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Counter-expertise on dose calculations for Pallas during normal operation

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Synopsis

Radiation dose for people who live near Pallas

At the end of 2022, construction work preparations started on a nuclear reactor on the grounds of the Energy & Health Campus in Petten. The reactor, called Pallas, is designed to produce medical isotopes needed for medical diagnoses and treatments, such as those for cancer. Pallas will replace the existing reactor.

When the reactor comes into operation, radionuclides will be emitted from the chimney. RIVM has calculated the radiation dose that people who live near the reactor are likely to receive. This radiation dose appears to be low and less than the so-called secondary level of 10 microsievert per year.

The radiation dose for adults at the perimeter of the Energy & Health Campus is highest east of the chimney next to the main road (Westerduinweg). This is 0.15 microsievert per year. The radiation dose has also been calculated for the two nearest residential areas: 0.011 microsievert per year in Petten and 0.014 in Sint Maartensvlotbrug, which is less than a 10,000th of the dosis cause by natural background. These towns are located approximately two kilometres from the location where the radionuclides are emitted.

About 70 percent of the radiation dose comes from the noble gas isotope argon-41. Tritium contributes about 25 percent of the radiation dose. The remaining 5 percent comes from other nuclides.

RIVM carried out these calculations on behalf of the Authority for Nuclear Safety and Radiation Protection (ANVS). The calculations are based on information from the ANVS about expected emissions. The assignment was to perform ‘counter-expertise’ on the construction consortium’s calculations.

Keywords: normal operations, model, ingestion dose, external radiation dose, PALLAS

Publiekssamenvatting

Stralingsdosis voor omwonenden van Pallas

Eind 2022 zijn de voorbereidingen voor de bouw van een nucleaire reactor op het terrein van de Energy & Health Campus in Petten begonnen. Deze reactor, Pallas genaamd, is speciaal ontworpen om medische isotopen te maken en vervangt de huidige reactor. Deze isotopen zijn nodig voor medische diagnoses en behandelingen, zoals bij kanker.

Wanneer de reactor in bedrijf gaat, zullen er via de schoorsteen radionucliden worden geloosd. Het RIVM heeft berekend wat de blootstelling aan deze radionucliden is voor omwonenden, en wat dan de stralingsdosis is. De stralingsdosis voor omwonenden blijkt heel laag te zijn: lager dan het zogeheten secundaire niveau van 10 microsievert per jaar.

De stralingsdosis voor volwassenen aan de rand van het terrein is het hoogst ten oosten van de schoorsteen naast de hoofdweg (Westerduinweg). Deze bedraagt 0,15 microsievert per jaar. Ook is de stralingsdosis berekend voor de twee dichtstbijzijnde woonkernen, die op ongeveer twee kilometer van de schoorsteen liggen. De dosis is 0,011 microsievert per jaar in Petten en 0,014 in Sint Maartensvlotbrug, dit is minder dan een tienduizendste van de dosis door natuurlijke achtergrondstraling.

Ongeveer 70 procent van de stralingsdosis komt van het edelgas isotoop Argon-41. Tritium draagt ongeveer 25 procent bij aan de stralingsdosis. De overige 5 procent betreft andere nucliden.

Het RIVM heeft deze berekeningen in opdracht van de Autoriteit Nucleaire Veiligheid en Stralingsbescherming (ANVS) uitgevoerd. De berekeningen zijn gebaseerd op de informatie van de ANVS over de verwachte uitstoot. De opdracht is een ‘contra-expertise’ op de berekeningen van het bouwconsortium.

Kernwoorden: normaal bedrijf, model, ingestiedosis, externe stralingsdosis, PALLAS

Contents

1 Introduction

The production of medical isotopes is performed at only a few nuclear reactors worldwide. The Energy & Health Campus (EHC) currently hosts one of the largest producers of medical isotopes in the world, the High Flux Reactor (HFR). The HFR has been operational for over sixty years and will come to the end of its life cycle in the next decade. The Pallas reactor is the intended successor to the HFR. The government and the province Noord-Holland chose the EHC in Petten as location of the new Pallas-reactor.

