KONSTANTINOS THEOTOKIS FLOUDAS

SCHOOL OF MECHANICAL ENGINEERING

Computational Assessment of Radiological Impacts from Near-Surface Disposal of Radioactive Waste

Sector: Nuclear Technology

Supervisor: Dimitrios Mitrakos, Assistant Professor NTUA

Athens 2022

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Konstantinos Theotokis Floudas

Many thanks to my professor, Dr. Dimitris Mitrakos for his continuous support, patience and our pleasant collaboration throughout this experience, to my family, which supports me every step of the way and to my friends, who take up the fight beside me.

Contents

1. Introduction – Thesis Organosis

Radioactivity is usually intertwined with nuclear power generation. The use of radioactivity, however, finds applications in many modern activities, even in non-nuclear countries. Fields of nuclear medicine utilize different types of radiation to either for diagnostic tests, or for treatment purposes(e.g. use of radiopharmaceuticals, radiation therapy). The nuclear research that takes place every day in research centres and universities contributes more and more to the familiarity of the public opinion with the term “radioactivity”, while adding small pebbles to the hill of humanity’s knowledge on the subject that only about 100 years ago began to bloom. For the sake of context, during the process of mining of Rare Earth Elements(REE), amounts of radioactive elements such as Uranium(U) and Thorium(Th) are produced. However, as far the country of Greece is concerned, the only nuclear installation is the National Centre for Scientific Research(NCSR) Demokritos, which is currently out of operation.
The aforementioned activities, along with many others, usually result in the production of radioactive waste(RW).

According to international standards(IAEA-Date of the Standard), RW is classified into classes based on their activity and half-life(Image 1):

- **Low-Level Waste/LLW**
  Waste and Components that contain small amounts of mainly short-lived radionuclides.
- **Intermediate-Level Waste/ILW**
  Components that contain higher amounts of radioactivity and need to be shielded and placed at greater depths(10m-60m)
- **High-Level Waste/HLW**
  They result from fission in a nuclear reactor. They contain the so-called fission products and superuranium elements produced in the reactor core, are highly radioactive and hot due to the heat of decay. They require careful cooling and handling. They are typically intended for geological disposal at great depths(some hundreds meters).

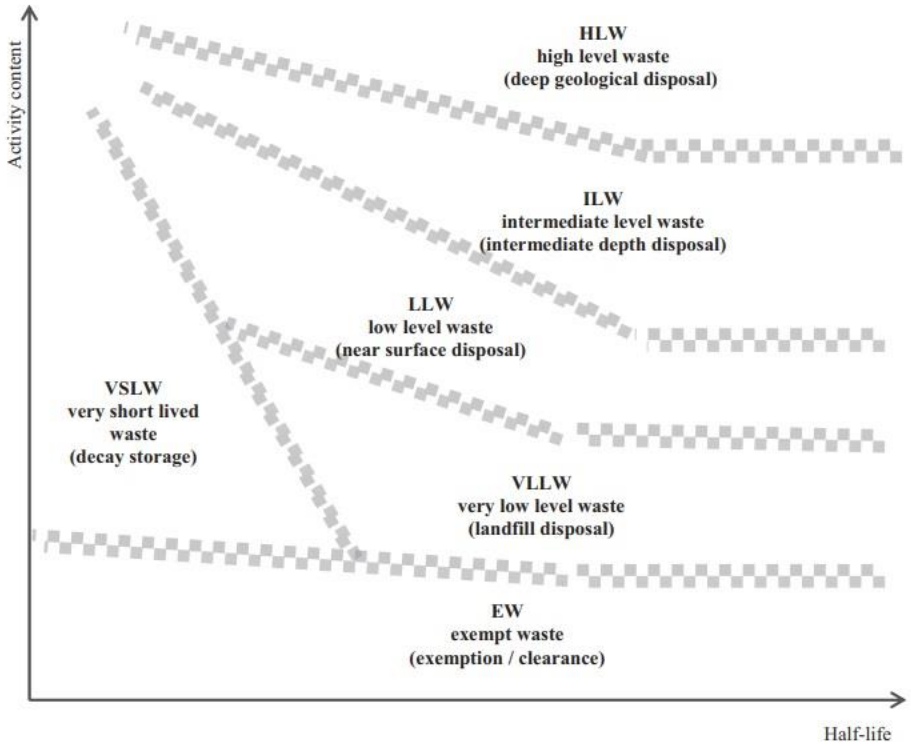


Image 1: Classification of Radioactive Waste in respect to their half-life

Radioactive waste, due to the danger it poses to human health and the environment, needs immediate short-term management by its respective producer, or long-term and organized management in special facilities approved by the State. According to international standards, the final management of radioactive waste can be done in two ways:

- By **Release into the environment**, as long as the statutory limitations are met. In the country of Greece, those limitations are defined in the Radiation Protection Regulations(p.d. 101/2018). These limitations have been established based on the annual radiation dose received by any individual due to exposition to the release facility. The annual radiation dose cannot exceed 10μSv. For the sake of completeness, the dose received by a person from all practical ionizing radiations per year should not exceed 1mSv.
- By **Deposition** in an approved facility. There are several types of Radioactive Waste Deposition Facilities, as in e.g. land field disposal, near surface disposal, deep geological disposal etc. The choice of the type of facility depends on a multitude of factors, such as the quantity and class of radioactive waste, its classification on the short-term-long-term scale, the set of procedures that have preceded the disposal, the environmental conditions expected to be

encountered by such a facility, the availability of premises and their location in relation to residential areas etc.

In Greece, there are no facilities for recycling radioactive waste, therefore our country is forced to send its radioactive waste to other EU countries, where the process of their treatment and ultimately their recycling can take place. In a more general context, according to the Directive 2011/70/Euratom, each EU member state must undertake the management of radioactive waste produced within its territory. Furthermore, the Greek state has the obligation to manage the radioactive waste produced by activities within the country and are under its jurisdiction, in accordance with the basic principles of "National Policy", as described in article 4 of the p.d. 122/2013, as amended and in force(see relevant informal codification of the two p.d.), and the National Program, as published in the Official Gazette 4317/B/02.10.2020.

Based on the IAEA standards, the management of radioactive waste can include several stages and procedures, such as:

i. **Planning and Preparation**

ii. **Waste Treatment**
It usually takes place shortly after the waste is generated. Treatment techniques vary depending on the type of waste and the intended disposal site. Examples of such techniques are disinfection, shredding, compression, drying and solidification of waste.

iii. **Packaging**
Most radioactive waste requires packaging in specially designed containers for their safe storage and disposal. It also allows for easier handling and transport.

iv. **Storage**
Interim storage facilities house specific types of waste until a suitable disposal site becomes available. Storage duration can vary from a few months to many decades.

v. **Disposal**
Disposal refers to the placement of waste after its storage in specially designed locations, where it will remain permanently.

After the processing and packaging stages, the waste can be disposed of. In general, the concentration, containment and isolation of radioactive waste from the biosphere is the accepted management strategy for most of it. Containment and isolation can be achieved through a series of supplementary safety barriers, e.g. based on the form of water, waste receptacles, other construction features related to the design of the facility and the local

environment. Each of these parameters can contribute to preventing the release of radionuclides from the waste, as well as limiting the release of radioactive elements from the facility into the environment.

It was mentioned, therefore, that the final stage of radioactive waste management is its disposal, i.e. its burial in specially designed facilities, in order to minimize the dose that will be received by both the population and the elements flora and fauna that live in the wider area. Disposal comes in a variety of forms, each of which presents significant advantages and disadvantages, always depending on the other factors surrounding the problem of radioactive waste to be managed. However, the types that are used more often are the following:

- **Near-surface disposal**
- **Deep geological disposal**

In more detail, Near-Surface Disposal refers to the placement of solid/solidified radioactive waste containing mainly radionuclides in a disposal facility located on or near the ground surface. The depth chosen for disposal and the type of facility to be developed depends on a number of factors, such as the nature and properties of the waste, as well as the local environment conditions at the proposed site. An important feature of near-surface disposal is the potential need to maintain institutional control of the site for a time period after its closure and sealing, due to the risk of disturbance of the facility and its contents by human activities. However, as stated in the IAEA Technical Document IAEA-TECDOC1097, ”The long-term safety of a radioactive waste disposal facility is required not to be dependent on active institutional control”.

Also, according to a publication of the Radioactive Waste Management Committee(RWMC) of the Nuclear Energy Agency in 2008(NEA-2008), a geological disposal system provides a unique level and time ceiling of protection for great concentrations of long-living radioactive waste . This concept exploits the potential of both the local geology and the available technical materials, in order to satisfy specific safety functions in a complementary way, providing multiple safety layers. The vast majority of scientific opinions worldwide agrees that geological disposal is technologically feasible and sustainable. This opinion is supported by the experimental data that has been collected and accumulated for various geological formations around the world and a wide variety of technical materials from investigations on the surface of the Earth, from underground research facilities, from the current situation to modelling techniques that can simplify the analysis and solving the problem of radioactive waste management, by the experience in operating underground repositories for other categories of waste(e.g. chemical waste) and, also, by advances in conducting safety assessments of potential disposal systems.

More specifically, for near-surface disposal at ground level, or at a depth of a few tens of meters, mainly LLW and/or ILW are available. It has been implemented for LLW in many countries, including the Czech Republic, Finland, France, Japan, the Netherlands, Spain, Sweden, the UK and the USA. For ILW, it has been applied individually in Finland and Sweden, near the Earth's surface due to favourable geological features.

For deep geological disposal(at depths between 250 and 1000 meters for mined deposits, or at depths of 2000 to 5000 meters for drilling), long-lived ILW and HLW(including spent fuel) are applied. Most countries have explored deep geological disposal and it is official policy in several countries of the world. In Finland, a deep geological disposal facility is under construction and is expected to start operating in 2023. In addition, the processes of selecting a suitable site for the installation of a geological repository have already started in the UK and Canada.

There is no nuclear waste in Greece, due to the lack of applications that could generate it(e.g. nuclear reactors). There is, however, production of small amounts of radioactive waste that need proper management.

In Greece, radioactive waste can be generated mainly through applications in the fields of medicine, research and industry. In their majority, this waste is very short-lived(VSLW), very low-level(VLLW) or low-level(LLW). A great part of the waste, after a relatively short storage time space, ceases to exceed the release limits and its release into the environment is now safe and feasible.

Nevertheless, in addition to the aforementioned, radioactive waste can be produced in such a way, that it cannot be disposed of through the release process in the environment, and requires other types of management. Characteristic examples are:

- Radioactive waste LLW/VLLW, which is produced during the stripping of the lightning rods or due to applications in research or medical laboratories(e.g. radioactively contaminated equipment or contaminated tools)
- Radioactive waste that may be generated during the decommissioning process of the NCSR "Demokritos" nuclear reactor, which is classified as LLW. Small amounts of ILW can also be produced. Furthermore, spent reactor fuel is also radioactive waste, which is considered HLW. This waste is returned to the manufacturing country(the USA in this case), so the issue of managing it is transferred away from our country
- NORM(Naturally Occurring Radioactive Materials) or TENORM(Technologically Enhanced Naturally Occurring Radioactive Materials), which can often be categorized as VLLW
- Radioactive sources that are no longer being used

It should be noted that in our country, as in every other country, there is waste produced by older processes and applications("legacy/historical waste"). Lists of all the radioactive waste that are being or have been produced in our country are included in the national reports, which are available on the official website of E.E.A.E.(Ελληνική Επιτροπή Ατομικής Ενέργειας).

The waste generated by applications in the field of medicine constitutes the largest percentage of radioactive waste produced in our country. The processes leading to its production take place primarily in nuclear medicine laboratories, where radiopharmaceuticals(pharmaceutical preparations containing a radioactive nucleus or a chemical compound labelled with radioisotopes) are used either for diagnostic or for therapeutic purposes. The main kinds of such waste are:

- Contaminated medical equipment, such as surgical instruments, patient dressings, syringes, vials, general items handled by the specialized staff of nuclear medicine laboratories.
- Clinic/hospital patient discharges with significant concentrations of radioactivity, e.g. thyroid cancer iodine therapy centres by administering I-131, which is radioactive. In such centres, there are facilities to store these secretions until the decay of the radioactive iodine.

Regarding the radioactive discharges of patients living in their homes, which usually follow disposal through sewers, they are considered municipal waste due to the very low radioactivity they contain. Therefore, they do not pose a risk and their disposal as common waste e.g. in a landfill, is acceptable.

As far as the radioactive waste management is concerned, in the country of Greece there is a legislation that defines the national policy and provides information about the required steps to be taken in this area. The national strategy is described below:

- Compliance of the Greek Constitution with Council Directive 2011/70/Euratom of 19th July 2011 on the establishment of a community framework for the responsible and safe management of spent fuel and radioactive waste, Presidential Decree 122, Official Gazette 177/A/12.08.2013
- Legislative framework and its implementation for the responsible and safe management of spent fuel and radioactive waste and amendment of Presidential Decree 122/2013, Presidential Decree 91, Gazette 130/A/01.09.2017
- Determination of the national policy for the management of spent fuel and radioactive waste, Decision 131207/I3/20.08.2015, Official Gazette 858/B/27.08.2015
- "National Program for the management of spent fuel and radioactive waste – Second Plan", Official Gazette 4317/B/02.10.2020

- Ratification of the Joint Convention on the safety of spent fuel management and the safety of radioactive waste management, Law 2824/2000, Official Gazette 90/A/16.03.2000

Regarding the financing of such a process, the drawing up of the plan and the search for funds is carried out by the National Committee for the Management of Radioactive Waste, while the creation of a reserve fund has also been foreseen. In addition, the respective producer of radioactive waste bears the cost of its management and is obliged to undertake the entire financing, logistical infrastructure and specialized human resources required for its safe management.
Although most of the radioactive material in the waste decays in short time periods ranging from minutes to several decades, a small fraction remains radioactive for much longer periods of time. Because of this, safety requirements have been established for the management of radioactive waste that include the assessment of radiological effects and their evolution over time.

In this thesis, the disposal of radioactive waste near the surface of the Earth is examined, according to the characteristics of the scenarios presented in a technical publishment by IAEA. Specifically, our work is based on IAEA Technical Document 1380 (IAEA-TECDOC1380), where a similar scenario is analysed. The purpose of this paper is to further analyse this general scenario, in order to evaluate the effect of various parameters and the model used and to estimate the variation of the radiological effects. Here, the RESRAD-OFFSITE software is used for this particular analysis, combined with an uncertainty analysis, in order to estimate the variation in population exposure. For the direct comparison of the approaches, the exposure is also calculated as a dose per unit of initial activity.

The RESRAD-OFFSITE software has been approved and is being used by the U.S.NRC(United States Nuclear Regulatory Commission) for the parameterization and simulation of radioactive waste disposal scenarios, and belongs to the “RESRAD” family of software. The first software in this family was RESRAD-ONSITE, which was used to calculate the radiological dose and cancer risk for a person living directly over a contaminated site(Gilbert 1989, Yu 1993;2001), and was intended for decommissioning and rehabilitation studies. It was developed by Argonne’s Environmental Assessment Division team in the 1980s, and has been used many times to study radioactively contaminated areas since its launch In 1989.

The development of the RESRAD-OFFSITE software as a continuation/improvement of the previous RESRAD-ONSITE began in the 1990s, during the BIOsphere Model Validation Study II/BIOMOVS II by IAEA, which compared radiological estimation models(Gnanapragasam and Yu 1997, IAEA 1996). More specifically, this study involved the creation of models with

the ability to predict exposure to an individual outside the footprint of the Primary Contamination/Contamination Zone.

In more detail, the RESRAD-OFFSITE software calculates the radiological dose and the excess cancer risk for a person that is exposed to radioactivity inside in/or outside the Primary Contaminated Zone. The Primary Contaminated Zone is a radius around the radioactive waste disposal site, which is the sole source of any release and is assumed to be below a soil layer at some depth. Its dimensions and physis depends on the concentration of the nuclides that are available, the form of the subsoil zone(wet/dry sand, soil, gravel, etc.), the climate of wider area (rainy, dry, etc.), the disposal depth etc.. All these factors are taken into account and can be calculated with the aid of the software.

The exposure pathways, whether they are terrestrial or water sources, can be located either inside or outside the area of primary contamination. The code takes into account releases of radioactive substances from the atmosphere's primary contamination, runoff to the land surface and from groundwater. In particular, it models the movement of contaminants from the contaminated zone to agricultural lands, pastures, residential areas, well and a surface water body. In addition, it has the ability to simulate the accumulation of contaminants in these locations. Any contribution of contaminants from the facility to water bodies and from water sources at land-based locations is also taken into account.

Regarding the exposure pathways, the software can simulate 9 types:

1) Direct exposure due to contaminated soil
2) Inhalation of particles
3) Inhalation of short-lived daughters of Rn-222
4) Plant foods Ingestion (π.χ. fruits, vegetables, cereals)
5) Meat Ingestion
6) Milk Ingestion
7) Aquatic foods Ingestion (π.χ. fish, crustaceans)
8) Water Ingestion
9) Unintentional Soil Ingestion (usually by children)

This particular software can be used το perform a Deterministic Analysis, as well as an Uncertainty Analysis.

In the Technical Document 1380, IAEA considers the disposal facility scenario with an impact on a residence that gets its water supply by a well and on agricultural-livestock lands. The nuclide transport takes place due to seepage effects into groundwater(leaching). In other words, the nuclides from the facility are transported

through groundwater. In the technical document, the activity of each nuclide is given for the conditions described in the next Chapter.

This scenario is examined in this particular thesis both deterministically, and also through an uncertainty analysis. In the Deterministic Analysis, a simulation of the scenario with all the nuclides takes place. Conditions are taken as listed in TECDOC1380. However, RESRAD-OFFSITE offers us the opportunity to describe the scenario with a greater number of variables. The Uncertainty Analysis examines the effect of each nuclide on the total dose that the person will receive. So, only one simulation takes place for each nuclide, so that its participation is clear. Thus, through this analysis, any scenario between the worst-case and the best-case can be considered, given the factor of uncertainty it contains. The variation in exposure due to each nuclide is estimated based on estimates of the range of several important parameters, such as the Distribution Coefficient K_d, the hydraulic conductivities in the saturated and unsaturated zone, as well as total and active porosities in them.

2. Scenario Presentation

As mentioned above, this particular thesis is effectively a more detailed analysis of the scenario in IAEA-TECDOC1380 with two methods: a Deterministic Analysis and a Probabilistic(Uncertainty) Analysis.

The facility under consideration is of the near-surface disposal type, without cover on the upper side, while a trench is also included in the plan. The radionuclides that are used and disposed of in this scenario are: **^{241}Am, ^{3}H, ^{14}C, ^{41}Ca, ^{55}Fe, ^{60}Co, ^{59}Ni, ^{63}Ni, ^{90}Sr, ^{93}Zr, ^{94}Nb, ^{99}Tc, ^{129}I, ^{134}Cs, ^{137}Cs, ^{151}Sm, ^{226}Ra, ^{228}Ra, ^{232}Th, ^{234}U, ^{235}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu**.

Table 1: Radionuclides and their Half-Life

Radionuclide	Half-Life (Years)
^{241}Am	432.2
^{14}C	5.70E+3
^{41}Ca	1.02E+5
^{60}Co	5.2713
^{134}Cs	2.0648
^{137}Cs	30.1671
^{55}Fe	2.737
^{3}H	12.32
^{129}I	1.57E+7
^{94}Nb	2.03E+4
^{59}Ni	1.01E+5
^{63}Ni	100.1
^{237}Np	2.144E+6
^{238}Pu	87.7
^{239}Pu	2.411E+4
^{240}Pu	6564
^{241}Pu	14.35
^{226}Ra	1600
^{228}Ra	5.75
^{151}Sm	90

^{90}Sr	28.79
^{99}Tc	2.111E+5
^{232}Th	1.405E+10
^{234}U	2.455E+5
^{235}U	7.04E+8
^{238}U	4.468E+9
^{93}Zr	1.53E+6

The way, in which radionuclides are transported from the facility into the soil is through the phenomenon of leaching. In more detail, leaching is a mass transfer process that takes place during the extraction of a substance from a solid material that has been in contact with the liquid. It is the mechanism, by which water-soluble substances from the soil or(in this case) waste is washed away.
It comes down to two main mechanisms taking place simultaneously:

I. Chemical Interactions with Surfaces
II. Natural Water Movement

Primary Contamination, efficiently has to do with the existence of a contaminated medium surrounded by initially clean soil. A critical parameter for the leakage and movement of nuclides in the facility and then in the geosphere zones is the Distribution Coefficient K_d of each radionuclide between the medium and the moisture in the soil. Both this coefficient and the movement of nuclides in the soil, depend on the properties of the soil.

In the scenario analysed by IAEA, the climate in the disposal facility site can be considered temperate. Regarding the facility, it contains a trench, with dimensions of 100m in length, 15m in width and 4m in depth. The width is assumed to be parallel to the flow in the aquifer.

Below the facility(i.e. the Contaminated Zone) lies the Unsaturated Zone, which can be defined as an initially contamination-free layer of soil located between the Contaminated Zone and the Water Table(Aquifer). The main characteristic of the Unsaturated Zone is the non-fullness of its pores with water. To be precise, the pores are partially full with air and water.

An aquifer(Saturated Zone) is a body of rock structures and/or sediments that hold groundwater, created by geological changes over the years. The Saturated Zone's pores

and structural voids are filled with water. These water bodies are the result of the water cycle, as rainfall/snowfall continuously penetrates and moves deep into the ground.

As mentioned above, the Distribution Coefficient K_d is an extremely important parameter regarding the dispersion of contaminants. More specifically, this coefficient describes the distribution of each nuclide between the aqueous and solid phases of soil, sediments or of the contaminated medium. Mathematically, it is defined as the ratio of the concentration of contaminants in the absorbed phase of the soil(or sediments) to the concentration of contaminants in the aqueous phase of the soil(or sediments). Its units are cubic centimetres per gram(cm^3/g). Its value depends on factors such as soil type(soil, sand, etc.), pH, redox potential ant the presence of other ions. The distribution coefficient shows a large variation between points even in the same location. In this particular thesis, this coefficient is obtained deterministically by taking the default values of the software, as well as through uncertainty analysis.

For each of the nuclides presented above, we have a specific initial concentration at the facility under analysis, which is determined in terms of the contaminated medium and is calculated as shown below:

As IAEA states, the results are given as initial activity, which causes a dose equal to 1mSv/year, i.e. as Bq/(mSv/year). Because of this, for each nuclide and initial activity equal to 1Bq is assumed. The RESRAD software requires the expression of the initial activity in terms of the mass of the contaminated zone, i.e. as Bq/gr. To determine the value, 1Bq is divided by the installation's total mass, which is calculated as follows:

The trench's volume is calculated, which in the context of the software is considered as a rectangular parallelogram:

$$V = 100m \times 15m \times 4m = 6.000\ m^3$$

The bulk density is given by the IAEA TECDOC and is equal to 1.6 kg/m^3. It is also given that the ratio of the total volume of the nuclides to the volume of the soil cover is equal to 2/1. So, to calculate the mass of available nuclides, it is required to multiply 1/3 of the trench volume by the density. This results in the mass M, i.e. the mass of each of each available nuclide. From the concentration's equation C = 1/M, the concentration that each nuclide will have in the facility is calculated, which is equal to C = 6.073E-11 Bq/g.

In addition to the references made above, the technical document gives further parameters, which were introduced into the problem. These parameters concern the entire installation, and are: the kinematic and total porosities, which have a value of 0.4, as well as the hydraulic conductivity, which is equal to 10^{-5} m/s.

An important part of the study being conducted is the topography of the disposal site. In this case, the soil can be considered a part of a sandy geosphere. IAEA considers the following characteristics for the geosphere:

- Unsaturated Zone Thickness = 2m
- Average Moisture Content in the Unsaturated Zone = 0.15
- Kinematic and Total Porosity = 0.3
- Density = 2000 kg/m^3
- Hydraulic Conductivity = 10^{-5} m/s
- Hydraulic Gradient = 0.02
- Saturated Thickness = 15m
- Longitudinal Dispersion = (Movement Distance)/10 (m)
- Transverse Dispersion = (Movement Distance)/50 (m)

The next category of variables listed in TECDOC 1380 regards those related to human behaviour, which is directly related to the dose that each individual will end up receiving. These variables are:

- Breathing Rate = 1 m^3/h
- Drinking Water Intake Rate = 0.73 m^3/y
- Freshwater Consumption Rate[1] = 2 kg/y
- Grain Consumption Rate = 148 kg/y
- Consumption Rate of Root Vegetables = 235 kg/y
- Consumption Rate of Green Vegetables = 62 kg/y
- Consumption Rate of Cow's Milk = 330 kg/y
- Beef Consumption Rate = 95 kg/y
- Dust Concentration = 10^{-6} kg/m^3
- Land Cover Factor = 0.034

Regarding cultivation, the IAEA considers the following characteristics:

- Irrigation rate per crop(in a temperate climate) = 0.3 m/y (without pasture irrigation

[1] In the results of those scenarios, it was observed that the dose corresponding to the consumption of fish with radioactive contaminants is infinitesimal compared to the other exposure pathways. Therefore, it was omitted in the calculations

- Soil Thickness = 0.25 m
- Interception factor = 0.33
- Grain Yield = 0.4 kg/(m^2y) (wet weight)[2]
- Yield of root vegetables = 3.5 kg/(m^2y) (wet weight)
- Yield of green vegetables = 3 kg/(m^2y) (wet weight)
- Pasture yield = 1.7 kg/(m^2y) (wet weight)[3]

Since in this scenario, the route of exposure via ingestion of meat(obviously animals living and feeding on the flora of the area around the disposal site) is also taken into account, data is required for this pathway as well, which is also given. Cattle breeding with the following characteristics is considered:

- Daily Water Consumption = 0.06 m^3/day
- Daily Soil Consumption = 0.6 kg/day
- Daily Grazing Intake (wet) [4]= 55 kg/day
- Average Animal Weight = 500 kg
- Average Annual Milk Production = 5500 kg/y
- Density of Animals on Livestock Land = 100 ζώα/km

Then, it is worth noting some equations that contribute to an easier and more realistic approach to such a scenario.

The simulation model of groundwater movement is reduced to certain “zones”:

1. Primary Contamination Zone
2. Zero to five horizontal layers of partially saturated zones
3. An initially non-contaminated and unbounded saturated zone

[2] Regarding the wet weight of vegetables and grains, the following detail must be clarified: The wet weight includes, in addition to the ingredient itself(grains, vegetables etc.), and the weight of the water that may be found in the area, from which the sample was taken. No water removal procedure is applied before calculating the weight of the sample.

[3] The pastures are considered to be contaminated by root uptake through the soil, which was previously used to grow irrigated crops.

[4] Again, the weight of the water is also taken into account.

Image 2 depicts a scenario, in which the primary contamination is located above the water table with two partially saturated zones.

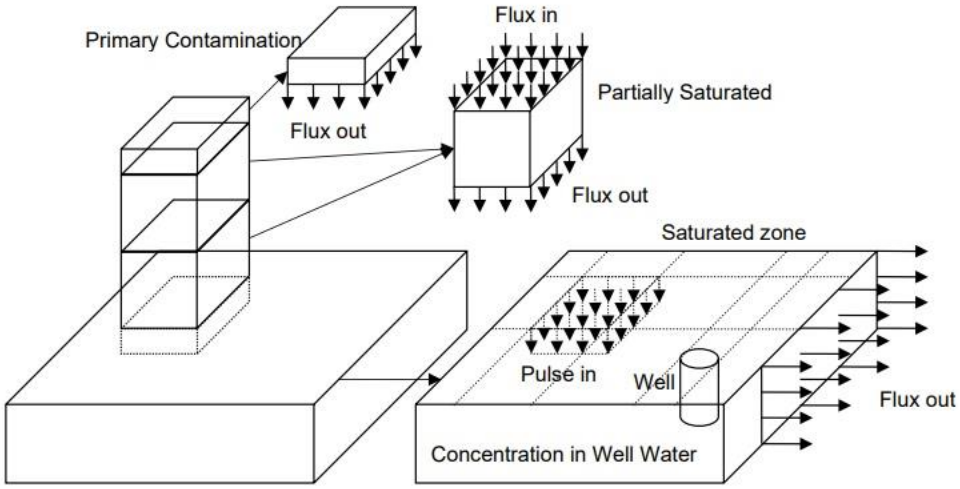


Image 2: Primary Contamination Zone and Saturated Zones

The Primary Contamination's top view(image in the horizontal plane) is assumed to be a rectangular parallelogram, with a pair of sides parallel to the direction of groundwater flow.

Water flow in both partially saturated zones and primary contamination is downward in the vertical direction. In the saturated zone and in the primary contamination below the water table, the flow moves in the horizontal direction.

Each transport zone is treated as a homogenous layer, i.e. properties such as density, porosity, hydraulic conductivity, dispersion and hydraulic gradient are assumed to be constant in value in each individual transport zone. The software is only interested in interconnected pores for modelling nuclide transport in groundwater, because isolated pores affect their movement.

The interconnected pores are split into 2 categories:

1. Mobile Pores
2. Immobile Pores

The pores depiction is shown in Image 3.

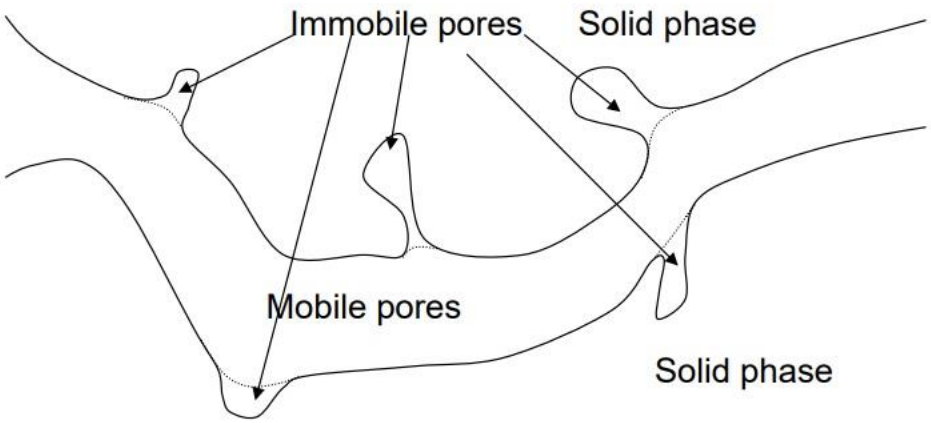


Image 3: Mobile and Immobile Pores

In mobile pores, water is free to move and contributes to the nuclide's rapid transport.

In immobile pores, moisture is trapped either because the pores themselves are "dead-end pores", or because it is tightly bound to the solid phase and does not contribute to nuclide transport.

The two types of pores and connected through the following equation:

$$\theta_m+\theta_{im} = \theta_t$$

Where:

θ_m is the kinematic porosity, that allows or contributes to the water movement

θ_{im} is the active porosity, that does not allow or contribute to the water movement

θ_t is the sum of the two porosities, i.e. the total porosity

Although nuclides are absorbed by the surface of soil solids, their concentration in soil is expressed in terms of mass of solids. The soil volume fraction associated with mobile pores(u_m) and the soil volume fraction associated with immobile pores (u_{im}) are assumed to have the same analogy as the porosities of those two phases. Ισχύει δηλαδή:

$$\frac{u_m}{u_{im}} = \frac{\theta_m}{\theta_{im}}$$

The partitioning of radionuclides between the aqueous phase in the pores and the solid phase absorbed on the surface is dynamic.

