Strål säkerhets myndigheten
Swedish Radiation Safety Authority

Report

Radiological Consequences of Fallout from Nuclear Explosions

Appendix 3 – Dispersion and Dose Calculations

2023:05e

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1. Introduction

This appendix describes the dispersion and dose calculations performed by the Swedish Radiation Safety Authority (SSM) for the purpose of assessing the radiological consequences of fallout from a nuclear explosion. Within the framework of the *ARGOS* decision and analysis support system, the *MATCH-BOMB* atmospheric dispersion model has been used, with historical meteorological data from the Swedish Meteorological and Hydrological Institute (SMHI) produced using a regional forecast model, *HARMONIE*.

Dispersion and dose calculations have been performed for the purpose of studying the potential radiological consequences of fallout from a nuclear explosion, where the stabilised cloud and a nuclide vector have been used as source term in the calculations. The calculation results show the projected radiation dose in the calculation area around the blast site based on air concentration and ground deposition of radioactive material, or ground deposition of the time-invariant deposition amount "H+1", which in turn can be linked to radiation doses using the nuclide vector. The desired result for each calculation criterion is the largest distance from the blast site to a point where the criterion is exceeded. Calculations have been made for a large number of criteria in order to interpolate results relating to different protective actions. The largest value for a quantity at specified distances has also been studied. By making calculations for a large number of different weather cases, statistical processing of the results is made possible.

A brief description of the meteorological weather forecast data, the dispersion model and the source term used are presented in this appendix. In addition, the radiation doses considered are presented, and how they have been calculated. The appendix also describes how the statistical processing of the results for the calculation cases has been carried out. Finally, there is a brief summary of selected parameter values for the calculations.

2. Atmospheric dispersion calculations

In the event of a nuclear explosion, various processes in the initial phase will cause a variety of radioactive substances that have been formed to enter the atmosphere in a “stabilised cloud”. Subsequently, radioactive material will be transported/dispersed in the surrounding atmosphere via physical processes and ultimately deposited on the ground.

The results of the dispersion calculations are usually expressed in terms of airborne activity, time-integrated airborne activity and ground deposition activity, per nuclide and as a function of time and spatial location. Radiation doses to humans through external and internal exposure from ionising radiation from radioactive material are estimated by using dispersion calculation results in dose models. In external exposure the radiation source is outside the body. This occurs when the radioactive plume passes or when there is radioactive material deposited on the ground. External exposure can also occur when radioactive material that contaminates the outside of the body delivers a radiation dose to the skin. In internal exposure, the radiation source is inside the body. This occurs with the inhalation of radioactive material in the plume which is then absorbed in the body and later decays, thereby contributing to the radiation dose even after the cessation of external exposure. Similarly, internal exposure may occur as a result of ingestion of contaminated foodstuffs (including drinking water) or inadvertent ingestion of radioactive material such as surface contamination on hands.

The estimated ground contamination can be used to study long-term effects such as transfer of activity to the feed and food chain or the need for decontamination.

In some cases, instead of dose or dose rate from ground contamination under different conditions, ground deposition of the time-invariant deposition amount “H+1” has been used as a calculation criterion (see example in Figure 1).

To obtain an understanding of the distances from a selected explosion site at which there may be a need for a particular protective action or other response action, dose criteria are used. A dose criterion can be a projected dose to a particular body organ and for a particular age group. Similarly, to study the need for combinations of protective actions, a generic criterion can be used. Furthermore, the effects of taking a protection action can be studied by finding the greatest distance at which a radiation dose is exceeded given a certain protection. The result depends upon the meteorological conditions prevailing during the time the activity is dispersed in the atmosphere. A large number of dispersion calculations are therefore needed to investigate at which distances from a given explosion site the studied criteria are exceeded under varying meteorological conditions.

For more detailed information on generic criteria and dose criteria, see Appendix 1 (Radiation Protection).

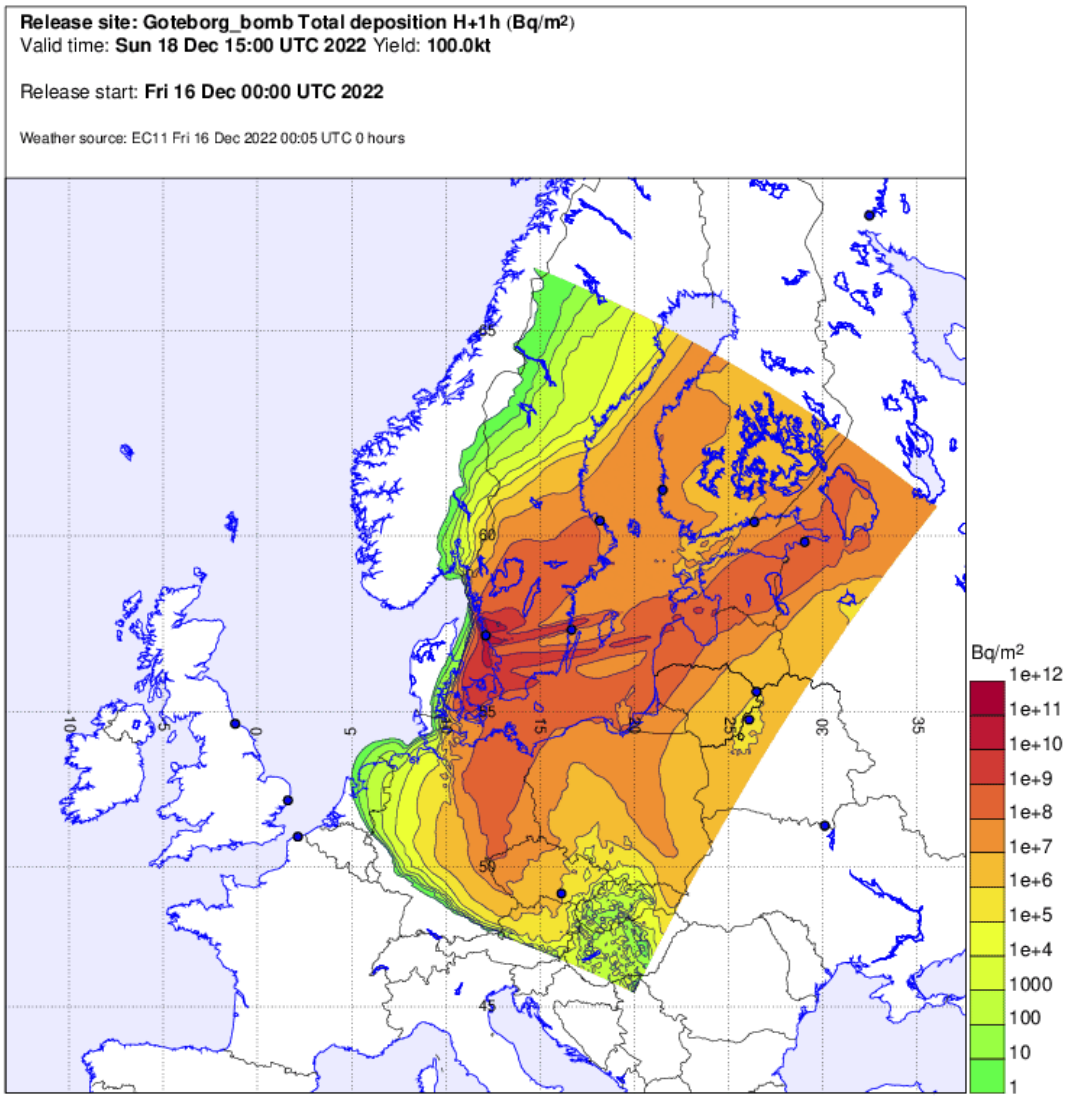

Figure 1. Example of results from an atmospheric dispersion calculation. The figure is based on a nuclear explosion with an explosive yield of 100 kt (50 % fusion fraction) at ground level and shows the resulting radioactive material deposited on the ground, expressed in becquerels per square metre (Bq/m^2) of H+1, 72 hours after the explosion. The calculation has been made using the SMHI *MATCH-BOMB* model (see Section 2.2).

