Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

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Review of Swedish emergency planning zones and distances, Appendix 2

Dispersion and dose calculations

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Contents

1. Introduction

This appendix is part of the report “Review of Swedish emergency planning zones and distances”. This appendix describes the models for atmospheric dispersion and dose calculations, RIMPUFF and PIGLET, which were used to assess the extent of the recommended areas that should be subject to emergency preparedness planning. These analyses used historical meteorological data from the Swedish Meteorological and Hydrological Institute (SMHI), produced using HIRLAM, a regional model for forecasting.

Dispersion and dose calculations were carried out on the part of all the postulated events at facilities belonging to emergency preparedness categories I and II. In each calculation, a release in accordance with the selected source term was applied. The calculation outcomes demonstrate the radiation dose received in the geographical domain of the calculation surrounding the outlet point, based on the air concentration and ground deposition comprising the radioactive substances. These outcomes are compared with dose criteria for different protective actions (evacuation, sheltering, and intake of iodine thyroid blocking) as well as intervention levels for different protective actions (such as relocation due to ground deposition, remediation or measures for production of foodstuffs). The outcome sought for each calculation criterion is the greatest distance from the outlet point to a point where this criterion is exceeded.

A brief account is provided of the atmospheric dispersion modelling, release in question (source term), the intervals of time, and the geographical domains of the calculations that are applied. Another area presented is the radiation doses discussed in this report, as well as their computation. The appendix also explains how statistical processing of the outcomes from the dispersion and dose calculations is carried out. Lastly, a summary account is provided of selected parameter values for the models.

2. Atmospheric dispersion calculations

The purpose of performing atmospheric dispersion calculations is to obtain information about how radioactive materials, released into the atmosphere by means of a known or an estimated process from the source, are spread into the surrounding atmosphere through physical processes, to ultimately form deposition on the ground and thereby give rise to ground deposition comprising radioactive materials. With knowledge about the behaviour of these substances in the atmosphere and as deposited activity on the ground, an estimate can be carried out on the radiation doses that the activity can give rise to.

The outcome of the dispersion calculations is commonly expressed in the form of airborne activity, time-integrated airborne activity and ground deposition activity; this is stated per nuclide and as a function of time and space. These quantities are subsequently used to derive quantities relating to dose and dose rate with the help of modelling. Depending on the model, radiation doses in both the short and long term can be estimated. The former encompasses doses received as a result of external exposure to passing of the radioactive plume[1]. The latter encompasses ground deposition of radioactive substances after the plume has passed, in addition to dose from inhalation of nuclides which are taken up by the body and subsequently decay, thus contributing to a radiation dose even after the external exposure has ceased.

Ultimately, the data provided by the dispersion calculations relating to ground deposition can also be used to estimate long-term effects of activity transfer to food and feed chains.

Atmospheric dispersion calculations are commonly used to obtain information about a geographical area that might be affected by a release from a given source at a certain point in time, in addition to the magnitude and time period of this effect. This outcome is usually presented in some type of geographical context, for example dispersion results depicted on a map illustrating one or more activity or dose quantities as a function of time (see Figure 1).

The types of questions formulated in this investigation are, however, somewhat different. For the purpose of identifying the extent of the areas that should be encompassed by emergency preparedness planning, there was a need to analyse the distance from a given outlet point where a predefined dose criterion or intervention level is exceeded. A dose criterion is (for example) the dose received by a certain organ and to a specific age group, and an intervention level may represent a certain magnitude of ground deposition comprising one or a few nuclides, or a combination of several nuclides. In this case, the absolute values over time are thus not of interest, nor is the specific extent of the geographical area affected. On the other hand, the maximum distance at which a given dose criterion or intervention level will be exceeded is dependent on the meteorological conditions prevailing during the period of time of the release, and during the period of time when the activity is being dispersed into the atmosphere. Consequently, there is a need to carry out a large number of dispersion calculations for each given outlet point in order to investigate at which distances the criteria studied are exceeded during variable meteorological conditions.

[1] A plume is a schematic description of the cloud of radioactive materials dispersed into the air following a release.

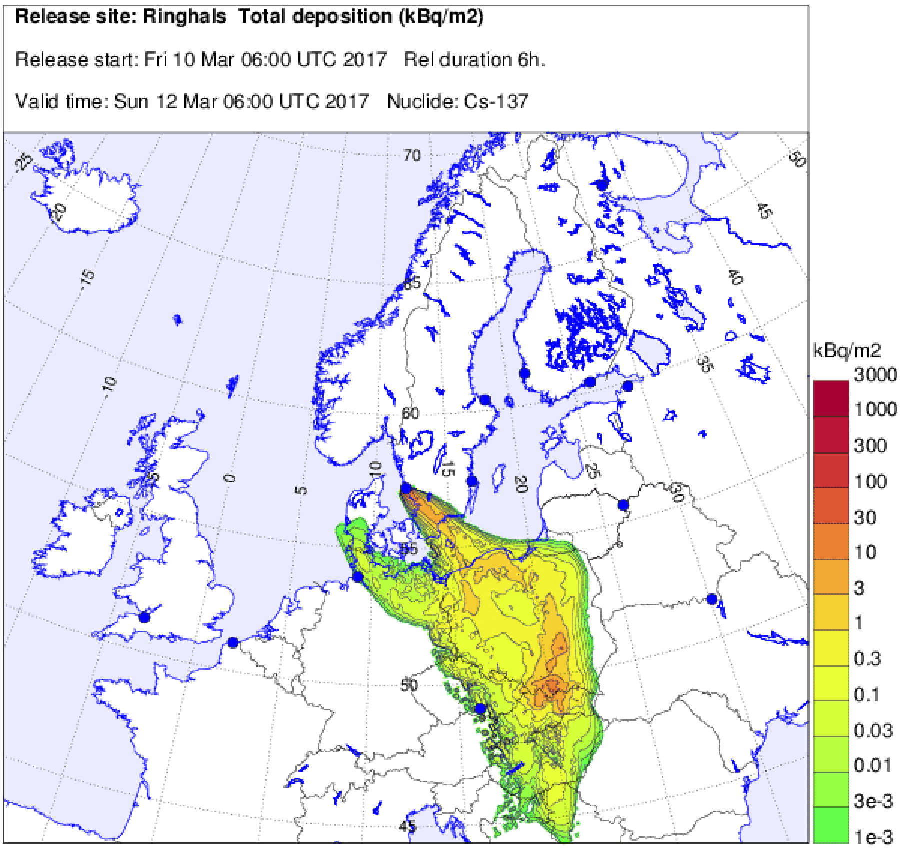

Figure 1. Example of outcome from an atmospheric dispersion calculation. The illustration is based on a fictitious release of Cs-137 from the Ringhals nuclear power plant, depicting the resulting ground deposition, expressed as kilobecquerel per square metre (kBq/m^2) that this release would result in 48 hours after the release commencing. This estimate was carried out using SMHI's dispersion model, MATCH.

2.1. Meteorological information

Atmospheric dispersion calculations presuppose access to meteorological data on atmospheric conditions as a function of the horizontal coordinates, height above ground, and time. The calculations performed were based on historical meteorological data in numeric form, extracted from tape archives at SMHI. This data, originally stored in GRIB format, underwent extraction, verification and format conversion into the format requested by SSM (the Swedish Radiation Safety Authority), ARGOS-HIRLAM, with subsequent delivery to the Authority.

The material represents a period of approximately 10 years (February 2006–February 2016), comprising 2.58 terabytes (TB) of supplied data. This series encompasses certain, primarily relatively short, periods of time for which data is missing due to technical reasons.

2.2. Meteorological data

The meteorological data is based on two different forecasting models, HIRLAM G05 and HIRLAM E05, which were applied during production at SMHI during the applicable period. From these models, a geographical subset of data was extracted comprising the relevant geographical domain of the calculation.

Both these forecasting models differ somewhat in the area of parameterisation. They nevertheless have the same horizontal resolution (approx. 5.5 km). Furthermore, the geographical data extraction was performed so as to make the respective data contained in HIRLAM G05 and HIRLAM E05 cover the same geographical area as shown in Figure 2.