Nuclides are absorbed at a rate dependent on their concentration in the aqueous phase. Conversely, nuclides absorbed from the surface desorb at a rate dependent on their concentration in the solid(absorbed) phase.

Over time, the two phases come to equilibrium and the nuclide partitioning between the aqueous and solid phases is characterized by a linear equilibrium distribution coefficient in RESRAD-OFFSITE, K_d:

$$K_d = \frac{s_m}{c_m} 10^6 = \frac{s_{im}}{c_{im}} 10^6$$

Where:

K_d the Distribution Coefficient (cm^3/g)

s_m. s_{im} Nuclides Concentrations in soil associated with mobile and immobile pores respectively (Bq/g)

c_m, c_{im} Nuclides Concentrations in mobile and immobile pores(Bq/m^3)

10^6 Conversion Coefficient (cm^3/m^3)

The amount of nuclides in an elementary volume unit in the soil is the sum of the amounts in the mobile and immobile pores and in the solid phase associated with those pores:

$$\begin{aligned}
&\theta_m c_m + \theta_{im} c_{im} + u_m \rho_b 10^6 s_m + u_{im} \rho_b 10^6 s_{im} \\
&= \theta_m c_m + \theta_{im} c_{im} + \frac{u_m}{u_m + u_{im}} \rho_b 10^6 s_m + \frac{u_{im}}{u_m + u_{im}} \rho_b 10^6 s_{im} \\
&= \theta_m c_m + \theta_{im} c_{im} + \frac{\theta_m}{\theta_m + \theta_{im}} \rho_b K_d c_m + \frac{\theta_{im}}{\theta_m + \theta_{im}} \rho_b K_d c_{im} \\
&= \theta_m c_m + \frac{\rho_b K_d}{\theta_t} \theta_m c_m + \theta_{im} c_{im} + \frac{\rho_b K_d}{\theta_t} \theta_{im} c_{im} \\
&= \left(1 + \frac{\rho_b K_d}{\theta_t}\right) \theta_m c_m + \left(1 + \frac{\rho_b K_d}{\theta_t}\right) \theta_{im} c_{im} \\
&= \frac{\theta_m c_m + \theta_{im} c_{im}}{\theta_t} (\theta_t + \rho_b K_d) \\
&= c_{av} (\theta_t + \rho_b K_d)
\end{aligned}$$

Where c_{av} the average concentration of the nuclides in the interconnected pores (pCi/m^3).

The change in the amount of radionuclides in the elemental volume of soil over time as a result of radiological transformations is given by the expression for the amount of nuclides per unit of volume of soil:

$$change = -\lambda c_{av}(\theta_t + \rho_b K_d)\delta x \delta y \delta z$$

This change is reduced to the difference between the amount of nuclides carried by the water entering the volume through the mobile pores and the amount of nuclides leaving it through the outflow from the mobile pores.

$$change = -V_m \theta_m \delta x \delta y \frac{\partial c_m}{\partial z} \delta z$$

Where V_m the average velocity of the water as it flows through the mobile pores(m/year)

As the contamination moves, the water entering the mobile pores contains radionuclides. In general, the radionuclides found in a pore(mobile/immobile) are transferred to the others at a rate that depends on their concentration in the former. Over time, the concentration of immobile pores increases, until an equilibrium is reached between the two(mobile and immobile pores).

To calculate the average concentration in the pores, a simplifying assumption has been made: If the time required to traverse a given volume of soil is much shorter than that required for the mobile and immobile pores to come to equilibrium, then the concentration in the latter is considered negligible compared to that in the former.

Under this condition, the average concentration in all pores is given by the following equation:

$$c_{av} = \frac{\theta_m c_m + \theta_{im} c_{im}}{\theta_t} \approx \frac{\theta_m}{\theta_\tau} c_m$$

Also, if the time required to traverse a certain volume of soil is much longer that that required for the mobile and immobile pores to reach and equilibrium, then the concentration in those two are equal.

Under this condition, the average concentration in all pores is given by the following equation:

$$c_{av} = \frac{\theta_m c_m + \theta_{im} c_{im}}{\theta_t} \approx \frac{\theta_t}{\theta_t} c_m = c_m$$

3. Analysis

3.1 Deterministic Analysis

The **Deterministic Analysis(1st Scenario)**, includes a single simulation, which contains specific variables, according to the parameter values in IAEA-TECDOC1380, as listed in Chapter 2. For parameters required by the RESRAD code, for which no values are given in TECDOC1380, the default values of the code are taken.

The analysis includes the simulation with all nuclides, with equal concentrations and all exposure pathways listed, in addition to ^{222}Rn and fish consumption, i.e. the list of nuclides in Table 1 with an initial concentration of 6.73E-11 Bq/g is used.

Image 4 shows the set of exposure pathways that can be entered into the scenario simulation.

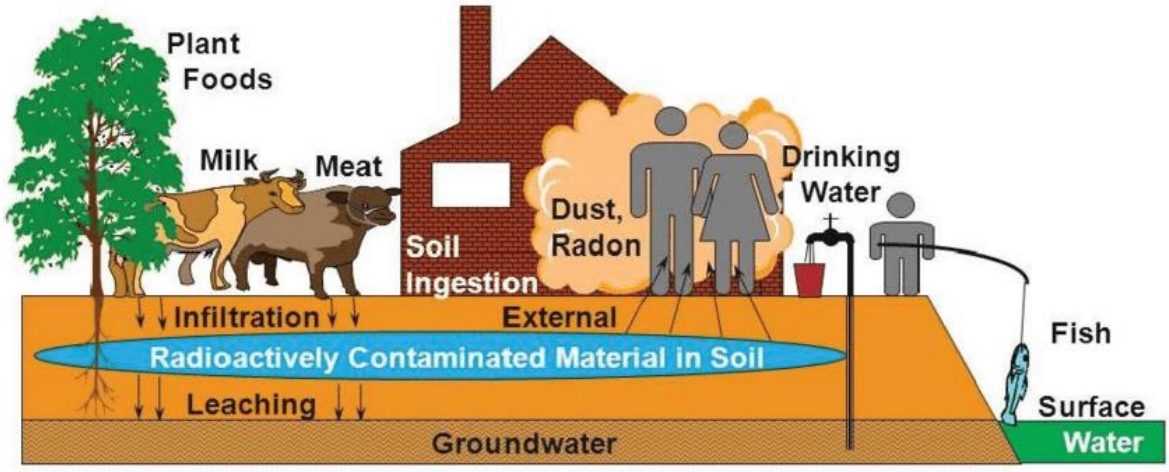


Image 4: Exposure Pathways in RESRAD-OFFSITE

The exposure pathways used in this scenario:

1. Direct exposure due to contaminated soil
2. Inhalation of Particles
3. Ingestion of plant foods(e.g. fruits, vegetables, grains)
4. Ingestion of Meat
5. Ingestion of Milk
6. Ingestion of Water
7. (Inadvertent) ingestion of soil(usually by children)

CONTAMINATED ZONE MODEL

Initially, the exponential release model of RESRAD-OFFSITE is not chosen as the simulation model. We chose a model, where the initial radioactivity of the nuclides is specified based on the total mass of the primary contamination, which is based on the publication in ICRP107. The properties of the primary contamination are used to calculate its transfer from the solid to the aqueous phase, as well as the transfer of radionuclides through it. Also, the radiological units used are Bq for radioactivity and mSv for dose. The basic radiological dose limit is taken at 0.25 mSv/year.

TIME FRAME

An important parameter is the time the simulation initiates with respect to the initial disposition. In this case, an institutional period of 100 years has been considered. That is, for the 100 years after the disposal of the radioactive waste and the closure of the facility, an annual inspection takes place at the site, the main purpose of which is to check the levels of radioactivity in the wider area and to detect any risk or defects of the installation.

BASIC PARAMETERS

One can easily understand that the most important factor regarding the exposure of the population is the nuclides that will be available, as well as their concentrations. The list of radionuclides is shown in Table 1. As explained in the 2nd Chapter, the initial concentration of radionuclides in the Contaminated Zone for unit total activity is calculated equal to 6.73E-11 Bq/g. It is worth noting that this list also includes the daughters of the original isotopes.

Next in order are series of data regarding the release to groundwater. The contaminant transfer mechanism chosen is Equilibrium Desorption Transfer. The main dispersion coefficients are those corresponding to the Contaminated Zone, the Unsaturated Zone and the Saturated Zone. The table of nuclides and their basic transfer coefficients is given below:

Table 2: Basic Nuclide Transfer Coefficients

Nuclide	Distribution Coeff. in Contaminated Zone(cm^3/g)	Distribution Coeff. In Unsaturated Zone(cm^3/g)	Distribution Coeff. In Saturated Zone(cm^3/g)
Ac-227	20	20	20
Am-241	20	20	20
C-14	0	0	0
Ca-41	50	50	50

Co-60	1000	1000	1000
Cs-134	4600	4600	4600
Cs-137	4600	4600	4600
Fe-55	1000	1000	1000
H-3	0	0	0
I-129	0.1	0.1	0.1
Nb-93m	0	0	0
Nb-94	0	0	0
Ni-59	1000	1000	1000
Ni-63	1000	1000	1000
Np-237	257	257	257
Pa-231	50	50	50
Pb-210	100	100	100
Po-210	10	10	10
Pu-238	2000	2000	2000
Pu-239	2000	2000	2000
Pu-240	2000	2000	2000
Pu-241	2000	2000	2000
Ra-226	70	70	70
Ra-228	70	70	70
Sm-151	825	825	825
Sr-90	30	30	30
Tc-99	0	0	0
Th-228	60000	60000	60000
Th-229	60000	60000	60000
Th-230	60000	60000	60000
Th-232	60000	60000	60000
U-233	50	50	50
U-234	50	50	50
U-235	50	50	50
U-236	50	50	50
U-238	50	50	50
Zr-93	2200	2200	2200

Also, distribution coefficients are defined foe the following categories:

- Suspended Sediment in Surface Water Body
- Bottom sediment in Surface Water Body
- Fruit,grain,nonleafy fields
- Leafy vegetable fields
- Pasture,silage growing areas

- Livestock feed grain fields
- Dwelling site

For each of those categories, the value of distribution coefficients has the same value for each nuclide and equal to that of Table 2.

Transfer factors from the environment to vegetables and other products are also very important:

i. Soil to plant transfer factor
It includes, in particular, coefficient for fruit, grain, non-leafy vegetables, for leafy vegetables, for pasture and silage and livestock feed grain.

ii. Intake to animal product transfer product
Such coefficients are found for milk and for meat.

iii. Water to aquatic food transfer factor
In this category, there are coefficients for fish and for crustacea.

Below, the table with the transfer coefficient values for each nuclide is presented.

Table 3: Nuclide Transfer Coefficients

Nuclide	Fruit, Grain, nonleafy vegetables [(Bq/kg)/(Bq/kg)]	Leafy vegetables [(Bq/kg)/(Bq/kg)]	Pasture, silage [(Bq/kg)/(Bq/kg)]	Livestock feed grain [(Bq/kg)/(Bq/kg)]	Meat [(Bq/kg)/(Bq/d)]	Milk [(Bq/L)/(Bq/d)]	Fish [(Bq/kg)/(Bq/L)]	Crustacea [(Bq/kg)/(Bq/L)]
^{227}Ac	0.0025	0.0025	0.0025	0.0025	0.00002	0.00002	15	1000
^{241}Am	0.001	0.001	0.001	0.001	0.00005	0.000002	30	1000
^{14}C	0.2667	0.06	0.06	0.2667	0.0105	0.00837	50000	9100
^{41}Ca	0.5	0.5	0.5	0.5	0.0016	0.003	1000	330
^{60}Co	0.08	0.08	0.08	0.08	0.02	0.002	300	200
^{134}Cs	0.04	0.04	0.04	0.04	0.03	0.008	2000	100
^{137}Cs	0.04	0.04	0.04	0.04	0.03	0.008	2000	100
^{55}Fe	0.001	0.001	0.001	0.001	0.02	0.0003	200	3200
^{3}H	4	4	4	4	0.005742	0.004312	1	1
^{129}I	0.02	0.02	0.02	0.02	0.07	0.01	40	5
^{93m}Nb	0.01	0.01	0.01	0.01	0.0000003	0.000002	300	100
^{94}Nb	0.01	0.01	0.01	0.01	0.0000003	0.000002	300	100
^{59}Ni	0.05	0.05	0.05	0.05	0.005	0.02	100	100
^{63}Ni	0.05	0.05	0.05	0.05	0.005	0.02	100	100
^{237}Np	0.02	0.02	0.02	0.02	0.001	0.000005	30	400
^{231}Pa	0.01	0.01	0.01	0.01	0.005	0.000005	10	110
^{210}Pb	0.01	0.01	0.01	0.01	0.0008	0.0003	300	100
^{210}Po	0.001	0.001	0.001	0.001	0.005	0.00034	100	20000
^{238}Pu	0.001	0.001	0.001	0.001	0.0001	0.000001	30	100
^{239}Pu	0.001	0.001	0.001	0.001	0.0001	0.000001	30	100

^{240}Pu	0.001	0.001	0.001	0.001	0.0001	0.000001	30	100
^{241}Pu	0.001	0.001	0.001	0.001	0.0001	0.000001	30	100
^{226}Ra	0.04	0.04	0.04	0.04	0.001	0.001	50	250
^{228}Ra	0.04	0.04	0.04	0.04	0.001	0.001	50	250
^{151}Sm	0.0025	0.0025	0.0025	0.0025	0.002	0.00002	25	1000
^{90}Sr	0.3	0.3	0.3	0.3	0.008	0.002	60	100
^{99}Tc	5	5	5	5	0.0001	0.001	20	5
^{228}Th	0.001	0.001	0.001	0.001	0.0001	0.000005	100	500
^{229}Th	0.001	0.001	0.001	0.001	0.0001	0.000005	100	500
^{230}Th	0.001	0.001	0.001	0.001	0.0001	0.000005	100	500
^{232}Th	0.001	0.001	0.001	0.001	0.0001	0.000005	100	500
^{233}U	0.0025	0.0025	0.0025	0.0025	0.00034	0.0006	10	60
^{234}U	0.0025	0.0025	0.0025	0.0025	0.00034	0.0006	10	60
^{235}U	0.0025	0.0025	0.0025	0.0025	0.00034	0.0006	10	60
^{236}U	0.0025	0.0025	0.0025	0.0025	0.00034	0.0006	10	60
^{238}U	0.0025	0.0025	0.0025	0.0025	0.00034	0.0006	10	60
^{93}Zr	0.001	0.001	0.001	0.001	0.000001	0.0000006	300	6.7

As far as atmospheric transport is concerned, the variables that contribute to the dispersion of radionuclides are the deposition velocity of respirable particles(m/s) and the deposition velocity of all particles(m/s). For both variables, the default values of the software are used.

STORAGE TIMES

Storage Times are defined as those time intervals, in which food and water are stored before being consumed. They receive specific values for each type of food or water source, as shown in Table 4:

Table 4: Edible/Potable Ingredient Storage Times

Food/Water	Storage Time(Days)
Surface Water	1
Well Water	1
Fruit, grain and non-leafy vegetables	14
Leafy vegetables	1
Pasture and silage	1
Livestock feed grain	45
Meat	20
Milk	1
Fish	7
Crustacea	7

PLACEMENT AND DIMENSIONS

Considering a Cartesian x-y coordinate system, the boundaries that play a role with respect to the scenario's data can be defined. Initially, it is assumed that the Contaminated Zone has dimensions (X,Y) = (100, 15m). The rest of the locations and zones are listed below:

Table 5: Facility Layout

Τοποθεσία	Length(m)[5]	Width(m)[6]	Starting X (m)[7]	Starting Y(m)
Fruit, grain and non-leafy vegetables	150	50	0	0
Leafy vegetables	150	50	0	0
Pasture and Silage	100	50	0	0
Grain Fields	100	250	0	50
Dwelling Site	20	20	0	0

The well is placed at the location with coordinates to the origin of the axes defined above (X,Y) = (50m, 0), i.e. at a distance of 50m from the Contaminated Zone.

BASIC ZONE CHARACTERISTICS

Tables 6,7 list the main characteristics of the zones taken into account in the calculations. The main hydrogeological characteristics of the zones, as mentioned, were obtained according to the values specified in TECDOC1380. All other parameters are obtained with the default values in the software.

Table 6: Primary Contamination Parameters

PCZ Variable	Value
PCZ Area	1500 m^2
Contamination Length parallel to the water table	15 m
Depth of Mixing Layer	0.15 m
Mass concentration of all particles	0.0001 grams/m^3
Deposition velocity for all particles	0.001 m/s

[5] Length refers to the distance covered on the X axis.
[6] Width refers to the distance covered on the Y axis.
[7] The Starting X,Y values refer to the starting point of the length and the width measurement

Respirable particles as a fraction of the total	1
Deposition Rate of respirable particles	0.001 m/s
Total irrigation per year	0.2 m per year
Evapotranspiration Coefficient	0.4
Runoff Coefficient	0
Slope-Length-Steepness factor	0.3
Cover and Management factor	0.003
Support practice factor	1
Fraction of primary contamination that is submerged	0

Table 7: Variables regarding the Soil Cover above the PCZ

Cover Variable	Value
Thickness	1 m
Soil Erodibility Factor	0.4 tons/acre
Dry Bulk Density	1.5 grams/cm^3
Erosion Rate	8.602E(-06) m/year
Total Porosity	0.4
Volumetric Water Content	0.05

SURFACE RUNOFF

After the corrosion that takes place in the primary contamination, a part of the materials that follow this process are removed through runoff. Through this, a prediction/analysis of the deposition location of these materials can be made. Thus, the following assumption can be made:

1) Fraction of corroded radionuclides deposited in the dwelling site: 0.2
2) Fraction of corroded radionuclides deposited on non-leafy vegetable crops: 0.2
3) Fraction of corroded radionuclides deposited on leafy vegetable crops: 0.2
4) Fraction of corroded radionuclides deposited on pasture: 0.2
5) Fraction of decayed radionuclides deposited on livestock feed grain crops: 0.2
6) Fraction of decayed radionuclides deposited in a surface water body: 0

AGRICULTURAL AND LIVESTOCK AREAS

Agricultural Areas are divided into fields cultivated with fruits, grains and non-leafy vegetables and fields cultivated with leafy vegetables. Livestock Feed Growing Areas are reduced to pastures and areas with silage and grain-growing areas. Finally, the dwelling site is also analysed, which obviously plays a very important part in the results forming. The computational parameters are given in Table 8.

Table 8: Variables of Agricultural, Livestock Areas and Dwelling Site

Variable	Value for fields cultivated with fruits, grain and non-leafy vegetables	Value for fields cultivated with leafy vegetables	Value for pastures and silage areas	Grain-growing Areas	Dwelling Site
Surface	7500 m^2	7500 m^2	5000 m^2	25000 m^2	400 m^2
Fraction of areas directly above the Primary Contamination	0.2	0.2	0.3	0	-
Irrigation Applied per Year	0.2 m	0.2 m	0.2 m	0.2 m	0.2 m
Evapotranspiration Coefficient	0.4	0.4	0.4	0.4	0.4
Runoff Coefficient	0	0	0	0	0
Mixing Layer Depth	0.15 m	0.15 m	0.15 m	0.15 m	0.15 m
Volumetric Water Content	0.3	0.3	0.3	0.3	0.3
Erosion Rate	1.147E(-5) m/year	1.147E(-5) m/year	1.147E(-5) m/year	1.147E(-5) m/year	0
Dry Bulk Density	1.5 grams/cm^3	1.5 grams/cm^3	1.5 grams/cm^3	1.5 grams/cm^3	1.5 grams/cm^3
Soil Erodibility Factor	0.4 tons/acre	0.4 tons/acre	0.4 tons/acre	0.4 tons/acre	0

Slope-Length-Steepness Factor	0.4	0.4	0.4	0.4	0.4
Cover and Management Factor	0.003	0.003	0.003	0.003	0.003
Support Practice Factor	1	1	1	1	1
Total Porosity	0.4	0.4	0.4	0.4	0.4
Proportion of Sediment Supply from Primary Contamination	0.2	0.2	0.2	0.2	0.2

WATER USE

Given the exposure pathways and radionuclides taken into account in the present thesis, the main channel of transmission and dispersion of radioactivity from Primary Contamination to the wider environment elements is water. Below, the most important variables related to its use are given.

Table 9: Water Use Variables

Variable	Value
Consumption per person	510 Lt/year
Consumption in the dwelling site per person	225 Lt/year
Cattle consumption(per animal)	50 Lt/year
Consumption of dairy cows(per animal)	160 Lt/year

Table 10: Corrosion at several facility locations

Variable	Value
Corrosion in fruit, grain and non-leafy vegetable crops	0.2 m per year
Corrosion in leafy vegetable crops	0.2 m per year
Corrosion in pastures and areas with silage	0.2 m per year

Corrosion in forage grain crops	0.2 m per year
Corrosion at the dwelling site	0.2 m per year

In addition, the following assumptions have been made:

- Coexistence of 4 people in the residence.
- The residence draws its water supply entirely from the well, while it receives zero amount from the surface water body.
- Well Pumping Rate equals 9565 m^3/year.

SATURATED-UNSATURATED ZONES

The Unsaturated Zone is defined as that zone just below the ground surface, which contains water and/or air in pores or structural voids. These pores are not completely full. The Saturated Zone is defined as that zone directly below the unsaturated one, which contains the same components with the latter, while its pores are full.
For both of these zones, important information is provided through variables, which were taken from the technical document in their entirety and are, in fact, amongst the most important factors of this study.
Tables with these variables are listed:

Table 11: Unsaturated Zone Variables

Variable	Value
Thickness	2 m
Dry Bulk Density	2 grams/cm^3
Total Porosity	0.3
Effective Porosity	0.3
Field Capacity	0.3
Hydraulic Conductivity	315.36 m/year
B parameter	5.3
Longitudinal Dispersivity	0.2 m

Table 12: Saturated Zone Variables

Variable	Value
Thickness	15 m
Dry Bulk Density	2 grams/cm^3
Total Porosity	0.3
Effective Porosity	0.3

Hydraulic Conductivity	315.36 m/year

Table 13: Hydraulic Variables for the Saturated Zone

Variable	Value relative to the well	Value relative to the surface water body
Hydraulic Gradient	0.02	0.02
Depth of Aquifer Contributing	12 m below the aquifer	5 m below the aquifer
Logitudinal Dispersivity	5 m	10 m
Horizontal Lateral Dispersivity	1 m	1 m
Vertical Lateral Dispersivity	1 m	0.06 m

INGESTION RATES

Ingestion rates are highly related to the exposure pathways chosen to simulate the given scenario, as almost all of them involve swallowing/consuming food/liquid. Also, for the sake of a more realistic analysis, the following assumption was made: the products consumed do not come in their entirety from the contaminated area, but only partly. These variables are given in the table below:

Table 14: Consumption Rates

Variable	Consumption Rate	Fraction of the Contaminated Zone
Drinking Water	510 Lt/year	1
Fish	5.4 kg/year	0.5
Crustacea and Mollusks	0.9 kg/year	0.5
Fruits, Grains and Non-Leafy Vegetables	160 kg/year	0.5
Leafy Vegetables	14 kg/year	0.5
Meat	63 kg/year	0.5
Milk	92 Lt/year	0.5
Soil(Unintentional)	36.5 grams/year	-

FLORA FACTORS

The flora variables relate to the fruits and vegetables that take part in the study. All were input as defaults by the RESRAD-OFFSITE software and obviously contribute significantly to the dose calculation due to the exposure associated with them. They are listed below:

Table 15: Flora Factors

Variable	Value for fruits, grains and non-leafy vegetables	Value for leafy vegetables
Crop Yield(Wet Weight)	0.7 kg/m^2	1.5 kg/m^2
Cultivation Period Duration	0.17 years	0.25 years
Foliage to Food Transfer Coefficient	0.1	1
Runoff Constant due to Weather Conditions	20 per year	20 per year
Foliage Interception Factor for Corrosion	0.25	0.25
Foliage Interception Factor for Dust	0.25	0.25
Roots Depth	1.2 m	0.9 m

LIVESTOCK INTAKES

Livestock Intakes have to do with their diet and the amounts of food they consume over a period of time. The table with these variables is given below:

Table 16: Livestock Intakes

Variable	Value for Cattle	Value for Dairy Cows
Water	50 Lt/day	160 Lt/day
Pasture and Silage	14 kg/day	44 kg/day
Grain	54 kg/day	11 kg/day
Soil from Pasture and Silage	0.1 kg/day	0.4 kg/day
Soil from Grain	0.4 kg/day	0.1 kg/day

In addition, there are factors related to livestock, just like the flora mentioned above. Respectively, we have the following table:

Table 17: Livestock Intake Factors

Variable	Value for Pasture and Silage	Value for Grain
Crop Yield(Wet Weight)	1.1 kg/m^2	0.7 kg/m^2
Cultivation Period Duration	0.08 years	0.17 years
Foilage to Food Transfer Coefficient	1	0.1
Runoff Constant due to Weather Conditions	20 per year	20 per year
Foliage Interception Factor for Corrosion	0.25	0.25
Foliage Interception Factor for Dust	0.25	0.25
Roots Depth	0.9 m	1.2 m

HUMAN BEHAVIOUR FACTORS

Obviously, the human behaviour of the inhabitants present in the simulation scenario described can greatly influence the final outcome of the results(essentially the dose each person will receive). An important parameter is the fraction of time each person spends in various parts of the facility, contaminated or not. Table 18 gives a first impression of the person's behaviour in this particular scenario, regarding the time spent in different parts of the facility.

Table 18: Human Behaviour Time Fractions

Location	Time Fraction
Dwelling Site(Inside)	0.4
Dwelling Site(Outside)	0.2
Fruit, grain and non-leafy vegetable fields	0.1
Leafy vegetable fields	0.1
Pasture and silage areas	0.1
Livestock Feeding Grain Fields	0.1

3.2 Uncertainty/Probabilistic Analysis

The uncertainty analysis involves a series of successive calculations with several different combinations of parameters. These parameters are randomly selected from a span that is specified for any one of them that participates as an uncertainty parameter. The remaining variables keep the constant values presented in paragraph 3.1.

Initially, in this scenario 27 simulations take place, one for each nuclide. The uncertainty variables are assumed to follow statistical distributions, choosing from the available software distributions. The sampling distribution is divided into a number of equally likely distribution segment, their number being equal to the desired number of observations. A sample is then randomly selected from each segment, ensuring that the samples cover the entire range of the distribution.
The number of observations is essentially the number of sample values to be generated by the software for each input variable. Also, it is considered important to repeat the analysis more than once, to assess the adequacy of the sections' number. Here, the number of observations is equal to 100 for each of the 3 repetitions.

The variables that are input to the uncertainty analysis for each simulation are given in Table 19.

Table 19: Statistics Variables in Uncertainty Analysis

Variable	Distribution	Mean Value (Mu)	Standard Deviation (σ)	Lower Quantile	Upper Quantile
K_d in Unsaturated Zone	Truncated Lognormal-N	8.17	1.7	0.001	0.999
K_d in Saturated Zone	Truncated Lognormal-N	8.17	1.7	0.001	0.999
Hydraulic Conductivity in Unsaturated Zone	Bounded Lognormal-N	2.3	2.11	0.004	9250
Hydraulic Conductivity in Saturated Zone	Bounded Lognormal-N	2.3	2.11	0.004	9250
Total Porosity in Unsaturated Zone	Truncated Normal	0.425	0.0867	0.001	0.999

Total Porosity in Saturated Zone	Truncated Normal	0.425	0.0867	0.001	0.999
Effective Porosity in Unsaturated Zone	Truncated Normal	0.355	0.0906	0.001	0.999
Effective Porosity in Saturated Zone	Truncated Normal	0.355	0.0906	0.001	0.999

The statistics required to fully describe the distributions of these variables(mean value, standard deviation, lower-upper quantile) were obtained from tables in the publishment NUREG/CR-7267, also published by U.S.NRC.(NUREG/CR-7267-Default Parameter Values and Distribution in RESRAD-ONSITE V7.2, RESRAD-BUILD V3.5, and RESRAD-OFFSITE V4.0 Computer Codes).

The various parameters may be related to each other. For example, the total porosity is related to effective porosity, as the greater the value of the former, the greater the value of the latter. This relation is taken into account and explained by appropriate correlation coefficients(U.S.NRC./NUREG/CR-7267). The parameters that are interdependent in the present calculations are given in Table 20. All correlations in Table 20 are considered positive. This means that each pair of variables is increasing or decreasing at the same rate.

Table 20: Variable Correlations

Kd in Unsaturated Zone	Kd in Saturated Zone
Effective Porosity in Saturated Zone	Effective Porosity in Unsaturated Zone
Effective Porosity in Saturated Zone	Total Porosity in Saturated Zone
Effective Porosity in Saturated Zone	Total Porosity in Unsaturated Zone
Effective Porosity in Unsaturated Zone	Total Porosity in Saturated Zone
Effective Porosity in Unsaturated Zone	Total Porosity in Unsaturated Zone
Total Porosity in Unsaturated Zone	Total Porosity in Saturated Zone
Hydraulic Conductivity in Unsaturated Zone	Hydraulic Conductivity in Saturated Zone

The greater the number of samples, the better the statistical reliability of the results. Due to time constraints during the thesis study, the value of 100 samples was chosen as an acceptable compromise, which is considered to ensure sufficient reliability and at the same time make the computational cost of the uncertainty analysis practically manageable.

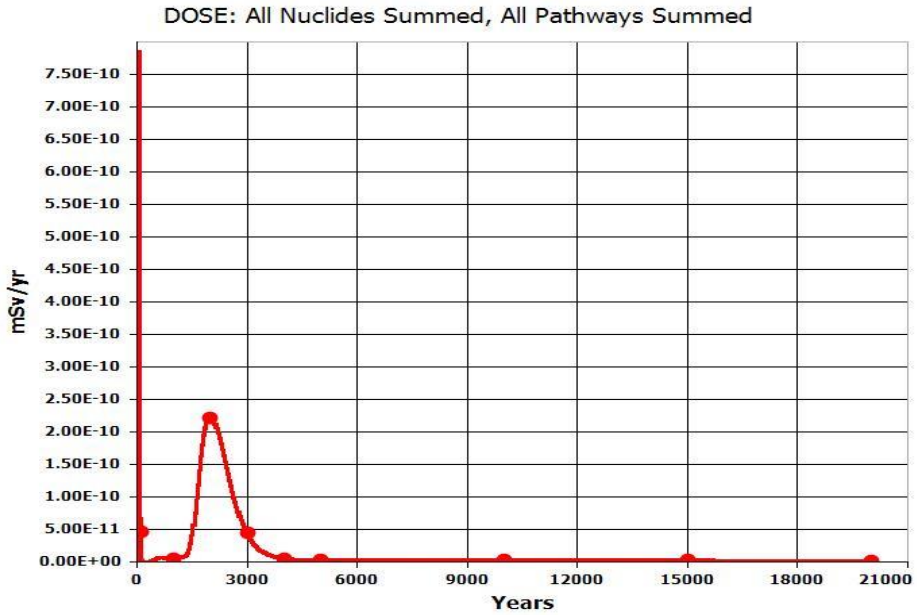
4. Results

Following the simulations, the results that came up are interpreted and analysed below, for both the Deterministic and the Uncertainty Analysis.