2.1. Meteorological information in the form of numerical weather data

Atmospheric dispersion calculations require access to meteorological information on the state of the atmosphere as a function of time and location. In these calculations, SSM has used historical meteorological data stored at the National Supercomputer Centre in Sweden (NSC) on behalf of SMHI.

The meteorological information is based on the *HARMONIE/AROME* high-resolution forecast model[1], which has been used in production by SMHI during the relevant period. The forecast model covers a geographical area shown in Figure 2.

[1] *HARMONIE* is the European NWP modelling system and *AROME is* the physical model included in the *HARMONIE* system.

Numerical weather data include four 6-hourly forecasts per day, with meteorological analyses at 00, 06, 12 and 18 UTC[2]. The forecasts have a horizontal resolution of about 2.5 km (0.03 degrees), a temporal resolution of one hour and include 65 altitude levels from the ground surface up to 10 hPa which corresponds to about 30 km, but the exact altitude for a given pressure level depends on the weather situation.

The historical meteorological data used represents a period of about one year (January 2021 – January 2022) and occupies about 14 terabytes of data storage space.

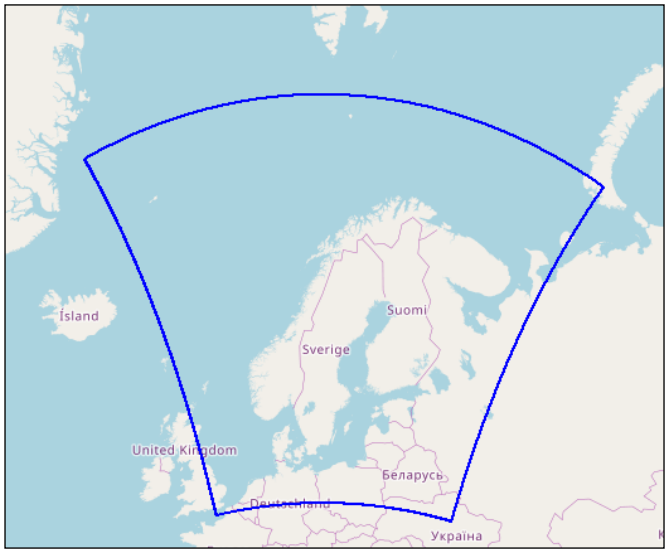

Figure 2. Geographical area for meteorological data (*HARMONIE*).

2.2. Dispersion model

MATCH-BOMB [1] [2] [3], the Eulerian dispersion model used in this study, is designed to calculate air concentration and ground deposition resulting from atmospheric dispersion of radioactive material in gaseous or aerosol form. The model employs weather data from numerical weather prediction models to describe transport and deposition. In the model, the volume of the atmosphere is divided into horizontal and vertical cells in the same way as the numerical weather data. However, to increase the resolution in the near-zone, a particle model (Lagrangian model) is initially used, in which the activity is initially represented by a large number of model particles that follow trajectories determined by the local wind direction and air turbulence. Half a million model particles are included in the particle phase, which has been optimised to a model duration of 2 hours, and then aggregated in the cells used by the Eulerian *MATCH* model. The transport of particles is modelled by assuming mass conservation between the computational cells including source and depletion processes. The ground contamination is influenced by particle size-dependent sedimentation rates, land use including surface roughness, and precipitation washout whose efficiency is dependent on particle size. Over time, percolation will affect the distribution of radioactive material in the soil. These processes are not included in the model.

[2] UTC stands for Universal Time Coordinated.

In this study, *MATCH-BOMB* has been used within the framework of the decision and analysis support system *ARGOS* [4].

2.3. Source term

In dispersion and dose calculations for radiological emergencies involving nuclear facilities, a source term is usually employed to describe the radioactive release into the atmosphere. The source term includes the composition and activity of different nuclides in the release, the timing of the release and, in some cases, the chemical form. The source term also includes information on the height or altitude distribution of the release and any heat content. Furthermore, the source term may include a description of particle size distribution and particle density.

In a nuclear explosion, radioactive materials are formed and released instantaneously (on the time scale of the dispersion model) and form a cloud that stabilises within a few minutes after the explosion. The stabilised cloud contains nuclides within and on the surface of particles of different sizes and densities.

The source in the dispersion modelling consists of this stabilised cloud, which is described in the form of a number of particle clouds consisting of activity-bearing particles of different sizes. In order to computationally handle the large range of particle sizes that occur, these are divided into 10 size intervals based on a lognormal distribution so that each sub-interval represents an equal amount of initial activity. The sub-intervals are then represented by model particles, the size of which is given by the expectation value of the radius of the particles in each interval, ranging from 1.1 to 378 micrometres for a ground-level explosion.

The horizontal and vertical distribution of particles in the stabilised cloud depends on a number of different parameters of the explosion (explosive yield, fission fraction, height, soil type, *etc*.) and is modelled using *NWSwamp* [5] which in turn is based on the *KDFOC3* parameterisation [6]. Output from *NWSwamp* is used by *MATCH-BOMB* to define the stabilised cloud and represent it as a number of cylinders centred over the explosion site. Each cylinder is assigned a certain height above the ground, a certain radius and a certain thickness. For each cylinder there is a separate particle size distribution.

In this study, calculations have been performed with a stable, non-decaying "nuclide", H+1, which represents the total activity one hour after the detonation. H+1 is distributed among the different particle size distributions in the stabilised cloud to avoid resource-intensive calculations of dispersion and deposition for each nuclide (more than 100) and its decay chains. In a post-processing step, the content of H+1 in the various calculation cells is instead multiplied by a nuclide vector containing at each time step each nuclide's share of total H+1, to obtain the activity of individual nuclides, in the air and on the ground. SSM's nuclide vector is described in more detail in Appendix 2 (Nuclide Composition). The nuclide vector method assumes that fractionation, *i.e*. that different nuclides are distributed to different particles, does not occur. The main report contains a discussion of fractionation.

The dispersion modelling has taken place under the assumption that all nuclides included in the source term occur in the form of aerosols, with a number of different aerosol diameters and under the assumption of a particle density of 2,500 kg/m^3. Iodine is also presumed to occur in aerosol form and therefore there is no special treatment of the

chemical form of iodine, as is usually done in dispersion and dose calculations with source terms from nuclear facilities.

Noble gases, both those formed during the initial fission processes and those later formed during decay, have been assumed to be bound to particles and thus follow them during the further dispersion process. This also means that they undergo deposition together with the particles to which they are bound. The noble gases formed in the material deposited on the ground are assumed to remain in the deposited material.

3. Calculation of radiation dose

Ionising radiation can give rise to different types of health effects depending on the radiation dose received. Health effects and radiation protection during fallout from a nuclear explosion are described in Appendix 1 (Radiation Protection).

The dose calculations included in the total effective dose (the sum of cloud dose, ground dose and inhalation dose) and the equivalent dose to the thyroid gland from inhalation of radioactive iodine are described below. Based on the equivalent dose to the thyroid, the RBE-weighted absorbed dose to the thyroid can also be estimated. The calculations performed in ARGOS apply to one-year-old children and adults exposed during different time periods after the explosion. In addition, doses related to severe deterministic health effects on the skin and red bone marrow, estimated using ground contamination of H+1, are described, as well as a discussion of the contribution to the dose of nuclides not included in the nuclide vector.