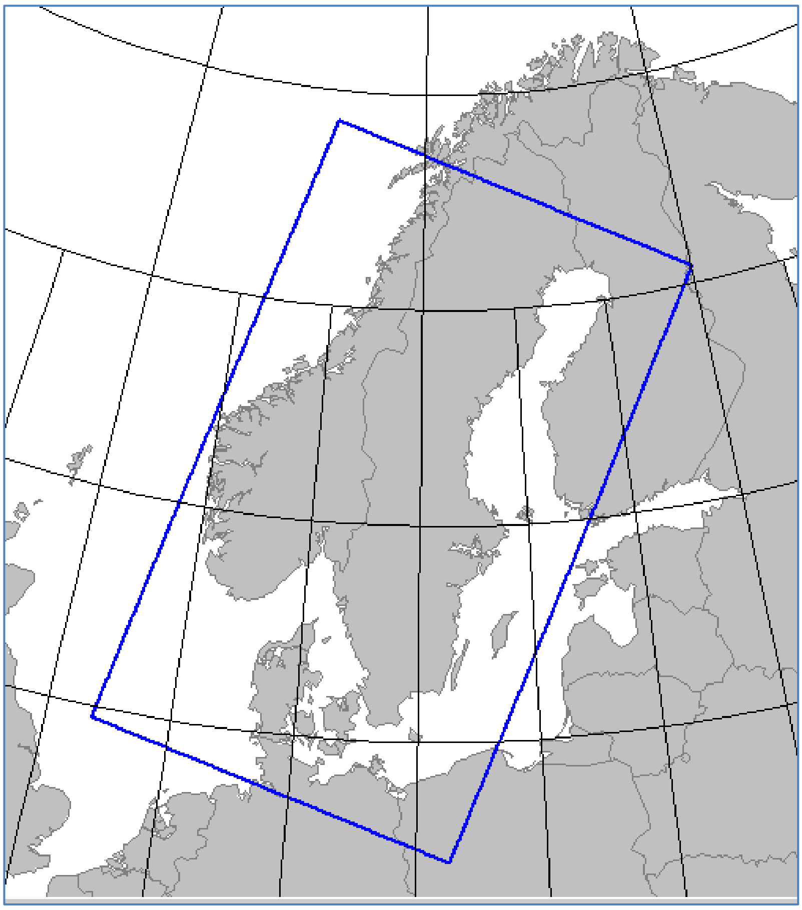

Figure 2. Geographical area for meteorological data (HIRLAM G05 and E05).[2]

2.2.1. HIRLAM G05

The delivery of HIRLAM G05 encompasses the period as of February 2006 up until June 2012. The data encompasses two 12-hour forecasts per 24 hour period, with a meteorological analysis at 00 UTC[3] and 12 UTC. These forecasts have a time resolution of 3 hours, including 36 altitude levels from the ground surface up to 4,910 m.

[2] The northernmost parts of Sweden are excluded from the meteorological data. This does not affect the outcomes, as the calculations performed extend no further than a maximum of 500 km from the outlet point.

[3] Coordinated Universal Time

2.2.2. HIRLAM E05

The supply of HIRLAM E05 data encompasses the period as of June 2012 until February 2016. After this point in time, SMHI terminated its filing of HIRLAM data, to be replaced by a newer model with higher resolution, HARMONIE. The data encompasses four 6-hour forecasts per 24-hour period, with a meteorological analysis at 00, 06, 12 and 18 UTC. These forecasts have a time resolution of 3 hours, including 42 altitude levels from the ground surface up to 5,260 m.

2.2.3. Generating wind roses

A wind rose summarises information about predominant wind directions and wind speeds at a specific location. The wind direction indicates from which direction the wind blows. Wind roses have been generated for the data point in the meteorological data (HIRLAM E05) that lies closest to the respective facility. Figures 3 to 6 show diagrams representing the nuclear power plants of Forsmark, Ringhals and Oskarshamn (also representing Clab, the central interim storage facility for spent nuclear fuel) and the fuel fabrication plant in Västerås. The wind rose illustrates the wind conditions at an altitude of 20 metres, divided into 24 wind directions and 8 wind speed intervals. Calm conditions and weak wind (below 0.5 m/s) are excluded in the wind rose as it is difficult to assess wind direction in these cases. These conditions constitute 0.2 per cent or less of the weather scenarios. As precipitation has a considerable impact on ground deposition of radioactive materials, it is also relevant to look into predominant wind directions during precipitation (here, the limit for precipitation is set at 0.2 mm/h of precipitation).

When assessing the extent of the proposed emergency planning zones and distances, SSM excluded consideration of the prevailing direction of winds; in other words, the same approximate distances were applied in all directions on the mainland as a basis for the recommendations. Predictions of total probability for a certain outcome, e.g. that a severe nuclear power accident occurs only during certain weather conditions, are so uncertain that they should not serve as a basis for a shorter or longer distance in certain directions from the facilities in question. Nonetheless, the figures give a schematic illustration of wind conditions at the outlet points used as a basis for SSM's dispersion and dose calculations. The figures also illustrate the presence of stronger winds occurring more frequently along Swedish coastlines, and that the prevailing directions of winds may change in connection with precipitation.

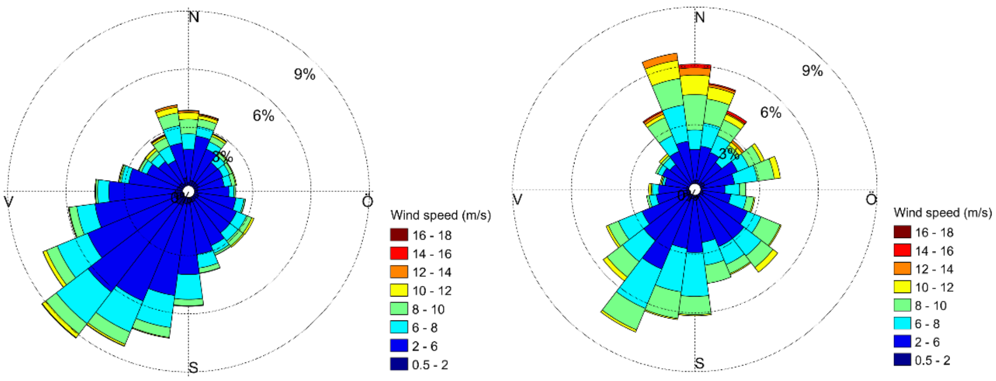

Figure 3. Wind rose for a location close to the Forsmark NPP: total (left-hand image) and during precipitation (right-hand image). Weak winds are not illustrated in the figures.

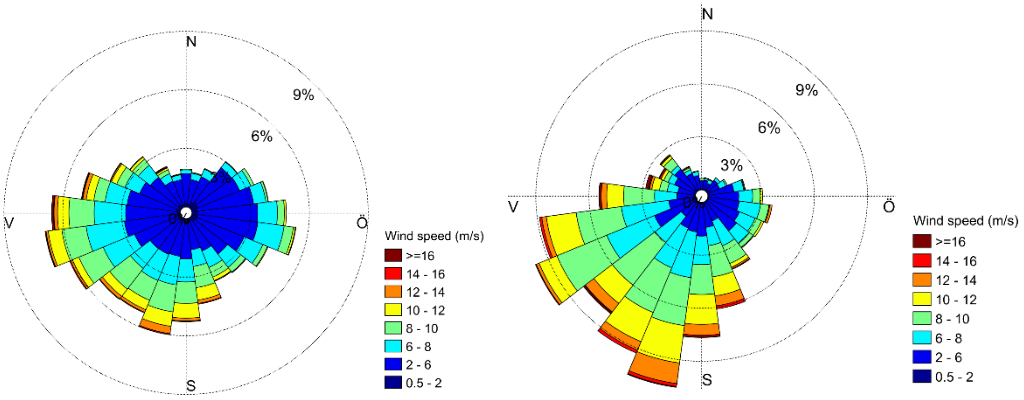

Figure 4. Wind rose for a location close to the Ringhals NPP: total (left-hand image) and during precipitation (right-hand image). Weak winds are not illustrated in the figures.

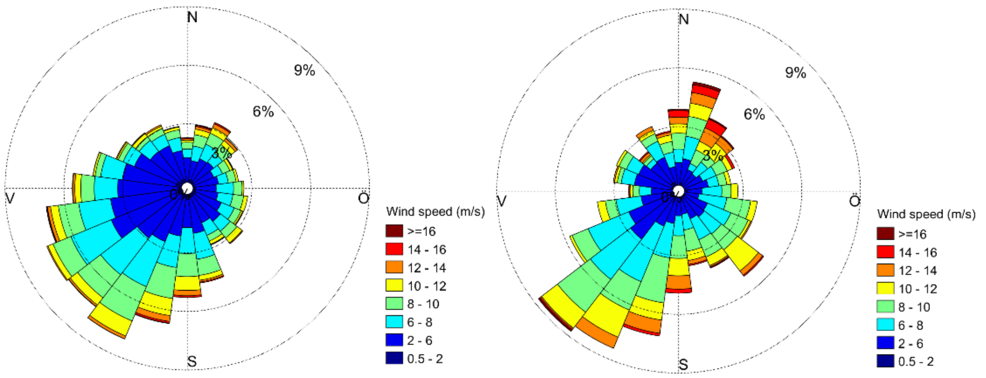

Figure 5. Wind rose for a location close to the Oskarshamn NPP and to Clab: total (left-hand image) and during precipitation (right-hand image). Weak winds are not illustrated in the figures.