Early on in 2004, the Nuclear Research Group (NRG), the current operator of the HFR, initiated ‘Pallas’ together with a group of companies and research institutes, i.e., Mallinckrodt Medical (currently Curium), TU Delft Reactor Institute (RID; part of the Delft University of Technology) and the European Institute for Energy and Transport (JRC-IET). NRG was involved in the initiative as its project manager and worked on the further elaboration and implementation of the project. The Foundation Preparation Pallas reactor (PALLAS) was established in 2013 and issued a tender for design and construction of the Pallas reactor. PALLAS chose ICHOS at the beginning of 2018: a consortium consisting of the Dutch companies Mobilis and Croonwolter&dros, part of the TBI (Techniek-, Bouw- en Infra-ondernemingen) holding, and the Argentinian INVAP (*inv*estigación *ap*licada).

As a fully independent organisation, RIVM was asked by the competent Authority for Nuclear Safety and Radiation Protection (ANVS) to perform an expert assessment of the annually received effective dose for members of the public due to the regular release of radionuclides from the Pallas reactor, once operational. The corresponding source term, annually released amount of radioactivity, has been provided by ANVS. A review of the actual figures in the source term was not part of the assignment, only the dispersion and dose calculations were.

Our atmospheric dispersion model is used to determine to what extent people living in the area around the EHC will be exposed to the emitted radionuclides. Dose conversion coefficients are used to convert the exposure to dose. We considered the effective dose received through the exposure pathways of inhalation, external radiation of all radionuclides, complemented with the ingestion dose of tritium. We focus on members of the public: one-year-olds and adults. We only consider the effective dose through the dispersion of the released radioactivity through air, as it is the main pathway affecting the health of the general public. Eye lens dose and skin dose are beyond the scope of our study. These exposure paths only become relevant when exposure to concentrations at least three orders of magnitude higher than during normal operation are expected. The next chapter describes this workflow for annual dose assessment in more detail.

2 Calculation methodology

2.1 Run set-up

The aim is to derive a representative estimate of the annual effective dose for residents in the area around EHC as a result of a continuous radionuclide release by Pallas. We focus on the effective dose for adults and for one-year-olds. Under the assumption of a Linear No-Threshold dose-response relation, we reach our goal by calculating the average effective dose due to exposure to many short releases, each containing the annually released radionuclides. Each release has a different start date and time within a three-year historical period. This computational algorithm is simpler to execute than calculating the effective dose from a continuous release. In more detail, we average the results of dispersion runs of 1012 subsequent releases. Each release has a during of one hour. The dispersion of the release is calculated for the next six hours. An evaluation period of six hours suffices for the dispersion, as the area where effective doses may exceed the natural background is limited, which is confirmed by control analyses. The first release uses the meteorological condition of 1 January 2015, while the last uses that of 31 December 2017. The time difference between each release is always 26 hours. In this way, existing daily and seasonal variations are included.

2.2 Dispersion and dose model

We use the Gaussian puff model NPK-PUFF originally developed by RIVM and the Royal Netherlands Meteorological Institute (KNMI) (Verver et al., 1990). Currently, NPK-PUFF is an atmospheric dispersion and dose model that can perform the effective dose assessment due to radioactive discharges. It describes the dispersion of clouds containing radioactivity, i.e., the combination of the advection by the local wind and the diffusion due to atmospheric turbulence. In addition, the processes of wet and dry deposition, as well as the decay of radioactivity, are considered. Different output quantities can be requested, such as radioactivity concentration in air, time-integrated radioactivity concentration, deposited radioactivity concentrations, and time of cloud arrival. Other radiological endpoints can also be acquired, such as effective dose estimates for different age groups, e.g., adults and one-year-olds, or separate organs. All output quantities are presented on user-defined grids. We use an equidistant grid of 100 x 100 cells covering a domain of 10 x 10 km, with the release point at the domain centre.