4.1 Results of Deterministic Analysis

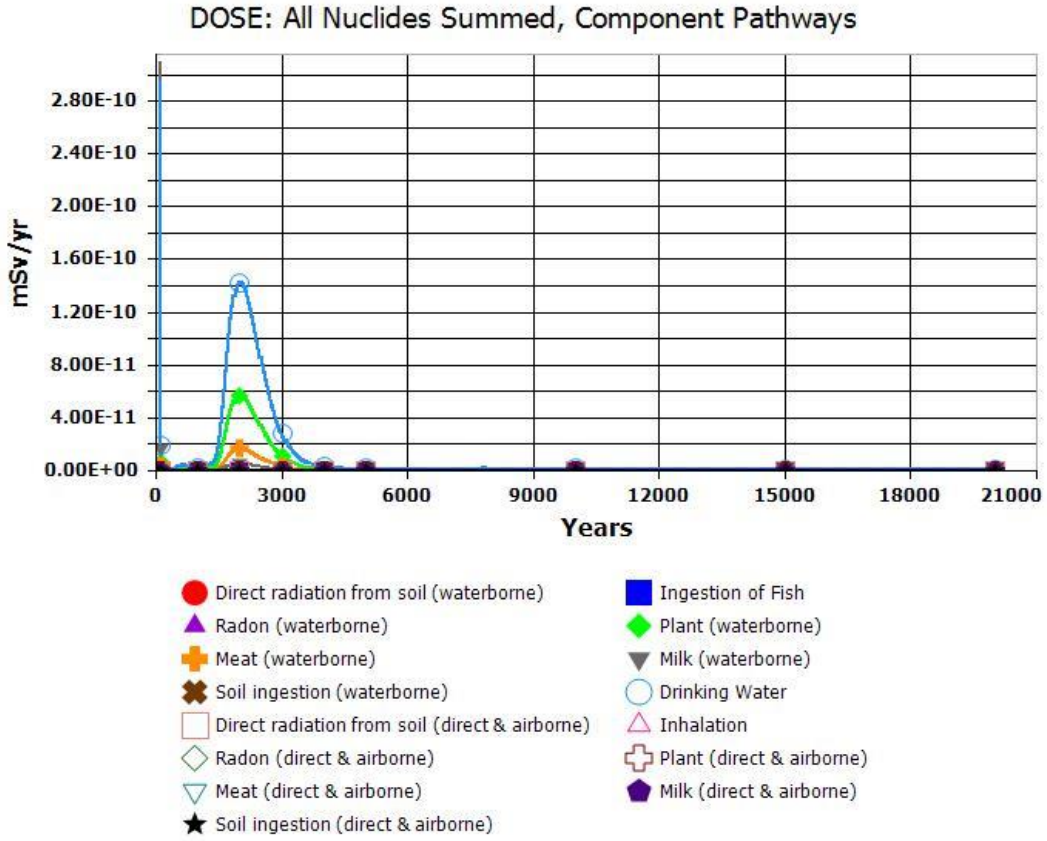
In the Deterministic Analysis model, a simulation was run using RESRAD software, which contained all the variables mentioned above and involved a disposal facility for all the radionuclides in the list(Table 1).

Graph 1 shows the annual dose as a function of time for the case of the deterministic simulation. Observing the graph, one can identify the maximum dose, which is equal to a little more that 7.5E-10 mSv/year and is detected in a relatively short time after the installation's sealing. It is recalled that the initial activity does not represent any real stock, but has been taken equal to 1Bq for all nuclides. Therefore, the dose is very small as an absolute value.
The reference to the institutional period, which here equals to 100 years and at the end of which is time zero for the particular scenario, should not be overlooked. Also, the dose is almost zero after a number of years, and this is due to the passing of a significant number of half-lives for each nuclide. Therefore, also a reduction to a significant extent of the radioactivity to be emitted can be expected.



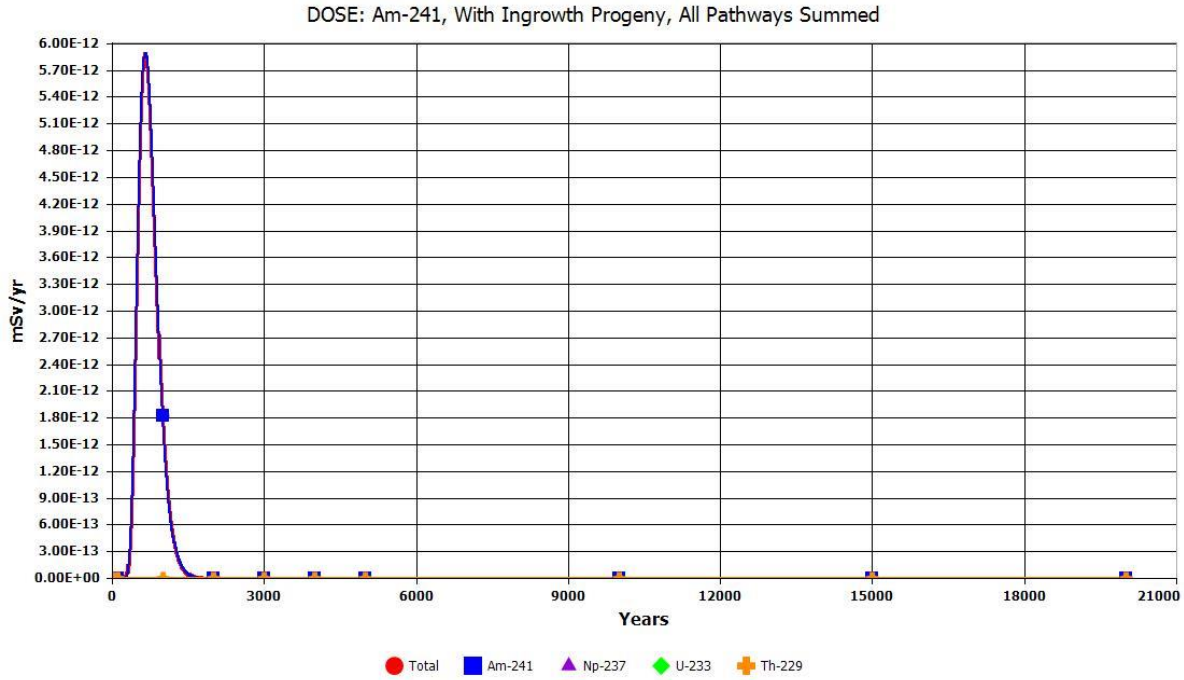
Graph 1: Total Dose for all nuclides as a function of time since the facility's closure

From **Graph 2**, which also includes the various exposure pathways, it appears that the pathways related to drinking water are primarily responsible for the individuals' exposure. Both in the first years after the sealing, and later(about 2000 years), this Is what gives the highest individualized dose according to the chart.

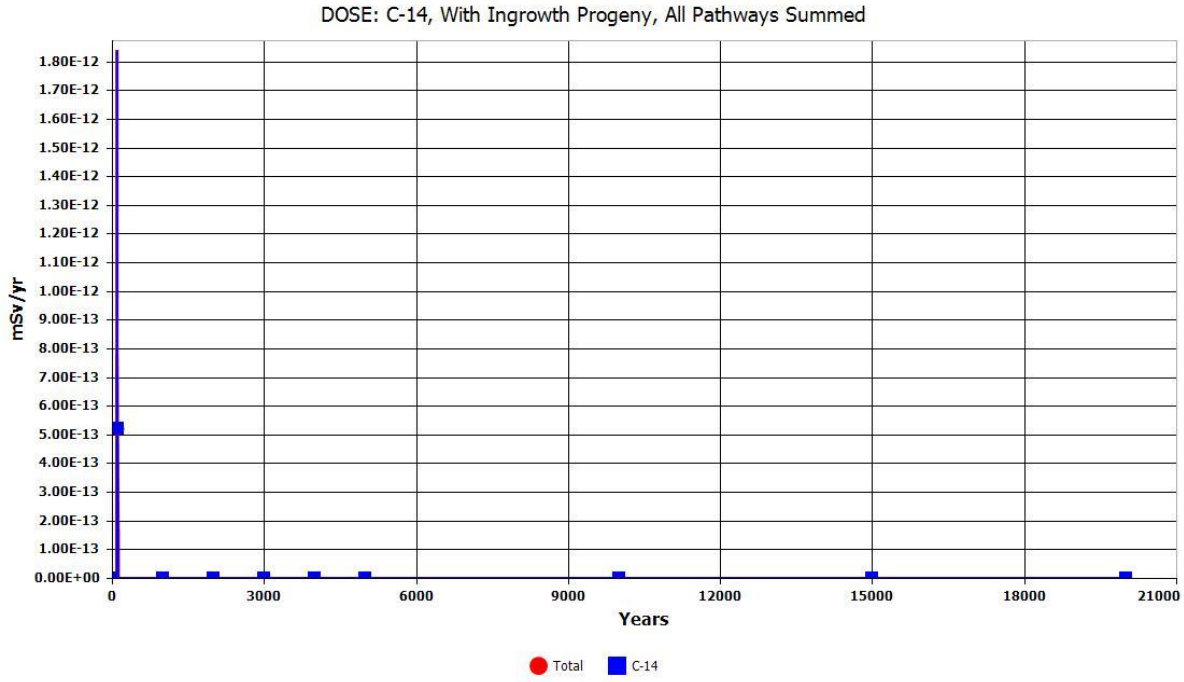


Graph 2: Total Dose for all nuclides as a function of time since the facility's closure with discrete values for each exposure pathway

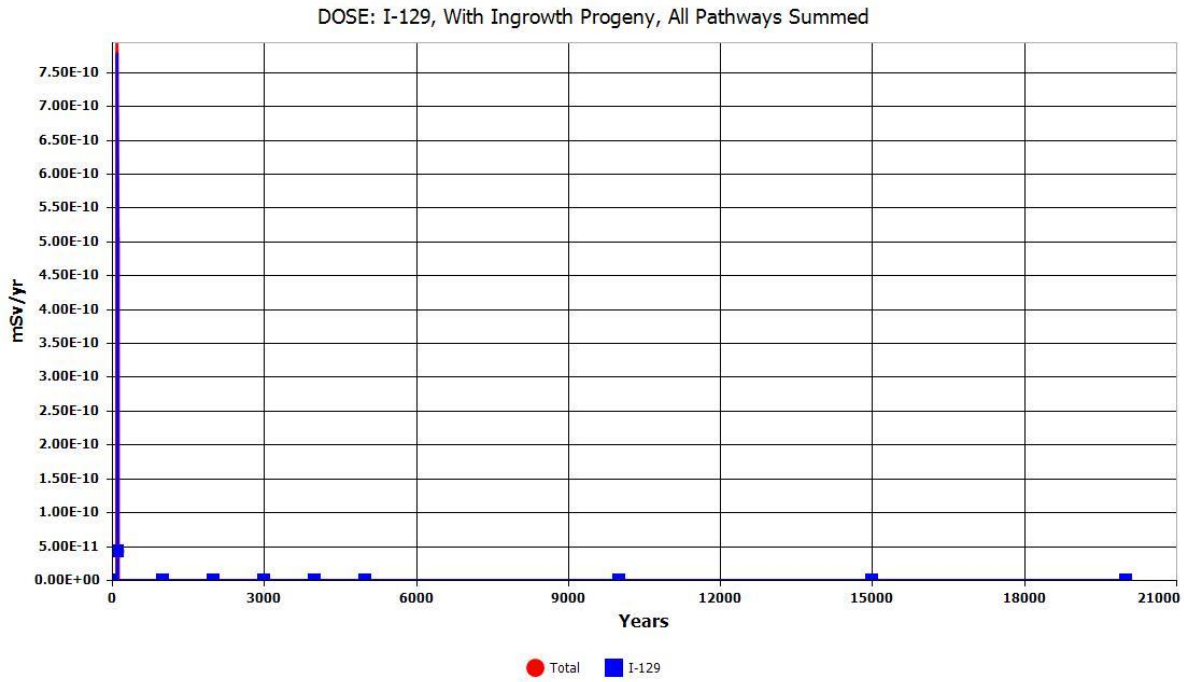
Below, one can observe graphs of some key nuclides that play a major role in the final dose's shaping.



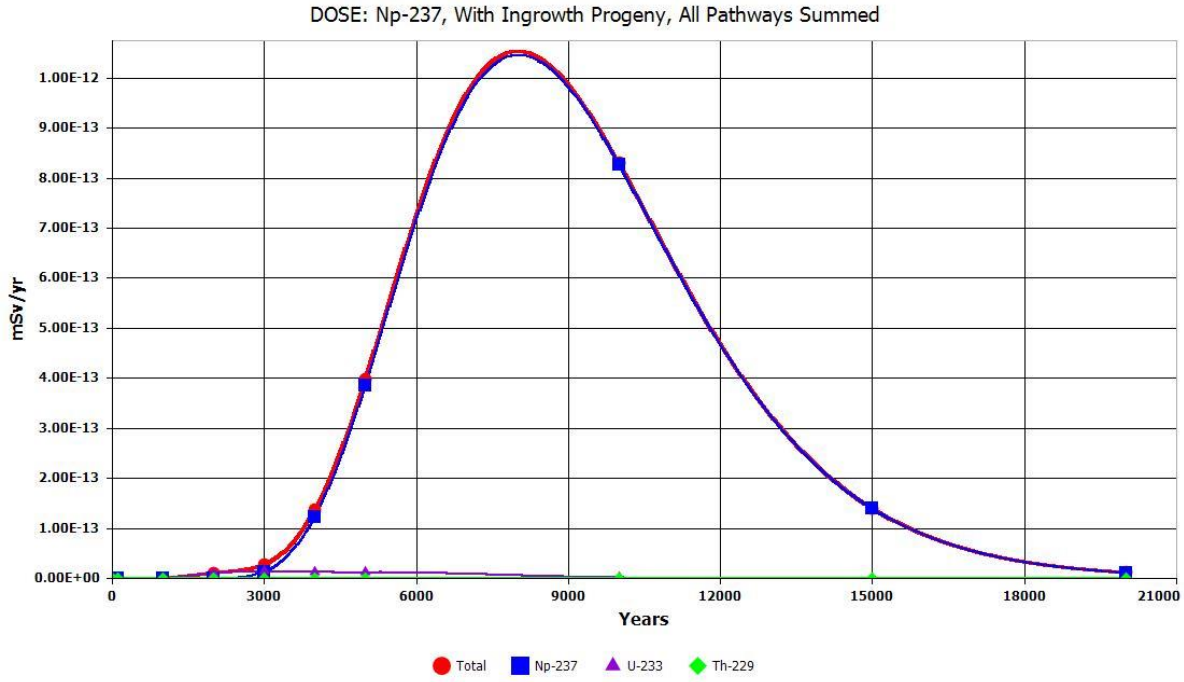
Graph 3: Contribution of Am-241 and its daughters to the total dose as a function of time



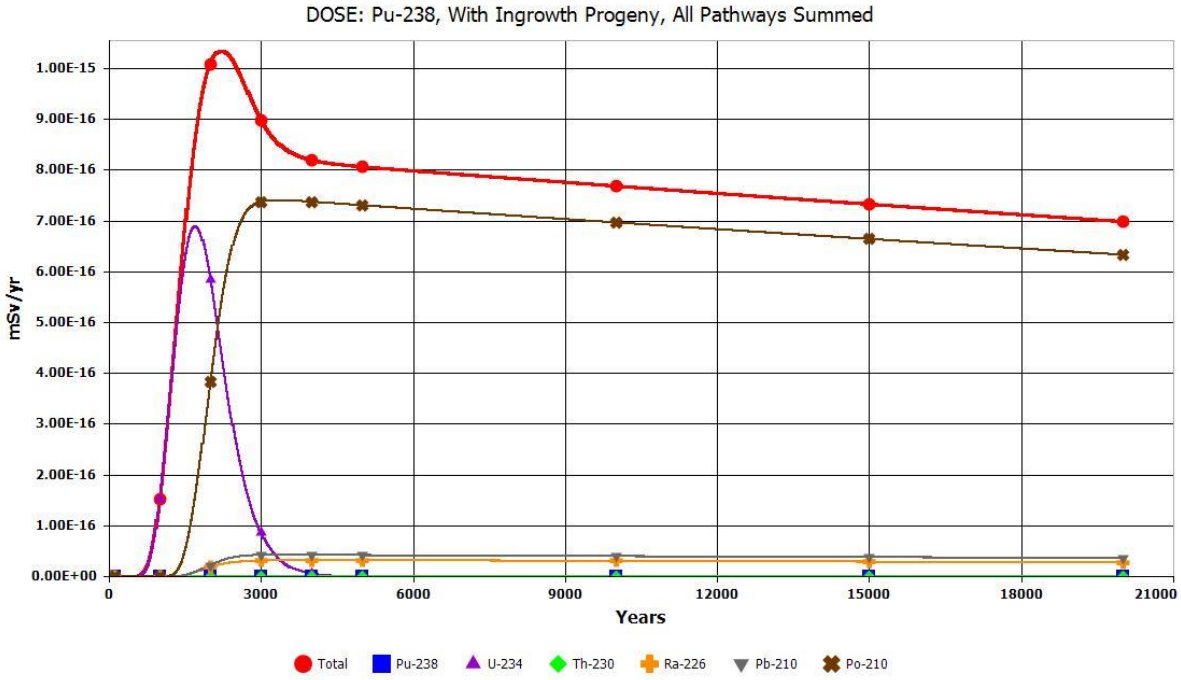
Graph 4: Contribution of C-14 to the total dose as a function of time



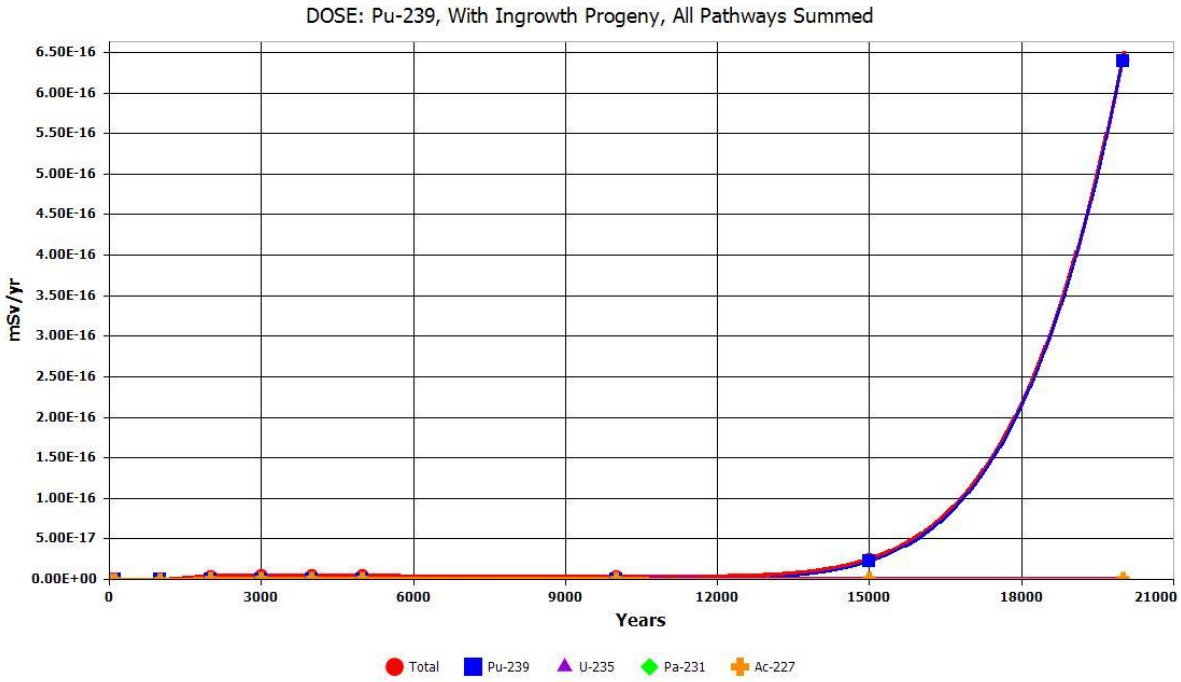
Graph 5: Contribution of I-129 to the total dose as a function of time



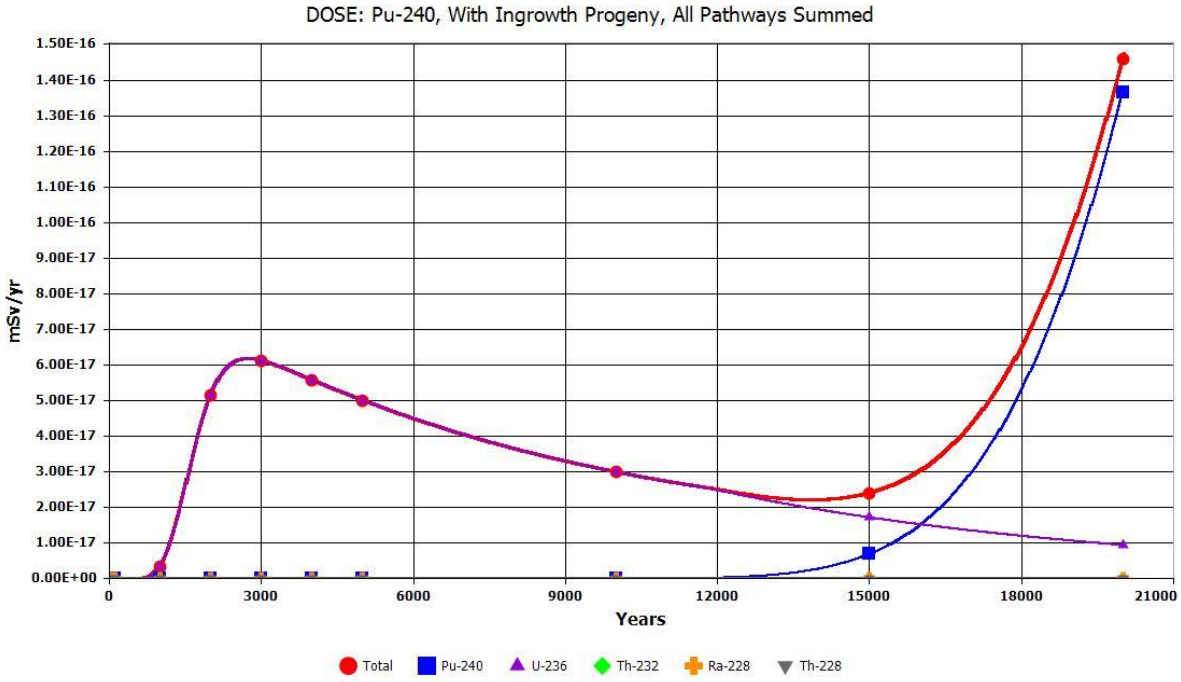
Graph 6: Contribution of Np-237 and its daughters to the total dose as a function of time



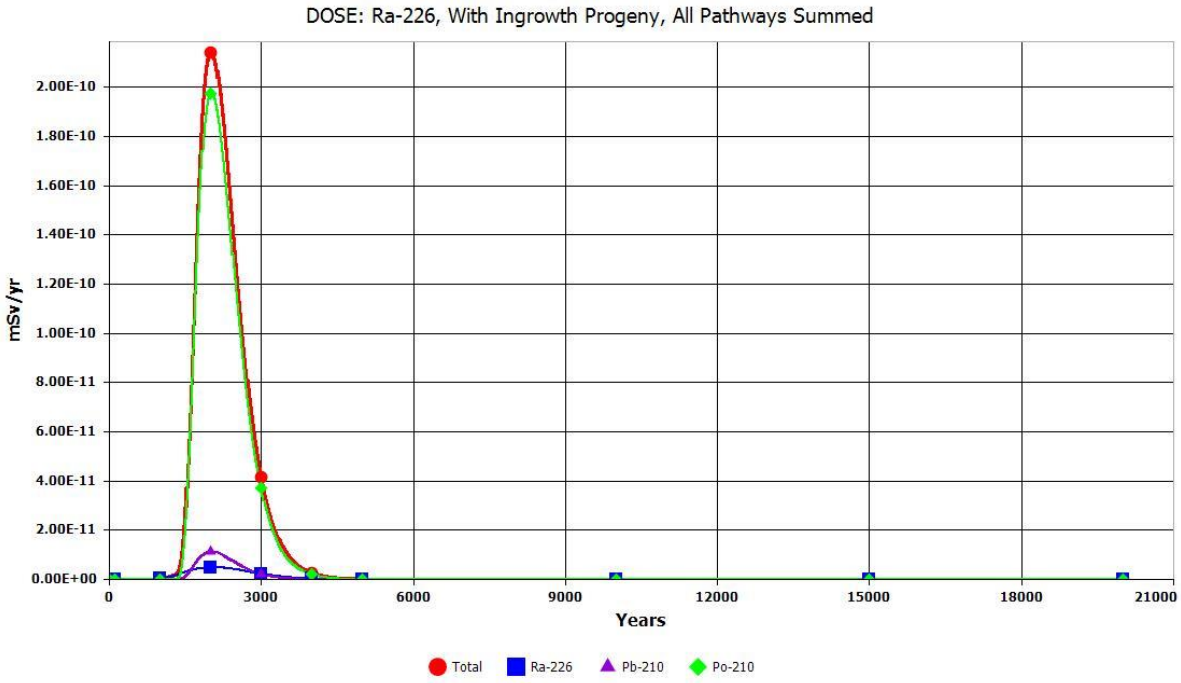
Graph 7: Contribution of Pu-238 and its daughters to the total dose as a function of time



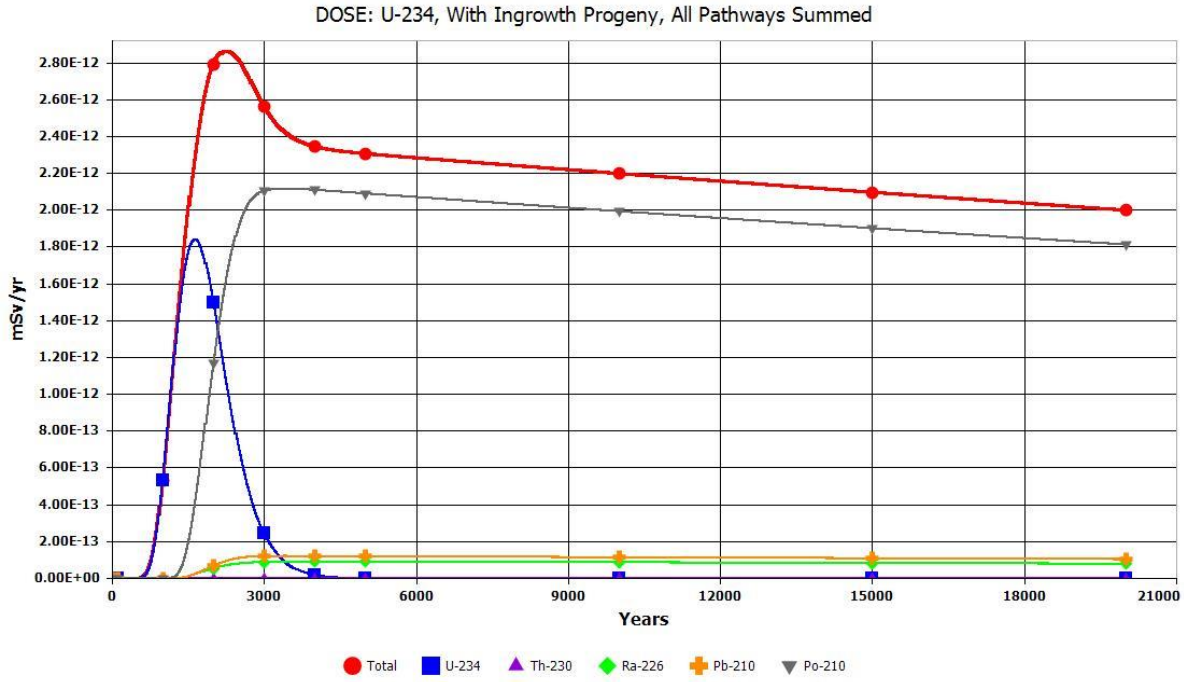
Graph 8: Contribution of Pu-239 and its daughters to the total dose as a function of time



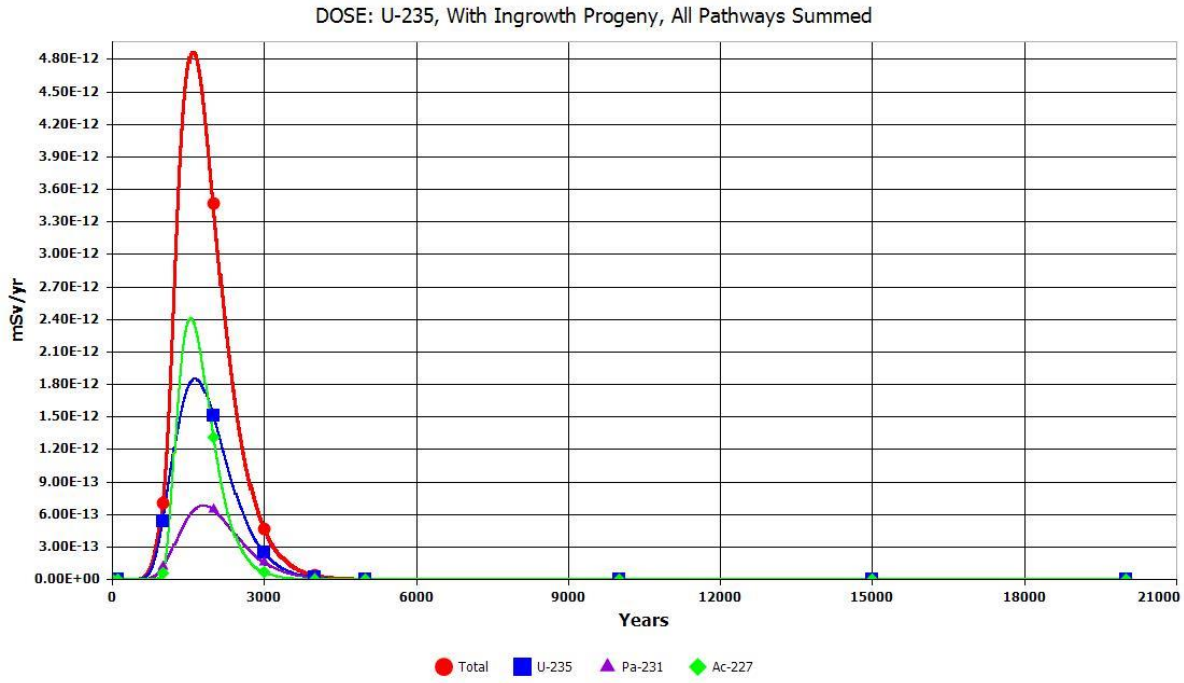
Graph 9: Contribution of Pu-240 and its daughters to the total dose as a function of time



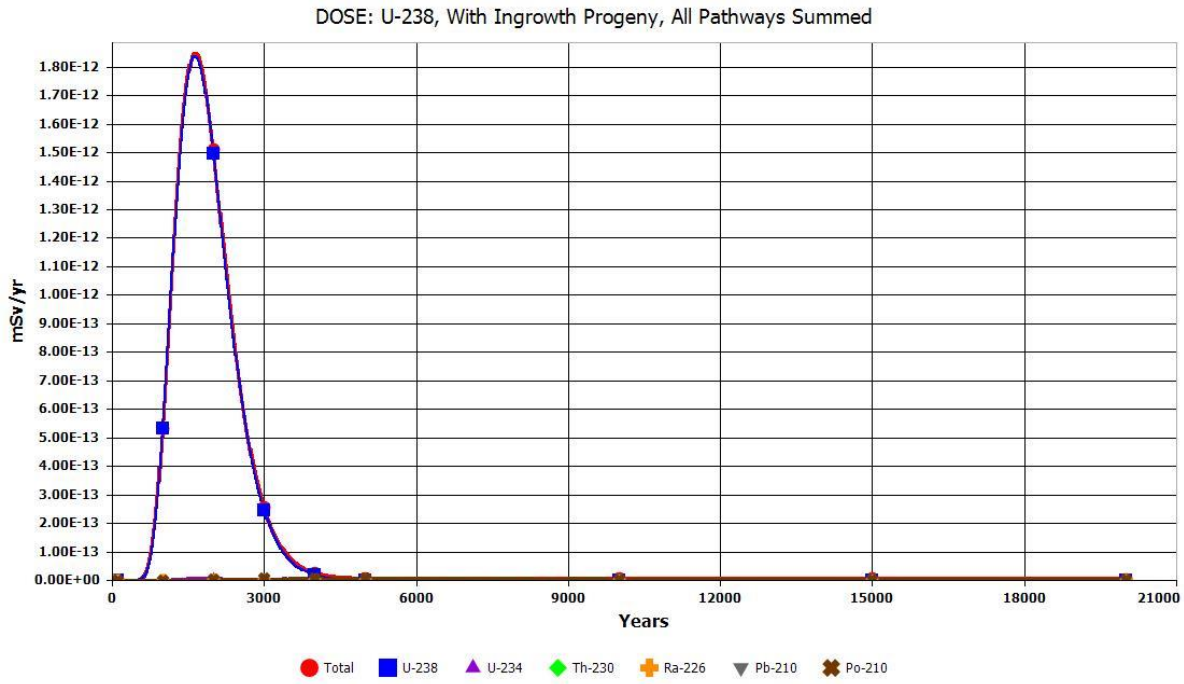
Graph 10: Contribution of Ra-226 and its daughters to the total dose as a function of time



Graph 11: Contribution of U-234 and its daughters to the total dose as a function of time



Graph 12: Contribution of U-235 and its daughters to the total dose as a function of time



Graph 13: Contribution of U-238 and its daughters to the total dose as a function of time

Some observations can be made about the shape of the graph for each nuclide.