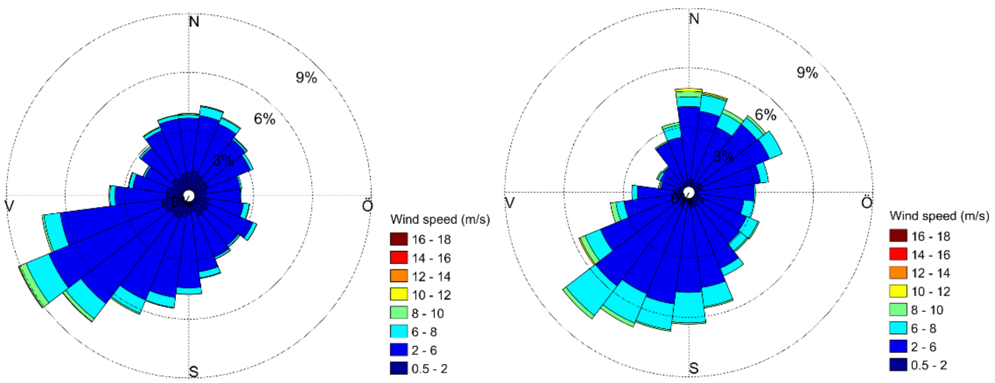

Figure 6. Wind rose for a location close to the fuel fabrication plant in Västerås: total (left-hand image) and during precipitation (right-hand image). Weak winds are not illustrated in the figures.

2.3. Atmospheric dispersion modelling

In this project, the main model used was the Gaussian puff model, RIMPUFF[4], developed by the Risø National Laboratory (presently DTU Nutech) in Denmark [1], [2]. Belonging to the Lagrangian group of mesoscale atmospheric dispersion puff models, RIMPUFF is designed to calculate air concentration and ground deposition resulting from atmospheric dispersion of radioactive substances in gas or aerosol form, in addition to the resulting radiation doses.

This model does not encompass analysis of atmospheric chemical processes, nor does it deal with sequences related to aerosol dynamics. The model deals with decay of parent nuclides and the ingrowth of decay products.

RIMPUFF is a well-established model that has been used for many years in a number of European countries. The model is also a component of several decision-making and analysis support systems used by radiation safety authorities in and outside of Europe. This project used RIMPUFF within the framework of ARGOS, a system for decision making and analysis support [3].

When calculating severe deterministic effects, which presupposes estimation of doses to specific organs and to the embryo and foetus, PIGLET, a dispersion and dose calculation model, was used [4]. Here, the rationale was that RIMPUFF, as implemented within ARGOS as used by SSM, does not calculate organ doses, with one exception: committed equivalent dose to the thyroid. The dispersion component of PIGLET is constituted by a probabilistic Lagrangian particle model, in which a release is simulated by a large number of released model particles that are assumed to follow trajectories formed by the prevailing wind direction and by air turbulence.

2.4. Source term

In this context, the concept of source term represents a description of the release of radioactive material into the atmosphere. The source term description also includes the composition and activity of nuclides in the release, the time period during which the activity is released, and, in certain cases, the chemical form. The source term also includes information about the release height(s) and possible heat content. In addition, the source term may contain a description of the distribution of particle size and particle density.

In this project, absolute source terms were used describing the released activity per nuclide. In many other contexts, relative source terms are used to model releases from reactors. Relative source terms describe the release in the form of percentages of the core inventory of substances categorised on the basis of volatility properties.

Generally, atmospheric dispersion modelling was performed on the assumption that all nuclides in the source term either behave in the form of gases (noble gases and elemental iodine), or in the form of aerosols. Here, an aerosol diameter of 1 µm and a particle density of 1 g/cm^3 were assumed.[5]

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[4] Risø Mesoscale PUFF Model

[5] In the case of the postulated event involving a fire with a release of uranium powder at the fuel fabrication plant in Västerås, other particle sizes and particle densities were assumed as well, since larger particle sizes are probable in this event.

Iodine isotopes are treated separately in the source term. In a general scenario, iodine occurs in three distinct forms in the release: in elemental gaseous form (I_2), in organic form (ordinarily methyl iodide), or in aerosol (particulate) form, which has a significant impact on the potential to limit the release by means of filtering. Another factor is that the three forms exhibit different properties in terms of dispersion in the atmosphere and deposition on the ground. For each release interval, the source term contains a description of the percentage of the iodine that is released in elemental, organic, and aerosol form. This description is assumed to apply generally to all iodine isotopes in the source term.

The release is assumed to occur at a certain release height at a predefined geographical point which may be presumed to represent the outlet point. The calculations assume that there is no plume rise owing to heat content (thermal lift) or vertical outflow velocity (mechanical lift). Calculations of plume rise are subject to great uncertainty. In order to exclude possible underestimation of the calculated doses, SSM has applied a conservative assumption that no plume rise will occur.

The representative source term for the respective postulated event is explained in more detail in the main report.

3. Calculating radiation dose

Ionising radiation can cause different kinds of effects depending on the radiation dose received. When the radiation dose reaches a high level, *deterministic effects* occur. Examples of these effects include reddened skin, sterility and malformation in the embryo and foetus. Radiation doses below these levels may still give rise to injury, but in this case, the radiation dose only affects the probability of injury occurring (*stochastic effects*). The latter category includes cancer and hereditary effects.

Radiation protection should be optimised to avoid *severe deterministic effects* and to reduce the risk of cancer and hereditary effects as far as reasonably achievable. In the case of severe deterministic effects, different *threshold doses* are applied. These are selected from the perspective of radiation protection, i.e. based on the most radiation-sensitive individuals belonging to a subgroup of a population.

The concept of *effective dose* is applied when studying the risk of stochastic effects. The effective dose reflects the total dose contributions to different organs or tissues to give the whole body dose. Thus, this is comparable to a reference level or dose criterion, regardless of the radioactive materials (energy and type of radiation), exposure pathway (intake or externally), or the sensitivity of different organs or tissues to exposure to ionising radiation. The dose to a particular organ or tissue is called *equivalent dose*.

The kinds of radiation doses analysed constitute effective dose and dose to certain specific organs, such as the thyroid, and whose total dose may be attributed to a number of exposure pathways. The external exposure that contributes to effective dose is, in the calculations, *cloud dose,* due to the presence of radioactive materials in the air, and *ground dose* from prospective radioactive ground deposition. The internal exposure that contributes to the effective dose in the calculations is *inhalation dose* due to the inhalation of radioactive materials in the air. The latter is a *committed effective dose*, which indicates that the radiation dose is integrated over the period of time that the nuclide remains present in the human body, which also takes into account dose contributions from any decay products arising in the body.

All the dose calculations refer to an unprotected individual from the population during a period of time comprising seven days after the event commencing.

A detailed description is provided below of the kinds of doses that have been discussed, their method of calculation, as well as their correlation. Unless stated otherwise, the description concerns calculations of stochastic effects, using ARGOS/RIMPUFF as a tool. The last section provides a summary account of calculations to estimate severe deterministic effects, using PIGLET.

3.1. Cloud dose

The cloud dose is constituted by the external dose attributed to gamma radiation from the passing plume. This dose is estimated by calculating for each nuclide the total gamma energy emitted per decay in four energy intervals. Table 1 shows intervals and examples for the nuclide Co-60.

Table 1. Examples of parameters for calculation of cloud dose from the nuclide Co-60. Interval 3 illustrates the total energy for the two gamma photons (1.17 MeV and 1.33 MeV, respectively) multiplied by their respective probability of photon emission per decay (1.0).

	Co-60		
Interval	Lower endpoint of the interval (MeV)	Upper endpoint of the interval (MeV)	Emitted energy (MeV)
Interval 1		0.35	~0
Interval 2	0.35	0.75	0
Interval 3	0.75	1.5	2.5
Interval 4	1.5		~0

The dose rate, which at any given time is present in a given point in the geographical domain of the calculation, is calculated by integrating the contribution from the activity which, on a given occasion, is present in the atmosphere. This is done by summing the contributions from the puffs that are present within the geographical domain of the calculation, while taking into account distances to puff centres and considering dispersion and attenuation effects within the four energy intervals. The cloud dose is then obtained by gradually integrating the dose rate over time.

The factors used for the emitted energy in the respective energy interval are described in more detail in section 6.3.1.

The cloud dose was calculated irrespective of age group, constituting a subcomponent of the total effective dose. The contribution from the cloud dose to total effective dose ceases when the plume has passed.

3.2. Ground dose

The ground dose is constituted by the external dose attributed to gamma radiation from the nuclides forming the ground deposition. This dose contribution is estimated by calculating for each nuclide the dose rate attributed to the deposited activity. Thereafter, the dose rate is integrated over time and ultimately totalled for all nuclides. This calculation presupposes approximation of the deposited activity by assuming an infinite surface deposition.

The factors used to convert deposited activity into dose rate are described in more detail in section 6.3.2, as are the considerations made in terms of penetration of the radioactive materials into the ground (vertical migration).