3.1. Cloud dose

The cloud dose is a component of the total effective dose and is the external dose resulting from gamma radiation from the passing plume. This dose is calculated by multiplying for each nuclide the time-integrated air activity in the layer closest to the ground by a nuclide-specific dose factor and finally summing over all nuclides. This calculation assumes that the time-integrated air activity can be approximated by a semi-infinite volume source. The contribution of the cloud dose to the total effective dose ceases when the plume has passed.

For adults, the cloud dose has been calculated using nuclide-specific dose factors for effective dose (Sv/s per Bq/m^3) from *DCFPAK* [7] (*air submersion*). For one-year-old children, cloud dose has been calculated using nuclide-specific dose factors for effective dose (nSv/h per Bq/m^3) for one-year-old children from ICRP 144 [8] (*air submersion*). For eight nuclides that are included in the nuclide vector but where dose factors for cloud dose are missing in ICRP 144 and *DCFPAK*, dose factors have been estimated. The dose factors used to convert time-integrated air activity to the dose are described in greater detail in Section 6.3.1 where the method for estimating missing dose factors is also described.

3.2. Ground dose

The ground dose is a component of the total effective dose and is the external dose resulting from gamma radiation from nuclides deposited on the ground. This dose contribution is calculated by multiplying for each nuclide and time step the ground deposited activity by a nuclide-specific dose factor, summing over time and finally summing over all nuclides. In this calculation, it is assumed that the deposited activity can be approximated by a semi-infinite ground contamination located in a slice. The contribution of the ground dose to the total effective dose continues to grow as long as activity remains and exposure continues.

For adults, ground dose has been calculated using nuclide-specific dose factors for effective dose (Sv/s per Bq/m^3) from *DCFPAK* [7] (*volume source in 1 cm soil*). For one-year-old children, the ground dose has been calculated using nuclide-specific dose factors for effective dose (nSv/h per Bq/m^2) for one-year-old children from ICRP 144 [8] (*soil contamination*, 0.5 g/cm^2). For eight nuclides included in the nuclide vector but for which dose factors for ground dose are missing in ICRP 144 and *DCFPAK*, dose factors have

been estimated. The dose factors are described in greater detail in Section 6.3.2, which also describes the methodology for estimating missing dose factors.

3.3. Inhalation dose

The inhalation dose is a component of the total effective dose and is the internal dose resulting from activity that is inhaled and can then be absorbed by the body and transported to different body organs. As the activity remains to some extent in the body, this dose is called the committed dose. The dose contribution of the inhaled activity is calculated over a period of 50 years after exposure for an adult, and over a period of 69 years for a one-year-old child.

The dose is calculated by multiplying, for each nuclide, the time-integrated activity concentration in the ground layer by a presumed respiratory rate and then applying a nuclide-specific dose coefficient. The dose contributions are then summed over all nuclides. The contribution from the inhalation dose to the total effective dose occurs during the plume passage apart from any additional contribution from resuspension.

The inhalation dose has been calculated using age-dependent, nuclide-specific effective dose coefficients (Sv/Bq) from ICRP 119 [9] (Annex G) for adults and one-year-old children. For 26 nuclides included in the nuclide vector but for which dose factors are missing in ICRP 119, dose coefficients have been estimated. The dose coefficients are described in greater detail in Section 6.3.3 of the report, where the method for estimating missing dose factors is also described.

3.4. Dose to the thyroid gland

Thyroid dose refers to the equivalent dose to the thyroid gland. In this report, only contributions to thyroid dose from inhaled radioactive iodine are considered. The thyroid dose is derived by *ARGOS* from the effective dose resulting from inhalation of the different iodine isotopes, taking the individual contributions of the different chemical forms of iodine (organic, elemental and aerosol) into account. In this study, iodine is assumed to occur only in aerosol form.

In the above, a simplified thyroid dose calculation procedure is normally applied by using a factor of 20 to multiply the effective inhalation dose from each iodine isotope to obtain the thyroid dose[3].

The thyroid dose has been calculated for each age group separately using age-dependent dose coefficients and respiratory rates.

SSM has also estimated the conditions under which fallout from a nuclear explosion could cause severe deterministic health effects on the thyroid gland via inhalation of radioactive iodine in the fallout.

The dose criterion used for severe deterministic effects on the thyroid gland was 2 Gy RBE-weighted absorbed dose to the thyroid, see Appendix 1 (Radiation Protection).

[3] The thyroid tissue weight factor is set at 0.05 in accordance with current inhalation dose coefficients based on the International Commission on Radiological Protection's Recommendations in ICRP 60 [9]. More recent ICRP Recommendations indicate a weighting factor of 0.04 [31].

The RBE-weighted absorbed dose to the thyroid can be estimated from the equivalent dose to the thyroid [10].

3.5. Total effective dose

The components summarised in the total effective dose are the cloud, ground and inhalation doses as described above.

The total effective dose relates to a given time *T* after the explosion, and describes the internal dose received for life (committed dose) and the external dose received during a continuous stay at the given location until time *T*. If the total effective dose is calculated for a time after the plume has passed and deposition of radioactive material on the ground has ceased, the residual activity on the ground will continue to contribute dose as long as the residence continues. Resuspension of activity from the ground could also contribute to an increase in the total inhalation dose. However, resuspension has not been considered in this study.

3.6. Dose to the skin

SSM has roughly estimated the conditions under which fallout from a nuclear explosion could cause severe deterministic health effects on the skin by depositing radioactive material on the skin. The dose criterion used for severe deterministic effects on the skin was 10 Gy RBE-weighted absorbed dose to a depth of 0.4 mm, see Appendix 1 (Radiation Protection).

To estimate the RBE-weighted absorbed dose to the skin from fallout deposited on the skin, the method described in [11] has been used. However, due to the rapid change in nuclide composition in the case of fallout from a nuclear explosion, the decay dynamics during exposure have been modelled in greater detail than was done for fallout from a nuclear power plant accident in [11]. The dose contribution from each nuclide in each decay chain starting with a nuclide initially deposited on the skin has been modelled individually, instead of including contributions from ingrowth of decay products in the dose coefficients of the initially deposited nuclides.

For a given duration of the exposure, starting at a given time after the explosion, nuclides and their activities in the nuclide vector have been calculated at the beginning of the exposure (*i.e.* when the fallout, which is assumed to arrive instantaneously, has just been deposited). The dose rate from each nuclide deposited or arising from the decay of deposited nuclides has been integrated over the duration of the exposure. This results in a total absorbed dose per deposition unit on the skin (Gy/Bq/cm²) from all nuclides for the given exposure situation. As in [11], a general "self-decontamination time" of 14.7 hours has been assumed, *i.e.* activity on the skin decreases exponentially due to abrasion, decay, *etc.* with the half-life of 14.7 hours in addition to the radioactive decay specific to each nuclide.

To give the RBE-weighted absorbed dose, the absorbed dose per deposition unit on the skin calculated for a given point in time for the time and duration of the exposure must be multiplied by the estimated deposition on the skin. The dispersion calculations provide a value for radioactive material deposited on the ground from the nuclear explosion. In order to estimate skin deposition, a correlation between ground contamination from fallout and skin contamination from fallout must be assumed. Such an assumption introduces a large

degree of scenario dependence and is subject to very large uncertainties. There is a detailed investigation in [12] of possible parameter choices suitable for different specific situations (*e.g.* affected body part, particle sizes, dry or humid environment), with associated uncertainties. Possible outcomes for different situations, including the estimated uncertainties, vary overall over many orders of magnitude.

