UK Health Security Agency

PACE 3.3.4 applied to the REPPIR 2019 Consequence Assessment Methodology

A worked example and template

PACE 3.3.4 applied to the REPPIR 2019 Consequence Assessment Methodology

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Abstract

The REPPIR 2019 Consequence Assessment Methodology (CAM) allows operators to meet the requirements of schedule 3 of REPPIR 2019, and to provide the local authority with suitable information for the development of an offsite plan. Several software tools could be employed to implement the methodology. This document describes how it might be approached with the PACE (Probabilistic Accident Consequence Evaluation) code version 3.3.4 developed by UKHSA.

This document presents a simplified worked example in which the CAM is applied to a hypothetical 'higher risk' facility in the UK using the PACE software along with the UK Met Office's NAME Model. For a useful illustration, an actual position in the UK must be chosen, but this is hypothetical, and no facility is currently located or planned to be located there to the authors' knowledge. The operations at the facility are not specified and the representative range of source terms used are simple and arbitrarily defined to illustrate the application of the CAM and not for realism.

The document has been structured so that it can be used as a template for REPPIR 2019 or a similar consequence assessment study. In addition, input files based on this report are available on the PACE website.

This work was undertaken under the Radiation Assessment Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standard ISO 9001:2015, Approval No: ISO 9001 - 00002655.

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Version history

Version	Release date	Notes
1	March 2023	
2	April 2025	Corrected error in Table 1, large source term

Contents

1 Introduction

The REPPIR 2019 Consequence Assessment Methodology (CAM) allows operators to meet the requirements of schedule 3 of REPPIR 2019, and to provide the local authority with suitable information for the development of an offsite plan (Bexon et al, 2019). Several software tools could be employed to implement the methodology. This document describes how it might be approached with the PACE (Probabilistic Accident Consequence Evaluation) code version 3.3.4 developed by UKHSA (Charnock et al, 2020).

This document presents a simplified worked example in which the CAM is applied to a hypothetical 'higher risk' facility in the UK using the PACE software along with the UK Met Office's NAME Model. For a useful illustration, an actual position in the UK must be chosen, but this is hypothetical, and no facility is currently located or planned to be located there to the authors' knowledge. The operations at the facility are not specified and the representative range of source terms used are simple and arbitrarily defined to illustrate the application of the CAM and not for realism.

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1.1 Different types of radiation dose

A radiation dose is a measure of the energy deposited in the body tissue. Strictly this is referred to as the absorbed dose and it is a physically measurable quantity defined as the energy deposited per unit mass and is expressed in gray (Gy). However, the relationship between the radiation dose and any subsequent health effects is complicated and therefore two other units of dose have been defined by the International Commission on Radiological Protection (ICRP) (ICRP, 1991; ICRP, 2007) to account for this. Firstly, the equivalent dose, which is expressed in sieverts (Sv). This is based on the absorbed dose and takes account of the fact that types of radiation that lose energy more rapidly are more damaging to cells. Hence, alpha radiation is more damaging per unit absorbed dose than gamma radiation. However, the results of such damage in terms of the health effect (e.g. cancer) will also depend on the organ and tissue being irradiated. This is taken into account in the second quantity, effective dose, also expressed in sieverts (Sv). This is based on equivalent dose and takes account of the fact that some cells, tissues and organs are more sensitive to radiation than others. Hence, effective dose is a measure of the energy deposited in the body tissue and the associated damage in terms of health effects.

Both equivalent dose and effective dose are defined by ICRP taking account of information on the health effects caused by different types of radiation. They provide a convenient method for the addition of doses received as a result of different types of exposure.

The quantity of committed dose is used to describe the effect of radionuclides being incorporated in the human body and then irradiating the tissues over a period of time. Therefore, where the dose to two days is discussed in this report, this includes the internal dose resulting from the initial two days of potential exposure, but which may be delivered over a longer period of time (over years in the case of some radionuclides).