The ground dose was calculated irrespective of age group, constituting a subcomponent of the total effective dose. The dose estimated from the ground deposition continues to accumulate over the duration of the remaining activity and period of exposure.

3.3. Inhalation dose

The inhalation dose is constituted by the internal dose attributed to inhaled activity which decays thereafter, and/or is absorbed by the body and transported further to different organs. This dose is expressed as committed dose due to the activity remaining in the body to some extent. This is because an estimate is made of the resulting dose contribution from inhaled activity during a period of 50 years after the exposure (in the case of children, the applicable integration period is up to age 70).

Dose is calculated for each nuclide by multiplying the time-integrated activity concentration in the air layer closest to the ground with an assumed inhalation rate, and thereafter applying a nuclide-specific dose coefficient. The dose contributions are subsequently added up for all the nuclides.

The factors used for converting time-integrated airborne activity to dose are described in more detail in section 6.3.3.

The inhalation dose has been calculated as a function of age group, constituting a subcomponent of the total effective dose. The committed effective dose is received in its entirety while the plume passes, aside from any potential additional contributions from resuspension.

3.4. Dose to the thyroid

Here, thyroid dose refers to dose to the thyroid gland by means of inhalation of radioactive iodine. Thyroid dose has been derived from the effective dose received as a result of inhaling the different iodine isotopes, taking into account the individual dose contributions in the case of the different forms of iodine (organic, elemental and aerosol forms).

Normally, in the above case, a simplified calculation procedure is applied to thyroid dose by using a factor of 20 for multiplying the inhalation dose from the respective iodine isotope in order to arrive at dose to the thyroid gland.[6]

Thyroid dose is calculated individually for the respective age group by using age-specific dose coefficients and inhalation rates.

3.5. Total effective dose

The components added up to arrive at total effective dose consist of cloud, ground and inhalation doses as described above. The dose contribution attributed to direct radiation from the source, for instance in connection with criticality events, is also to be viewed as a component of the total effective dose. Note that this dose contribution is discussed separately, see the main report.

The total effective dose is attributed to a given point in time *T* after the release commencing, and indicates the dose received over a lifetime (committed dose) in connection with an uninterrupted occupancy at the given location up until *T*. If the total effective dose is calculated for a point in time after the plume has passed and the ground deposition has ceased, remaining activity on the ground will continue to provide a dose contribution for the duration of such occupancy. Resuspension of activity deposited on the ground may also potentially contribute to an increase in the total dose inhaled. However, resuspension has

[6] Current dose coefficients for the public are based on the recommendations of the International Commission on Radiological Protection, published in ICRP 60 [15]. The tissue weighting factor for the thyroid is thus set at 0.05 in accordance with ICRP 60, and not at 0.04 in accordance with ICRP 103.

not been analysed as part of this project as resuspension is assumed to give rise to a negligible proportion of the total effective dose.

In the main report and its appendices, the term *effective dose* is used, though consistently having the definition of *total effective dose*.

3.6. Severe deterministic effects

Apart from the kinds of dose described above, dose to red bone marrow, dose to an embryo and dose to the brain of a foetus from the different exposure pathways have been calculated to identify any possible assumptions for giving rise to severe deterministic effects. As these calculations cannot be carried out using the RIMPUFF model otherwise used, the PIGLET model has been used instead. This software enables setting of hypothetical organ-specific dose coefficients in relation to the different exposure pathways. The software's calculation modules are largely an adaptation of corresponding modules in the LENA program [5].

Doses estimated using PIGLET are calculated separately for the nuclides specified in the source term. In the case of iodine, separate calculations are performed for iodine in aerosol form, elemental iodine and organic iodine.

The cloud dose estimated using PIGLET was calculated on the basis of the emitted particles' duration in the model's three dimensional grid. When calculating, the doses were corrected for finite cloud extension.

In PIGLET, the inhalation dose is calculated based on the time-integrated activity concentration in the air layer closest to the ground, with an assumed breathing rate and dose coefficients giving the dose per inhaled quantity of activity.

In PIGLET, the ground dose is calculated by integrating the dose rate from the accumulated activity within the near ground grid as of the point in time when the deposition takes place up until the integration time for which the dose is to be calculated. Decay is taken into account during the period of transport and after the deposition. Deposition of activity on the ground is calculated using PIGLET once a particle moves sufficiently close to the ground. This calculation presupposes approximation of the deposited activity by assuming an infinite surface deposition. Effects of gradual ground penetration are taken into account, see section 6.5.

In these calculations, PIGLET takes into account the first generation of decay products (daughter nuclides) during the period of transport and after the deposition. However, PIGLET does not take into account further decay as part of a potential decay chain. The latter simplification has a negligible impact on the doses calculated for these estimates.

For a more detailed description of PIGLET, see [4].

4. Calculation presumptions

Atmospheric dispersion calculations are resource intensive in terms of computing time and storage capacity. This is partly due to these calculations being based on numerical weather data, which describes atmospheric conditions in the three-dimensional space plus time. Depending on the complexity of the source term and the scope of the calculations in time and space, these calculations may require many hours of calculation time per weather scenario, giving outcomes which may also presuppose considerable data storage capacity due to their comprising large quantities of data. This includes air concentration and ground deposition as a function of time and space per nuclide modelled. This is in addition to calculations of resulting dose rates and doses, which add additional dimensions to processing of outcomes and data storage.

In order to enable an analysis of a large quantity of weather and release scenarios, a criterion-based approach has been used [6]. This was done by focusing on three types of outcomes that can be derived from the dispersion calculations: total effective dose, dose to the thyroid, and deposition of activity on the ground. For each sought quantity, one or more criteria were selected in the form of a dose criterion (Sv) or intervention level (Bq/m^2). The latter refers to a single nuclide, or the total of a number of nuclides. Examples of criteria are given in Table 2.

Thereafter, outcomes for each individual case of atmospheric dispersion modelling were analysed on the basis of each individual criterion. Dose and ground deposition values were calculated on the part of each point within the geographical domain of the calculation. If the value received exceeded the given criterion, the information about the point was recorded. Following analysis of the entire geographical domain of the calculation, the only information retained was about the point located at the greatest distance from the outlet point, and for which the criterion was exceeded. For this point, information about coordinates, distance and angular direction, the calculated value, etc. was recorded and retained for further processing.

The above analysis only took into account points of data over land. Here, the rationale is that processes affecting atmospheric dispersion over large bodies of water generally result in the activity being dispersed over greater distances from the outlet point compared to dispersion over land. If this fact is disregarded, this would result in greater distances where the criteria are exceeded in the case of facilities close to a Swedish coastline. As this factor is less relevant for establishing emergency planning zones and distances over land, outcomes over water bodies were consequently excluded in the final analysis. However, data points located on islands (e.g. Öland) were taken into account.

For a more detailed description of the analysis process, see Chapter 5.

Table 2. Examples of calculation criteria.

Quantity	Unit	Age group	Integration period	Nuclides
Total effective dose	Sv	1 year old child	7 days	All
Total effective dose	Sv	Adult	7 days	All
Dose to the thyroid	Sv	1 year old child	Lifelong	Iodine isotopes
Dose to the thyroid	Sv	Adult	Lifelong	Iodine isotopes
Ground deposition	Bq/m^2			Co-(58, 60)
Ground deposition	Bq/m^2			Co-60
Ground deposition	Bq/m^2			Sr-(89, 90)
Ground deposition	Bq/m^2			Sr-90
Ground deposition	Bq/m^2			I-131
Ground deposition	Bq/m^2			Cs-(134, 137)
Ground deposition	Bq/m^2			Cs-(134, 136, 137)
Ground deposition	Bq/m^2			U-(234, 235, 238)
Ground deposition	Bq/m^2			Cm-242

Consequently, in this case, the final outcome of atmospheric dispersion modelling comprises one, and only one, data entry per criterion, representing the geographical point located the greatest distance from the outlet point at which the given criterion was exceeded. This assumes meeting the specific criterion within the geographical domain of the calculation. No information about the specific extent of the plume or deposition area in time or space is recorded for further processing. In this way, the volumes of data needing storage for further processing are reduced to a minimum. This factor is crucial, since a large number of atmospheric dispersion modelling scenarios need to be performed to illustrate the effects of various weather scenarios.

The main report contains a more detailed description of the specific criteria defined for the respective calculation scenario.

4.1. Configuring the geographical domain of the calculation

Dispersion calculations using the RIMPUFF model were performed out to a distance of a maximum of 500 km from the outlet point. This distance may be assumed to constitute an outer limit for when the model formulation used in RIMPUFF might be deemed applicable. There is, however, a technical limit to the method of calculation in terms of a manageable model area in relation to the geographical resolution in the outcomes. Consequently, for the purpose of achieving the greatest possible accuracy in the analyses, a number of modelling cases were created for each calculation scenario using gradually increasing modelling distances and cell sizes (see Table 3). Thereafter, the outcomes obtained were combined and processed by identifying for each dose criterion and intervention level the calculation configuration offering the highest geographical resolution, without causing the maximum criterion distances to end up on the borders of the geographical domain of the calculation, or outside the domain.