NPK-PUFF is currently the operational model in the Dutch nuclear emergency response system and has been used before in atmospheric dispersion studies, e.g., Tomas et al. (2021a), and De Meutter et al. (2021). Tomas et al. (2017) assessed how the atmospheric dispersion model NPK-PUFF compares to two widely used dispersion models. Additionally, in Tomas et al. (2021b), the performance of NPK-PUFF was tested further, using the European Tracer Experiment dataset (Nodop et al., 1998).

The transport of radioactivity is modelled in NPK-PUFF using the Gaussian puff methodology. The released radionuclides are distributed over 'puffs' that move with the local wind velocity (advection). For each puff, the concentration distribution is assumed to be Gaussian. The diffusion is modelled for each puff by the increase over time of the standard deviation of the concentration distributions in the horizontal and vertical directions. The increase of these standard deviations depends on the local level of atmospheric turbulence and the calculation timestep. Separate diffusion characteristics are considered for the regions above and below the mixing height.

2.3 Source Term

The annual released amount of radioactivity, the source term, is made available to RIVM by the ANVS. The source term comprises 89 isotopes that are all included in our dispersion calculations. Table 1 gives a summary of the source term, listing the isotopes that contribute the most to the effective dose. The ancillary parameters that are part of the source term are the release height, the heat content and the distribution of the iodine radionuclides over their chemical state (aerosol bound, organically bound and elementary).

Table 1 The annually released activities of eight radionuclides that make the largest contribution to the total effective dose.

Radionuclide	Release [Bq/year]	Radionuclide	Release [Bq/year]
H-3	3.6E11	I-132	2.4E5
Ar-41	1.4E12	I-133	1.3E6
Kr-87	2.0E10	I-134	4.1E6
Kr-88	3.9E10	I-135	4.0E6

2.4 Meteorological data

The coastal weather characteristics, such as the prevailing wind direction, will probably be reflected in the patterns of received effective dose for people living in the area. Therefore, it is important that wind fields used in the assessment of the annual effective dose are applicable to a coastal area, and to the area of Petten. RIVM has access to archived data from the meteorological model HARMONIE-AROME for the 2015-2017 period (Bengtsson et al. 2017). HARMONIE covers latitudes from 55.9 down to 49.0, and longitudes from 0 to 11.1, roughly from London to halfway Germany in the East-West direction, and from Luxembourg to Edinburgh in the South-North direction. The data has a horizontal resolution of approximately 2.5 km and a temporal resolution of 1 hour. There are 5 wind levels that reach up to a height of approximately 500 m; the first level is at a height of 10 m. Hence, HARMONIE data is applicable to model the dispersion of surface releases at Petten.

2.5 Dose estimates

We consider the exposure pathways submersion, inhalation, and groundshine. We obtain the effective doses for submersion, inhalation, and groundshine, by applying the corresponding dose conversion coefficients (DCCs) to the concentrations of radionuclides in air, time-integrated air concentrations and deposited concentrations, respectively. We use the DCC data from the most recent ICRP report 119 Eckerman et al. (2013). Table 2 lists the DCCs for radionuclides that make the largest contribution to the annual dose (Table 1). The breathing rates are set to 0.92 m^3/h and 0.22 m^3/h for adults and one-year-olds, respectively. Since noble gasses do not interact or deposit, they have DCCs for the cloud submersion only.

It is assumed that indoors, the external radiation is partially shielded, but that people do not stay in their homes full time. In the current implementation in NPK-PUFF, this assumption leads to a reduction of the external radiation to 74% of the dose received while being outdoors full-time. The calculation of the ingestion dose is explained in more detail in the next paragraph, as the annually released activities include the nuclide tritium, which behaves quite differently from other radionuclides that may yield an ingestion dose.

Table 1 DCC values for adults and one-year-olds for ingestion, inhalation and cloud exposure (submersion). A respiration rate of 0.92 m^3/h for adults and 0.22 m^3/h for one-year-olds is used.