The contribution of the most nuclides to the final dose is depicted by a graph of a single peak, after which a decrease in dose with time is observed(e.g. Graphs 3, 4, 5, 6, 7, 10, 11, 12, 13).

There is also the example of Graph 9, where after the first peak there is an increase in dose. In a longer time span(beyond this graph), a second peak is expected to appear, which is also followed by a drop in dose.

Also, the case of Graph 8 is encountered, where after a respectable period of a few thousand years, the dose appears and its curve tends to form a peak later.

In Graph 1(Total Dose), the form of two peaks is observed. The first peak corresponds to the radionuclides with high mobility inside the pores, i.e. those having a low value of the Kd constant. The second peak corresponds to the radionuclides with a higher value of Kd, which have a longer delay in their participation to the total dose, hence the later dose peak. Due to its lower height, we can conclude that the second category either contains a low number of radionuclides, or those that do not have the ability to give a large dose.

Below, a comparison between the results of the thesis and those of IAEA-TECDOC1380 is shown.

Table 21: Comparison of Deterministic Analysis and TECDOC1380 Results

Radionuclide	Thesis Results (Bq/g)	TECDOC1380 Results (Bq/g)	Results Ratio (IAEA/Thesis)
^{241}Am	7.942E+10	7E+14	8.82E+03
^{14}C	1.672E+11	9E+11	5.382
^{41}Ca	3.367E+13	2E+12	5.94E-02
^{60}Co	1.494E+15	1E+20	6.69E+04
^{134}Cs	2.232E+17	1E+20	448
^{137}Cs	3.154E+16	1E+20	3.170E+03
^{55}Fe	8.474E+30	1E+20	1.18E-11
^{3}H	7.518E+17	7E+11	9.31E-07
^{129}I	2.875E+10	4E+08	1.396E-02
^{94}Nb	2.232E+13	4E+12	0.1792
^{59}Ni	2.538E+15	3E+14	0.1182
^{63}Ni	1.706E+37	1E+20	5.86E-18
^{237}Np	6.329E+11	1E+11	0.158
^{238}Pu	5.181E+14	4E+13	7.72E-02
^{239}Pu	9.803E+14	1E+11	1.02E-04
^{240}Pu	4.149E+15	3E+11	7.23E-05
^{241}Pu	2.688E+12	2E+16	7.440E+03
^{226}Ra	2.923E+09	1E+12	342
^{228}Ra	3.623E+14	1E+20	2.76E+05
^{151}Sm	4.484E+36	1E+20	2.23E-17
^{90}Sr	6.097E+17	8E+13	1.312E-04
^{99}Tc	5.263E+13	2E+10	3.8E-04
^{232}Th	1.436E+14	3E+10	2.088E-04
^{234}U	2.212E+11	2E+10	9.04E-02
^{235}U	1.300E+11	2E+10	0.1538
^{238}U	3.436E+11	2E+11	0.582
^{93}Zr	2.347E+12	2E+12	0.852

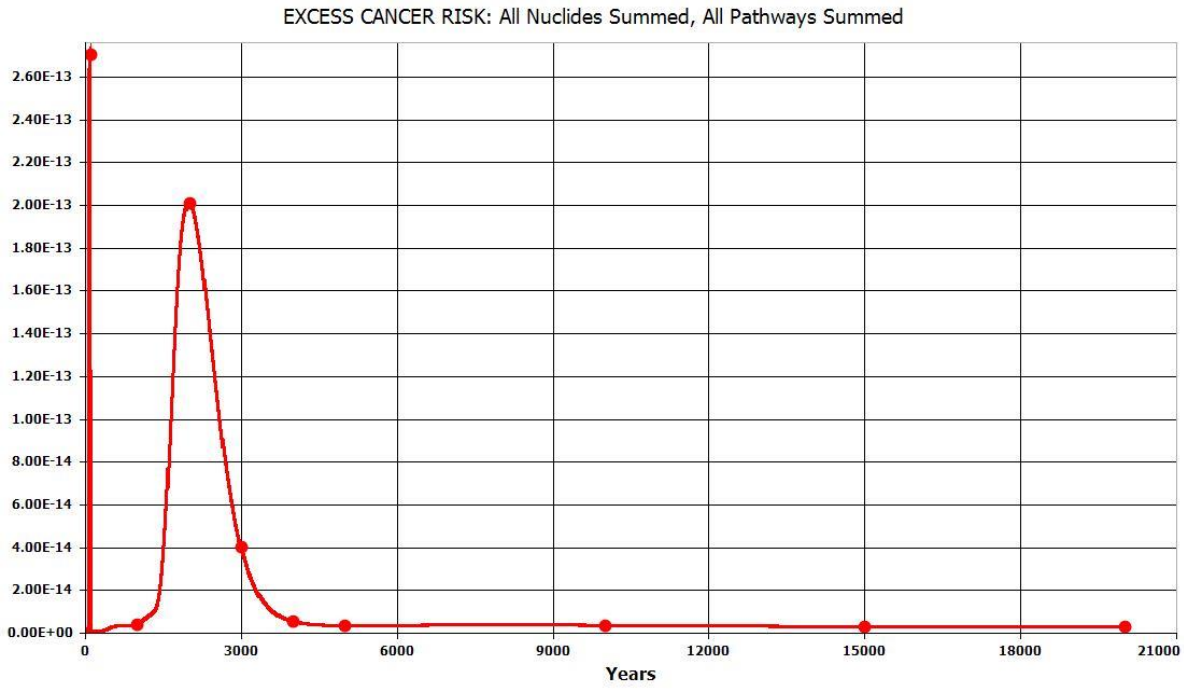
Through the results, one can form an image of the installation that corresponds to reality to a satisfactory degree. The radioactivity, to which residents in the wider area are

exposed, both for the institutional period of 100 years and for later periods, is very low. Compares to the average annual dose that a person receives today(2mSv), the results of the analysis have a much lower value. This fact is due to the low activity available from each nuclide, but one should not overlook the effectiveness of the specific waste management method.

In the simulation that took place, in order to be able to safely assess the risk faced by the residents of the area, the logic of a worst-case scenario was adopted. So, the calculations regard people who live very close to the location of the disposal facility, and therefore people who will receive a larger dose that those who live further away.

Also, a finding regarding the exposure pathways can be made. Here, pathways such as ingestion of meat, milk and plant products, inhalation of particles through radioactive plume circulating in the atmosphere, direct exposure due to radioactive soil above and right next to the facility etc. were considered. However, most of the dose received by each person is reduced to drinking water, as it can be seen in Graph 2. This is due to the design basis of this scenario, as the phenomenon of leaching takes place. When using the well for drinking water intake, exposure to radioactivity is obvious. Subsequently, in order of "responsibility", follow the ingestion of vegetables and meat. These are ranked so high because of the water that can be stored inside them. The remaining pathways play almost no part in the final results formation.

Then, exposing a person to radiation can many times lead to cancer development. Graph 14 shows the risk of cancer development for a person receiving dose from the facility. These results concern estimates per unit of initial disposal activity.



Graph 14: Risk of Cancer Development for a person receiving dose from the facility as a function of exposure time

In general, the average lifetime probability of cancer development for an individual is between 10^{-5} and 10^{-6}, in a non-occupational exposure scenario, where the probability value is multifactorial.
According to Graph 14, the probability of cancer development for people participating in this simulation lies around 10^{-13}, which is directly related to the small value of the dose calculated previously. Compared to the average probability, this value could be used for a rough estimation of the effects based on some real stock.

4.2 Results of Uncertainty/Probabilistic Analysis

In the Uncertainty Analysis, significant differences are found compared to the Deterministic.

In the Uncertainty Analysis Scenario, 27 simulations took place(one for each available radionuclide). Here too, the same disposal facility for all nuclides is being studied, but, in this case, individually for each one of them.

Instead of limiting the analysis to a description of the best-case or worst-case scenario, through the introduction of uncertainty, it is possible to analyse each case in between. This analysis takes place based on the probability distribution for each of these cases, while the

calculation time for the distribution also needs to be specified. The calculation time is expected to be longer than that in the Deterministic Analysis. It is also based on dispersion models or experimental dispersions.

As before, the thesis' spine is reduced to the comparison of the results of our analyses with those of TECDOC1380. The parameters are the same as those of the previous analysis, as it is again necessary to compare the two scenarios as accurately as possible. However, for the sake of a complete description and completion of the analysis, it is also required to determine it from a statistical point of view.

Each variable is defined statistically through its Mean Value, its Standard Deviation and Upper-Lower Quantiles. Their values are taken from an external source(NUREG/CR-7267). The distribution of each of these statistical elements is used to generate some theoretically possible outcomes for the given scenario.

Input Rank Correlation, as shown in Table 20, helps measure the strength and direction of the relationship between two ranked variables. Essentially, it gives the measure of monotonicity between variables, that is, how well the relationship between them could be expressed using a monotonic function. It is shown by the Correlation Coefficient R^2, which is taken equal to 0.9999 for each pair of variables, so that the correlation between them is optimal.

In Table 21, one can recognise the results of the technical document, their analysis and comparison with those of the thesis. In general, as expected, there is some discrepancy between the two, which is due both to the variables takes as defaults by the software or as user inputs, and to the software itself, since the procedure followed for the extraction of the TECDOC1380 results is not known to us, and a failsafe should always be a part of the study. In particular, due to the longer maximum reference time in the present analysis(20.000 years after the end of the institutional period), lower levels of radioactivity per unit mass are observed, given the decays that take place in this time period.

Also worth mentioning is the difference between the maximum dose for each nuclide in the Deterministic Analysis and the Uncertainty Analysis. In fact, in the latter, a higher dose per unit mass is generally observed. Again, however, the doses turn out to be very small compared to the average dose a person receives on a yearly basis(2-6mSv).

Table 22 presents the results of the Uncertainty Analysis for each nuclide individually. For each nuclide, the peak of the annual dose is given, along with the time it appears, the concentration that came up from the simulations, the concentration that is written in the Technical Document and corresponds to 1mSv per year, the ratio of the two latter, the

mean[8] and median[9] values of the results, and the corresponding graph's peak in the Deterministic Analysis.

Table 22: Uncertainty Analysis Results

Nuclide	Max Dose (mSv/year)	Max Dose Time (year)	Concentration Analysis (Bq/g)	Concentration TECDOC1380 (Bq/g)	Ratio	Mean Value	Median Value	Deterministic Peak
^{241}Am	4.19E-11	231	2.39E+10	7.00E+14	2.93E+04	8.39E-13	1.69E-17	1.26E-11
^{14}C	4.7E-12	103	2.13E+11	9.00E+11	4.23E+00	5.78E-14	0	5.98E-12
^{41}Ca	5.72E-14	218	1.75E+13	2.00E+12	1.14E-01	1.22E-14	2.59E-15	2.97E-14
^{60}Co	6.69E-16	9.78	1.49E+15	1.00E+20	6.69E+04	6.69E-16	6.69E-16	6.69E-16
^{134}Cs	4.48E-18	9.78	2.23E+17	1.00E+20	4.48E+02	4.48E-18	4.48E-18	4.48E-18
^{137}Cs	2.95E-15	125	3.39E+14	1.00E+20	2.95E+05	5.89E-17	2.53E-17	3.17E-17
^{55}Fe	9.17E-28	148	1.09E+27	1.00E+20	9.17E-08	1.83E-29	9.93E-33	1.18E-31
^{3}H	1.2E-18	144	8.33E+17	7.00E+11	8.4E-07	1.24E-19	5.54E-23	1.33E-18
^{129}I	3.67E-11	100	2.72E+10	4.00E+08	1.47E-02	1.12E-12	1.94E-18	3.49E-11
^{94}Nb	1.98E-14	132	5.05E+13	4.00E+12	7.92E-02	3.96E-16	1.9E-16	4.48E-14
^{59}Ni	1.85E-15	5290	5.41E+14	3.00E+14	5.55E-01	1.7E-16	3.13E-22	3.94E-16
^{63}Ni	2.08E-16	237	4.81E+15	1.00E+20	2.08E+04	4.17E-18	0	5.86E-38
^{237}Np	3.63E-12	156	2.75E+11	1.00E+11	3.63E-01	8.03E-13	2.18E-13	1.58E-12
^{238}Pu	1.88E-14	340	5.32E+13	4.00E+13	7.52E-01	7.85E-16	4.56E-17	1.93E-15
^{239}Pu	1.03E-12	739	9.71E+11	1.00E+11	1.03E-01	6.72E-14	4.35E-18	1.02E-15
^{240}Pu	7.85E-13	948	1.27E+12	3.00E+11	2.36E-01	1.86E-14	2.52E-17	2.41E-16
^{241}Pu	5.74E-13	487	1.74E+12	2.00E+16	1.15E+04	2.87E-14	4.28E-18	3.72E-13
^{226}Ra	2.4E-10	2950	4.17E+09	1.00E+12	2.40E+02	5.45E-12	1.59E-15	3.42E-10
^{228}Ra	2.76E-15	9.78	3.62E+14	1.00E+20	2.76E+05	2.76E-15	2.76E-15	2.76E-15

[8] The Mean Value is the integral of a continuous function of one or more variables over a given study range, divided by that range.

[9] The Median Value is the average value of a group of numbers ordered by size. It is the number that is exactly in the middle, so that 50% of the number are above it and the remaining 50% are below it.

^{151}Sm	3.39E-16	156	2.95E+15	1.00E+20	3.39E+04	6.79E-18	0	2.23E-37
^{90}Sr	3.27E-13	129	3.06E+12	8.00E+13	2.62E+01	6.59E-15	3.08E-21	1.64E-18
^{99}Tc	1.9E-14	112	5.26E+13	2.00E+10	3.80E-04	1.76E-15	9.61E-20	1.9E-14
^{232}Th	7.59E-12	20000	1.32E+11	3.00E+10	2.28E-01	8.49E-13	6.95E-15	6.96E-15
^{234}U	4.02E-11	20000	2.49E+10	2.00E+10	8.04E-01	2.72E-12	9.91E-14	4.52E-12
^{235}U	8.82E-12	2790	1.13E+11	2.00E+10	1.76E-01	7.19E-13	3.12E-14	7.69E-12
^{238}U	5.47E-12	206	1.83E+11	2.00E+11	1.09E+00	3.76E-13	1.22E-14	2.91E-12
^{93}Zr	4.12E-13	13200	2.43E+12	2.00E+12	8.24E-01	8.17E-14	2.04E-14	4.26E-13

Coming to the comparison of the results with those of TECDOC1380, one easily observes through Table 22, that the differences between the two studies are obvious. Similar to the previous analysis, these differences are mainly due to the user's inputs in the software, as variables that are not listed in the document were also introduced. Furthermore, some observations can be made about the facility's behaviour and the radionuclides within it.

Initially, the radionuclides are located within the disposal facility. Through the exposure pathways listed in Chapter 3.1, each one of them escapes and reaches the well water. The rate, at which each nuclide escapes depends on the distribution coefficient K_d. If this coefficient has a low value, the nuclide is rapidly transferred to the installation's water. As can be seen in Graphs 7, 10, 22, 43 and 46, nuclides that give their dose relatively early are ^{14}C, ^{129}I, ^{232}Th, ^{137}Cs, ^{55}Fe. Otherwise, for higher values of K_d, we have a slower transfer of the nuclide. Typical examples are ^{237}Np, ^{239}Pu and ^{59}Ni, which are shown in Graphs 13, 16 and 55 respectively.

Then, an important factor for the final dose's shaping is the half-life of each nuclide. If its half-life is short, by the time it reaches the facility water, its activity will have been significantly reduced and will not play a key role in the final dose formation. Such nuclides are ^{232}Th, ^{137}Cs and ^{63}Ni, whose doses are given in Graphs 22, 43 and 58 respectively. On the contrary, if the nuclide has a long half-life, the activity will not have time to decrease significantly until the nuclide's arrival in the water, making its participation in the final dose crucial. Such examples are shown in Graphs 4, 10 and 19, for the respective nuclides ^{241}Am, ^{129}I and ^{226}Ra.

The thesis results show more activity than those of the technical document. This happens because of the possible production of a particular nuclide as a daughter of other nuclides, or because of its very long half-life. Then, it does not have time to have any significant rate of decay. To overcome this "anomaly", the number of reference points within the time span was increased. These points were left equal to 2048(on a linear axis) for the most

nuclides that did not present this problem. In this case, however, regarding the rest of the radionuclides used in this thesis, it was required to increase the number of points to 8192 on a linear axis as well, so that there is a good discrimination between the values at the reference checkpoints used in this study.

In general, due to the shorter and more condensed study reference times in the technical document, the results of the present study are expected to show higher amounts of radioactivity with respect to TECDOC1380.

As far as the graphs are concerned, these are the most "direct" results of the analysis, as they can give a clear picture of the role of each nuclide in shaping the final dose.

For each nuclide, 3 graphs are given.

1)The Graph of Total Dose due to the nuclide and its daughters as a function of time, where each exposure pathway listed in Chapter 3.1 is taken into account. The objective of this particular graph is the showing of the nuclide's and its daughters' participation in the analysis, thus the dose that the individual will receive, as well as the time that it will be maximized. Those graphs are the following: Graph 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 45, 48, 51, 54, 57, 60, 63, 66, 69, 72, 75, 78, 81, 84, 87, 90, 93.

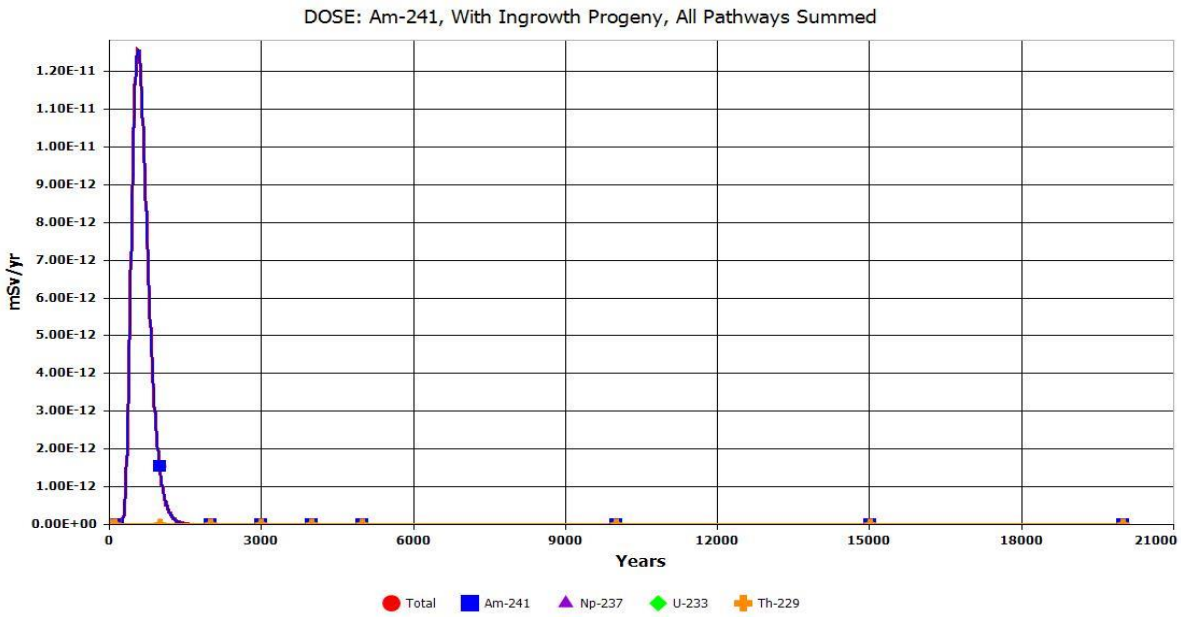
2) The Graph of the Median Value of the dose due to each nuclide, as a function of time for the three repetitions of the analysis. Based on the procedure of its calculation, which is described in Chapter 3, the median value indicates the central value of the nuclide's dose. Thus, a statistical analysis of the doses over time can be made and compared to this central value. Those graphs are the following: Graph 16, 19, 22, 25, 28, 31, 34, 37, 40, 43, 46, 49, 52, 55, 58, 61, 64, 67, 70, 73, 76, 79, 82, 85, 88, 91, 94.

3) The Graph of the Mean value [10] of the dose due to each nuclide, as a function of time for the three repetitions of the analysis. The mean value is used to give an average indicative description of the scenario, so that one can do quick calculations without having to go deep into the analysis. Those graphs are the following: Graph 17, 20, 23, 26, 29, 32, 35, 38, 41, 44, 47, 50, 53, 56, 59, 62, 65, 68, 71, 74, 77, 80, 83, 86, 89, 92, 95.

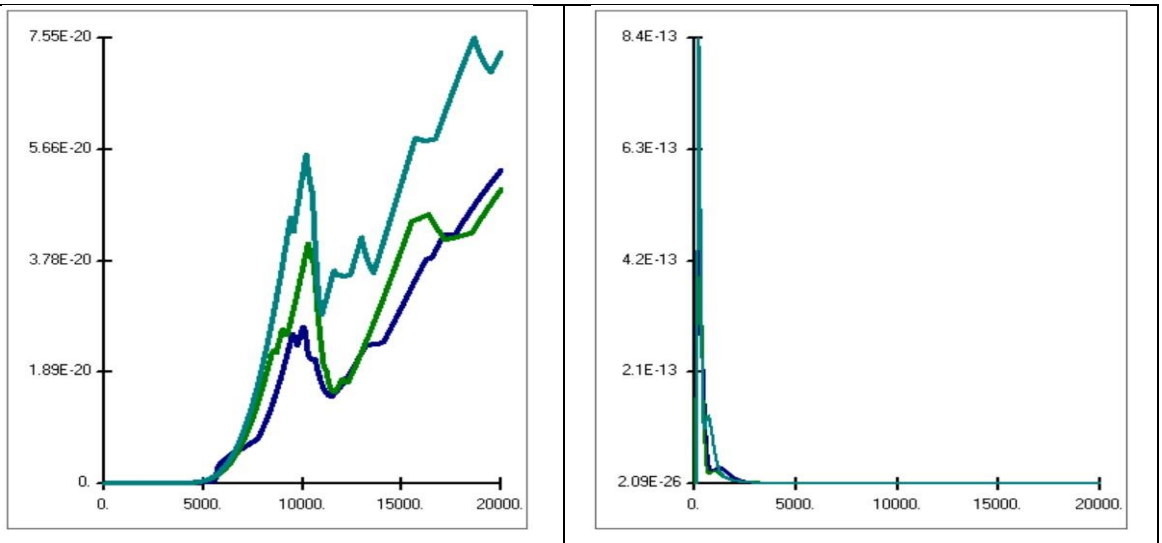
Below, the graphs of the nuclides that have the most significant contribution to the total dose are shown. The rest nuclides can be found in the appendix.

[10] By comparing the Mean and Median values, one can get an idea of the dose distribution.

^{241}Am

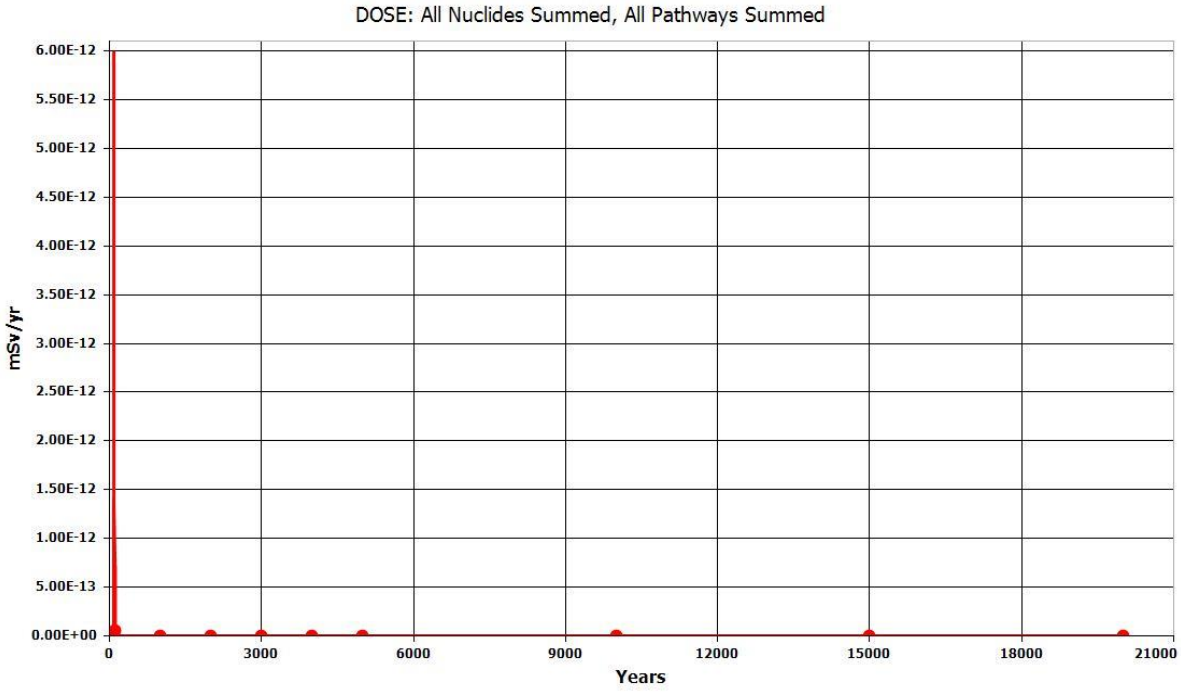


Graph 15: Total Dose due to ^{241}Am and its daughters as a function of time

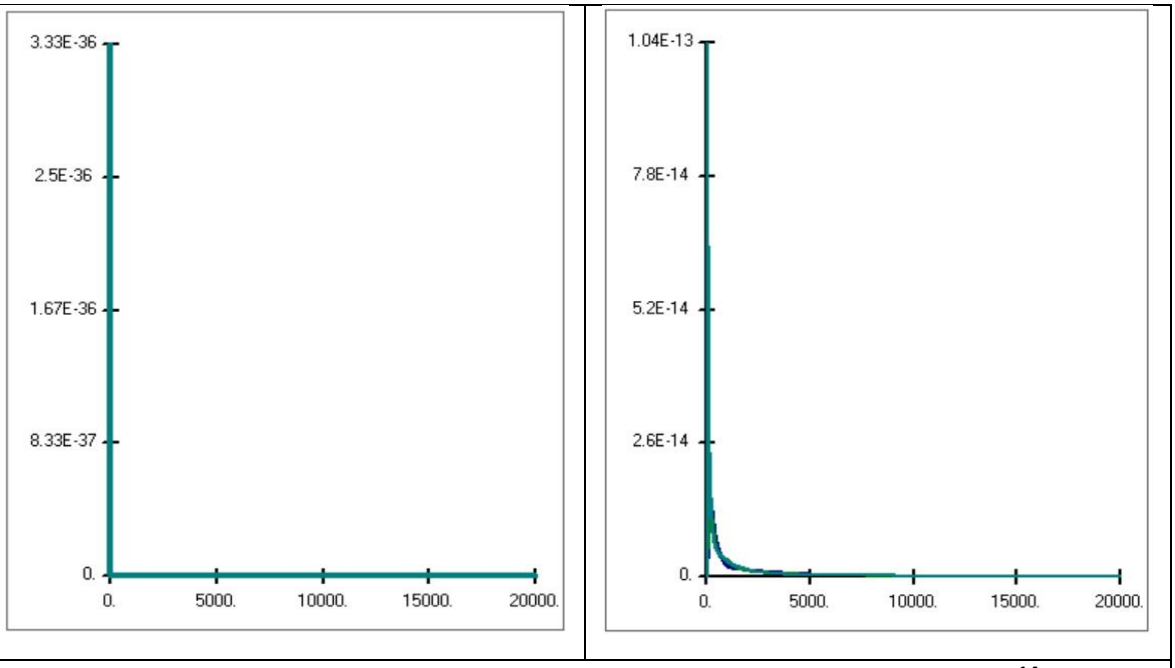


Graph 16-17: Median(left) and Mean(right) value of the total dose due to ^{241}Am and its daughters as a function of time