Table 3. Configuring the geographical domain of the calculation.

Configuration	Parameters		
	Cell size (m)	Calculation radius (km)	Number of cells
B0	50	5	4.0E+04
B1	100	20	1.6E+05
B15	250	50	1.6E+05
B2	1,000	150	9.0E+04
B25	2,000	300	9.0E+04
B3	5,000	500	4.0E+04

Corresponding calculations using the particle-based PIGLET model consistently use a quadratic grid comprising 201×201 cells having a cell size of 100×100 m. The cell size is based on a balance between resolution and statistical uncertainty. Larger cells would achieve reduced statistical uncertainty as this would imply a larger number of particles per cell; however, at the same time, this would result in a systematic underestimation of the level of activity at short distances. Smaller cells would result in inferior statistics without necessarily giving more accurate values at very short distances.

4.2. Meteorological calculation scenarios

A large number of dispersion calculations were performed to illustrate effects during the variable meteorological conditions that may occur. The calculations were performed for the respective facility and postulated event, with variable points in time of releases distributed over a ten-year period. In order to take into account not only 24-hour but also seasonal variations, the calculations were performed assuming a release taking place every 26th hour during the period. Thereafter, each event was modelled using the RIMPUFF model during a period of 72 hours or until all airborne activity had passed from the geographical domain of the calculation.

In the PIGLET scenario, a release commencing every 21st hour during the period was initiated, followed by the event being modelled during a period of 72 hours.

4.3. Sensitivity studies

The outcomes produced by means of atmospheric dispersion modelling depend on both the model used as well as the setting of parameters for the given model. Modelling times generally increase with increasing complexity in the modelled processes. In a particle-based model such as PIGLET, the statistical uncertainty is reduced by increasing the number of model particles, at the cost of increased calculation time. The kind of puff model that RIMPUFF belongs to implies increasing the calculation time by using a larger number of model puffs. In addition, the outcomes are affected by the assumptions made in terms of dispersion and deposition parameters, etc.

This work has not allowed the possibility of, nor had the aim of, carrying out a more detailed analysis of the effect on calculation outcomes due to variations in the individual model parameters. Instead, the parameterisation was selected on the basis of reasonable parameter choices given some consideration to calculation performance.

However, one specific choice of parameters in terms of RIMPUFF has been studied in more detail, as this choice could potentially have a significant impact on the outcomes. It was established during the initial investigatory work that enabling trifurcation of calculation puffs[7] had a sharp impact on calculation times, as trifurcation results in a much larger number of puffs within the geographical domain of the calculation, specifically in connection with modelling at greater distances from the outlet point and during longer periods of time. Thus, trifurcation was disabled during the subsequent calculations.

For the purpose of looking into how electing to exclude trifurcation has an impact on the calculated distances in relation to the selected criteria, a larger number of calculations during a period of three years were performed for a specific release scenario with the trifurcation enabled. The calculations focused on the criteria met at greater distances, as the significance of this setting of parameters may be assumed to be of greatest significance at larger distances from the outlet point. The outcomes indicate that the calculated distances for these criteria are reduced by approximately 10 per cent with trifurcation enabled, signifying that the results of this study in this respect tend to be somewhat conservative.

[7] Trifurcation means that an individual puff is divided into three puffs in the vertical dimension and constitutes the process through which wind shear (sudden changes in wind direction, and/or wind speed over a relatively brief distance) is dealt with by the RIMPUFF model.

5. Statistical processing of data

5.1. Calculation of maximum distances

The outcome from a single dispersion and dose calculation is given in the form of a greatest distance at which a dose criterion or an intervention level has been exceeded. Thereafter, the distances are compiled in the form of cumulative histograms. For a certain dose criterion or a certain intervention level, each histogram illustrates the percentage of weather scenarios encompassed as a function of distance. The average value and uncertainty where a given percentage of the weather scenarios analysed exceed a defined criterion were estimated through statistical data analysis. This method of analysis is described in detail in this chapter. The distances which, according to the above-mentioned analysis, encompass a certain percentage of all the weather scenarios (70, 80 or 90 per cent), serve as a basis for the proposed ranges of the emergency planning zones and emergency planning distances. The main report discusses the number of weather scenarios taken into account by the suggestions relating to the different facilities that should have emergency planning zones.

5.2. Cumulative frequency distributions

Outcomes from dispersion and dose calculations are obtained in the form of rows of outcomes containing the furthest distance from the outlet point where a given dose criterion has been exceeded. One way of compiling the greatest distances at which a given dose criterion or intervention level is exceeded is to collect data on the distribution of distances and to present it in the form of a cumulative histogram. Provided that the statistical basis is adequate, in other words, if the dispersion calculations have taken into account a sufficient number of weather scenarios, the cumulative distribution of distances gives information about the distance within which a certain percentage of all observations are expected to be distributed, i.e. the 'percentile'. Thus, a histogram is calculated per dose criterion or intervention level associated with a certain protective action. Each histogram indicates the respective percentile at a certain level. For example, the 80th percentile, P_{80}, gives information about the greatest distance at which a certain dose criterion or an intervention level is exceeded if 80 per cent of the weather scenarios are taken into account.

5.2.1. Bins

When calculating histograms, input data needs to be distributed into a number of intervals, referred to as 'bins'. All histograms are divided into 30 bins of equal size, regardless of the scale of the geographical domain. A larger number of bins make it possible to achieve a higher resolution when calculating percentiles. However, an excessive number of bins in relation to the underlying data risks giving rise to greater uncertainty when estimating percentiles, as the data density in certain bins risks becoming too low. In the assessment of SSM, 30 bins illustrate a sufficient level of detail, without the data density in each bin becoming too low.

5.3. Classification of data points

5.3.1. Zeros

In cases where a certain dose criterion is never exceeded in a dispersion and dose calculation, no outcome row is generated. When the criterion is not exceeded, this needs to be reflected by the cumulative histogram. This is done by adding a zero. In this context, a zero signifies a row with the greatest distance of 0 km. The dispersion calculations only take into account the outcome where a criterion is exceeded over land. A single dispersion calculation, involving a release passing directly over the sea and subsequently resulting in a certain criterion being exceeded at some distance over the open sea, thus generates no outcome row. In this case as well, the omission also needs to be represented by a zero in the histogram. The number of zeros, n_z, which are added to the histogram in this way, are described by the equation

$$n_z = n - n_r$$

where n represents the total number of dispersion calculations, and n_r represents the number of dispersion calculations in which the criterion is exceeded, thus giving rise to a greatest distance.

If the data analysis has the aim of establishing percentiles for greatest distance over the mainland, this needs to be reflected by the analysis of data from the calculation of dose and dispersion. Thus, in relevant cases, outcomes for islands are replaced by using zeros to provide an accurate illustration of the percentiles for distances over the mainland. The different methods for calculation of cumulative histograms are described below.

5.3.2. All data points

In the case of the fuel fabrication plant in Västerås, which is not located near a coastline, or where the distances serving as a basis for the size of the emergency planning zones become relatively small, all outcome rows from dispersion calculations may be dealt with similarly without this resulting in skewed distances. In this case, all the distances are over the mainland, with no omissions in the dispersion calculations due to the anticipated greatest distance at which a certain criterion is exceeded being over the open sea. The method for calculating cumulative histograms in this way is referred to in this appendix as 'Method A', and is illustrated by the example shown in Figure 7 in section 5.5.

5.3.3. Distances on the mainland

For reasons of physics, transport of radioactive materials differs depending on whether the plume passes over a body of water or across a body of land. This factor is taken into account by the atmospheric dispersion modelling, but it also needs to be taken into account when calculating the greatest distances at which a dose criterion or an intervention level is exceeded. On average, the greatest distance where a dose criterion or an intervention level is exceeded is somewhat larger at islands out to sea than compared with a situation where the release might only have passed over the mainland. As the main range of the emergency planning zones and distances is over the mainland, this should be taken into account in the analysis of data in order to prevent islands from skewing the outcome towards larger distances that are unwarranted.

For this reason, the data analysis defines a coastline, for instance in the case of the nuclear power plant at Oskarshamn, as outside the mainland in the Baltic Sea. In combination with the position information from the dispersion and dose calculation, the coastline definition is used to categorise the outcome as ‘mainland’ or ‘non-mainland’. In the final step, the outcomes over the mainland are attributed a weighting factor together with the total number of dispersion calculations performed. This results in the percentiles accurately reflecting the greatest distance at which a certain percentage of the weather scenarios analysed have their respective criteria exceeded over the mainland. The method for calculating cumulative histograms in this way is referred to in this appendix as ‘Method B’, as illustrated by the example shown in Figure 8. Method B takes into account the fact that the plume might move in the direction of the sea. This would indicate that the greatest distances at which a given criterion is exceeded become somewhat smaller over the mainland, assuming that all the weather scenarios are taken into account.