Nuclide	Cloud submersion [Sv/h per Bq/m^3]		Ingestion [Sv / Bq]		Inhalation [Sv / Bq]	
	Adults	one-year-olds	Adults	one-year-olds	Adults	one-year-olds
H-3	(9.05E-19)[+]	(2.02E-19)	4.20E-11 1.80E-11[*]	1.20E-10 4.80E-11[*]	4.10E-11	2.50E-10
Ar-41	2.19E-10	2.47E-10	-	-	-	-
Kr-87	1.39E-10	1.71E-10	-	-	-	-
Kr-88	3.51E-10	4.28E-10	-	-	-	-
I-132	3.78E-10	4.80E-10	4.30E-09	2.40E-09	9.40E-11	2.30E-09
I-133	9.97E-11	1.28E-10	1.10E-10	4.40E-08	4.00E-09	4.10E-08
I-134	4.38E-10	5.54E-10	9.30E-10	7.50E-10	1.50E-10	6.90E-10
I-135	2.75E-10	3.43E-10	4.30E-09	8.90E-09	9.20E-10	8.50E-09

[*] Organically bound H-3 and HTO

[+] Values in brackets are so low that they are uncertain and can be ignored

2.5.1 *Ingestion dose*

Multiplying the annually released radioactivity by the DCC for ingestion already shows that only tritium can potentially lead to an ingestion dose of any significance. The sum of these multiplications leaves only 0.07% for the nuclides other than tritium. Tritium, and carbon-14 for that matter, display different behaviours compared to the other depositing radionuclides, given that they are the main components in hydrocarbon molecules. We follow the reasoning of Smith (2009) where it is explained that after its uptake in plants, tritium is returned to the atmosphere in a biological timescale that is short compared to its decay half-life time. It can therefore be assumed to come into equilibrium with the environment, meaning that the radioactivity concentration of tritium in organisms is a function of the air concentration of tritium outside of the organisms. We ran the PC-CREAM 08 model (Smith, 2009) to determine that the equilibrium factor for tritium is at 100 [Bq/kg] in vegetables per unit air concentration tritium [Bq/m^3]. Therefore, the annual ingestion dose owing to tritium at a specific location is equal to the average air concentration at that location multiplied by 100, the consumption rate of vegetables, and the DCC for ingestion. The average air concentration at a specific point follows from the dispersion calculations described above. An additional route of tritium to enter the body is through the skin. However, in the situation at hand, where ingestion and inhalation of tritium are described, this additional route has a negligible contribution, as follows from the model by Killough (1982).

We use the value of 202 g per day for the habitual intake of vegetable consumption by adults, i.e., the 95th percentile of food consumption by men and women aged between 19 and 69 years (Geurts *et al.,* 2016). For one to three-year-olds a range of 50 to 100 g per day is advised by The Netherlands Nutrition Centre (Voedingscentrum, 2023). Since Geurts *et al*. (2016) do not provide numbers for one-year-olds, we use the upper value of the advised consumption rate of 100 g/day for one-year-olds. It could be conceivable that by eating only one’s own home-grown vegetables, one would incur the estimated ingestion dose, as the area required to produce the annual consumption of one person is in the order of 40 m^2 (assuming a production of 2 kg of vegetables per m^2 per year (Blaauboer, 2002)).

3 Results

Figures 1 and 2 show contour plots of the calculated annual effective dose for adults (red in Figure 1) and one-year-old children (purple in Figure 2). The contours for one-years-olds are slightly larger than those for adults. In both figures, a bulge is observed roughly perpendicular to the coastline, probably an effect of the land-sea breezes that can form near the coast. The maximum value for the annual effective dose on-site is 0.5 microSv (adults) and the largest value along the fence is 0.15 microSv at a location east of the stack next to the main road (Westerduinweg, orange line). The annual effective dose for adult residents at the closest towns Petten (52.769 °N; 4.665 °E) and Sint Maartenvlotbrug (52.786 °N; 4.708 °E) is 0.011 microSv and 0.014 microSv, respectively, while for one-year-olds, we find the values 0.012 microSv and 0.016 microSv.