^{14}C

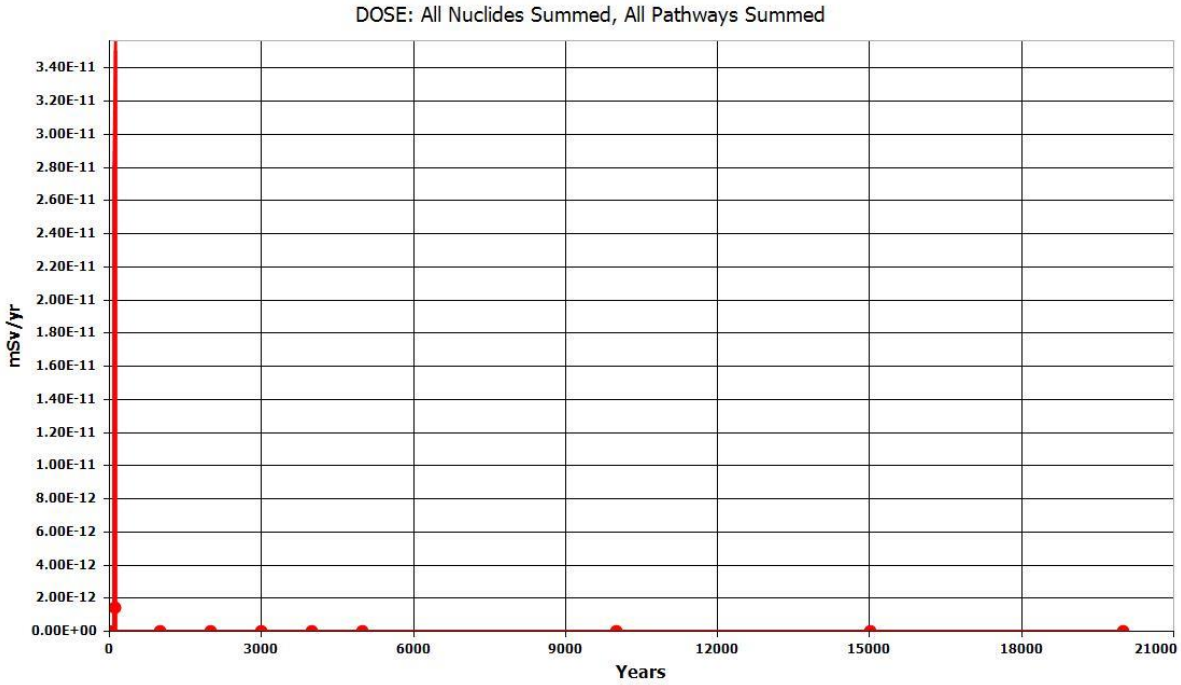


Graph 18: Total dose due to ^{14}C as a function of time

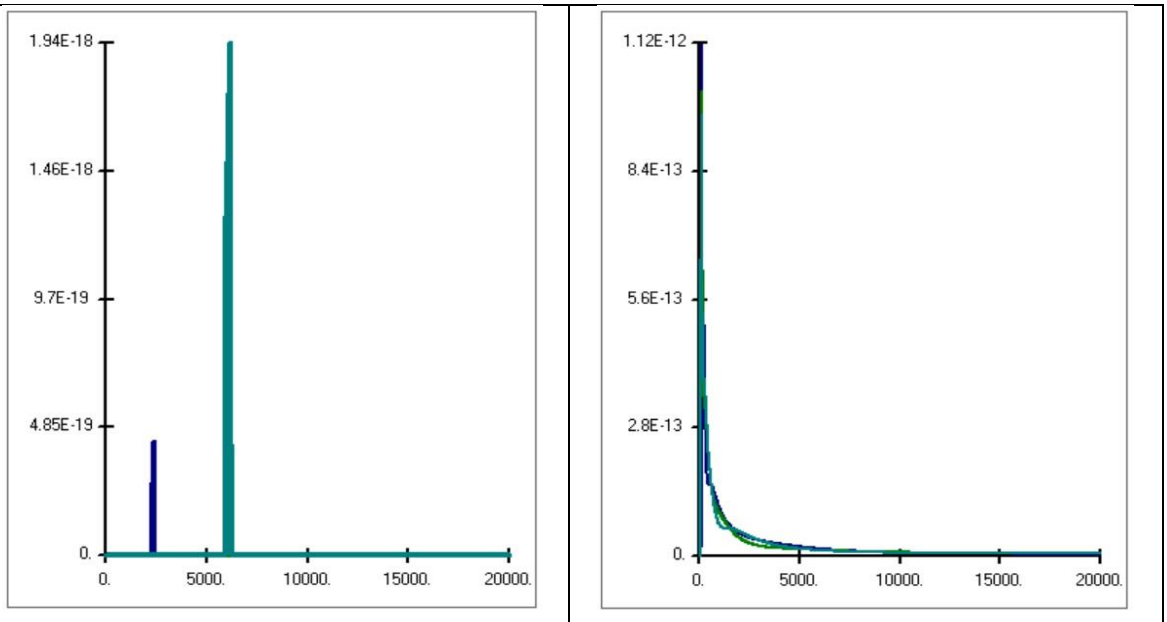


Graph 19-20: Median(left) and Mean(right) value of the total dose due to ^{14}C as a function of time

^{129}I

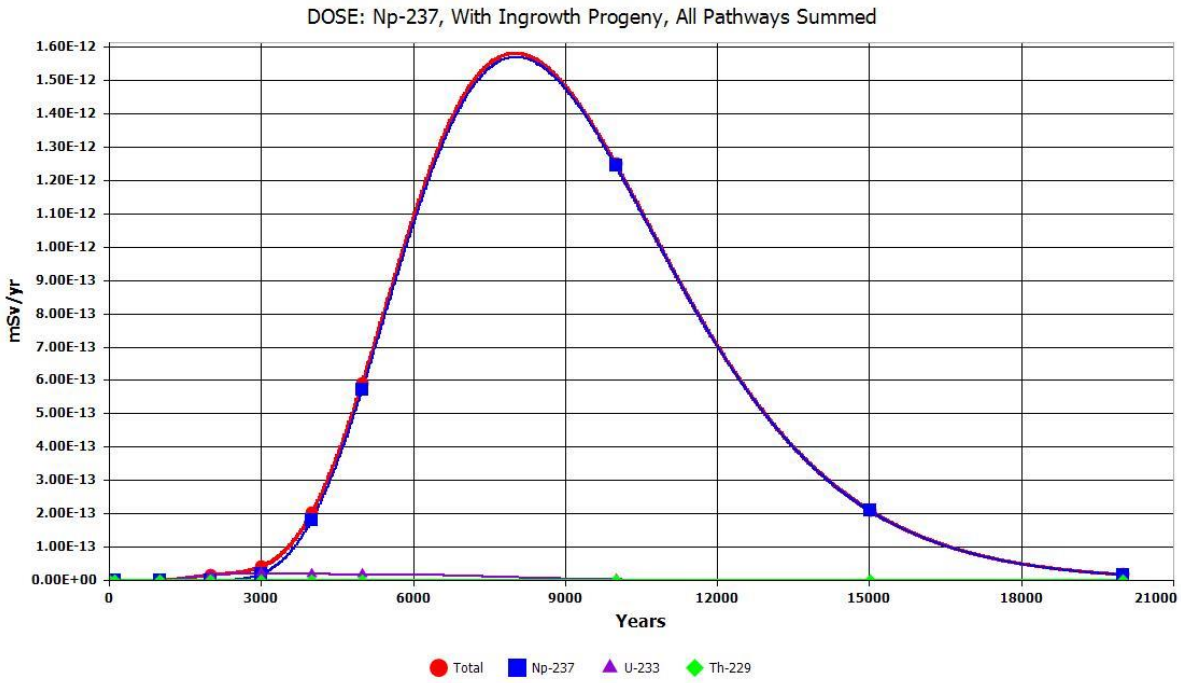


Graph 21: Total dose due to ^{129}I as a function of time

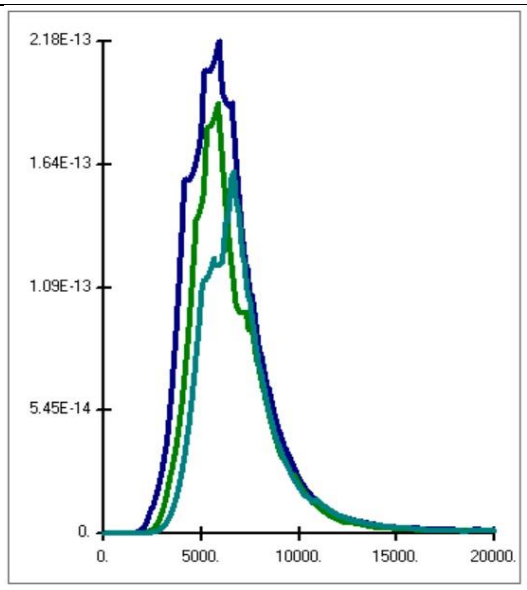


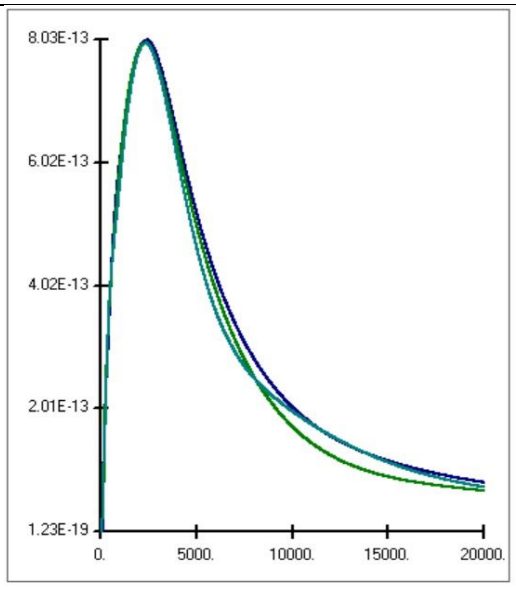
Graph 22-23 : Median(left) and Mean(right) value of the total dose due to ^{129}I as a function of time

^{237}Np



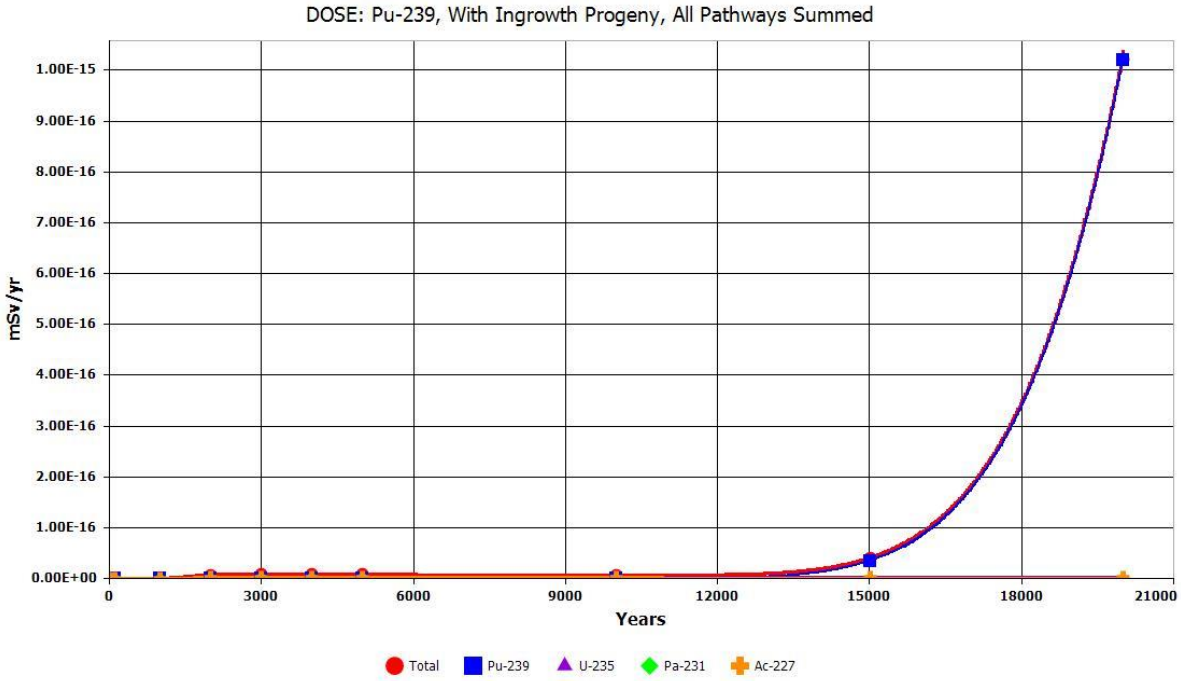
Graph 24: Total dose due to ^{237}Np and its daughters as a function of time



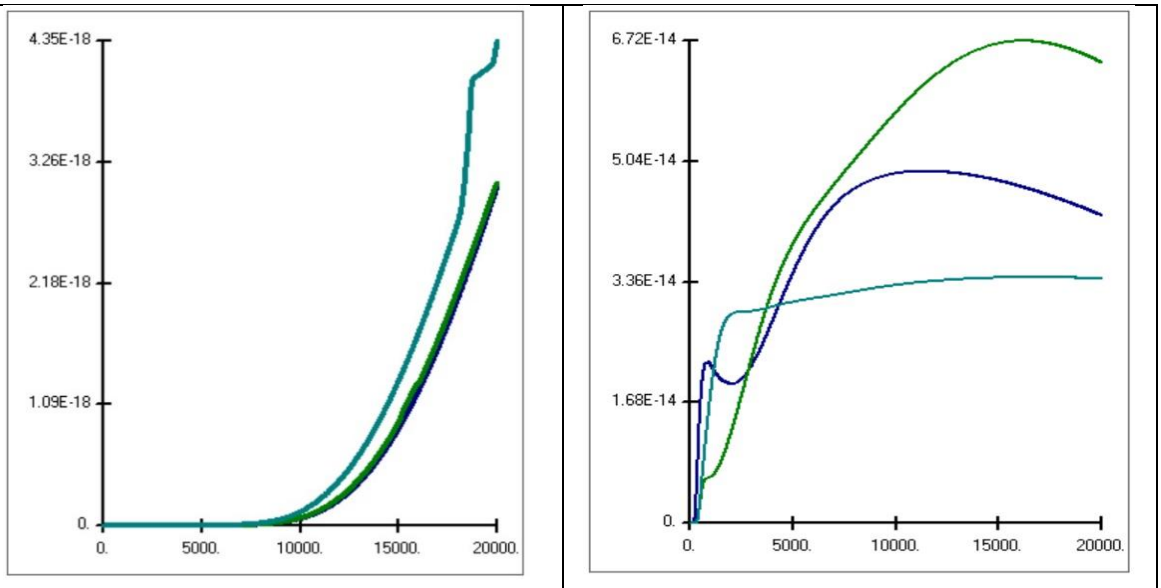


Graph 25-26: Median(left) and Mean(right) value of the total dose due to ^{237}Np and its daughters as a function of time

^{239}Pu

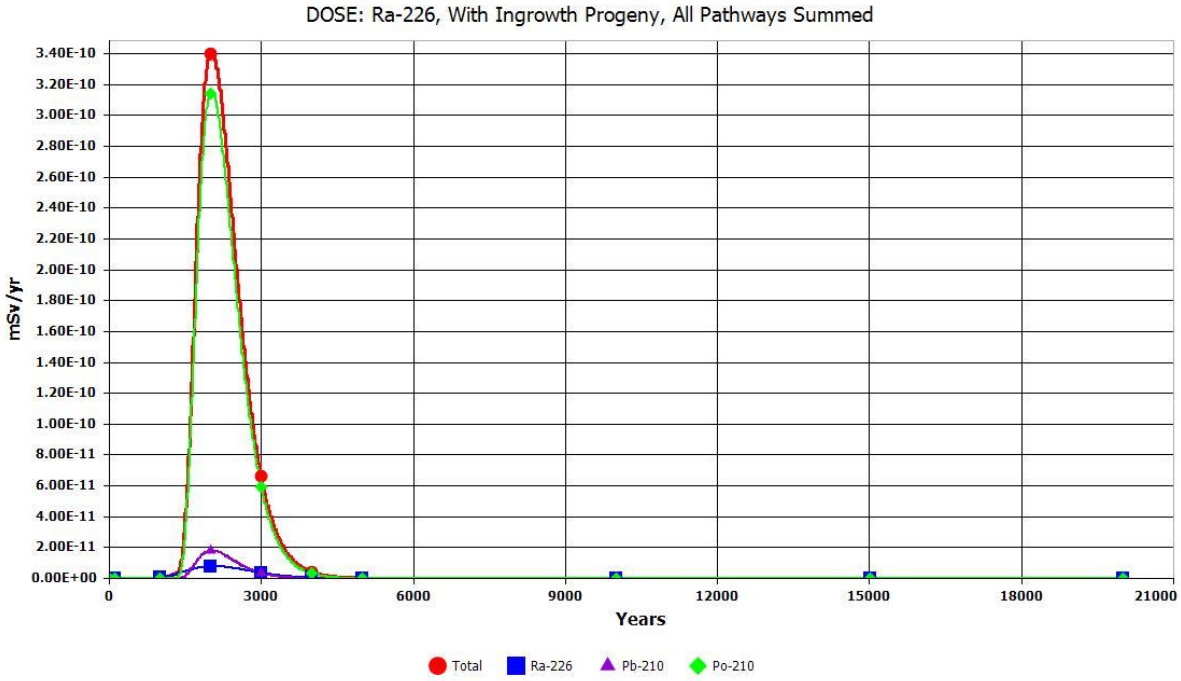


Graph 27: Total dose due to ^{239}Pu and its daughters as a function of time

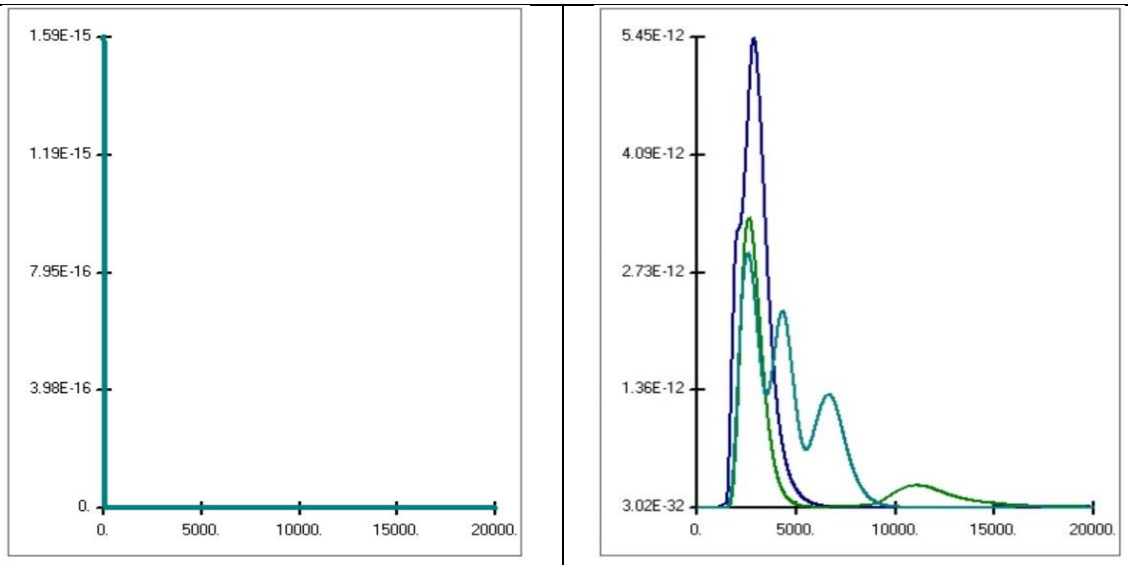


Graph 28-29: Median(left) and Mean(right) value of the total dose due to ^{239}Pu and its daughters as a function of time

^{226}Ra

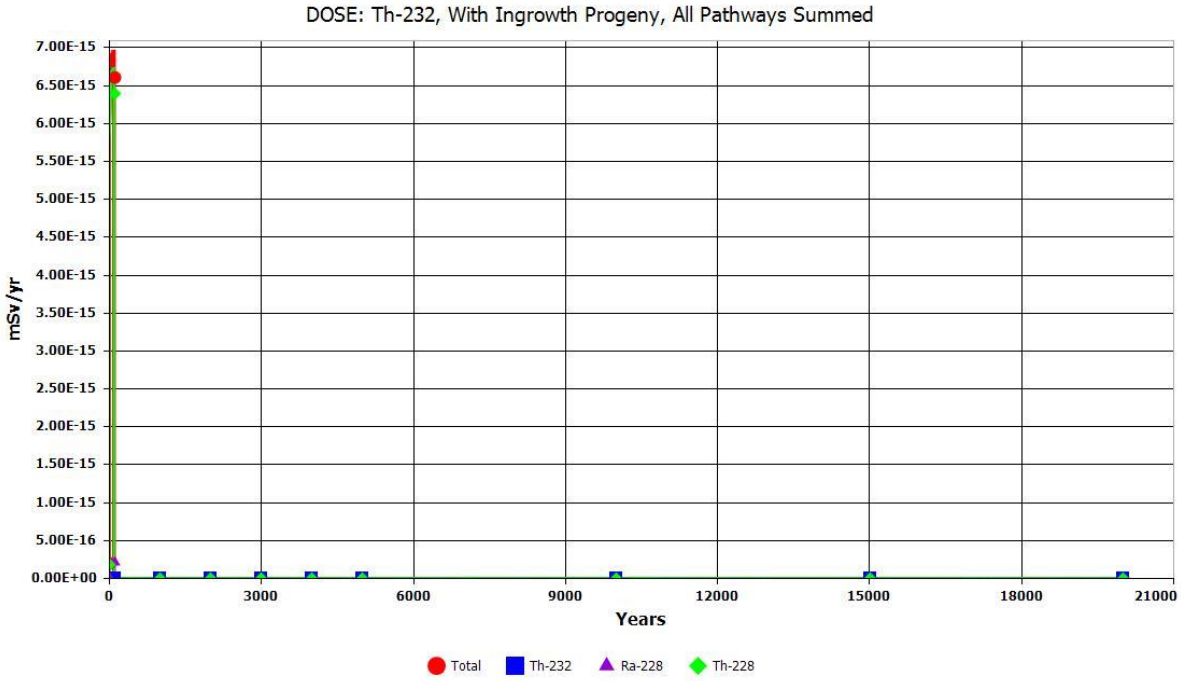


Graph 30: Total dose due to ^{226}Ra and its daughters as a function of time

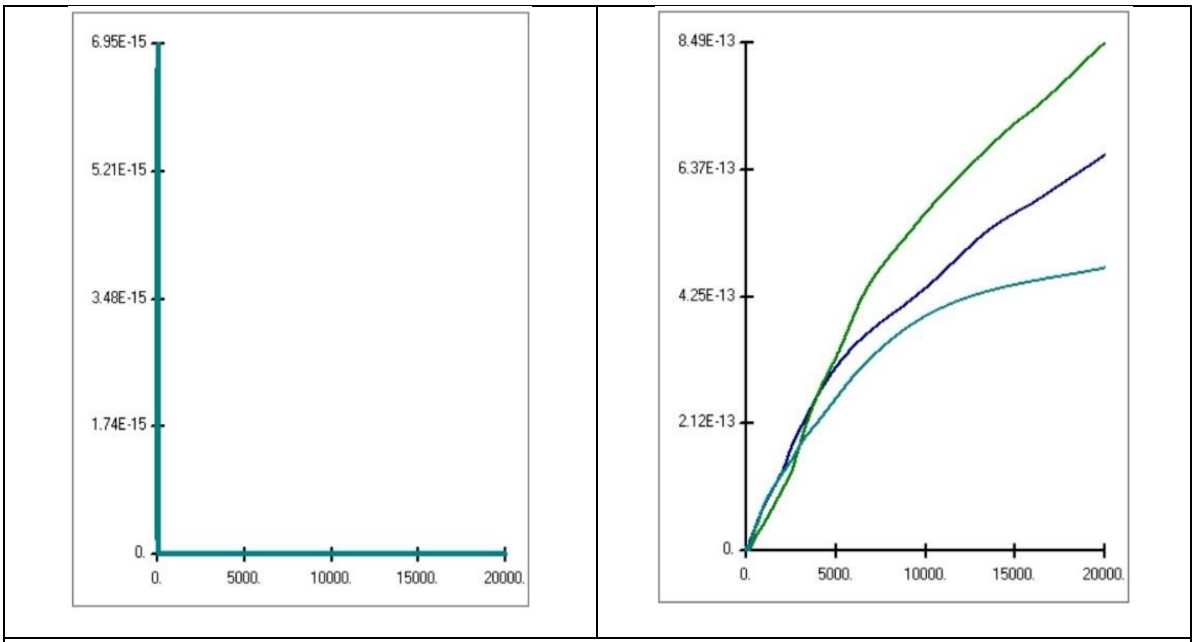


Graph 31-32: Median(left) and Mean(right) value of the total dose due to ^{226}Ra and its daughters as a function of time

^{232}Th

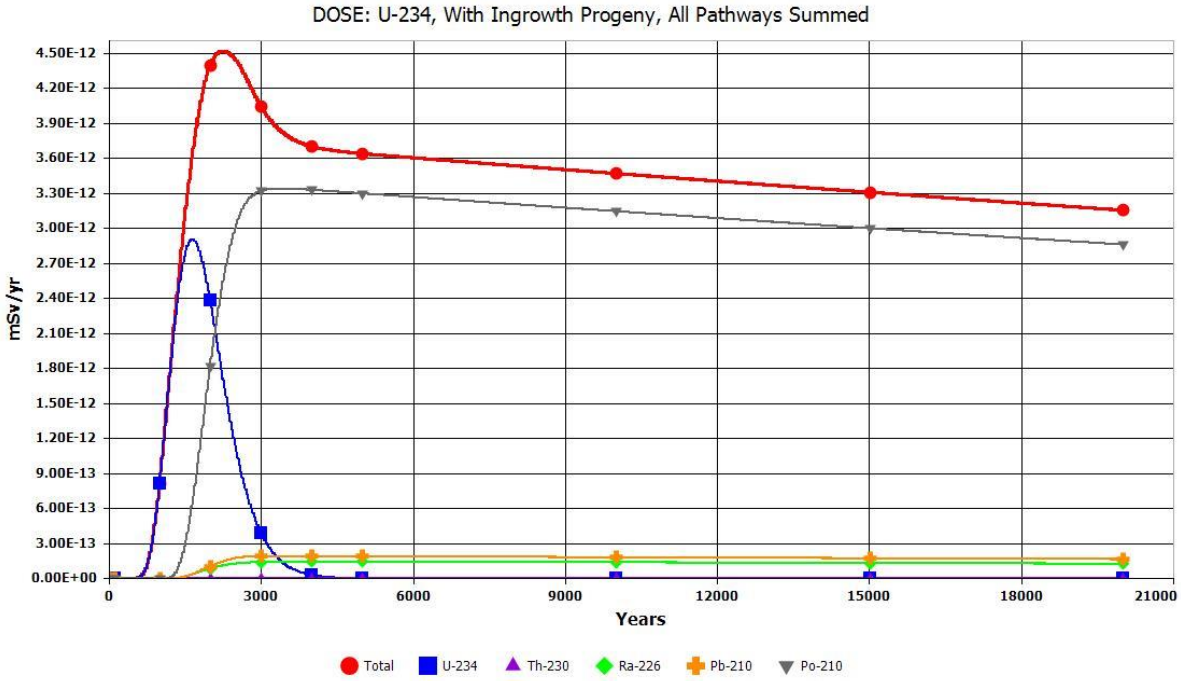


Graph 33: Total dose due to ^{232}Th and its daughters as a function of time

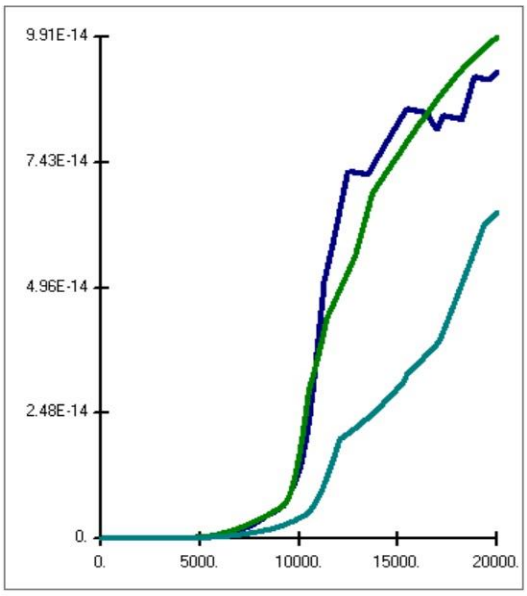


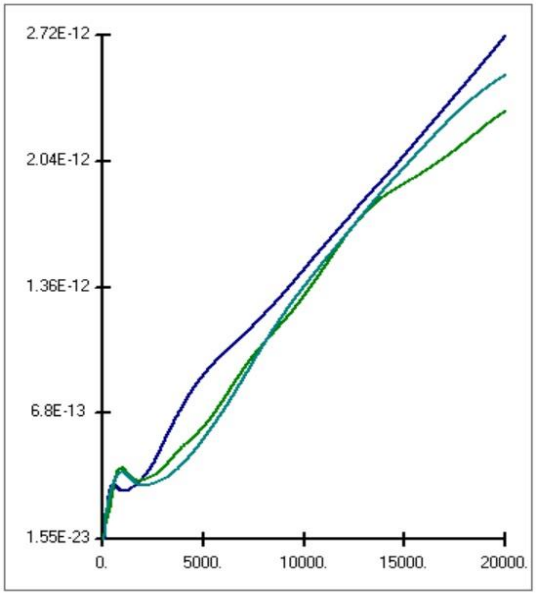
Graph 34-35: Median(left) and Mean(right) value of the total dose due to ^{232}Th and its daughters as a function of time

^{234}U



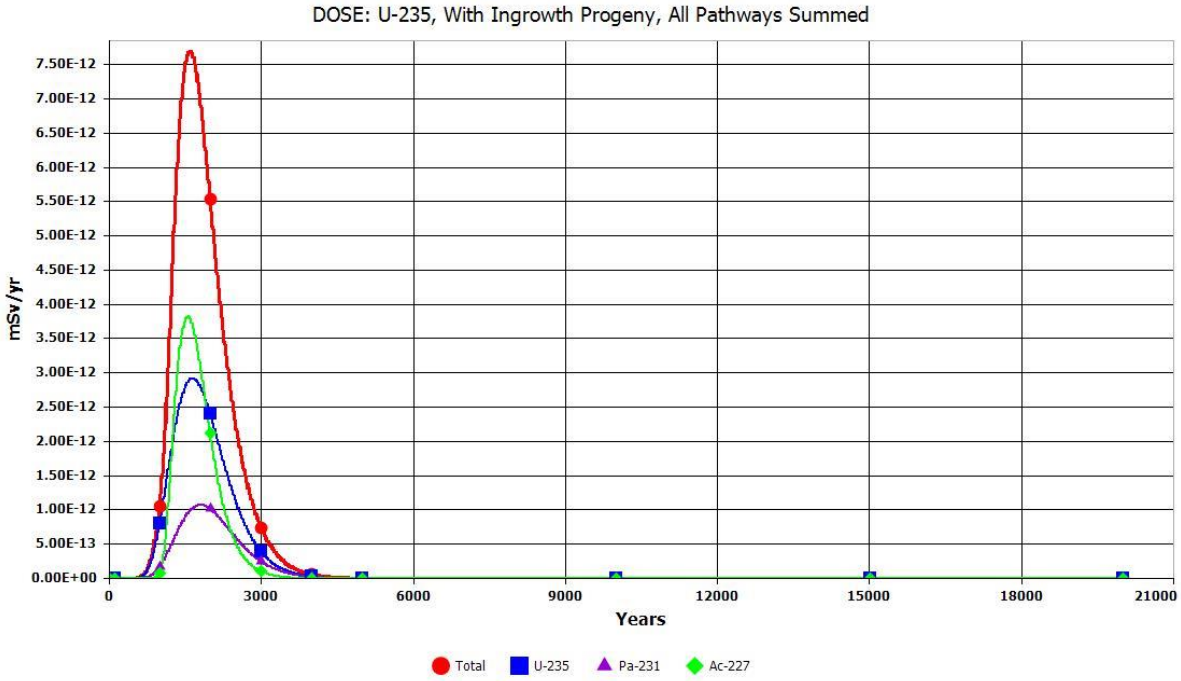
Graph 36: Total dose due to ^{234}U and its daughters as a function of time