The purpose of the skin dose estimate in this study is to get a rough idea of whether radiation doses from contamination on the skin may generally need to be considered at a distance from a nuclear explosion. This being the case, there appears to be little basis, and little evidence, to set the factor expressing the relationship between skin contamination and ground contamination at anything other than unity. It was therefore assumed that the fallout causes the same activity concentration on the skin as on the ground. However an assumption based on the expected particle size distribution has been made that self-shielding of fallout particles on the skin reduces the dose rate by 20 % on average. The assumption is based on the discussion of self-shielding of deposition particles in [12] and on the observation, after detailed study of some calculation cases, that the particle size distribution in the radioactive material deposited on the ground at distances out to ~100 km seems to be best described by what in [12] is referred to as "*large particles*"[4].

3.7. Absorbed dose to red bone marrow

SSM has estimated distances at which fallout from a nuclear explosion could cause severe deterministic health effects on red bone marrow via external exposure from radioactive material deposited on the ground. The dose criterion for severe deterministic effects on red bone marrow was 1,000 mGy RBE-weighted absorbed dose to red bone marrow (adults and children), see Appendix 1 (Radiation Protection).

To enable dose calculations for external exposure from the nuclide vector, SSM's *DosCalc*[5] software has been adapted to calculate equivalent doses to individual tissues or organs. Equivalent doses to red bone marrow could then be calculated for a given ground contamination. In this case, where the dose comes from external exposure, the equivalent dose to red bone marrow can be assumed to provide a good estimate of the absorbed RBE-weighted dose [13]. SSM has therefore assumed that the RBE-weighted absorbed dose to red bone marrow is identical to the equivalent dose to the red bone marrow.

Doses to red bone marrow to adult women and men, and to one-year-old girls and boys, have been calculated using the main scenario nuclide vector starting at different times after the detonation. The doses do not differ much between genders, however the limiting doses for adults are doses to women and the limiting doses for one-year-old children are doses to boys. Consequently these groups have been chosen to represent adults and one-year-old children in the results.

3.8. Un-fissioned plutonium

The impact of un-fissioned plutonium, *i.e.* plutonium that was fission fuel in the nuclear weapon but was not consumed in fission reactions, is disregarded in this report. This section estimates the impact that un-fissioned plutonium could have on the calculation results,

[4] "*Large particles*" are defined in [12] as most particles having a diameter greater than 50 µm and a median diameter greater than 100 µm. The modelling does not provide exactly these size distribution parameters, but for the calculation cases studied, the mean particle diameter at the distance of 100 km is significantly larger than 50 µm, and at least for distances less than 75 km, a significant proportion of the particles in the radioactive material deposited on the ground have a diameter greater than 100 µm.
[5] DosCalc v 1.0 (Manual 20-914)

using some simple but conservative assumptions (*i.e.* assumptions that are likely to overestimate its impact).

The entire fission yield (50 kilotons) in the main scenario (100 kilotons ground-level explosion with 50 % fusion contribution) is assumed to come from fission of Pu-239, *i.e.* the possibility that a large proportion of the fission yield could come from, for example, fusion neutrons causing fission of uranium in other parts of the weapon is not considered. In addition, it is assumed that the efficiency of the warhead design relating to fission of plutonium is on a par with the first US nuclear weapons test in New Mexico in 1945: *i.e.* approximately 15 percent [14]. To the extent that there is reason to assume that more modern nuclear warheads utilise the plutonium fuel more efficiently than this, this assumption will overestimate the amount of remaining plutonium. Taken together, these assumptions should lead to a significant overestimation of the amount of plutonium remaining after the explosion.

The remaining plutonium can be expected to have an isotopic composition affected by very large neutron fluences during an explosion, and the isotopic composition will play a significant role in the dose impact. Here too, cautious assumptions are made, *i.e.* assumptions that probably overestimate the proportion of plutonium isotopes with high dose impact – to some extent Pu-240 but primarily Pu-241. The plutonium found in the fallout is presumed to be typical of plutonium from explosions with very high explosive yield and a high proportion of fusion. Such plutonium is characterised by relatively high levels of Pu-240 and Pu-241 relative to Pu-239. Based on the high end of values observed in fallout, it is presumed that the activity ratio Pu-241/(Pu-239+Pu-240) = 26 and the atomic ratio Pu-240/Pu-239 = 0.3 [15] [16] [17].

The above assumptions regarding the amount and composition of un-fissioned plutonium mean that un-fissioned plutonium could contribute a share of about 10^{-12} to the ground dose rate from the fallout after 10 minutes (compared to the ground dose rate from the nuclide vector in the main scenario), and a share of about 10^{-6} after 365 days (when many other nuclides in the fallout have decayed). Therefore from a ground dose point of view, there is no need to consider un-fissioned plutonium.

Furthermore, if the activities of un-fissioned plutonium are totalled, weighted by dose coefficients for the committed effective dose via inhalation, and compared with the same quantity for the nuclide vector, the assumptions imply that un-fissioned plutonium could add 1 % to the inhalation dose at the time 60 minutes after the explosion and 16 % at the time 200 minutes after the explosion. While these contributions are not negligible, given the limited role of inhalation as an exposure pathway overall (see main report), it can be concluded that a contribution to the inhalation dose from un-fissioned Pu would not alter the conclusions of this report. Furthermore, the assumptions made as described above must be regarded as being very cautious. If one instead uses estimates of the total amount of plutonium injected into the global environment by above-ground nuclear weapons tests (approx. 400 kCi Pu-239 and Pu-240 [18]) and of the combined fission explosive yield of these nuclear weapons tests (about 190,000 kilotons [19]) and uses the resulting average value together with the same estimate of the proportion of Pu-241 as above, the additional contribution of un-fissioned plutonium to the inhalation dose is instead 0.06 % at the time 60 minutes after the detonation and 1 % at the time 200 minutes after the explosion.

The above conclusions apply for the time frame and for the exposure pathways considered in this study. For other exposure pathways, especially in a longer time frame, the picture

might be different with regard to how important it is to take the dispersion of plutonium into account compared to the fission and activation products included in the nuclide vector. This could include, for instance, long-term impact on the food supply or inhalation doses from resuspension of fallout on the ground.

3.9. Tritium and C-14

Tritium (H-3) is formed in fusion reactions when a nuclear weapon with a fusion component is detonated, and is in principle consumed at the rate it is formed in further fusion reactions. Some of the tritium produced is not consumed in the explosion, however, and a small amount of tritium is also produced by neutron reactions on nitrogen in the surrounding air. Neutron reactions on nitrogen in the air also form C-14. Both tritium and C-14 have been disregarded in the present study.

A parameterisation in [19] estimates the amount of tritium and C-14 added to the atmosphere from various mechanisms per kiloton of fusion and per kiloton of fission in a nuclear explosion, and implies the formation of about $3.7 \cdot 10^{16}$ Bq of tritium and about $5.7 \cdot 10^{13}$ Bq of C-14 in the main scenario. Both tritium and C-14 are pure beta emitters and therefore provide no external dose from radioactive material deposited on the ground. At 60 minutes after the detonation, tritium and C-14 contribute an additional inhalation dose by a factor of $7 \cdot 10^{-5}$ and $2 \cdot 10^{-6}$, respectively, compared to the nuclide vector in the main scenario, and at 200 minutes after the detonation by a factor of $1 \cdot 10^{-3}$ and $3 \cdot 10^{-5}$ respectively. Neither tritium nor C-14 would therefore affect the conclusions of this study.