5.3.4. Distances off the mainland

By conducting a special analysis of the complement in relevant cases, islands excluded in the analysis using Method B above are instead taken into account in the overall assessment of the emergency planning zones’ and distances’ ranges. In this case, the probability distribution is instead studied directly in the form of a histogram. Thus, the outcome over an island in the sea is reflected in the histogram in the form of an increased distance frequency for the distances from the outlet point encompassed by the island in question. The method for calculating histograms in this way is referred to in this appendix as ‘Method C’, as illustrated by the example shown in Figure 9. This method illustrates the conditional probability that the greatest distance at which a certain criterion is exceeded is *d* km, given that the plume is moving across the sea.

5.4. Average values and uncertainty

In order to estimate the greatest distance at which a certain criterion is exceeded and the uncertainty associated with this distance, bootstrap analysis is used. This method is based on the observed probability distribution that underpins the cumulative histogram. By performing repeated random sampling from the probability distribution observed, and based on the samples, once again calculating the percentile at a certain level, the average value and variance indicated for a certain area of the cumulative histogram corresponding to a certain percentile can be estimated. The uncertainty of the average value is obtained by calculating the standard deviation and multiplying it by a coverage factor, k, in order to take into account k standard deviations. In this project, all outcomes are presented as a distance in kilometres (the average value), with the defined uncertainty having coverage factor k=2. As the histograms are produced in discrete steps, the uncertainty is sometimes zero. It is important to keep in mind that the uncertainty reflected by the percentiles for the greatest distances consequently only takes into account the statistical proportion of the analysis. This implies that assumptions made during previous analysis steps, plus any potential systematic deviations in dose and dispersion calculations, are not taken into account when estimating the uncertainty.

5.5. Examples of analysis methods

The following examples are based on the same dispersion and dose calculations, and thus the same underlying data. Outcomes for specific intervention levels in relation to different methods of analysis (described in section 5.3 above) are illustrated by Figures 7 to 10. They emphasise the significance of a carefully considered method of analysis.

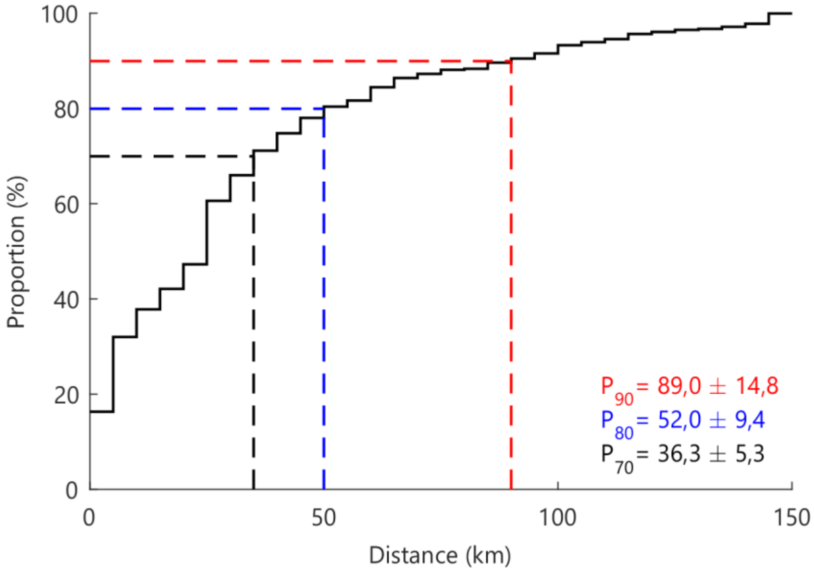

Figure 7. Example of a cumulative histogram, calculated in accordance with Method A, as described in section 5.3.2 above. Each bin (stairstep) illustrates the percentage of the weather scenarios analysed that are at the selected criterion (in this case an intervention level) for a certain distance. It can be interpreted from the figure that the distance where this intervention level is exceeded in 80 per cent of the weather scenarios will have an outcome shorter than 52 ± 9.4 km.

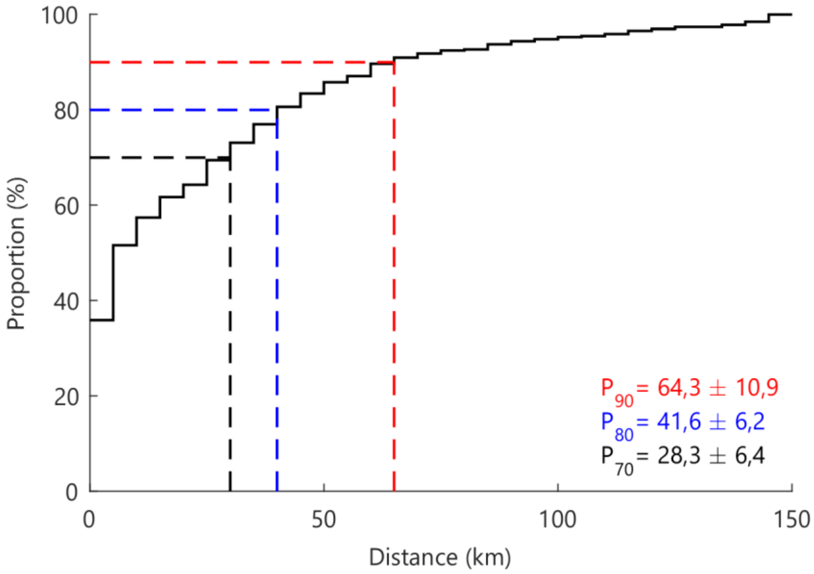

Figure 8. Example of a cumulative histogram, calculated in accordance with Method B, as described in section 5.3.3 above. Each bin (stairstep) illustrates the percentage of weather scenarios encompassing the selected intervention level for a certain distance, given the release passing over the mainland. It can be interpreted from the figure that the distance for this intervention level will be shorter than 41.6 ± 6.2 km in 80 per cent of the weather scenarios. Consequently, the outcomes for the corresponding percentile are approximately 10 km shorter than compared with using Method A.

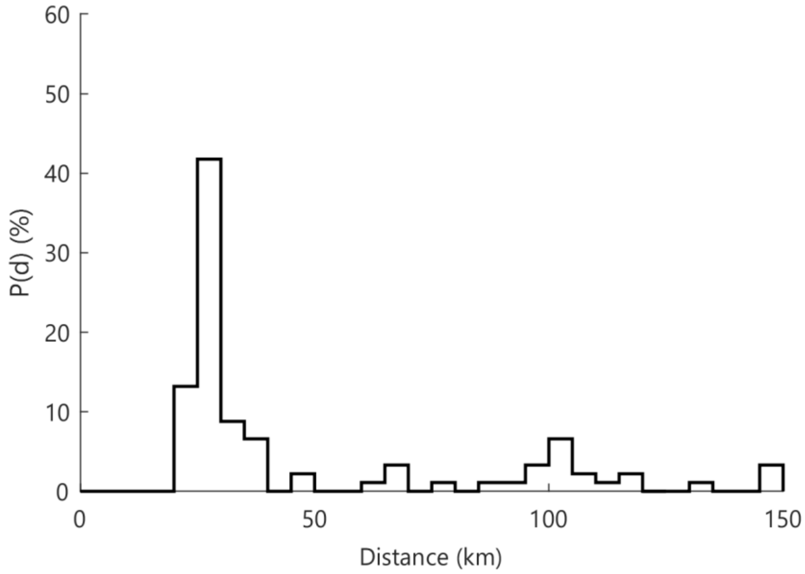

Figure 9. Example of a probability distribution, calculated in accordance with Method C, as described in section 5.3.4 above. Each bin (bar) illustrates the probability, P, that the greatest distance at which the selected intervention level is exceeded, d, lies within the interval, given that the plume has moved towards, and passes over, the sea. A clear influence of an island at a distance of approximately 30 km can be interpreted from this figure.