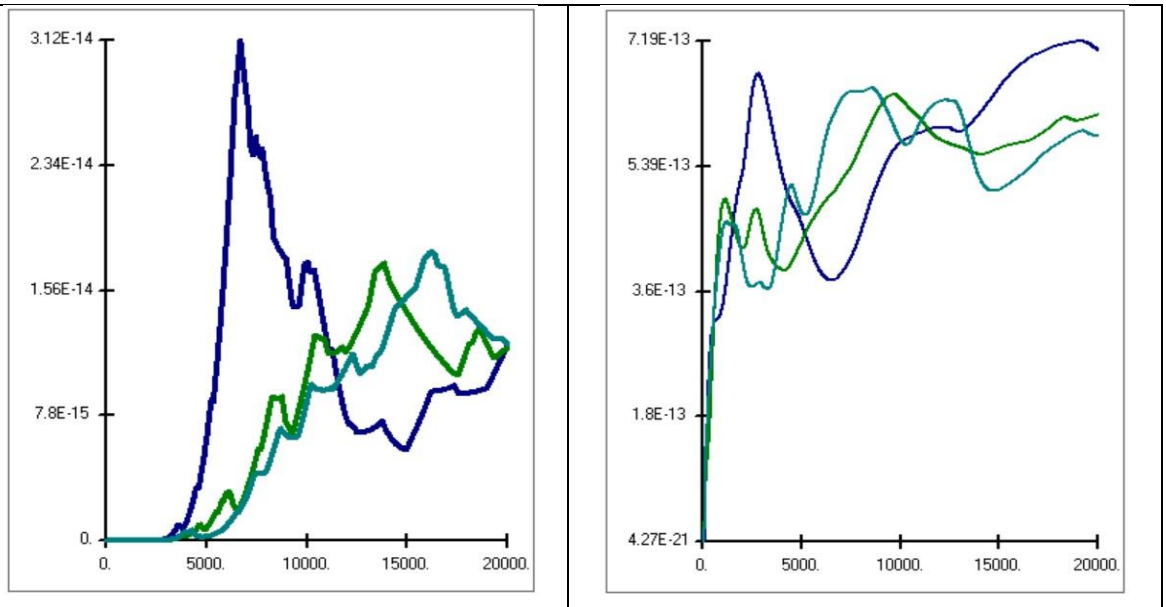


Graph 37-38: Median(left) and Mean(right) value of the total dose due to ^{234}U and its daughters as a function of time

^{235}U

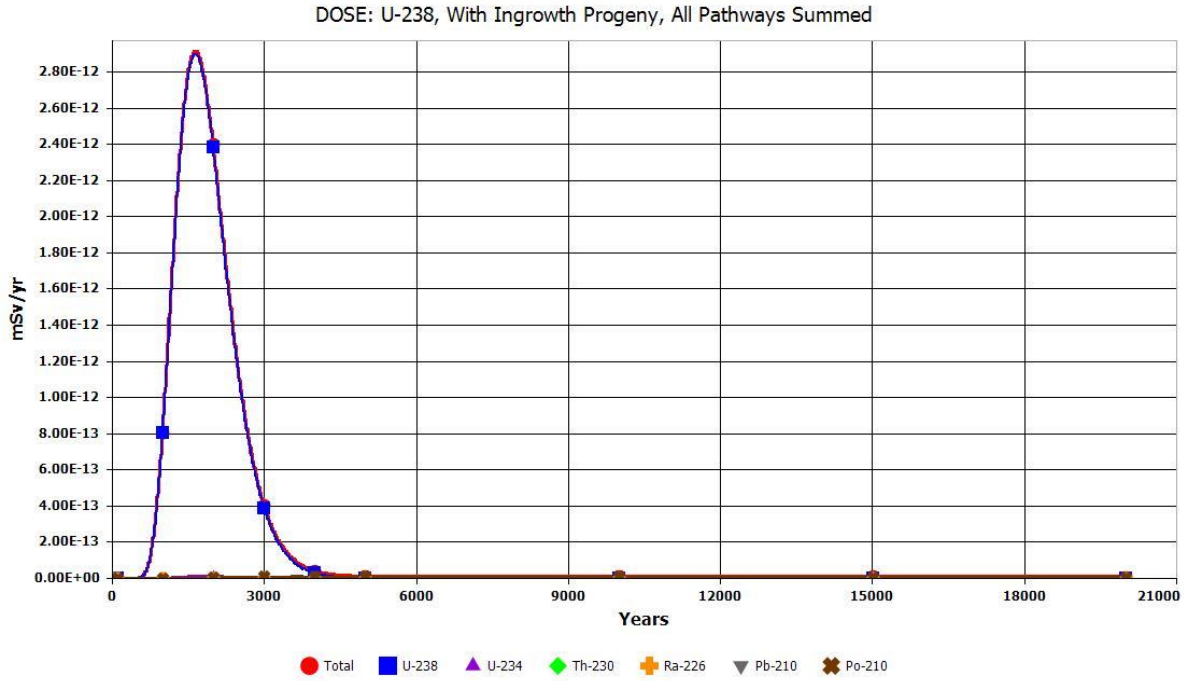


Graph 39: Total dose due to ^{235}U and its daughters as a function of time

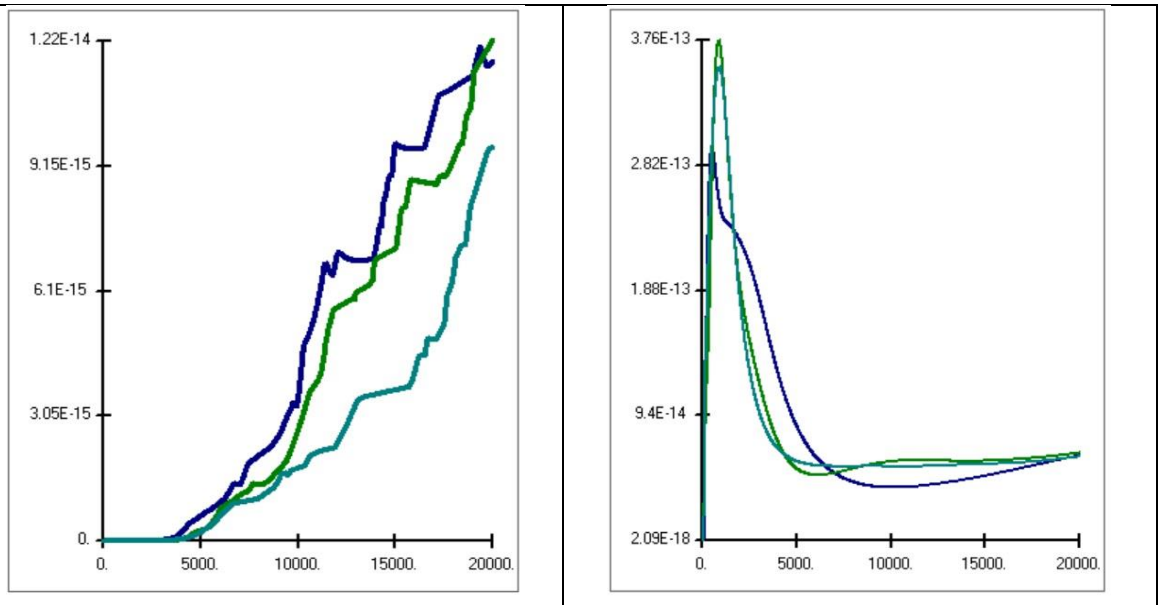


Graph 40-41: Median(left) and Mean(right) value of the total dose due to ^{235}U and its daughters as a function of time

^{238}U



Graph 42: Total dose due to ^{238}U and its daughters as a function of time



Graph 43-44: Median(left) and Mean(right) value of the total dose due to ^{238}U and its daughters as a function of time

5. Conclusions

The present thesis is an attempt to simulate a radioactive waste disposal facility and the assessment of the effects that can occur on people living un the wider area around it. Its objectives are to understand the operation of such a facility and to predict the dose and risk to those people as accurately as possible. Based on a similar study listed in IAEA Technical Document TECDOC1380, a comparison can be made between those results and those presented above. Obviously, the initial conditions and, more generally, the variables that describe the two systems should be as similar a possible, so that the comparison can give a clear perspective on the interaction of the installation with both humans and its environment.

With the aid of the RESRAD-OFFSITE software, the multitude of factors describing such a scenario did not stand in the way and it was possible to determine in sufficient detail the conditions that come with the theoretical scenario.

Therefore, two analyses took place, a **Deterministic Analysis** and an **Uncertainty/Probabilistic Analysis**.

5.1 Deterministic Analysis Conclusions

In general, a Deterministic Analysis aims to prove the installation's tolerance to identified faults/errors that are found within the "design basis", thus defining the limits of its safe operation. Here, the design basis relies heavily on either TECDOC1380, or the variables defaulted in the RESRAD-OFFSITE software.

Here, with the Deterministic Analysis, a first estimate of the installation's behaviour was given, based on the parameters introduced in Chapter 3.1. Its results, as shown in Graphs 1 and 2, show the total dose resulting from the scenario simulation.

The participation of each nuclide, as shown in Graphs 3 to 13, describes the behaviour of each one, which is determined both by the problem's conditions and by the characteristics of the nuclide itself.

In addition, the physical significance of the results is worth mentioning. The nuclides with the most important contribution per Bq are: ^{241}Am, ^{129}I, ^{237}Np, ^{226}Ra, ^{234}U. Nuclides such as ^{241}Am and ^{226}Ra, whose dose peaks relatively early(around 1000 to 2000 years), as seen in Graphs 3 and 10, show the highest dose of all the rest. A comparatively large dose, but with a much earlier peak(Graph 5), is ^{129}I. In each of these three nuclides, the decline after the peak is relatively steep. On the contrary, the dose due to 234U, after the peak that appears around 2500 years, shows a linear decline in respect to time(Graph 11). This

decline, however, is relatively slow and there is a statistically significant dose beyond 21000 years. Then, another nuclide that presents a significant contribution to the total dose is 237Np. Based on Graph 6, the peak of the dose is observed around 7500-8000 years, while a relative symmetry can be distinguished on either side of this peak.

For all these nuclides, the exposure takes place through the pathways listed in Chapter 3.4. The main ones that contribute significantly to the final dose's formation are drinking water, edible fruits, vegetables(aquatic) and meat.

5.2 Uncertainty/Probabilistic Analysis Conclusions

With the Uncertainty Analysis, the worst-case scenario was defined, as the maximum dose was calculated. The scenario's description gives us a very good estimate of the facility's behaviour under the conditions of the specific scenario. Based on the probabilistic nature of the analysis, all scenarios between the worst and the best-case scenario can also be presented.

The analysis for each nuclide helped identify the contribution of each to the final dose. This contribution varies according to the nuclide's nature (daughters, Kd constant), the deposited concentrations, the exposure pathways that were selected etc. With respect to the participation of each nuclide in the final dose's formation, its level of importance can be estimated.

Here too, however, the maximum annual dose from any nuclide does not exceed the value of 1E-10 mSv, as can be seen from the results of Chapter 4.2. As observed in this chapter, the nuclides that give the largest maximum dose are the following: 241Am, 14C, 129I, 237Np, 226Ra, 232Th, 234U, 235U. Thus, a statement about the results' variation can be made: It is observed that from the minimum to the maximum value, the difference is about 5-6 orders of magnitude, an amount that is not negligible.

Finally, based on the thesis' initial goal, the comparison between the two results groups is worth mentioning. After observing Table 22, one can find that the results of the particular thesis are generally close to those of IAEA. Some difference between the two is reasonable and expected, based on the initial conditions used here and of course the use of the RESRAD-OFFSITE software. More specifically, however, the ratio calculated and listed in Table 22 is positive for the nuclides' majority. This means that the concentration calculated by IAEA is generally greater than the one calculated in the present study. Therefore, the assumption that the dose per Bq was underestimated can be made, i.e. there is enough margin for the disposal of larger quantities and activities of the specific nuclides, at the particular facility under the aforementioned conditions.

5.3 Thesis Conclusions

In summary, radioactive waste is produced and stored in most countries of the world, from many and various secondary sector processes. Therefore, their management is a major issue for every State, both for safety reasons of its inhabitants, as well as for the protection of its facilities.

From the comparison between the results of the present thesis and those of TECDOC1380, one notices that these results differ. This difference shows how important the parameters, assumptions and model used for the analysis can be. It also appears that the deterministic analysis based on some representative-average values may give results that can be significantly off the maximum possible exposure value to some extent. Thus, the uncertainty analysis is considered as a more appropriate approach, with, however, a smaller parameters' variation range based on actual data and studies of the area and its hydrogeological results.

6. Tables List

7. Images List

8. Graphs List

9. Bibliography – Reference List

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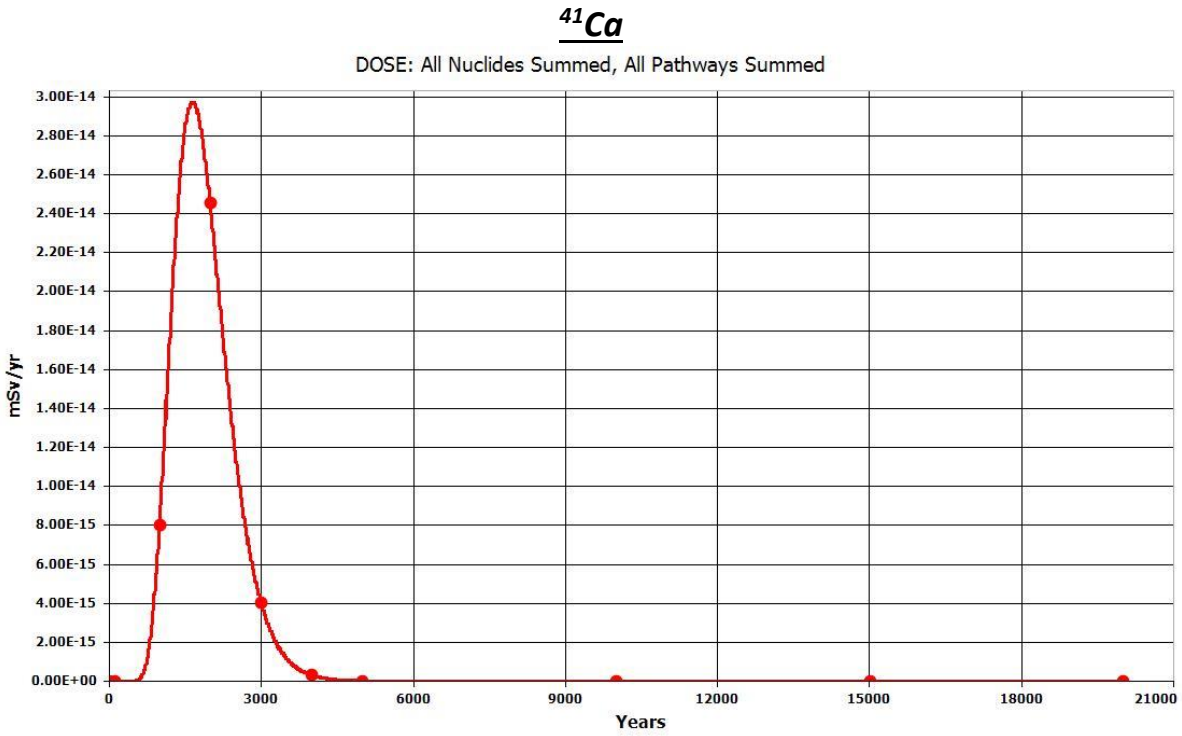
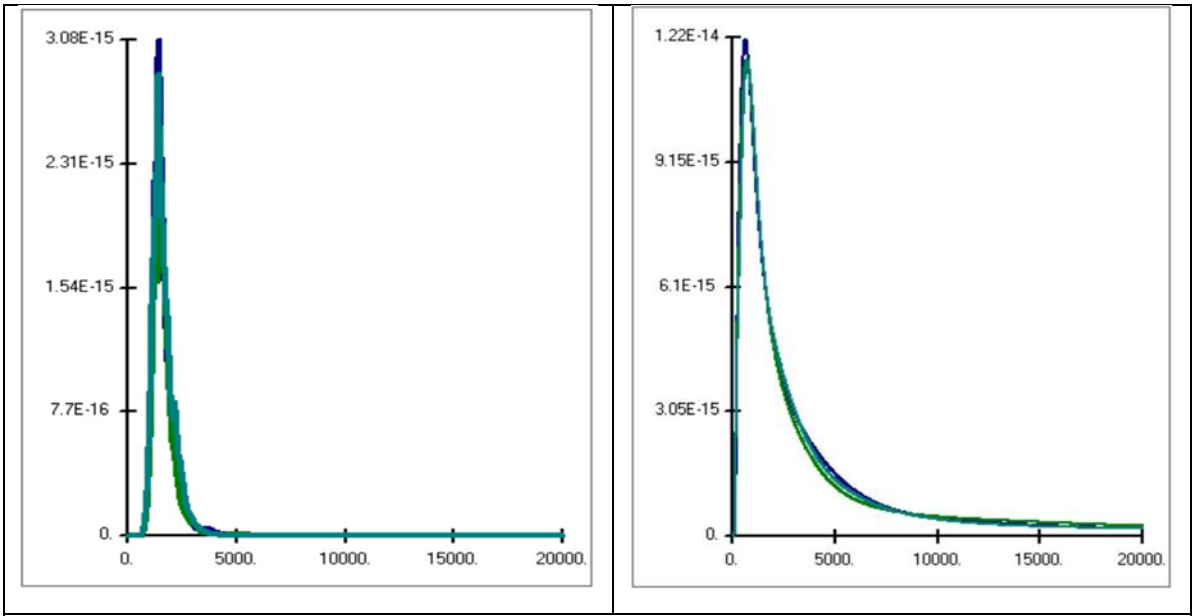
10. Appendix

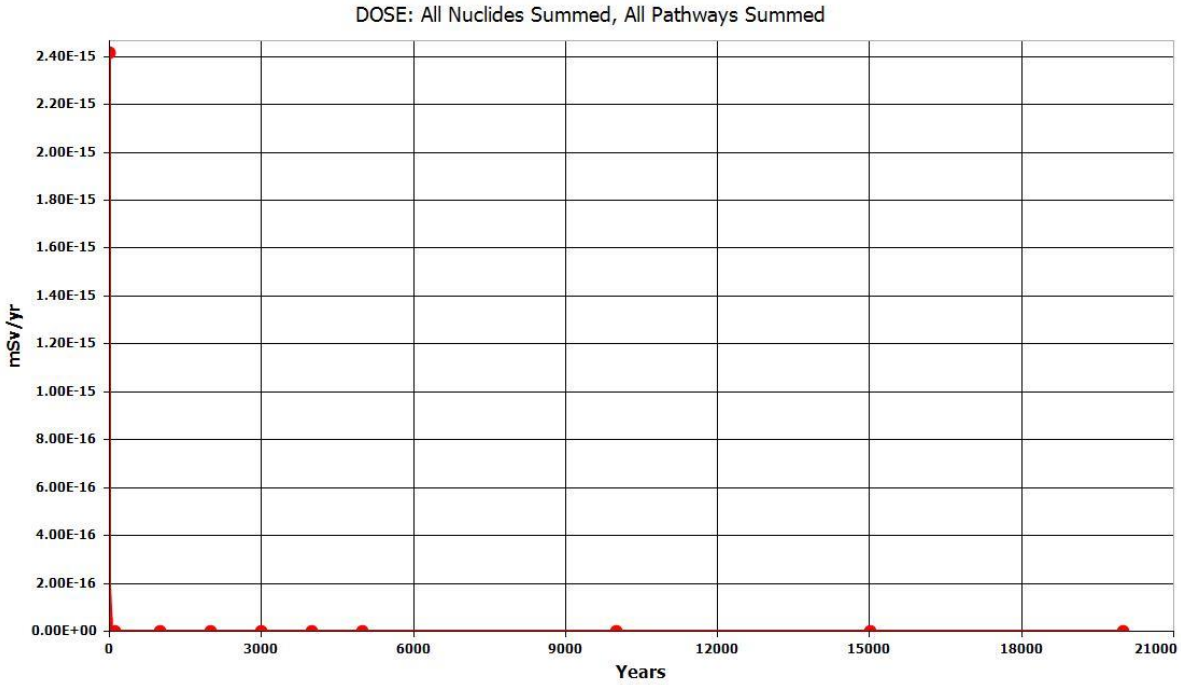


Graph 45: Total Dose due to ^{41}Ca as a function of time

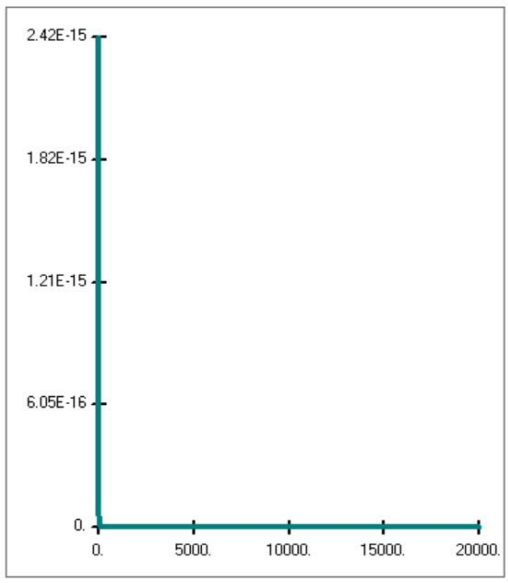


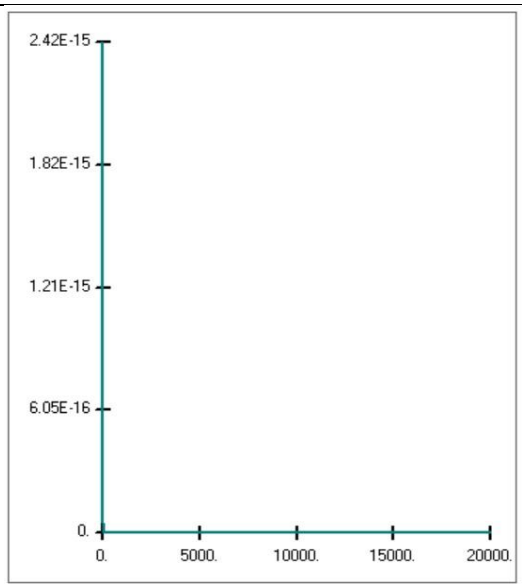
Graph 46-47: Median (left) and Mean (right) value of the total dose due to ^{41}Ca as a function of time

^{60}Co



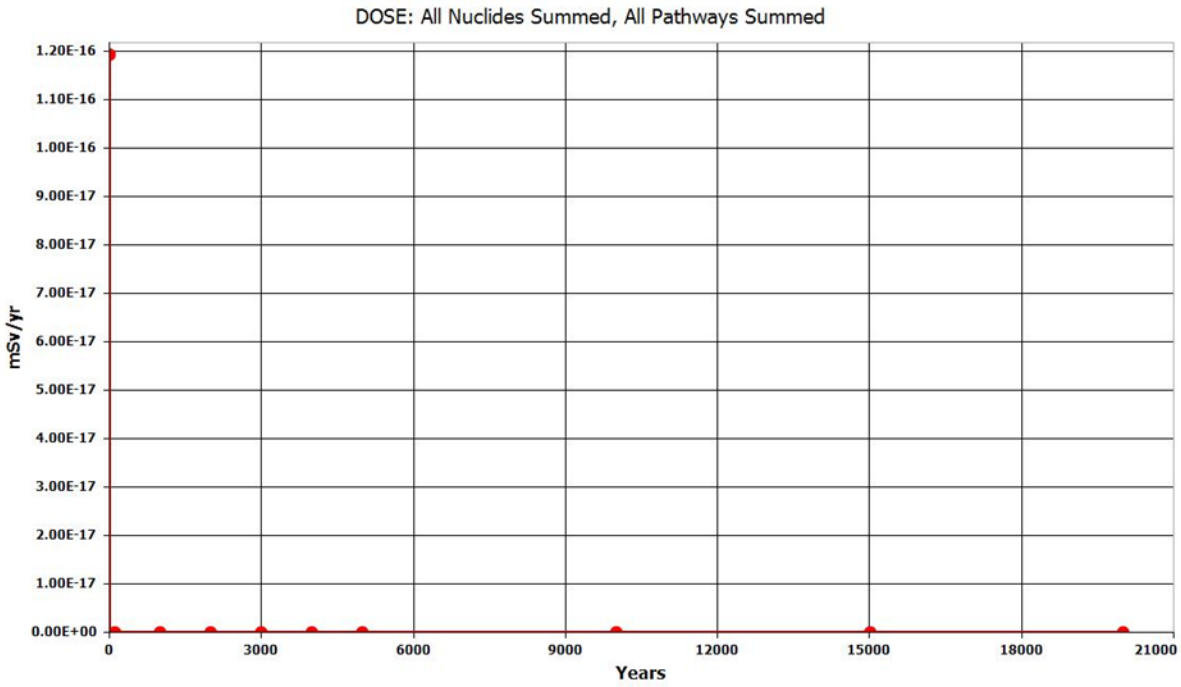
Graph 48: Total Dose due to ^{60}Co as a function of time



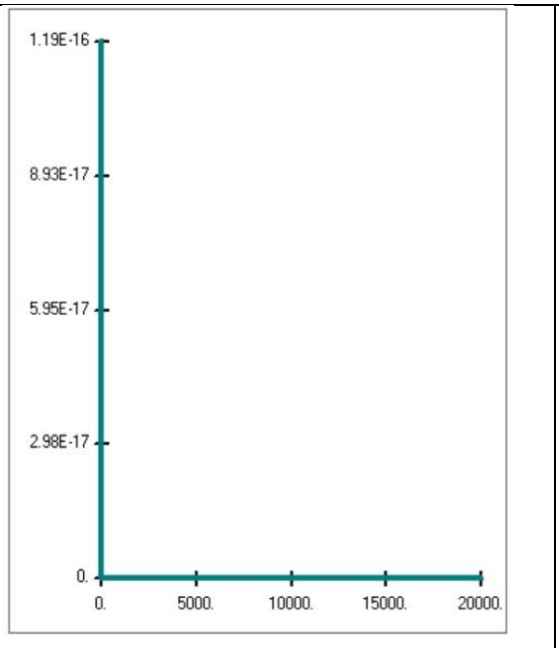


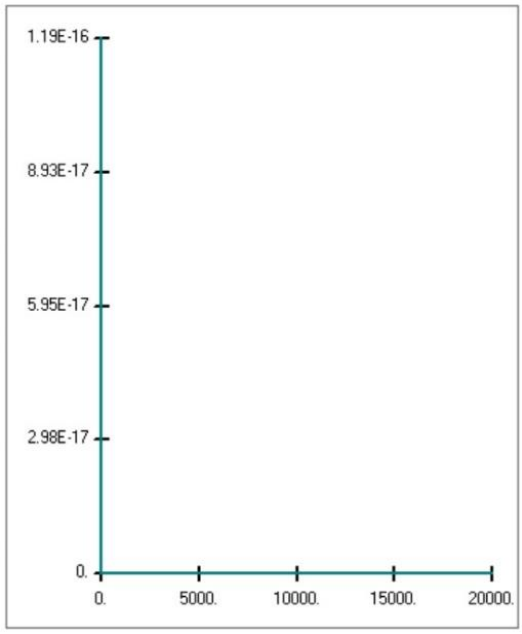
Graph 49-50: Median (left) and Mean (right) value of the total dose due to ^{60}Co as a function of time

^{134}Cs



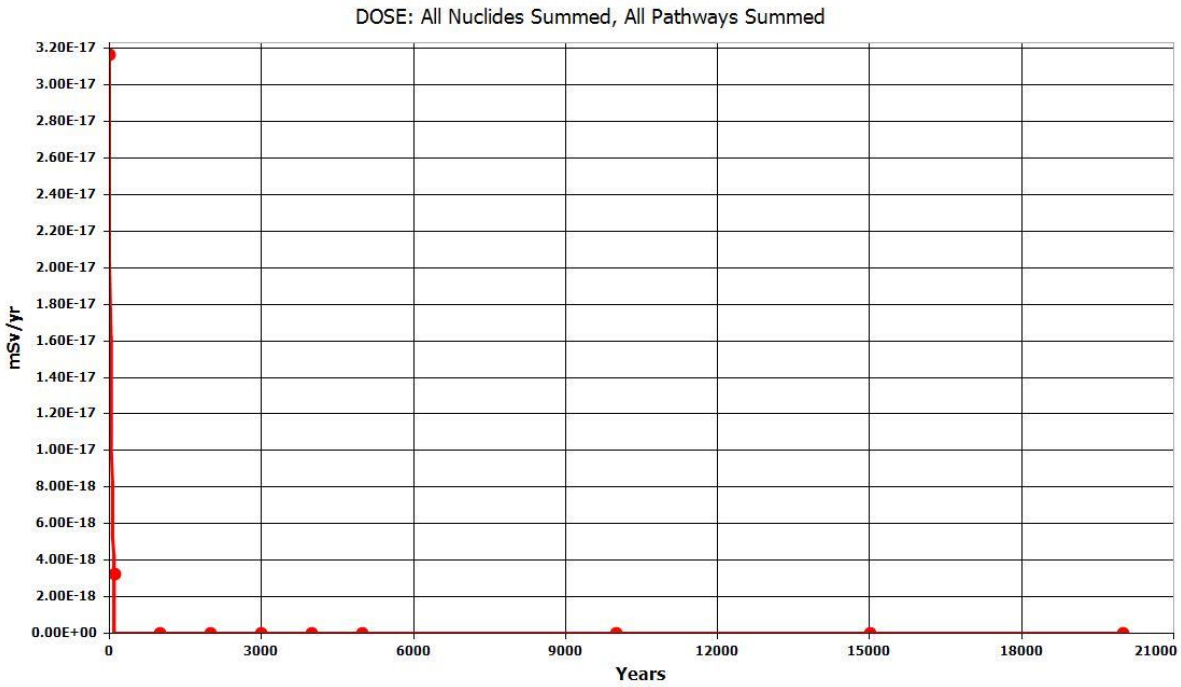
Graph 51: Total Dose due to ^{134}Cs as a function of time