As with un-fissioned plutonium (Section 3.8), this applies within the scope of the study and the picture could be different in a longer time frame or if other exposure pathways are considered.

4. Assumptions for calculations

4.1. Dispersion and dose calculations

Atmospheric dispersion calculations are demanding in terms of computational power and storage capacity. The results include large amounts of data containing air concentration and radioactive material deposited on the ground as a function of time and space per modelled nuclide, and thus also requires considerable data storage capacity. In addition, calculations of resulting dose rates and doses require additional resources for the processing of the data results and data storage.

To facilitate an analysis of a large number of weather cases, a criteria-based approach has been used in the same way as in SSM's previous study for a hypothetical Swedish nuclear power plant accident [20]. For each requested result in the form of total effective dose, the equivalent dose to the thyroid gland or the deposition of activity on the ground, one or more calculation criteria are established in the form of a value for the dose (Sv) or the ground contamination (Bq/m^2), the latter for H+1. In addition, a large number of calculation criteria are introduced in *ARGOS* to allow retrospective interpolation.

The outcome of each individual dispersion and dose calculation is been analysed based on the calculation criteria entered into *ARGOS* and only information on the geographical point for which the criterion was exceeded at the greatest distance from the blast site is recorded and stored in *ARGOS*. The final result of a dispersion and dose calculation consists of one data record per fulfilled calculation criterion, with information on coordinates, distance, and bearing from the blast site, calculated value, *etc*. for further processing. The number of cells where the criterion was exceeded in total and in different directions, distributed over 12 sectors is also been saved.

Altogether, such a large number of calculation criteria are introduced in *ARGOS* that interpolation tables are obtained, from which the greatest distance for exceeding an arbitrary calculation criterion can be estimated. This makes it possible to evaluate combinations of different protection during the initial phase and protection during the remainder of the year.

In some cases, the largest dose or ground contamination of radioactive material at a specified distance from the blast site is also used as a calculation criterion. The largest value of the required result is then obtained along a distance circle from the blast site.

Examples of calculation criteria, either defined in *ARGOS* or interpolated, can be found in Table 1. For more information on generic criteria, dose criteria and protection factors, see Appendix 1 (Radiation Protection).

For a more detailed description of the further processing of the *ARGOS* results, refer to Chapter 5.

Table 1. Examples of calculation criteria.

Quantity *	Age group	Generic criterion (G) or dose criterion (D)	Protective action (protection factor)	Calculation criterion
Total effective dose	One-year-old child	D: 100 mSv	Sheltering indoors, house (0.4)	250 mSv
Equivalent dose to the thyroid gland	One-year-old child	D: 50 mSv	Sheltering indoors, house (0.5) plus ingestion of iodine tablet (0.1)	1,000 mSv
Ground deposition (H+1)	One-year-old child	G: 500 mSv in 1 year (ground dose)	Complete protection for 3 days (0) then normal residence in a house (0.52)	335 GBq/m^2
Ground deposition (H+1)	Adults	G: 500 mSv in 1 year (ground dose)	Complete protection for 3 days (0) then normal residence in a house (0.52)	443 GBq/m^2
Ground deposition (H+1)	-	G: 10 Gy for 10 hrs (skin **)	Unprotected	152 GBq/m^2
Ground deposition (H+1)	Adults	G: 1,000 mSv in 10 hrs (red bone marrow ***)	Unprotected	606 GBq/m^2
Cloud dose	One-year-old child	-	Unprotected	30 km
Ground dose	One-year-old child	-	Unprotected	30 km
Inhalation dose	One-year-old child	-	Unprotected	30 km

* Total effective dose is integrated over 1, 2, 3, 7, 30 days and one year. Equivalent dose to the thyroid gland is integrated over 2 days. Ground deposition (H+1) is at 2 days (end of dispersion phase). Cloud dose and inhalation dose are integrated over 2 days and ground dose is integrated over 1 and 2 days.

** RBE-weighted absorbed dose to the skin (0.4 mm) from fallout deposited on the skin, for a 10-hour exposure starting 3 hours after the explosion.

*** Equivalent dose to red bone marrow from the ground, for exposure during 10 hours, starting 3 hours after the explosion.

4.2. Meteorological calculation cases

To illustrate effects under the varying meteorological conditions that can occur, a large number of dispersion calculations have been performed. The calculations have been made for a nuclear explosion at a selected location, and with varying start times dispersed over a year. In order to capture both diurnal and seasonal variations, calculations have been made assuming a nuclear explosion every 13 hours during the period. In total, calculations were performed for 663 different weather cases.

5. Statistical data processing

The methods that SSM has previously used [20] for statistical processing of modelling outcomes (maximum distance at which given calculation criteria for radiation dose or ground contamination were exceeded) were also deemed useful for an analysis of fallout from a nuclear explosion. Other formulations of modelling outcomes (largest dose or ground contamination at a specified distance) have also been used to some extent in this study. The following describes the calculations of maximum distance given a certain calculation criterion (hereafter the shorter "criterion" is used) and the calculation of value given a certain distance.

5.1. Calculation of maximum distance

The results of the dispersion and dose calculations are given in the form of a greatest distance at which a criterion has been exceeded. The distances are then summarised in cumulative histograms. Each histogram presents for a particular criterion the proportion of weather cases where the criterion is not met, as a function of distance. The mean and uncertainty at which a given proportion of the analysed weather cases exceed a particular criterion has been estimated by statistical data analysis. The analysis method is described in detail in this chapter. The distances that according to the above analysis contain a certain proportion of all occurring weather cases (70, 80 or 90 percent) are the basis for the results described in the results appendices (4-6) and in the main report.

5.2. Cumulative frequency distributions

Results from the dispersion and dose calculations are obtained in the form of a row of results with distances to a point furthest from the explosion where a given criterion has been exceeded. One way to summarise the greatest distances where this criterion is exceeded is to compile the distance distribution and present it in the form of a cumulative histogram. If the statistical basis is good enough, *i.e*. if the dispersion calculations have taken into account enough weather cases, the cumulative distance distribution provides information on the distance within which a certain proportion of all observations are expected to fall, the so-called percentile. A histogram is thus calculated per criterion, and from each histogram the percentile at a certain level can be derived. For example, the eighth percentile, P_{80}, provides information on the greatest distance at which a certain criterion is exceeded if 80 percent of the weather cases are taken into account.

Similarly, percentiles of the largest doses at a specified distance can be calculated. The difference here is that instead of proportion (%) as a function of distance, it is proportion (%) as a function of dose, otherwise the data analysis is identical. The method was used, among other things, to study dose contributions from different exposure pathways (cloud, inhalation, and ground) and total effective dose at a specified distance.

5.2.1. Intervals

When calculating histograms, input data need to be divided into a number of bins. All histograms are divided into 30 equal intervals, regardless of the scale of distance or dose. More intervals enable a higher resolution when calculating percentiles, but too many intervals in relation to the underlying data risk giving rise to greater uncertainty in the percentile estimate as the data density risks being too low in certain intervals. SSM has

made the assessment that 30 intervals offer a sufficient level of detail without the data density within each interval being too low.

5.2.2. Zeros

In those cases where a particular criterion is never exceeded in a dispersion or dose calculation, no result row is generated. When the criterion is not exceeded, this needs to be reflected in the cumulative histogram by adding a zero. A zero in this context means a row with a maximum distance of 0 km. Unlike in the previous study, in this study SSM has not made any distinction between outcomes over land or over water. In the data analysis, therefore, all results where a criterion is exceeded are taken into consideration, regardless of whether it occurred over land or over water. The number of zeros (n_z) added to the histogram in this way is described by the equation

$$n_z = n - n_r$$

where n is the total number of dispersion calculations and n_r is the number of dispersion calculations where the criterion was exceeded and thus gave rise to a maximum distance.

