	8.7E-08	3.1E-03
I-131	3.0E-02	1.4E-13	6.5E-14	1.2E-03	1.1E-07	1.2E-05	3.1E-02
Lu-177	1.7E-05	1.1E-14	5.2E-15	1.9E-05	2.1E-09	9.3E-07	3.8E-05
Lu-177m	1.4E-09	8.5E-18	3.9E-18	1.7E-08	4.0E-12	1.4E-08	3.3E-08
Pb-211	5.9E-05	1.1E-14	5.1E-15	1.1E-175	5.7E-10	1.9E-06	6.1E-05
Pb-212	3.8E-05	1.3E-16	6.1E-17	2.4E-15	3.7E-08	1.8E-06	4.0E-05
Po-212	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Po-215	0.0E+00	2.8E-17	1.3E-17	0.0E+00	0.0E+00	3.7E-09	3.7E-09
Po-216	0.0E+00	2.1E-20	9.4E-21	0.0E+00	0.0E+00	2.1E-10	2.1E-10
Ra-223	1.9E-02	2.0E-14	9.0E-15	4.1E-03	3.2E-07	2.6E-06	2.3E-02
Ra-224	9.7E-05	1.2E-17	5.6E-18	5.2E-06	1.3E-07	1.3E-07	1.0E-04
Rn-219	0.0E+00	9.0E-15	4.1E-15	0.0E+00	0.0E+00	1.2E-06	1.2E-06
Rn-220	0.0E+00	8.1E-19	3.7E-19	0.0E+00	0.0E+00	8.5E-09	8.5E-09

Isotope	Exposure pathway dose -Adults (μSv/y)						
	Fish ingestion	Boating	Swimming	Ing. Crops	Inad. Ingestion	External irradiation	Total dose per isotope
Sc-46	7.2E-08	2.0E-17	9.3E-18	1.3E-08	1.8E-12	1.6E-08	1.0E-07
Th-227	8.0E-06	9.5E-17	4.3E-17	3.3E-06	2.2E-09	1.9E-07	1.1E-05
Th-228	1.4E-04	3.2E-18	1.5E-18	1.6E-04	1.5E-07	2.3E-08	3.1E-04
Tl-207	3.7E-06	1.1E-15	5.1E-16	0.0E+00	2.2E-11	6.8E-07	4.3E-06
Tl-208	1.0E-08	1.4E-15	6.6E-16	0.0E+00	6.3E-12	1.6E-05	1.6E-05
Total dose per pathway	5.2E-02	2.0E-13	9.3E-14	6.1E-03	1.1E-06	4.0E-05	**5.8E-02**