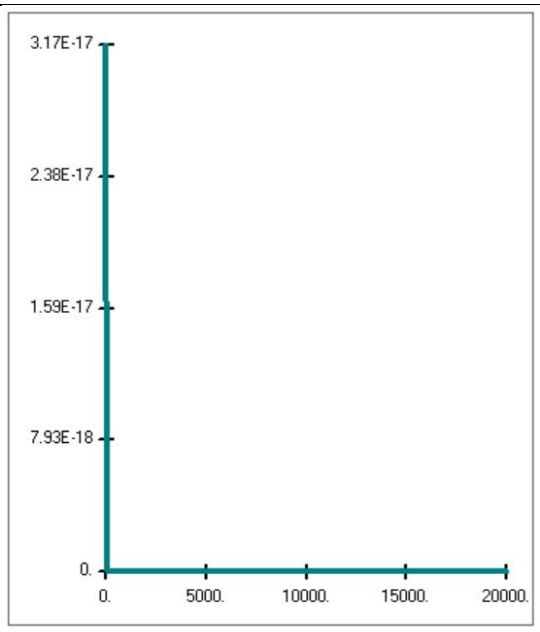


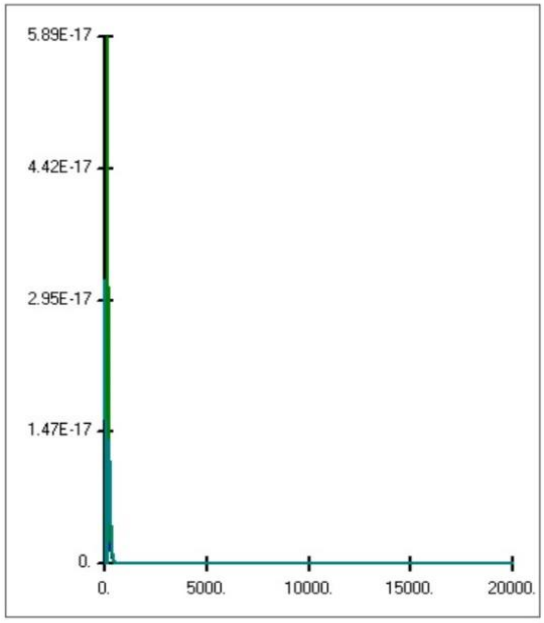
Graph 52-53: Median (left) and Mean (right) value of the total dose due to ^{134}Cs as a function of time

^{137}Cs



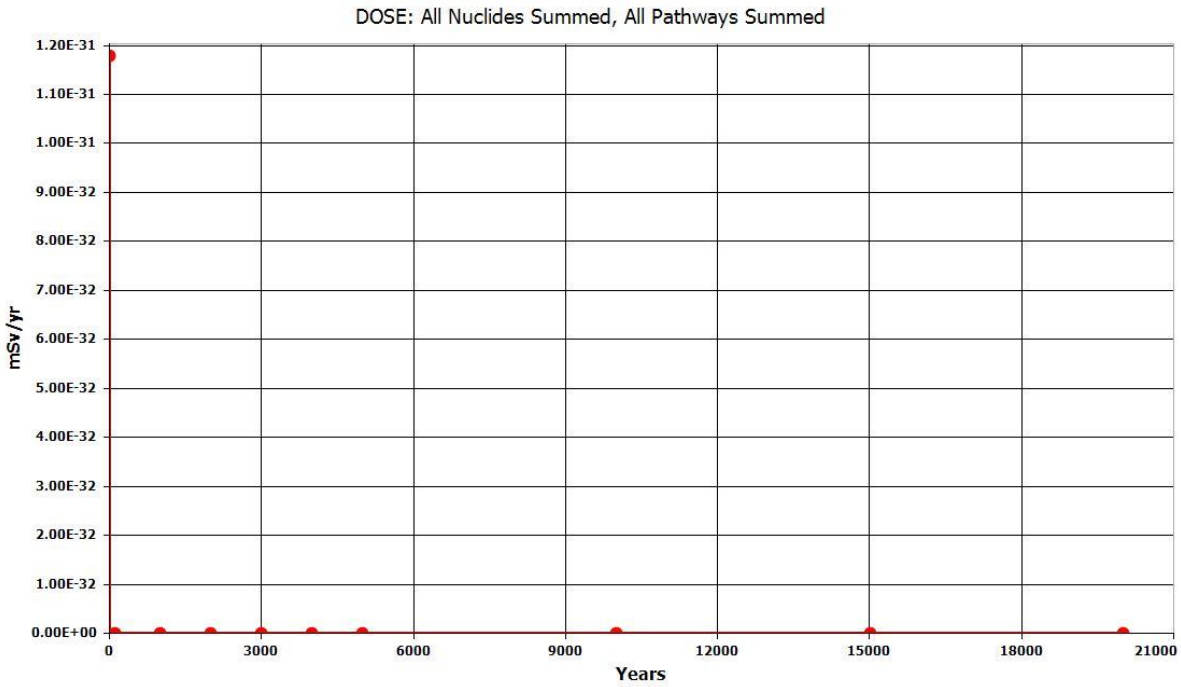
Graph 54: Total Dose due to ^{137}Cs as a function of time



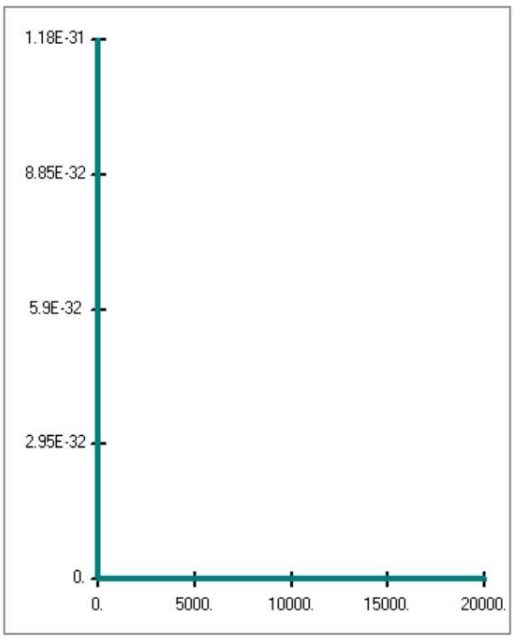


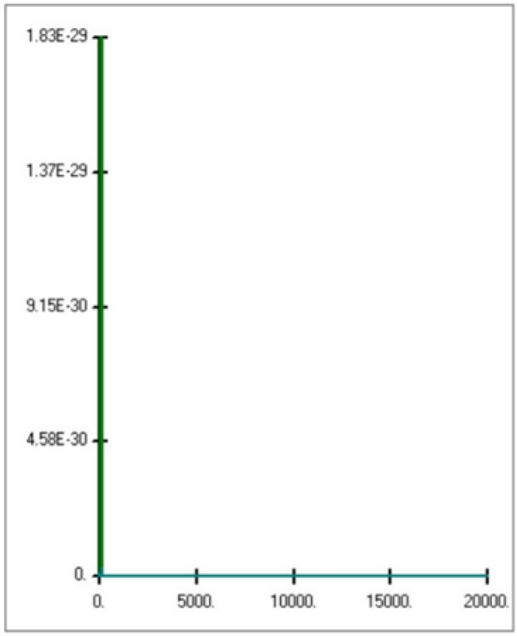
Graph 55-56: Median (left) and Mean (right) value of the total dose due to ^{137}Cs as a function of time

^{55}Fe



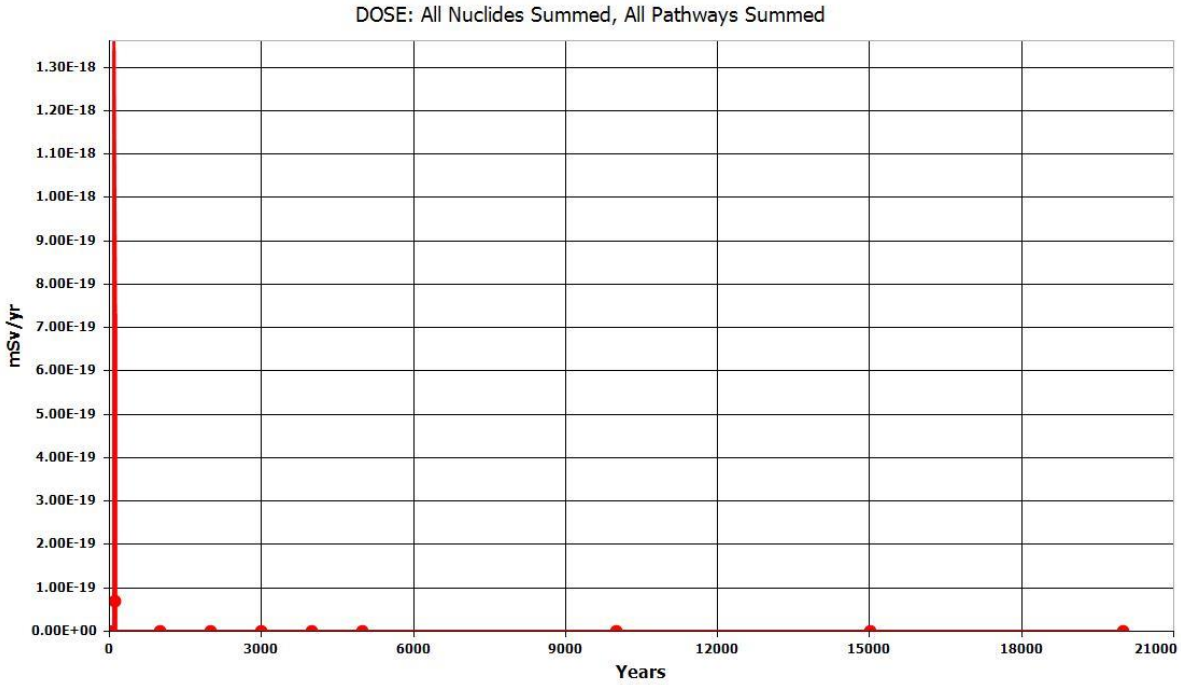
Graph 57: Total Dose due to ^{55}Fe as a function of time



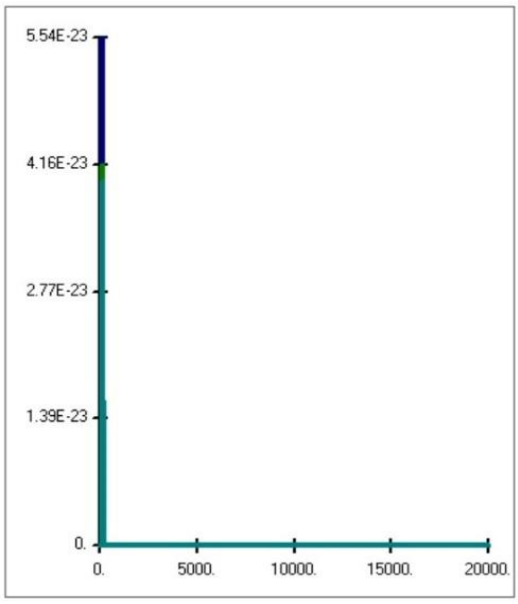


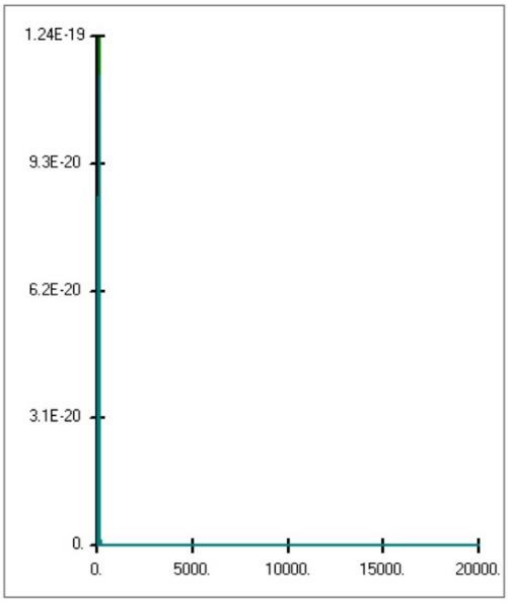
Graph 58-59: Median (left) and Mean (right) value of the total dose due to ^{55}Fe as a function of time

^{3}H



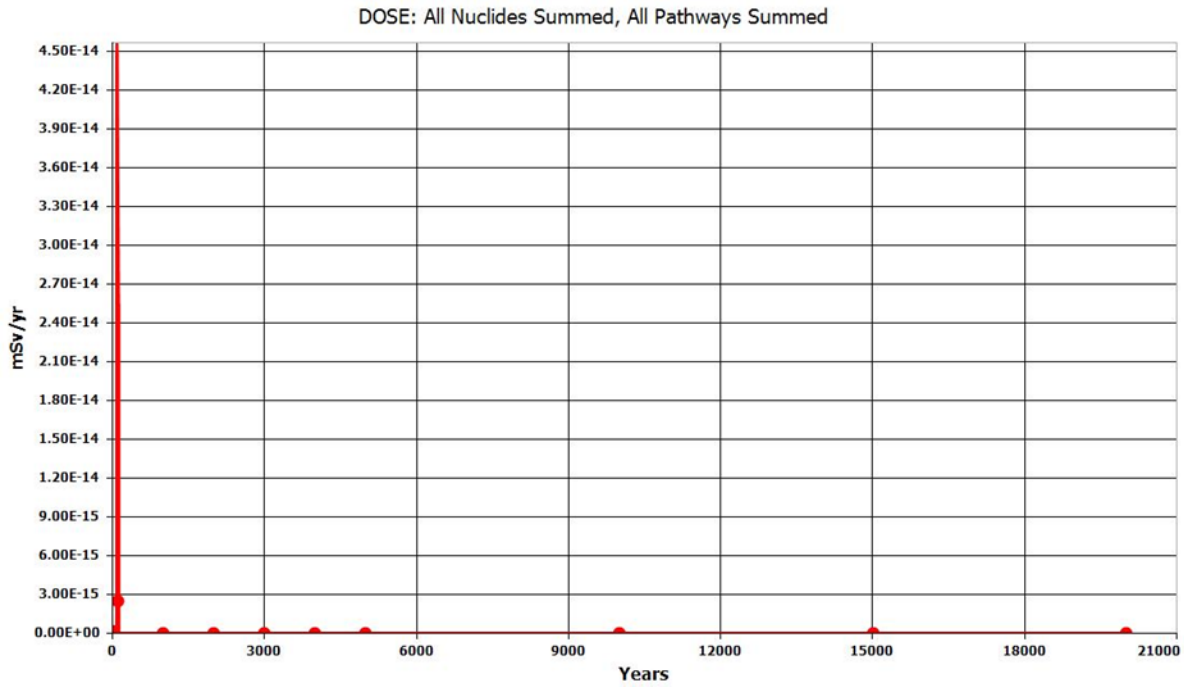
Graph 60: Total Dose due to ^{3}H as a function of time



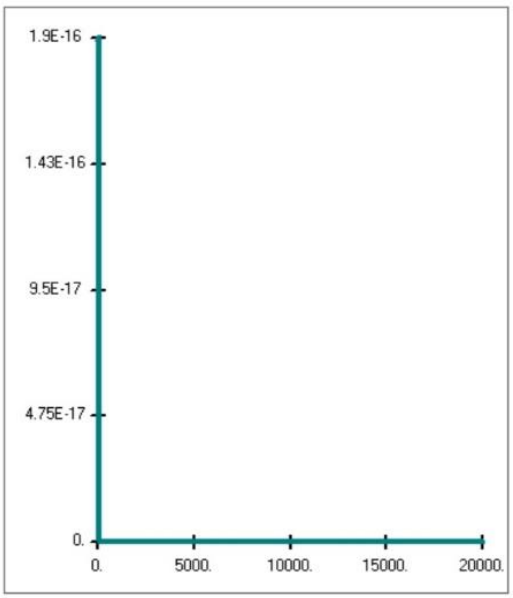


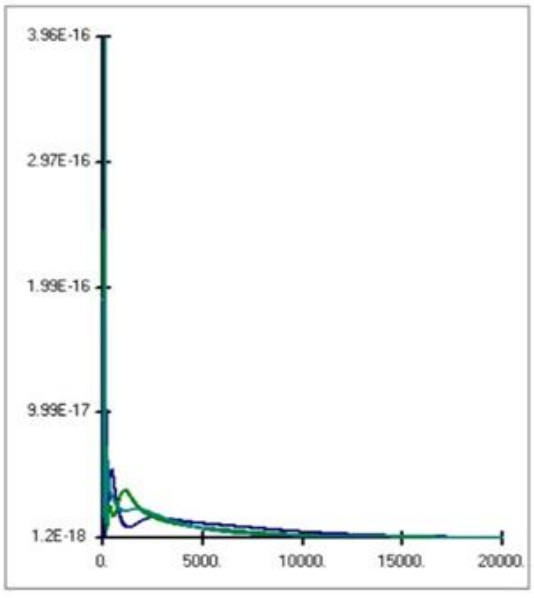
Graph 61-62: Median (left) and Mean (right) value of the total dose due to ^{3}H as a function of time

^{94}Nb



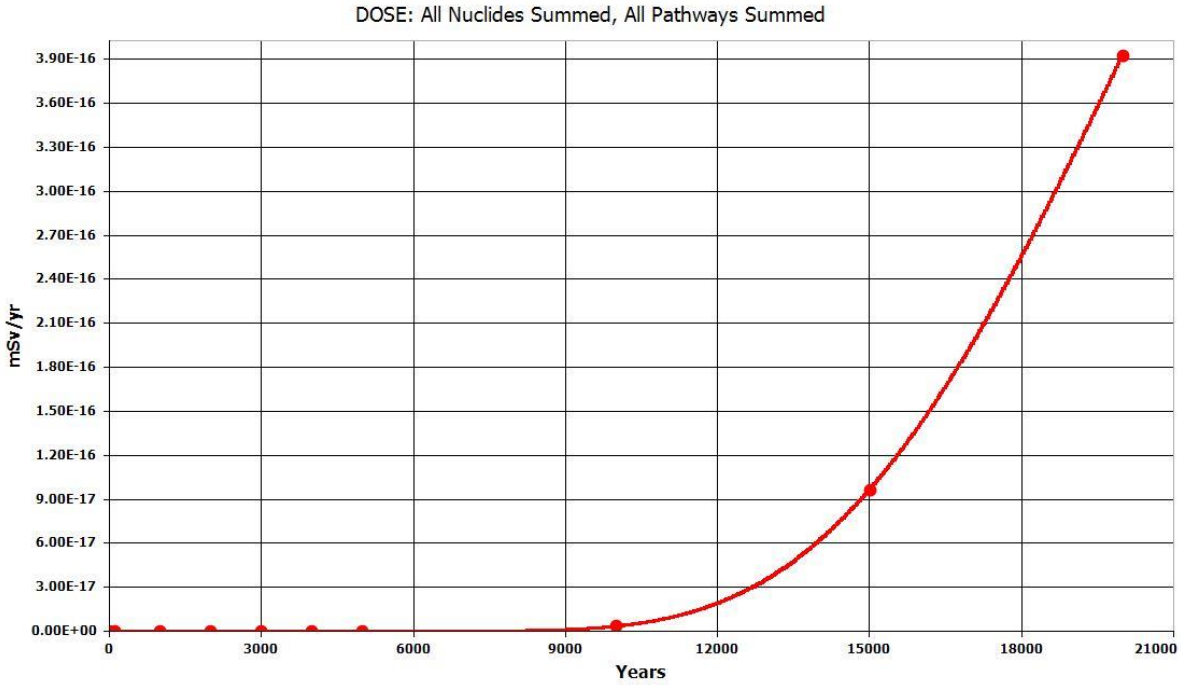
Graph 63: Total Dose due to ^{94}Nb as a function of time



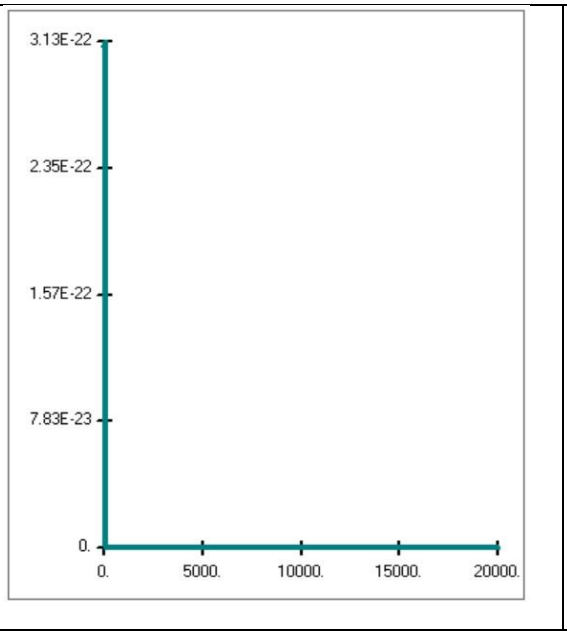


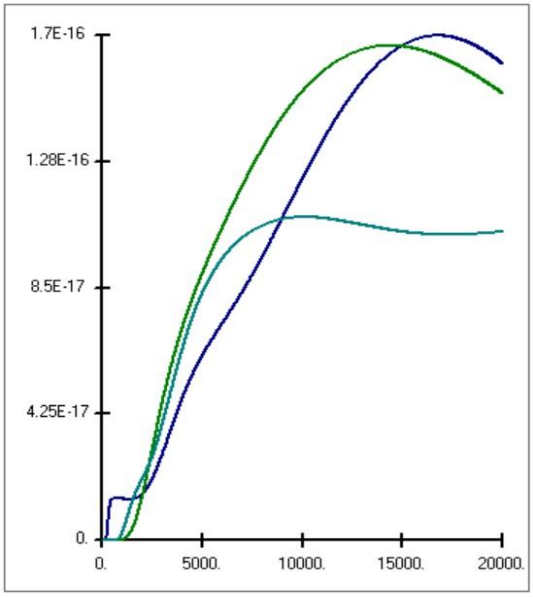
Γράφημα 64-65: Median (left) and Mean (right) value of the total dose due to ^{94}Nb as a function of time

^{59}Ni



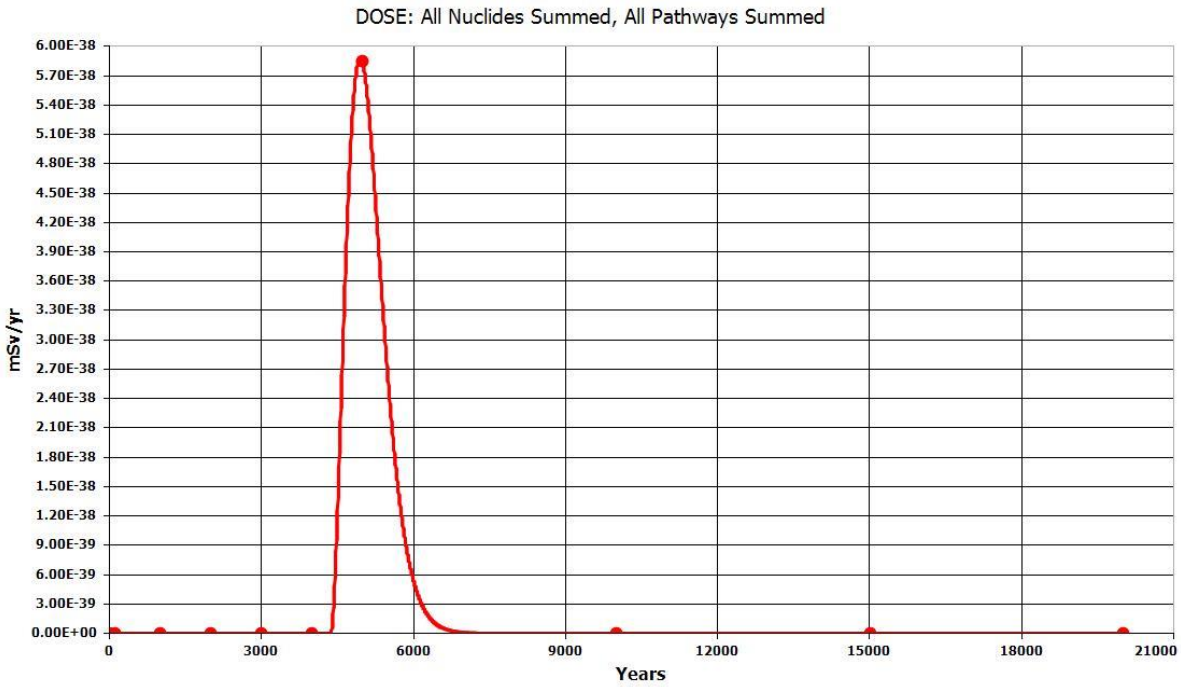
Graph 66: Total Dose due to ^{59}Ni as a function of time



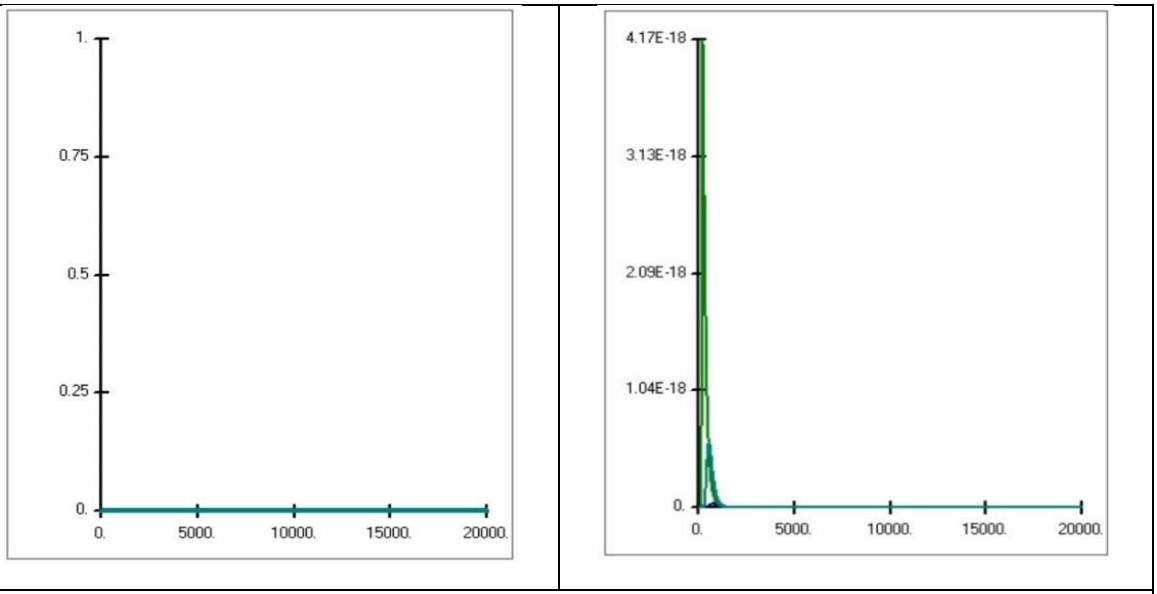


Graph 67-68: Median (left) and Mean (right) value of the total dose due to ^{59}Ni as a function of time

^{63}Ni

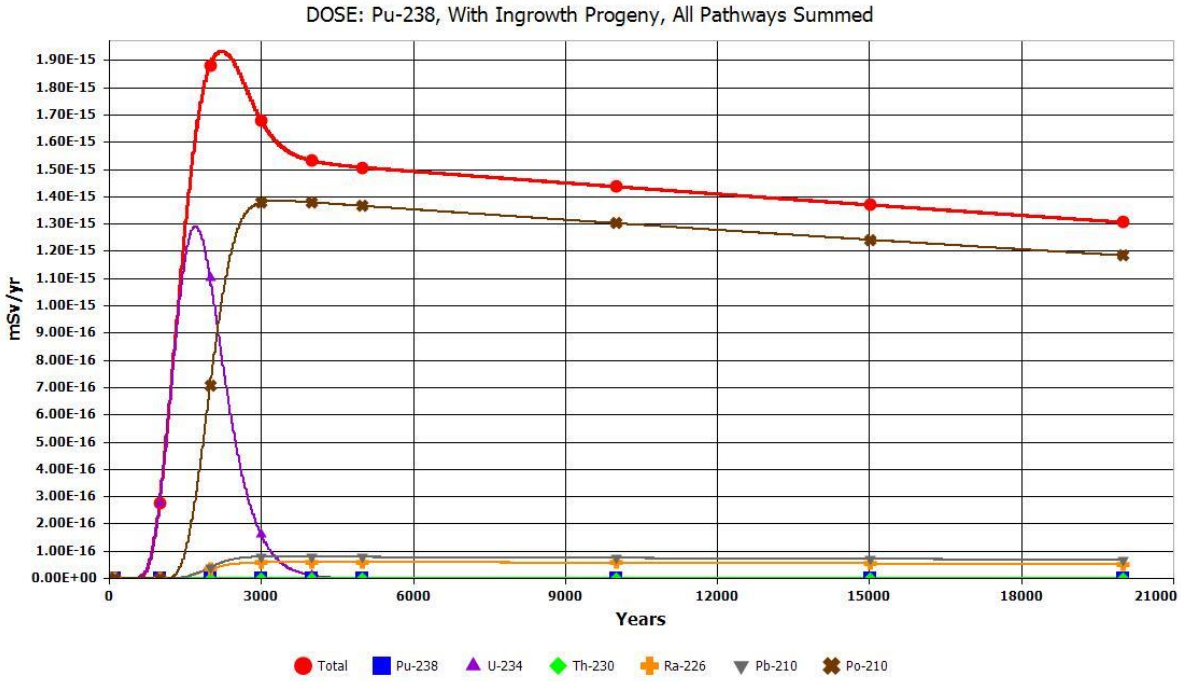


Graph 69: Total Dose due to ^{63}Ni as a function of time

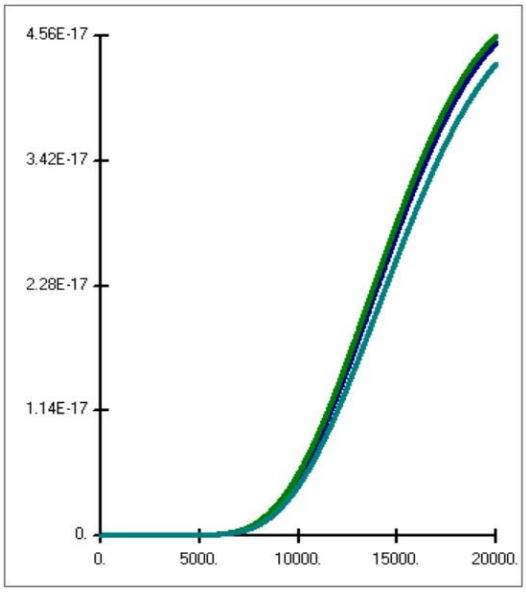


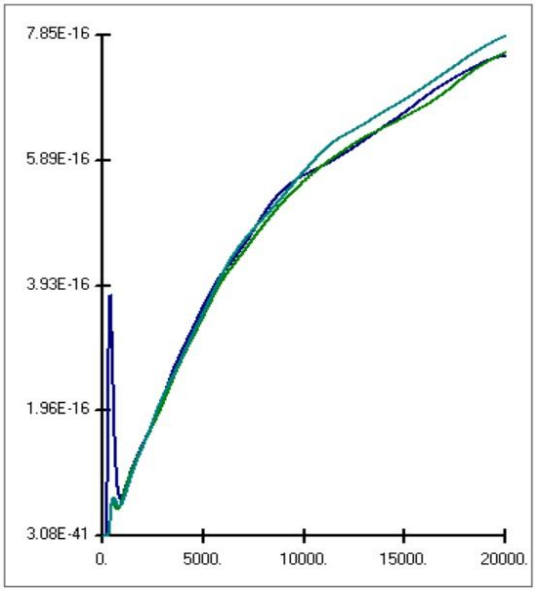
Graph 70-71: Median (left) and Mean (right) value of the total dose due to ^{63}Ni as a function of time