5.3. Averages and uncertainties

In order to estimate the greatest distance where a certain criterion is exceeded, taking a certain percentage of the occurring weather cases and the uncertainties in this distance into account, a "boot strap analysis" is used. This method is based on the observed probability distribution that describes the cumulative histogram. By repeatedly drawing a number of random samples from the observed probability distribution and using these samples to re-calculate the percentile at a particular level, the mean and variance of a particular part of the cumulative histogram corresponding to a particular percentile can be estimated. The uncertainty in the mean is then obtained by calculating the standard deviation and multiplying by a coverage factor (k), to encompass k standard deviations. All results in this study are presented as a distance in kilometres (the average) with the specified uncertainty with a coverage factor k=2. Because the histograms contain discrete steps, the uncertainty is sometimes zero. It is worth noting that the uncertainty in the percentiles for the maximum distances thus only takes the statistical part of the analysis into account, which means that assumptions made in previous analysis steps and any systematic errors in dose and dispersion calculations are not taken into account in the uncertainty estimate.

5.4. Examples of analytical methods

Two examples are given where cumulative histograms have been calculated and percentiles and uncertainties have been estimated as above. The first example is illustrated in Figure 3 and gives, for a given criterion, the proportion of weather events as a function of distance (km). The second example is illustrated in Figure 4 and gives, for a specified distance, the proportion of weather cases as a function of effective dose (mSv).

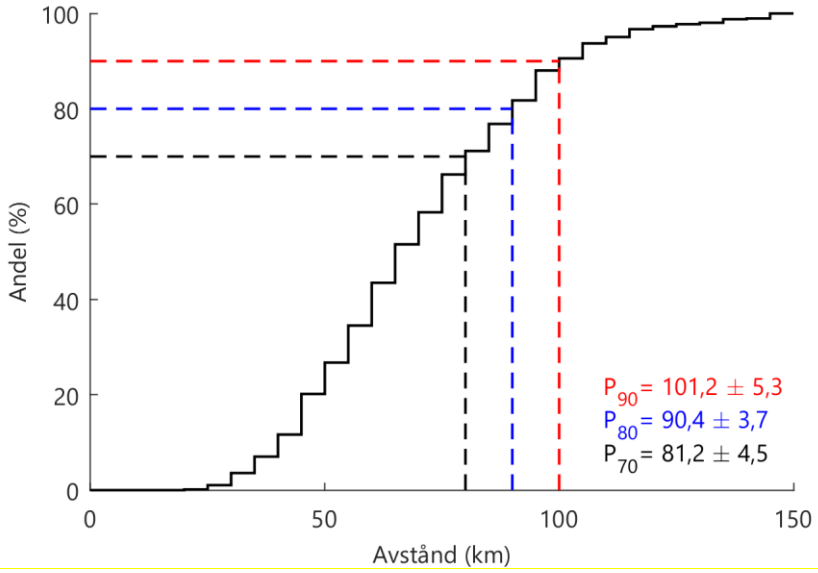

Figure 3. Example of a cumulative histogram for calculating the greatest distance for a given criterion. Each interval (step), describes the proportion of the analysed weather cases that for the selected criterion are contained for a certain distance. The figure shows that the distance where this criterion is exceeded is less than 90.4 ± 3.7 km in 80 percent of the weather cases.

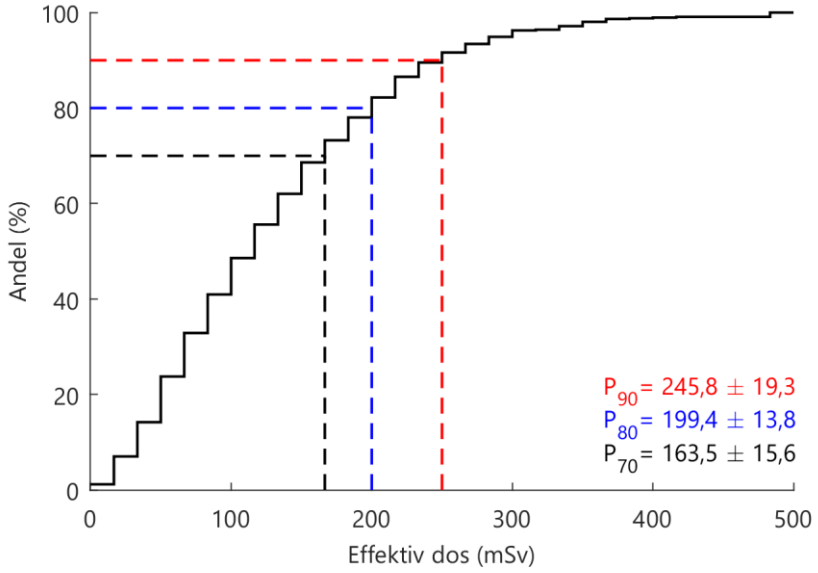

Figure 4. Example of a cumulative histogram for calculating maximum effective doses at a given distance. Each interval (step) describes the proportion of weather cases that are contained by a particular effective dose at the selected distance. It can be seen from the figure that the effective dose at this distance is less than 199.4 ± 13.8 mSv in 80 percent of weather cases.

6. Choice of parameters

The following describes the meteorological data used for dispersion modelling. It also describes the parameterisation of the deposition calculations in *MATCH-BOMB*. Finally, the derivation of dose coefficients for the dose calculations made in *ARGOS* is described in more detail.

6.1. Calculation area and meteorological data

Historical meteorological data for the period January 2021 – January 2022 from the *HARMONIE* model have been used for the dispersion calculations carried out with the *MATCH-BOMB* model. The calculations cover a maximum distance of about 440 km from the explosion site in a square grid of 350×350 cells, with a cell size of about 2.5×2.5 km, *i.e.* the same cell size as the numerical weather data set. The sampling frequency is set to 1 hour and the forecast duration to 48 hours.

6.2. Deposition parameters in *MATCH-BOMB*

A number of deposition parameters are used to calculate the deposition to the ground. For deposition under dry weather conditions, there are a number of deposition processes of which sedimentation (gravity) dominates for most particle sizes larger than 1 µm. The sedimentation rate per particle size divided into the ten different sub-intervals during a ground-level explosion is given in Table 2. In addition, the deposition of particles is also influenced by land use via surface characteristics, see Table 3.

Wet deposition can occur, for example, via in-cloud scavenging by precipitation and sub-cloud scavenging by raindrops (or ice crystals) due to collisions below the clouds. *MATCH-BOMB* presumes that all wet deposition is directly deposited on the ground regardless of the altitude at which the precipitation occurs. Wet deposition inside clouds is calculated by a factor (the product of a deposition factor multiplied by the rain intensity (mm/h) raised to 0.79). The exponent is used to reduce the trapping effect during heavy rainfall. Wet deposition under clouds is calculated with a factor in a similar way, where a collision coefficient is multiplied by the deposition factor and the rain intensity (mm/h). Parameters for wet deposition in the different particle intervals of a ground-level detonation are presented in Table 4.

Table 2. Sedimentation rates per aerosol radius (expectation value per interval) [2], [3].

Radius (µm)	Sedimentation rate (cm/s)
1.1	0.04
2.1	0.13
4.0	0.49
7.7	1.8
14.7	6.3
28.2	21.0
54.0	60.6
103	144

Radius (μm)	Sedimentation rate (cm/s)
197	292
378	536

Table 3. Deposition rates per type of land usage [2], [3].