The largest contributions to the effective dose for adults and children originate from Ar-41 (around 71%) through submersion and from tritium (around 25%) through ingestion. Hence, almost the entire dose comes from these two radionuclides.

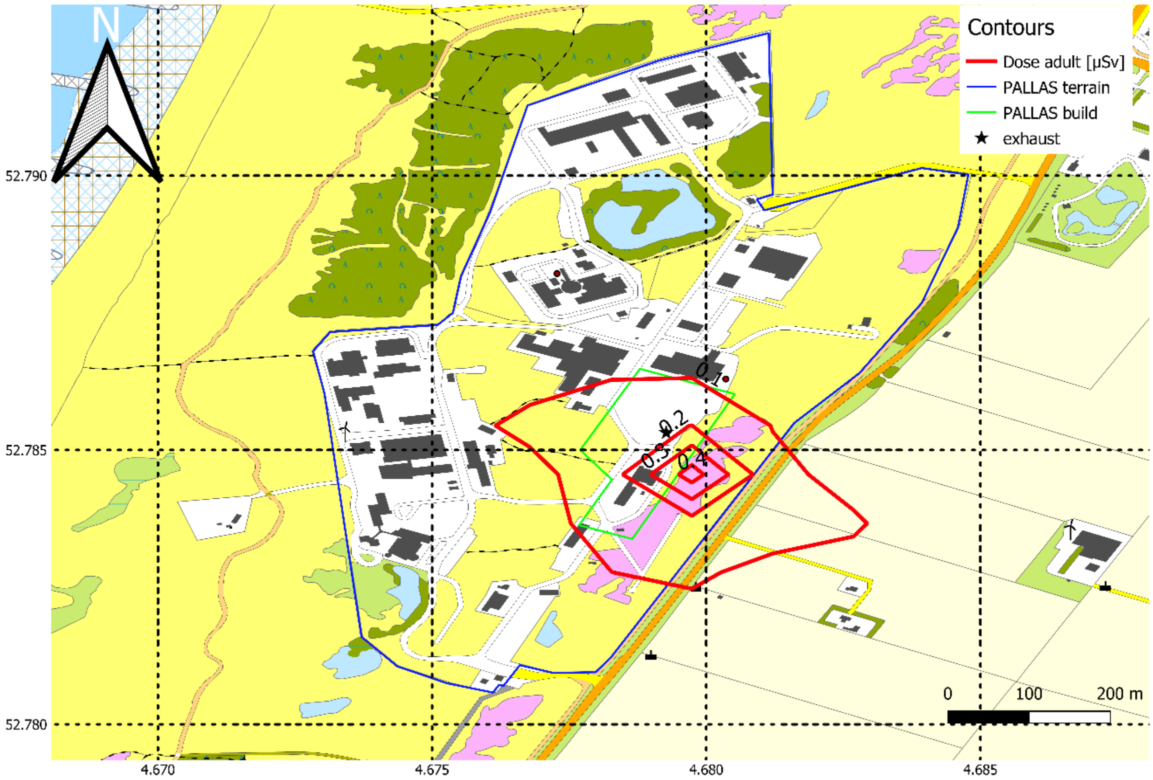

Figure 1 Contours (in red) of the calculated annual effective dose for adults. The legend lists the EHC-fence as "Pallas terrain" (blue line). "Pallas build" indicates the location of the new building. "exhaust" (black star) indicates the location of the emission.