^{238}Pu



Graph 72: Total Dose due to ^{238}Pu and its daughters as a function of time

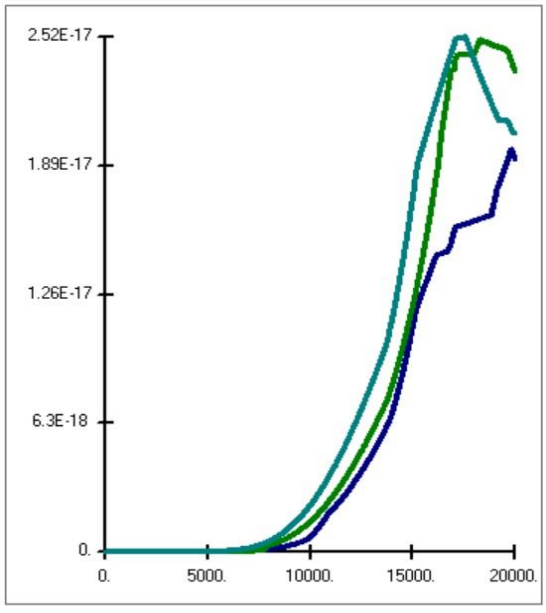


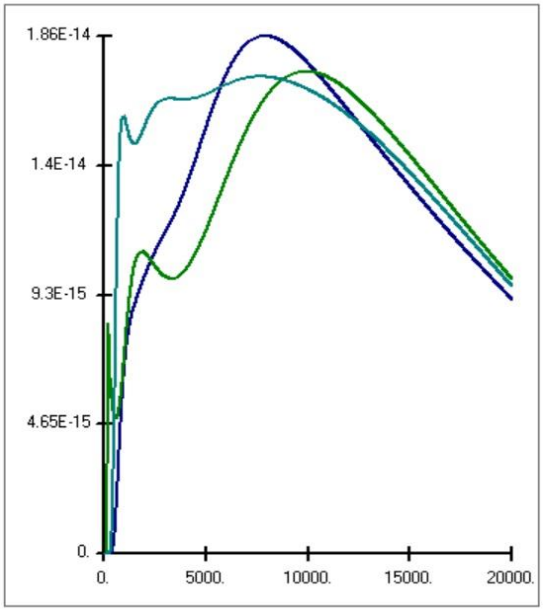


Graph 73-74: Median (left) and Mean (right) value of the total dose due to ^{238}Pu as a function of time

^{240}Pu

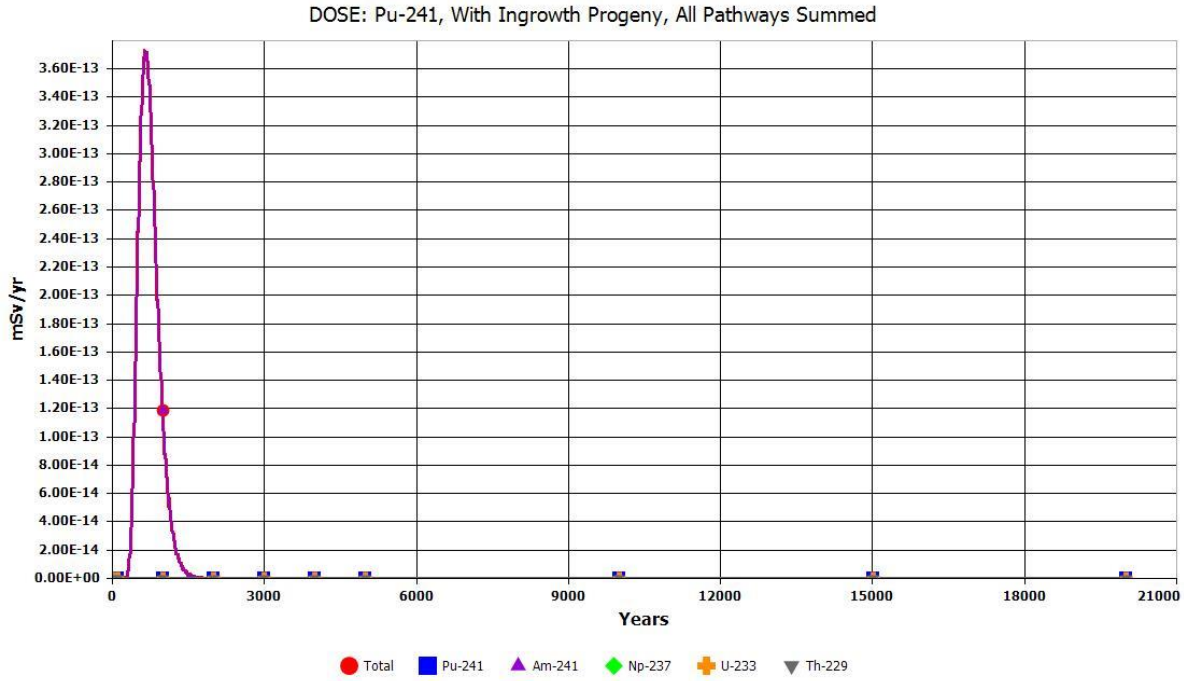
Graph 75: Total Dose due to ^{240}Pu and its daughters as a function of time



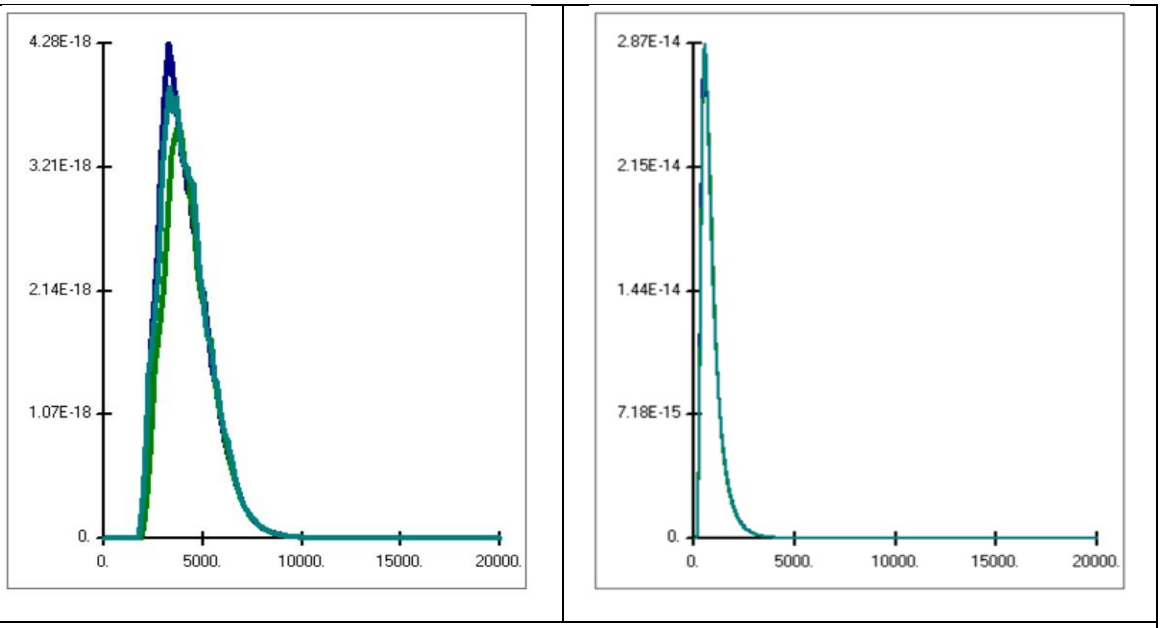


Graph 76-77: Median (left) and Mean (right) value of the total dose due to ^{240}Pu as a function of time

^{241}Pu

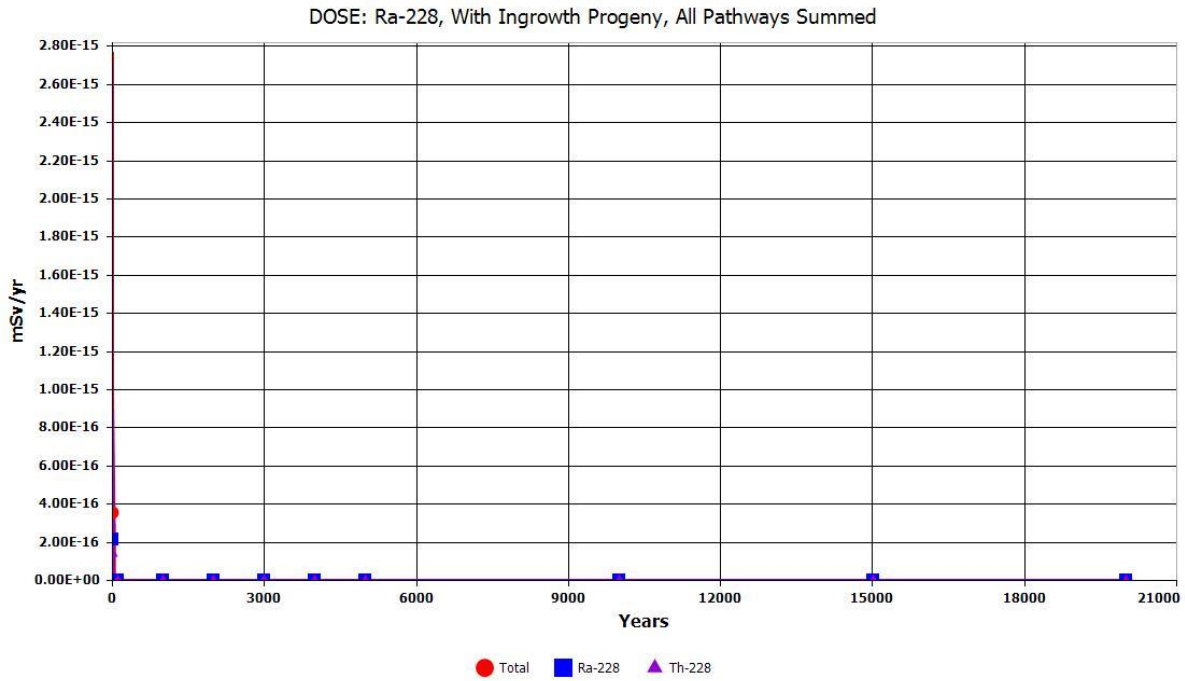


Graph 78: Total Dose due to ^{241}Pu and its daughters as a function of time

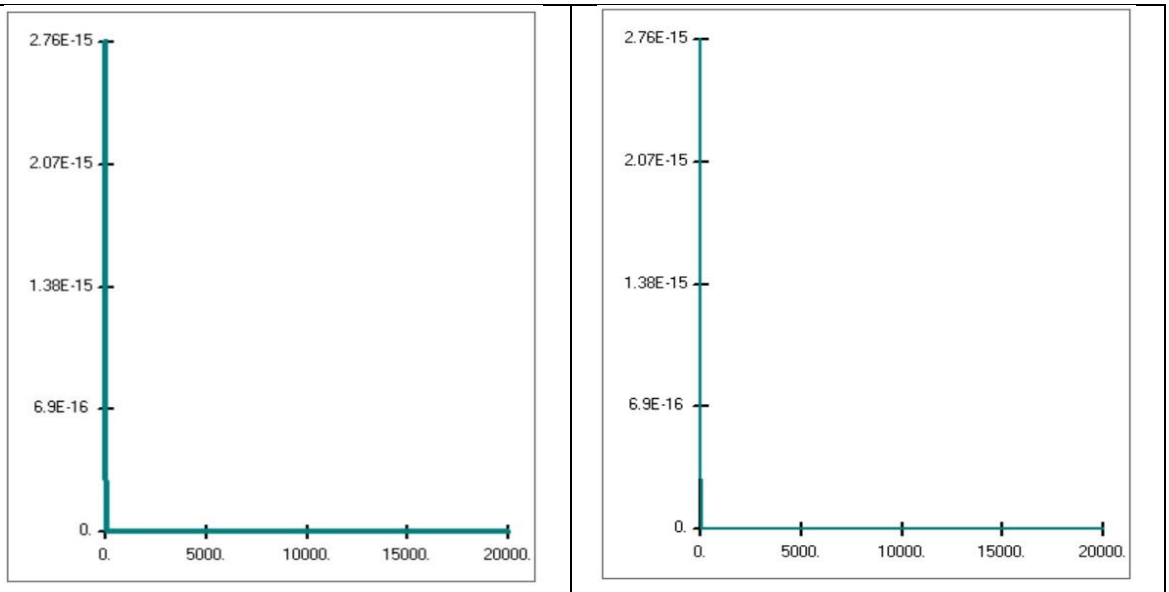


Graph 79-80: Median (left) and Mean (right) value of the total dose due to ^{241}Pu as a function of time

^{228}Ra

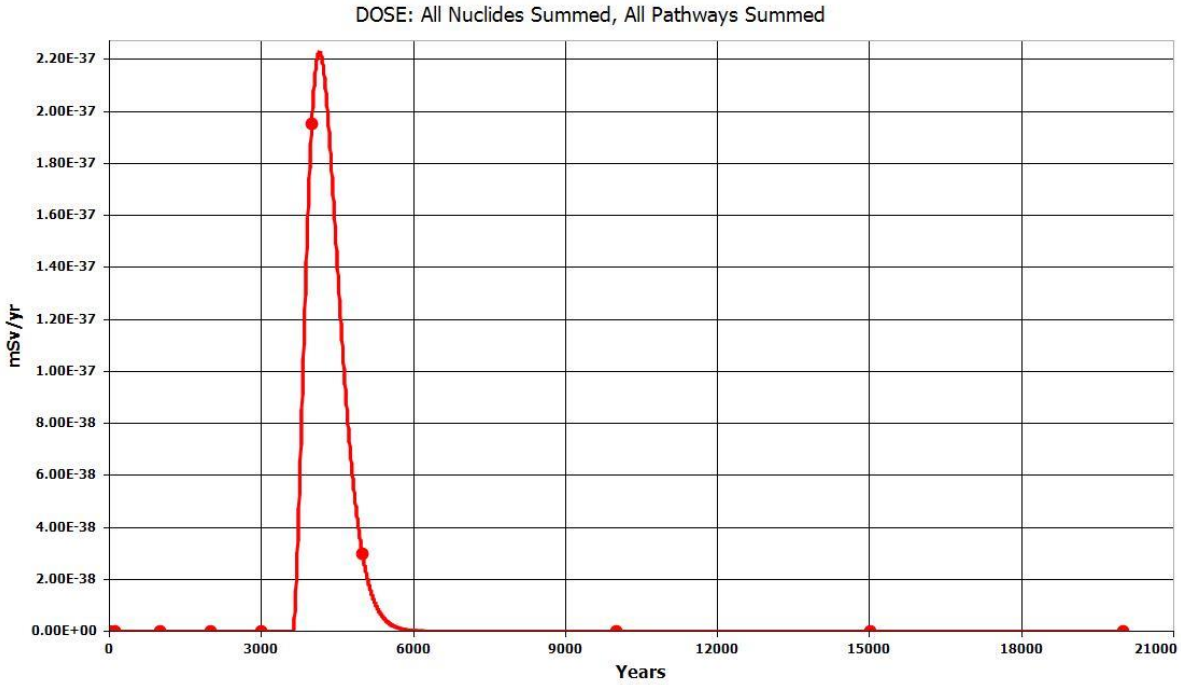


Graph 81: Total Dose due to ^{228}Ra and its daughters as a function of time

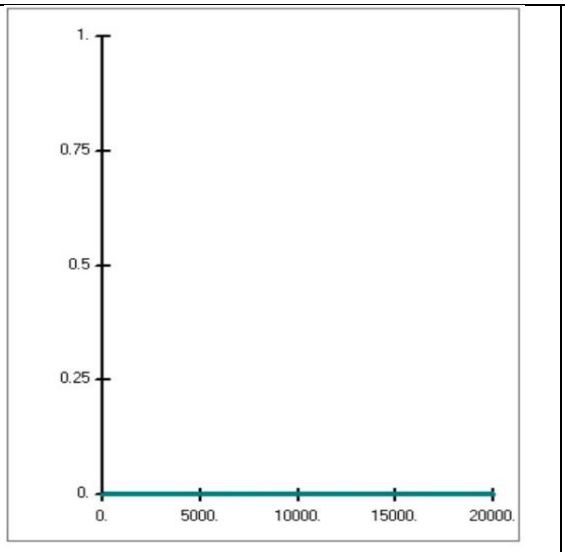


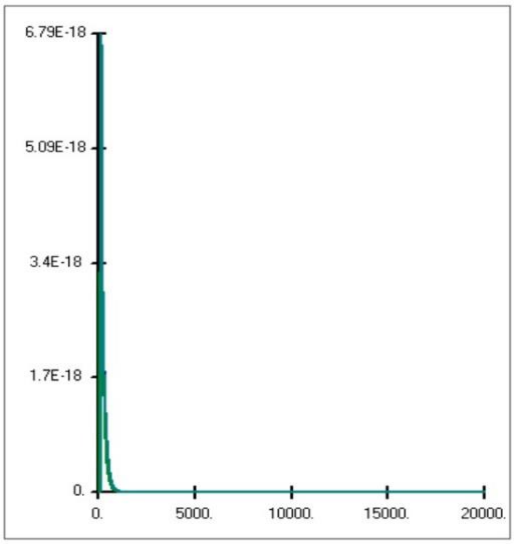
Graph 82-83: Median (left) and Mean (right) value of the total dose due to ^{228}Ra as a function of time

^{151}Sm



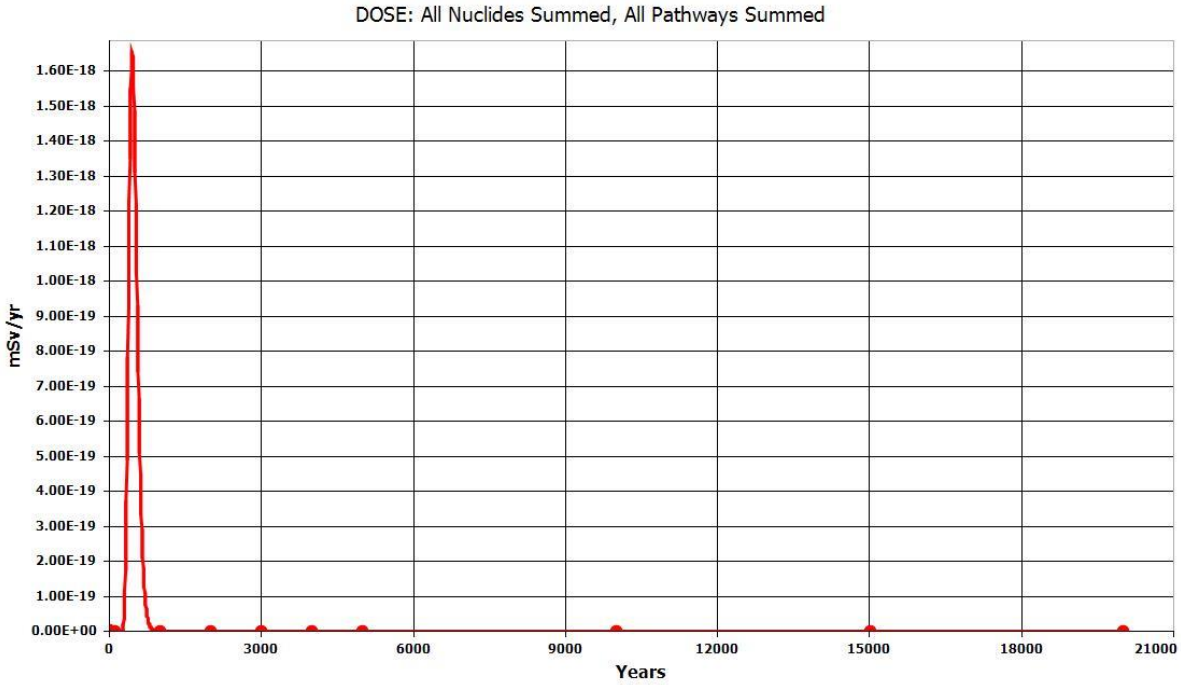
Graph 84: Total Dose due to ^{151}Sm as a function of time



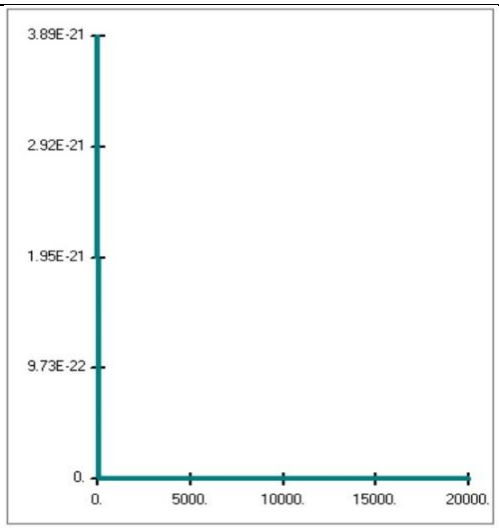


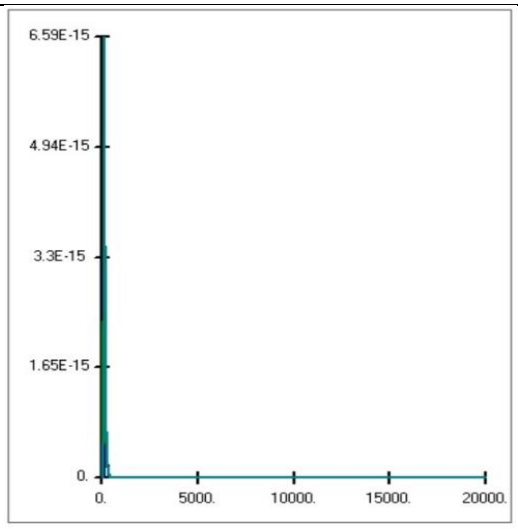
Graph 85-86: Median (left) and Mean (right) value of the total dose due to ^{151}Sm as a function of time

^{90}Sr



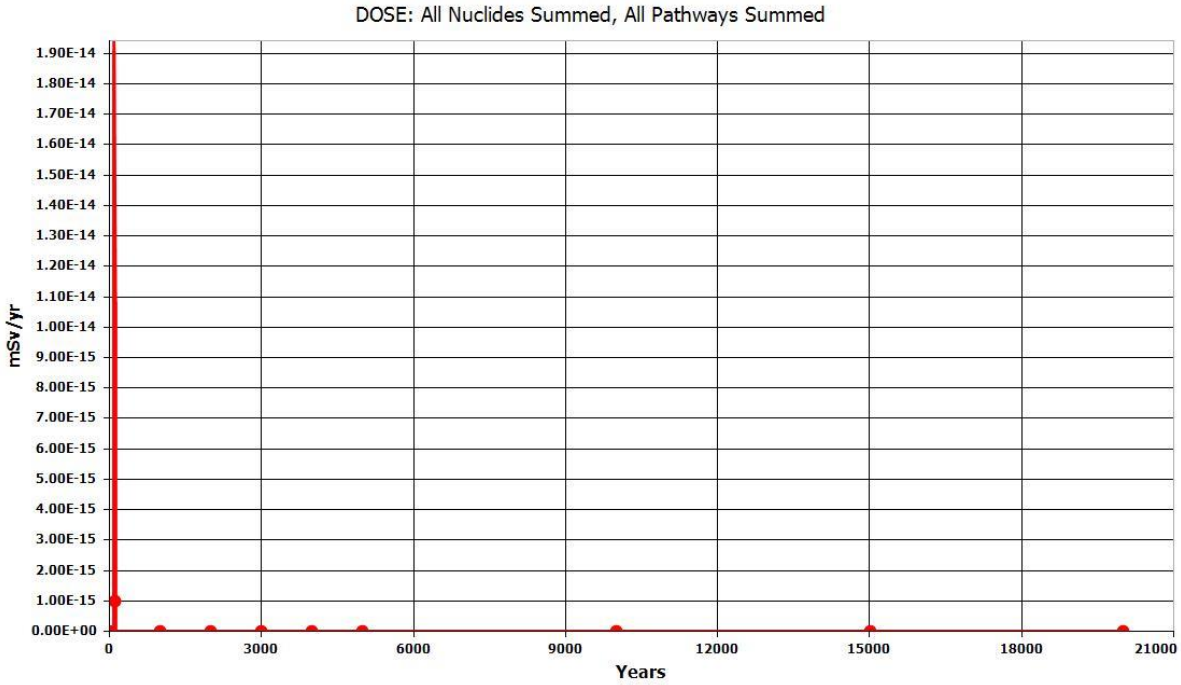
Graph 87: Total Dose due to ^{90}Sr as a function of time



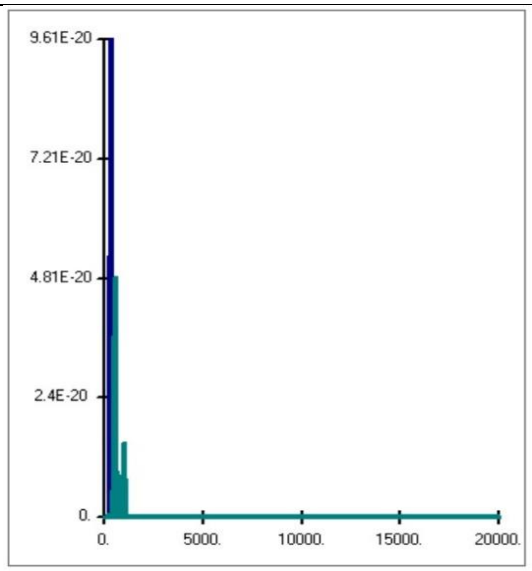


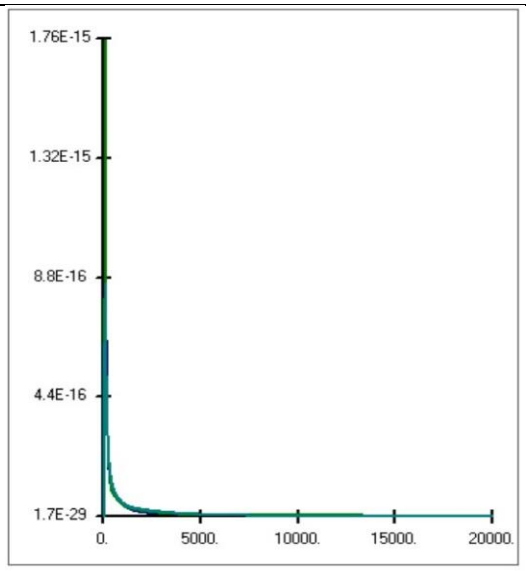
Graph 88-89: Median (left) and Mean (right) value of the total dose due to ^{90}Sr as a function of time

^{99}Tc



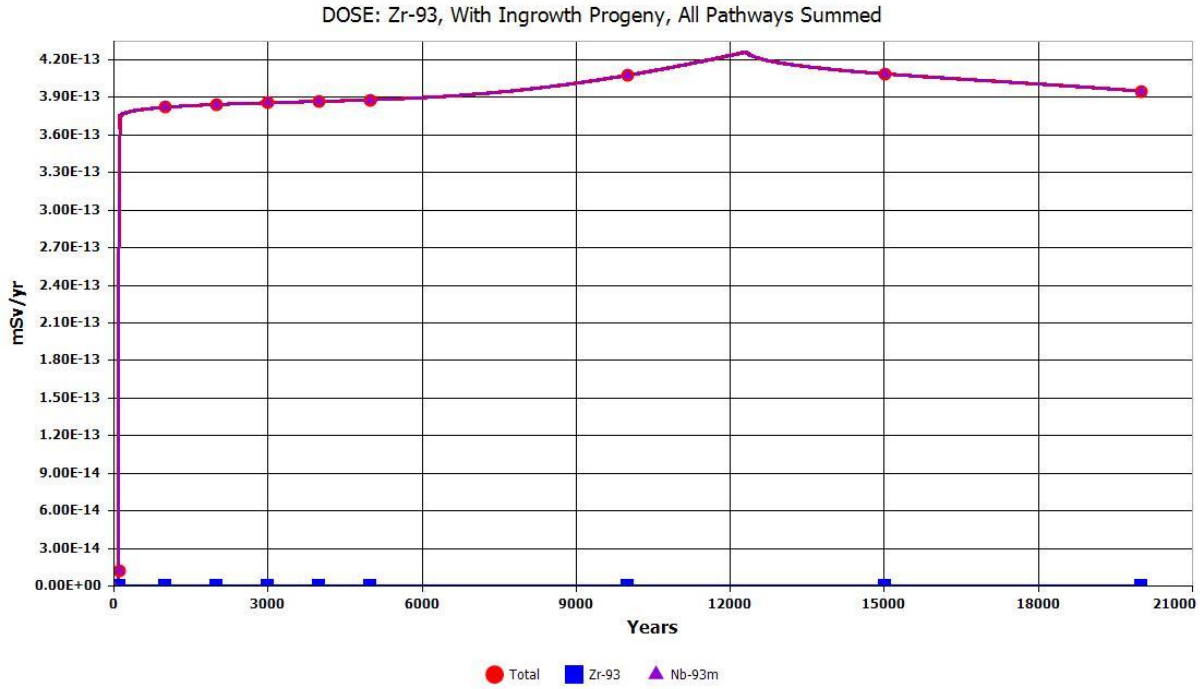
Graph 90: Total Dose due to ^{99}Tc as a function of time



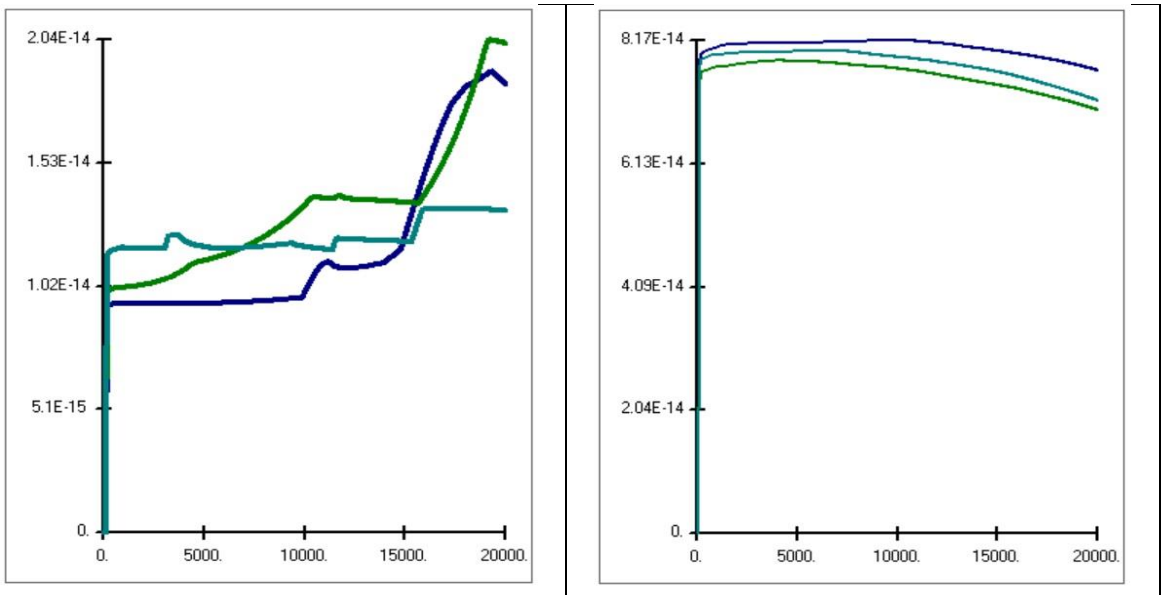


Graph 91-92: Median (left) and Mean (right) value of the total dose due to ^{99}Tc as a function of time

^{93}Zr



Graph 93: Total Dose due to ^{93}Zr and its daughters as a function of time



Graph 94-95: Median (left) and Mean (right) value of the total dose due to ^{93}Zr as a function of time