Land usage	Deposition rate (cm/s)
Urban environment	0.02
Aquatic	0.0
Rural area	0.02
Forest	0.04

Table 4. Parameters for calculating wet deposition [21].

Radius (μm)	Wet deposition factor, in-cloud (1E-4/(s*mm/h))	Collision coefficient, sub-cloud
1.1	0.47	0.02
2.1	1.12	0.02
4.0	1.98	0.02
7.7	2.71	0.02
14.7	2.78	0.4
28.2	2.78	0.4
54.0	2.78	0.4
103	2.78	0.4
197	2.78	0.4
378	2.78	0.4

6.3. Dose coefficients

The following details the choice of dose factors and dose coefficients for calculations when loading external models into *ARGOS* as in the case of *MATCH-BOMB*.

6.3.1. Cloud dose

The effective dose from radioactive material in the atmosphere ("cloud dose") has been calculated using nuclide-specific effective dose factors (nSv/h per Bq/m^3) from ICRP 144 [8] ("*air submersion*") for a one-year-old child and from *DCFPAK* [7] (*air submersion*, Sv/s per Bq/m^3) for adults, as described in Section 3.1. For eight nuclides included in the

nuclide vector but for which dose factors for cloud dose are missing in ICRP 144 or *DCFPAK*, dose factors have been estimated. For the purpose of calculating the cloud dose in *ARGOS* for the respective age groups, the input data needed to be changed between calculations, as SSM had already used dose factors from *DCFPAK* for adults.

Supplementing dose factors

Dose factors for eight nuclides that are included in the nuclide vector but where dose factors for cloud dose are missing in ICRP 144 and *DCFPAK* have been estimated based on tabulated values of effective dose (*E*) for monoenergetic photon energies from a semi-infinite volume of air, together with summaries of known gamma transitions and probabilities. The dose factor for a particular nuclide is then calculated as the weighted total average of the contributions from all gamma transitions.

Data on the effective dose (*E*) from monoenergetic photon energies (E_γ) have been taken from [22] which gives values for 12 energies between 0.01 and 5 MeV. The same report also gives the effective dose from activity homogeneously dispersed in a semi-infinite volume of air. Values for energies (E_γ) between those tabulated were estimated by curve fitting $\ln(E)$ to $\ln(E_\gamma)$ (using cubic splines). The intermediate values for monoenergetic photons are not expected to differ by more than 1 % from the correct ones.

The estimated cloud dose factors presented in Table 5 have been applied to *ARGOS*.

Table 5. Estimated dose factors (effective dose, adult) for eight nuclides missing from ICRP 144 and *DCFPAK*. The dose factors have been calculated for a semi-infinite volume of air with the activity homogeneously dispersed in the air.

No.	Nuclide	Dose factor, adult (Sv/s per Bq/m^3)
1	Y-93m	3.01E-14
2	Nb-97m	3.38E-14
3	Rh-105m	1.08E-15
4	Sb-129m	7.03E-14
5	Sb-132	1.13E-13
6	Sb-132m	1.10E-13
7	Sn-129m	7.03E-14
8	Ce-146	1.35E-14

The corresponding estimate of dose factors for a one-year-old child have not been made, instead the dose factors for adults have been used. This is expected to underestimate the dose contribution of these eight nuclides in dispersion and dose calculations for a one-year-old child. In relation to the total effective dose for a one-year-old child, this underestimation is nevertheless expected to be negligible (<< 1 %). This is partly because the ground dose is the predominant exposure pathway plus partly because the nuclides listed in Table 5 together represent only a minor part of the total cloud dose.

In some cases, the *ARGOS* dose factors for a given decay parent nuclide also include the contributions from its daughter nuclides, taking into consideration possible branching

ratios. This is the case when the daughter nuclide has a half-life that is rather brief relative to the time that the activity is airborne. Furthermore, the half-life of the daughter nuclide must be significantly shorter than the parent nuclide, which means that activity equilibrium in the decay chain is achieved within the time interval relevant to the dispersion calculation. In the present work, this has been implemented in *ARGOS* for the pairs Cs-137/Ba-137m and Ru-106/Rh-106. Other nuclides have been treated individually.

6.3.2. Ground dose

The calculation of the effective dose from radioactive material deposited on the ground ("ground dose") is described in Section 3.2. The ground dose is calculated by converting deposited activity to effective dose rate using nuclide-specific dose factors (nSv/h per Bq/m²) from ICRP 144 [8] (*soil contamination*, 0.5 g/cm²) for a one-year-old child. The activity is assumed to be in a slice at a depth of 0.5 g/cm² (independent of soil density). For adults, dose factors from *DCFPAK* [7] (*volume source*, Sv/s per Bq/m^3) were used, where the activity is located in the top (1 cm) of the soil (density 1.6 g/cm³). In order to calculate ground dose in *ARGOS* for the different age groups, it is necessary to change input data between calculations, because SSM has previously used dose factors from *DCFPAK* for adults.

In previous studies, SSM has also used the penetration model in *DCFPAK* with homogeneous distribution to a depth of 1 cm with a density of 1.6 g/cm³. This model has continued to be used for the calculation of the ground dose to adults. The model used for the one-year-old child is recommended by ICRU and ICRP to represent a certain amount of shielding and penetration into the soil during fresh deposition. The difference between ICRP (0.5 g/cm^2) and *DCFPAK* (1 cm) for the nuclide vector is also marginal, about 2 % for an adult. However, the ICRP factors have the advantage that dose factors for a one-year-old child are also reported. For a one-year-old child, the dose factors are about 30 % higher than for an adult. A further advantage is that the ICRP provides dose factors for ambient dose equivalent H*(10), which allows estimates of measured values based on a given ground deposition.

A special procedure has been applied to calculate the dose rate, and thus the dose, from the radioactive material deposited on the ground after the *MATCH-BOMB* dispersion modelling, and thus the deposition, has ceased (48 hours). The exposure to radiation from activity deposited on the ground depends on how the nuclides in the fallout decay and grow in with time. This means that the process needs to be modelled from the end of the dispersion calculation until the time *T* for which the contribution of the ground dose to the total effective dose is to be determined. This modelling is done by including a library with the external software *DosCalc* in *ARGOS*. The library contains dose coefficients for the studied age group. For adults, the original library with dose factors from *DCFPAK* has been used, and for children, dose factors from ICRP 144 have been used as above.

Finally, the ground dose from deposited activity is integrated over the total time period.

Supplementing dose factors

As part of the investigation of the nuclide vector, dose factors have been estimated for a number of nuclides that could potentially make a non-negligible contribution to the total dose but are missing from ICRP 144 and *DCFPAK*. Dose factors for the ground dose have been estimated using the same method as described above for cloud dose factors. Tabulated values of effective dose (*E*) for monoenergetic photon energies from an infinitely extended surface, together with summaries of known gamma transitions and probabilities were used.

The dose factor for a particular nuclide is then calculated as the weighted sum of the contributions from all gamma transitions. The estimated dose factors for the eight nuclides listed in Table 6 were loaded into *DosCalc* and *ARGOS*. The selection is described in greater detail in Appendix 2 (Nuclide Composition).

Data on effective dose (E) from monoenergetic photon energies (E_γ) were taken from [22] which gives values for 12 energies between 0.01 and 5 MeV. Furthermore, the same report gives effective dose from an infinite ground plane and effective dose from activity homogeneously dispersed in the top 1 cm of an infinite ground plane. Values of energies (E_γ) between the tabulated ones were estimated by polynomial fitting of ln(E) to ln(E_γ). The intermediate values for monoenergetic photons are not expected to differ by more than 1 % from the correct ones. As mentioned above, the differences between this procedure, based on 1 cm of homogeneous activity, and the ICRP 144 model at a depth of 0.5 g/cm^2, are expected to be marginal.