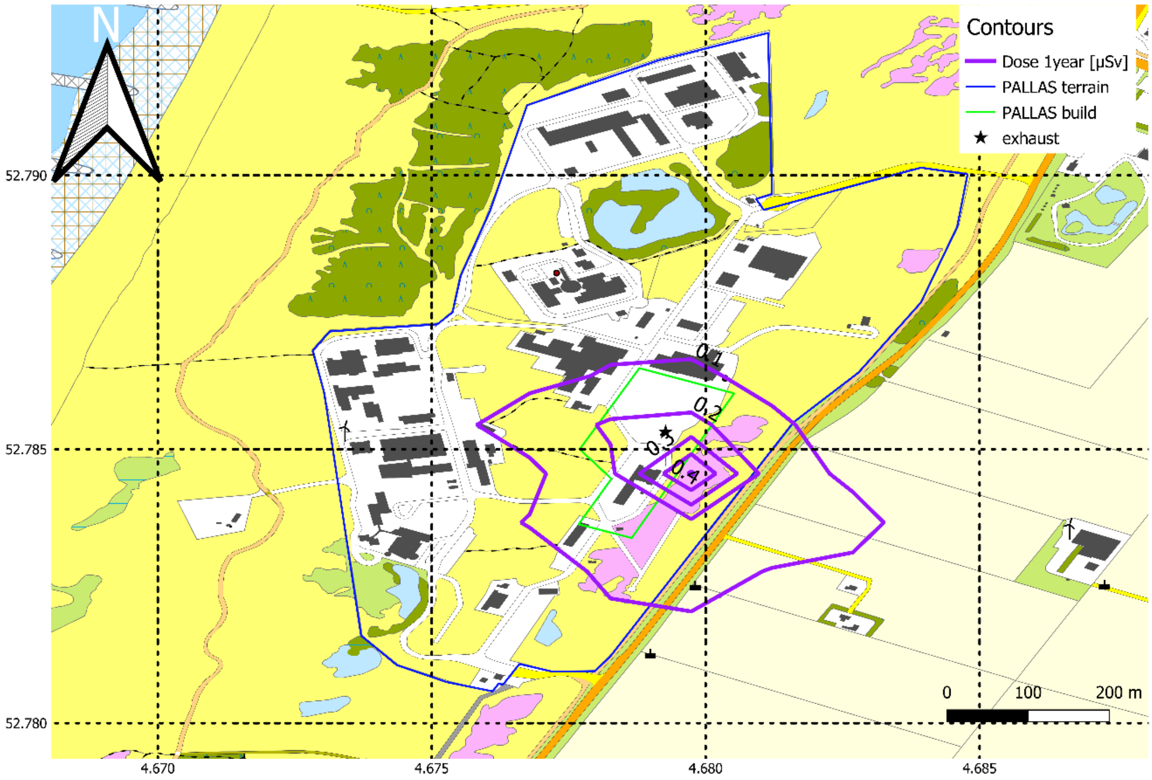

Figure 2 Contours (in purple) of the calculated annual effective dose for one-year-olds. The legend lists the EHC fence as "Pallas terrain" (blue line). "Pallas build" indicates the location of the new building. "exhaust" (black star) indicates the location of the emission.

An overall picture for the dose as a function of the distance is obtained by grouping the grid results with respect to their distance to the source in 100 m bins. The average annual effective dose within each bin is determined and plotted in Figure 3. We find values for adults below 0.1 microSv per year at distances greater than 185 m from the emission point; beyond 2150 m, the effective dose is smaller than 0.01 microSv per year. For one-year-olds, the distances are 230 m and 2500 m, respectively.