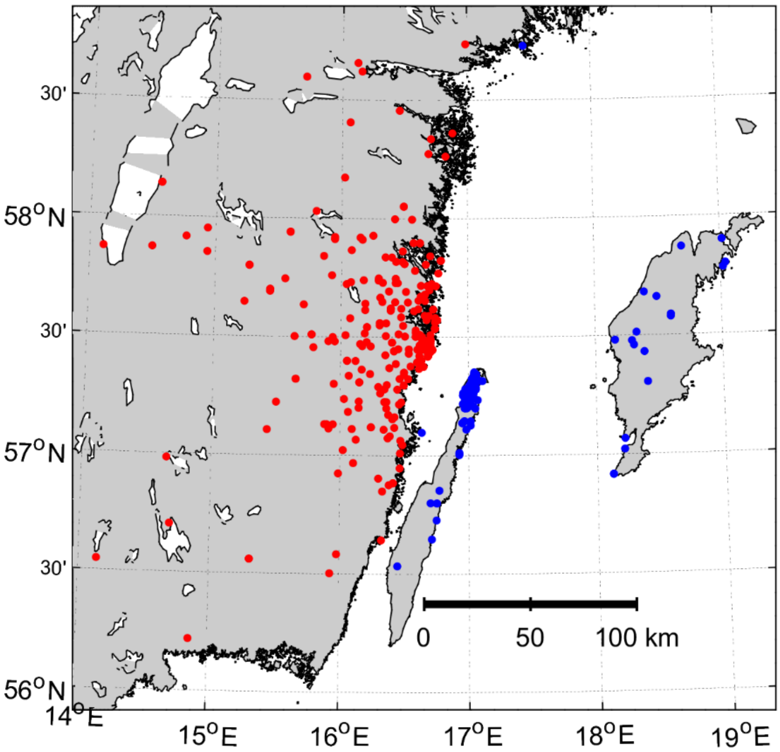

Figure 10. An example of categorisation of outcomes in the form of mainland locations (red dots) and non-mainland locations (blue dots). From the categorisation illustrated above, it can be observed that the differences in outcomes between Methods A and B depend on the outcomes from the islands of Öland and Gotland, which were excluded when using Method B. The peak levels shown for the respective distances of approximately 30 km and 100 km in the figure for Method C (Figure 9) are consequently the result of outcomes on these islands.

5.6. Selection of analysis method

Method A was used to calculate distances at which dose criteria and intervention levels may possibly be exceeded around the fuel fabrication plant in Västerås. In the specific case of this plant, the largest distances for all the dose criteria and intervention levels are relatively short (a few kilometres). No open sea is present that might have an impact on dispersion within these distances. Thus, Method A is directly applicable.

In the case of the nuclear power plants and Clab, which are located along coastlines, Method B is instead used when calculating distances at which dose criteria and intervention levels may be exceeded. This method gives outcomes that are identical to those produced using Method A, provided that the greatest distances at which the criteria are exceeded are short and thus not skewed by the presence of islands.

Method C was only used in the proposal for the UPZ to surround the nuclear power plant of Oskarshamn, in which case the outcome over Öland needs particular consideration.

6. Selection of parameters

The following section provides a more detailed account of the meteorological data used for atmospheric dispersion modelling. Another area covered is the specific parameter settings for the atmospheric dispersion model used. Lastly, an explanation is provided on derivation of the adopted dose coefficients, as well as the considerations made when selecting the specific parameters.

6.1. Meteorological data

Historical meteorological data for the period February 2006–February 2016 was used for the dispersion calculations. Table 4 shows the days during the period for which data is lacking or is incomplete, implying that calculations over the affected period could not be carried out.

Table 4. Missing meteorological data in the archives of SMHI (Swedish Meteorological and Hydrological Institute) during the processed period of time, from February 2006 to February 2016.

	Lack of data		
Model	Period (starting)	Period (ending)	Number of days
G11	20070101	20070101	1
G11	20070215	20070215	1
G11	20081119	20081120	2
G11	20090509	20090510	2
G11	20090801	20090901	32
G11	20101001	20101118	49
G11	20120417	20120426	10
E11	20120904	20120904	1
E11	20120930	20121101	33
E11	20131023	20131024	2
E11	20131031	20131031	1
E11	20131123	20131124	2
E11	20140331	20140401	2
E11	20140513	20140513	1
E11	20140811	20140812	2
E11	20140918	20140919	2
E11	20150621	20150621	1
E11	20151001	20151101	32

6.2. Parameterisation of RIMPUFF

The table below shows the parameter values selected for the RIMPUFF model. This table is limited to the parameters accessible from the interface of ARGOS, the system used for decision making and analysis support. For a more detailed description of the RIMPUFF model and the significance of the respective parameter, see [7].

Table 5. Parameter settings for the RIMPUFF model.

	Parameters		
Configuration	Unit	Value	Nomenclature
Gamma Dose Rate from Plume	Y/N	Yes	
Gamma Dose Rate from Ground	Y/N	Yes	
Puff Released Every	Min.	10	
Outdata Every	Min.	60	
Trajectory	Y/N	No	
Local Scale Model Chain		No	
Minimum Relative Concentration of Interest		0.001	CHEMIN
Number of Advection Steps per Released Puff		10	TAU/ NTADV
Pentafurcation of Puffs	Y/N	No	
Trifurcation of Puffs	Y/N	No	
Stability		Similarity	
Number of Interpolations for Each Wind Field		6	
Wind Shift per 100 m	Degree	5	
Wind Speed Gradient	m/s	2	
Max Number of Trifurcations		2	
Maximum Pentafurcations		2	
Minimum Sigma for Pentafurcation	m	300	
Puff Centre Rise		Shear Rise	
Initial Puff Size [Sigma Y]	m	10	
Initial Puff Size [Sigma Z]	m	10	
Sigma Y Advection Factor		0.5	
Methodology for Deposition Velocities		Land Use	
Start of Long Parameterisation		1000	

The parameter of deposition velocity is used to calculate dry deposition on the ground. The parameters for aerosols are selected on the basis of assumed particle diameter of 1 µm (see Table 6).

Table 6. Dry deposition velocities in RIMPUFF.

Group	Deposition velocity (m/s)
Iodine, aerosol form	0.001
Iodine, organic form	0.0005
Iodine, elemental	0.01
Noble gases	0
Other nuclides (aerosol)	0.001

The above table illustrates the generally applied setting of parameters. In the case of the postulated event of a fire with a release of uranium powder in the Västerås fuel fabrication plant, however, different particle sizes and densities were assumed in the dispersion calculations. This justifies the need to adapt deposition velocities on the basis of these variables. For a more detailed description of how this was implemented in RIMPUFF, see [8].

Dry deposition is also influenced by surface roughness (friction), which in its turn depends on the properties of the ground. This is taken into account by multiplying the general values for dry deposition with a factor specific to the land cover type.

RIMPUFF uses a classification of land cover type broken down into five categories (see Table 7). These categories are derived from data produced by CORINE[8]. In their turn, these five categories were established by merging the categories belonging to the original CORINE dataset.

Table 7. Multiplication factors for categories of land cover types in RIMPUFF.

Land Cover	Factor
Forest	2.0
Water	0.1
Urban	0.1
Grass	1.0
Rural	1.0

Wet deposition is calculated by using a deposition factor multiplied by the rain intensity (mm/h) raised to a power of *n*, where *n* is the exponent. The values used in RIMPUFF are shown in Table 8. In RIMPUFF, no wet deposition is employed for a rain intensity below 0.001 mm/h.

[8] CORINE: Coordination of Information on the Environment [18].

Table 8. Deposition factors and exponents for wet deposition in RIMPUFF [9].

Group	Deposition factor (wet deposition) (1/s)	Exponent
Iodine, aerosol form*	0.000084	0.79
Iodine, organic form	0.0000008	0.6
Iodine, elemental	0.00008	0.6
Other nuclides (aerosol*)	0.000084	0.79

* Applies to aerosols comprising particle diameters below 2.8 µm. In the case of larger particle size, an expression is employed including an additional number of parameters in accordance with [9].

6.3. Dose coefficients for RIMPUFF

The following section provides a detailed account of selection of dose coefficients when performing calculations using the RIMPUFF model.

6.3.1. Cloud dose

Calculations of cloud dose presuppose that the total emission of gamma energy per decay in four energy intervals may be calculated for each nuclide in the source term, as described in section 3.1. These four gamma factors were derived from data sourced from the nuclear data libraries JEFF 3.1 [10] and ENDF/B-VII.1 [11].

In some cases, the gamma factors for a given parent nuclide also include contributions from its decay products, having taken into account any branching ratios. This case applies when the daughter nuclide has a half-life that is short in relation to the period of time when the activity is airborne. Another prerequisite is that the half-life of the daughter nuclide is substantially shorter than that of the parent nuclide, resulting in achievement of activity equilibrium in the decay chain within the interval of time applicable to the dispersion calculation. An example of this procedure is to consider Cs-137, with a half-life of approximately 30 years. Cs-137 decays primarily into Ba-137m via beta decay, and thereafter to stable Ba-137 (half-life of approx. 3 min.). In this decay chain, the gamma emission takes place in connection with the decay of Ba-137m. In this case, the gamma emitted is taken into account by the gamma factors for Cs-137, meaning that no modelling is needed for Ba-137m.

6.3.2. Ground dose

Calculation of ground dose was carried out as described in section 3.2. The factors used for conversion of deposited activity into dose rate were derived from DCFPAK 3.02 [12], whereby a ground penetration of 1 cm was assumed, signifying that the radioactive materials are evenly distributed in the uppermost centimetre of a layer of soil having a density of 1.6 g/cm^3.When selecting the level of ground penetration, consideration was given to the primary factor that the seven-day dose was analysed, and that the activity during the period of time may to some extent be assumed to have penetrated into the ground. No further modification of the conversion factors was carried out to take into account surface roughness. This impact was considered as an inherent effect of the ground penetration.