Table 6. Estimated dose factors (effective dose, adult) for eight nuclides added to *ARGOS*. The dose factors were calculated for a surface source (0 cm) and a source with activity evenly dispersed in the top centimetre.

No.	Nuclide	Dose factor (Sv/s per Bq/m^2)	
		0 cm	1 cm
1	Y-93m	6.57E-16	4.24E-16
2	Nb-97m	7.19E-16	4.62E-16
3	Rh-105m	2.53E-17	1.64E-17
4	Sb-129m	1.49E-15	9.58E-16
5	Sb-132	2.34E-15	1.51E-15
6	Sb-132m	2.30E-15	1.49E-15
7	Sn-129m	2.26E-15	1.46E-15
8	Ce-146	3.03E-16	1.95E-16

Corresponding estimates of ground dose factors for a one-year-old child were not made; instead, adult dose factors were used. This is expected to underestimate the dose contribution of the eight nuclides included in the nuclide vector in dose calculations for a one-year-old child. However, the nuclides listed in Table 6 together represent only a small part of the total ground dose. Thus, the underestimation is anticipated to be marginal (< 1 %) in relation to the total effective dose for a one-year-old child.

6.3.3. Inhalation dose

The calculation of a committed effective dose from inhalation ("inhalation dose") is described in Section 3.3. The respiratory rates of 6.02-10^{-5} m^{3}s have been used for a one-year-old child and 2.57-10^{-4} m^3/s for an adult (*indoors worker*), both from [23].

The dose factors used to convert inhaled activity to a committed effective dose have been taken from ICRP 119 [9]. The inhalation dose has been calculated using age-dependent, nuclide-specific dose factors for committed effective dose (Sv/Bq) for 1 µm diameter

aerosols AMAD[6] from ICRP 119 for adults and one-year-old children, Annex G (Table G1, *members of the public*). The dose coefficients have generally been selected based on the ICRP recommended absorption type[7] (F/M/S), see Table 7.

Table 7. Type of absorption assumed for the calculation of inhalation dose.

Element	Absorption type	Element	Absorption type
Silver (Ag)	M	Lead (Pb)	M
Barium (Ba)	M	Palladium (Pd)	F
Beryllium (Be)	M	Promethium (Pm)	M
Bromine (Br)	M	Praseodymium (Pr)	M
Cadmium (Cd)	F	Rubidium (Rb)	F
Cerium (Ce)	M	Rhodium (Rh)	M
Cobalt (Co)	M	Ruthenium (Ru)	M
Caesium (Cs)	F	Antimony (Sb)	M
Iodine (I) (aerosol)	F	Selenium (Se)	F
Indium (In)	F	Tin (Sn)	F
Krypton (Kr)	-	Strontium (Sr)	M
Lanthanum (La)	M	Technetium (Tc)	M
Manganese (Mn)	M	Tellurium (Te)	M
Molybdenum (Mo)	M	Uranium (U)	S
Sodium (Na)	F	Xenon (Xe)	-
Niobium (Nb)	M	Yttrium (Y)	S
Neodymium (Nd)	M	Zirconium (Zr)	M
Neptunium (Np)	M		

A number of nuclides included in the nuclide vector are missing from ICRP 119. For 26 nuclides in the nuclide vector, dose coefficients have been used from other sources (19 nuclides [7] [24] [25]) or from estimates using the method described by Forrest [26] (7 nuclides). These nuclides with the dose coefficients and absorption types used are presented for the one-year-old child in Table 8. Corresponding values have also been produced for the adult.

Where the source DCAL is given, calculations of dose coefficients for age-dependent effective dose were made with the software *DCAL* [24]. The settings used were *inhalation, equivalent dose, environmental exposure*, ICRP 66 model, AMAD 1 µm and *absorption type* as specified in Table 7.

[6] AMAD stands for *Activity Median Aerodynamic Diameter*.
[7] F/M/S denotes different rates (*Fast, Medium,* and *Slow*) of absorption in the human body after inhalation.

Table 8. Dose coefficients for nuclides in the nuclide vector not listed in ICRP 119. The dose coefficients are given in effective dose for a one-year-old child per Bq inhaled.

Nuclide	Absorption type	Dose coefficient (Sv/Bq)	Source
Rb-90	F	2.5E-11	DCAL [24]
Rb-90m	F	4.2E-11	DCAL
Sr-93	M	1.1E-10	DCAL
Y-93m	S	3.9E-14	Forrest's method [26]
Nb-97m	M	7.4E-12	Forrest's method
Mo-102	M	1.6E-10	DCFPAK [7]
Tc-102	M	6.6E-13	DCAL
Tc-105	M	9.9E-11	DCAL
Rh-105m	M	4.9E-13	Forrest's method
Rh-106	M	3.7E-12	DCAL
Rh-107	M	9.3E-11	DCAL
Ru-107	M	4.2E-11	DCAL
Pd-112	F	4.1E-9	DCFPAK
Sn-127m	F	2.9E-11	DCAL
Sn-129m	F	1.0E-10	Forrest's method
Sn-130	F	5.2E-11	DCAL
Sb-129m	M	3.4E-10	Forrest's method
Sb-130m	M	6.8E-11	DCAL
Sb-132	M	8.1E-11	Forrest's method
Sb-132m	M	1.2E-10	Forrest's method
Sb-133	M	8.4E-11	DCAL
I-134m	F	1.9E-11	DCAL
Cs-139	F	7.4E-11	DCAL
Ce-145	M	3.2E-11	DCAL
Ce-146	M	1.6E-10	JAERI [25]
Pr-146	M	1.9E-10	DCFPAK

6.3.4. Dose to the skin

For the more detailed modelling of skin dose described in Section 3.6, dose coefficients are needed that relate only to a single nuclide and never include decay daughters. Therefore it has been necessary to estimate a large number of dose factors from conversion electron,

beta and photon spectra. The estimates were made using the method described in [27] (Appendix VI) for the estimation of dose factors (Gy/s per Bq/m^2) for RBE-weighted absorbed dose to the skin (depth 0.4 mm) from radioactive contamination on the skin. For this purpose, the contribution from monoenergetic electrons has been estimated using the same empirical formula as in [27] (with the original reference [28]) and the contribution from photons has been taken either (as in [27]) from [29] or neglected where data are not available in [29]. The omission of photon contributions for a number of nuclides is expected to cause some underestimation of the overall dose factors. However, for the most nuclides, the main part of the dose to the skin from deposited fallout is expected to come from electrons. This is confirmed by a comparison of the photon and electron contributions for those nuclides for which both are available, so the underestimation due to the neglect of some photon contributions is assumed to be marginal. Decay data including conversion electron and beta spectra for summation and integration over the contributions from monoenergetic electrons have been obtained from ENDF/B-VIII.0. Appropriately discretised beta spectra have been obtained using the web-based tool *JANIS Web* [30].

6.3.5. Absorbed dose to red bone marrow

The calculation of the equivalent dose to red bone marrow from ground contamination (ground dose) is described in Section 3.7. The dose factors used to convert deposited activity to an equivalent dose rate are taken from ICRP 144 [8]. The ground dose was calculated using age-dependent, nuclide-specific dose factors for equivalent dose to red bone marrow (nSv/h per Bq/m^2) from ICRP 144 (soil contamination, 0.5 g/cm^2) for an adult and a one-year-old child. As in the effective dose case, the activity is presumed to be in a slice at a depth of 0.5 g/cm^2.

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