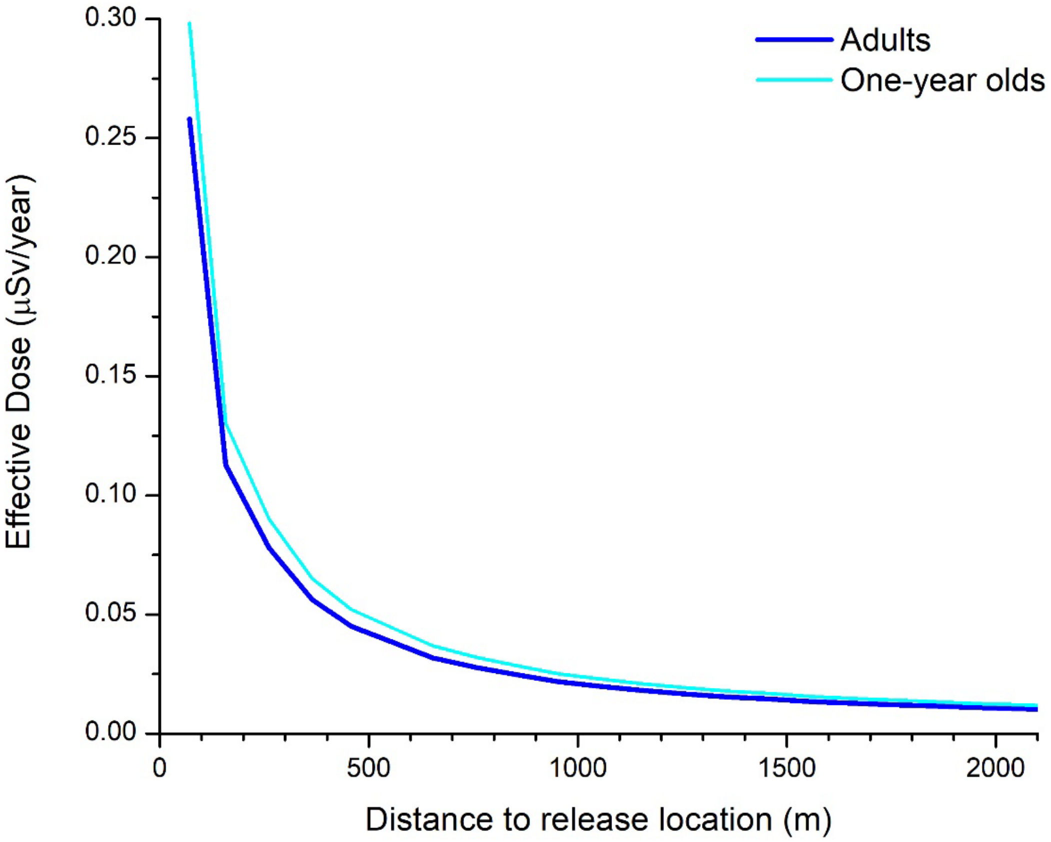

Figure 3 The annual effective dose for adults and one-year-olds as a function of the distance to the release location.

4 Conclusions

RIVM conducted an assessment of the expected annual effective dose for people living in the surroundings of the Energy & Health Campus (EHC) owing to the expected emission of radionuclides during normal operation of the planned Pallas reactor. The Pallas reactor is to be built on the premises of the EHC. The numbers for the expected emissions of radionuclides were provided by the competent Authority for Nuclear Safety and Radiation Protection (ANVS).

The maximum value for adults at the fence is 0.15 microSv for a location east of the stack next to the main road (Westerduinweg). In the towns of Petten and Sint Maartenvlotbrug, this value is a tenth of the dose at the fence, i.e., 0.011 and 0.014 microSv per year, respectively. Both towns are located at a distance of approximately 2 km from the release location. For adults, we find values below 0.1 microSv per year for distances greater than 185 m, while beyond 2150 m, the annual effective dose is less than 0.01 microSv per year. For one-year-olds these distances amount to 230 m and 2500 m, respectively. The doses for adults and one-year-olds are approximately 71% from Ar-41, via external radiation, and approximately 25% from tritium through ingestion; other isotopes make small contributions.

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6 Abbreviations and names

ANVS	Authority for Nuclear Safety and Radiation Protection
DCC	dose conversion coefficients
EHC	Energy & Health Campus
HFR	High Flux Reactor
ICHOS	Building consortium with INVAP and previous also TBI
ICRP	International Commission on Radiological Protection
INVAP	*inv*estigación *ap*licada
JRC-IET	European Institute for Energy and Transport
KNMI	Royal Netherlands Meteorological Institute
NRG	Nuclear Research Group
Pallas	The nuclear reactor to be built on the EHC
PALLAS	Foundation Preparation Pallas-reactor
PC-CREAM	Model for build-up of radionuclides in the environment
RID	Reactor Institute Delft
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Public Health and the Environment)
TBI	Techniek-, Bouw- en Infra-ondernemingen

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