A particular procedure was applied for calculation of dose rate, and thus the dose, from ground deposition after the termination of the atmospheric dispersion modelling (normally 72 hours after a release). The exposure to radiation from activity deposited on the ground depends on the decay and growth over time of nuclides belonging to the deposition. Consequently, this process requires modelling as of finalisation of the dispersion calculation up until point in time *T* for which the contribution of ground dose to total effective dose is to be determined (7 days). This modelling took place by using a software component belonging to FDMT [13]. This component comprises a separate dose model with associated dose coefficients. In contrast to corresponding calculations in RIMPUFF, this dose modelling is performed per age group. Once final calculations of total (age-group independent) combined ground dose from deposited activity have been made, the ground dose to adults derived using FDMT was applied to the period after the deposition had ceased.

6.3.3. Inhalation dose

When calculating inhalation dose, inhalation rates by age group were used in accordance with Table 9.

Table 9. Inhalation rates as a function of age group, derived from the category [14] 'Indoor Worker'.

Age group	Inhalation rate (m^3/s)
Child, 1 year of age	0.0000602
Child, 5 years of age	0.000101
Child, 10 years of age	0.000177
Child, 15 years of age	0.000233
Adult	0.000257

The nuclide-specific and age-specific dose coefficients used are derived from ICRP 119 [15], Table G1 (aerosols) and Table H1 (reactive gases).

In the case of aerosols, the coefficients were generally selected on the basis of the absorption type recommended by the ICRP (F/M/S)[9], see Table 10.

[9] The abbreviations F, M and S signify different rates (Fast, Medium and Slow) in connection with uptake by the body after inhalation.

Table 10. Assumed absorption type when calculating inhalation dose.

Element	Absorption type	Element	Absorption type
Ag	M	Np	M
Am	M	Pm	M
Ba	M	Pr	M
Ce	M	Pu	M
Cm	M	Rb	F
Co	M	Rh	M
Cs	F	Ru	M
Fe	M	Sb	M
I (aerosol)	F	Sr	M
La	M	Tc	M
Mn	M	Te	M
Mo	M	Th	S
Nb	M	U	S
Nd	M	Y	S
Ni	M	Zr	M

6.4. Parameterisation of PIGLET

Calculations were performed using PIGLET with a release rate of one particle every 10 seconds. Each released particle is associated with a certain released quantity of activity of the nuclides in the source term.

The parameter of deposition velocity is used to calculate dry deposition on the ground (see Table 11).

Table 11. Dry deposition velocities in PIGLET.

Group	Deposition velocity (m/s)
Iodine, aerosol form	0.001
Iodine, organic form	0.0005
Iodine, elemental	0.001
Noble gases	0
Other nuclides (aerosol)	0.001

PIGLET applies a classification of land use into four categories in accordance with Table 12.

Table 12. Multiplication factors for categories of land cover types using PIGLET.

Land Cover	Factor
Forest	2.0
Water	0.1
Urban	0.5
Other	1.0

Wet deposition is calculated by using a deposition factor multiplied by the rain intensity (mm/h) raised to a power of *n*, where *n* is the exponent. The values used by PIGLET are shown in Table 13.

Table 13. Deposition factors and exponents for wet deposition used by PIGLET.

Group	Deposition factor (wet deposition) (1/s)	Exponent
Iodine, aerosol form	0.0001	0.8
Iodine, organic form	0.000001	0.8
Iodine, elemental	0.0001	0.8
Other nuclides (aerosol)	0.0001	0.8

6.5. Dose coefficients for PIGLET

The following section provides a detailed account of selection of dose coefficients when performing calculations using the PIGLET model. The description is limited to coefficients used for calculating severe deterministic effects.

Table 14 below shows sources of dose coefficients for calculating absorbed dose to red bone marrow on the part of adults and children, effective dose to an embryo[10], and absorbed dose to the brain of a foetus.

[10] This analysis sets effective dose to an embryo as equivalent to absorbed dose to an embryo.

Table 14. Sources of the dose coefficients used by PIGLET**.**

Dose	**Reference**
Absorbed dose to bone marrow, adults, in connection with cloud and ground exposure. Absorbed dose to the uterus in connection with cloud and ground exposure.*	Eckerman K.F. and Leggett R.W. [12]
Absorbed dose to bone marrow, one year old child, in connection with cloud and ground exposure.	Jacob et al. [16]
Absorbed dose to the brain of a foetus and effective dose to an embryo, due to inhalation by the mother.	ICRP 88 [17]
Absorbed dose to bone marrow, adults and one year old child, due to inhalation. Absorbed dose to the uterus due to inhalation.*	ICRP 119 [15]

* In the case of nuclides for which dose coefficient values were missing for absorbed dose to the brain of a foetus and effective dose to an embryo, dose to the uterus was applied instead.

The dose coefficients for ground dose were multiplied by 0.65 to compensate for gradual ground penetration during the period comprising seven days for which the calculations were performed.

The dose from inhalation was calculated using an integration period of 50 years for adults, and 69 years for a one year old child. The same inhalation rates as in RIMPUFF (see Table 9) were used. However, in the case of pregnant women, the value 0.000206 m^3/s was used [17].

References

[1] S. Thykier-Nielsen, S. Deme and E. Láng, "Calculation method for gamma-dose rates from spherical puffs," Risø-R-692 (EN), Risø National Laboratory, 1993.

[2] S. Thykier-Nielsen, S. Deme and E. Láng, "Calculation method for gamma-dose rates from spherical puffs," Risø-R-775 (EN), Risø National Laboratory, 1995.

[3] S. Hoe, P. McGinnity, T. Charnock, F. Gering, L. H. Schou Jacobsen, J. Havskov Sørensen, K. G. Andersson and P. Astrup, "ARGOS Decision Support System for Emergency Management," Proceedings (online), 2009.

[4] SSM, *Partikelmodellen PIGLET. Modellbeskrivning och användarhandledning*, SSM2017-4413-1, 2017 (The PIGLET particle model: Description of the model and users' manual).

[5] SSM, *Lena version 5.0. Användarhandledning*, SSM2017-4413-2, 2017 (Lena, version 5.0: Users' manual).

[6] H. Walter, F. Gering, K. Arnold, B. Gerich, G. Heinrich and U. Welte, "RODOS-based simulation of potential accident scenarios for emergency response management in the vicinity of nuclear power plants," Bundesamt für Strahlenschutz (Federal German Office for Radiation Protection), 2015.

[7] S. Thykier-Nielsen, S. Deme and T. Mikkelsen, "Description of the Atmospheric Dispersion Module, RIMPUFF," RODOS(WG2)-TN(98)-02, 1999.

[8] P. Astrup, "Atmospheric dispersion of particles larger and heavier than aerosols," PREPARE(WP4)-3-01, 2016.

[9] A. Baklanov and J. H. Sørensen, "Parameterisation of Radionuclide Deposition in Atmospheric Long-Range Transport Modelling," Physical Chemistry Earth (B), Vol. 26, No. 10, pp. 787-799, 2001.

[10] OECD/NEA, "The JEFF 3.1 Nuclear Data Library," No. 6190, https://www.oecd-nea.org/dbdata/nds_jefreports/jefreport-21/jeff21.pdf, 2005.

[11] M. Chadwick, M. Herman, P. Obložinský, et al., "Special issue on ENDF/B-VII.1 library," Nuclear Data Sheets, Vol. 112, No. 12, 2011.

[12] K. Eckerman and R. W. Leggett, "DCFPAK 3.02 (Dose Coefficient Data File Package)," Oak Ridge National Laboratory, 2013.

[13] H. Müller, F. Gering and G. Pröhl, "Model Description of the Terrestrial Food Chain and Dose Module FDMT in RODOS PV 6.0," RODOS(RA3)-TN(03)06, 2003.

[14] ICRP, "Human Respiratory Tract Model for Radiological Protection," ICRP Publication 66. Ann. ICRP 24 (1-3), 1994.

[15] ICRP, "Compendium of Dose Coefficients based on ICRP Publication 60," ICRP Publication 119. Ann. ICRP 41 (Suppl.), 2012.

[16] P. Jacob, H. Rosenbaum, N. Petoussi and M. Zankl, "Calculation of Organ Doses from Environmental Gamma Rays using Human Phantoms and Monte Carlo Methods. Part II: Radionuclides Distributed in the Air or Deposited on the Ground," GSF Report 12/90, Gesellschaft für Strahlen- und Umweltforschung (National Research Center for Environment and Health), Munich, 1990.

[17] ICRP, "Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother," ICRP Publication 88. Ann. ICRP 31 (1-3), 2002.

[18] European Union, "CORINE land cover," European Environment Agency, https://www.eea.europa.eu/publications/COR0-landcover, 1995.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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