1.2 Different types of exposure

Since different types of radiation can travel different distances through body tissue, the distribution of dose and effects will depend on the type of radiation. It will also depend on whether it is received from a source outside the body (external exposure) or from a source inside the body (internal exposure). In the case of gamma radiation, the dose from a wide beam of radiation from a source outside a person will be the same as that from the same source distributed in the body. However, for alpha and beta radiation which travel much smaller distances, doses from external and internal sources will be different. For example, an alpha source is not generally a hazard if it is outside the body because the radiation cannot penetrate the layer of dead cells on the outside of the skin. However, it is hazardous if ingested or inhaled as it could become incorporated in tissues and cells and cause localised damage. Even from an internal source, alpha or beta radiation will not travel as far as gamma radiation in body tissue. Therefore, the dose will be delivered in a smaller area of the body tissue, and the damage will depend on the sensitivity of the irradiated cells. Dose models are used to calculate doses to different body organs and tissues from external and internal sources.

1.3 Relationship between dose and health effects

Exposure to radiation can lead to two types of health effects. Deterministic health effects (or tissue reactions) generally occur when high doses are received over short time periods and can include fatal and non-fatal effects. Deterministic health effects caused by ionising radiation result from damage to a significant number of cells within tissues, for which there is invariably a dose threshold. These health effects generally appear within a few months of the exposure, and, in the case of very high doses, onset may occur within an hour. By contrast, stochastic health effects can occur when low doses are received over short or long time periods and include fatal and non-fatal cancers which may not appear in the exposed population until many years after exposure. Stochastic health effects are those which have their origins in the probabilistic induction of self-replicating mutations in cells within tissues and for which there is believed to be no dose threshold.

At very low levels of dose (for example, a few tens of microsieverts) the assumed increase in the risk is too small to be detectable in epidemiological studies, so it is not possible to determine whether there is a dose level below which no effects occur at all. However, for protection purposes, it is commonly assumed that there is no “safe dose” threshold, so that any level of exposure, however small, may cause harm. It is also assumed that the relationship between risk and dose is linear, with the increased risk being proportional to the dose received. These assumptions are known as the linear no-threshold model (LNT) and the estimates of health risks from radiation in the ICRP system of radiation protection are based on this model. It is likely that dose-response relationships are different for different cancer types, but linearity is regarded as a good overall assumption for radiological protection purposes. For example, it is suggested by some that the relationship between risk and dose is linear but only above a threshold, or that the relationship is supra-linear, or that at low doses, ionising radiation has a protective effect on cells. The CERRIE (Committee Examining Radiation Risks of Internal Emitters) report (CERRIE, 2004) discusses a number of possible

dose/response relationships. UKHSA's view is that the LNT model is a scientifically defendable assumption for radiation protection purposes.

The potential numbers of health effects expected to occur because of the postulated radiological releases have not specifically been calculated as part of this study.

1.4 PACE

PACE (Probabilistic Accident Consequence Evaluation) is a software tool developed by UKHSA for calculating the consequences of a short-term release of radionuclides to the atmosphere. It runs within a geographic information system (ESRI ArcGIS Desktop™).

PACE models the transfer of radionuclides through the environment, the subsequent dose distributions in the population, the impact of protective actions which might be introduced to reduce the doses, the health effects in the population and the economic costs of the health effects and urgent protective actions. In the present study, PACE has been used to estimate doses and consider protective actions. Other endpoints have not been considered.

PACE operates by simulating a release under many different meteorological conditions and in this way can establish the ranges and limits of the consequences (Charnock et al, 2020). More specifically, PACE builds up a picture of the possible ranges of consequences by repeatedly modelling the atmospheric dispersion and deposition of radionuclides for a given accident scenario using meteorological sequences drawn from a large historical dataset of weather conditions.

The tool was developed under the ISO9001:2015 certificated quality management system and verification of the software package itself has focused primarily on extensive software testing and peer review while the environmental transfer models included in the programme have been subject to their own separate verification and validation (Smith et al, 2022).

The calculation of the dispersion of radionuclides in the atmosphere is performed using the NAME (Numerical Atmospheric-dispersion Modelling Environment) model which has been developed by the UK Met Office. More details about NAME are given in the following section. PACE uses NAME's estimated activity concentrations in air to calculate doses from direct inhalation of the dispersing plume and external exposure to gamma radiation from the plume. NAME also calculates deposition of material onto the ground which is used for input to PACE's calculation of dose from ingestion of foods, exposure to gamma emitters deposited on the ground and inhalation of resuspended material.

Transfer of radionuclides through the terrestrial food chain is modelled using FARMLAND (Brown and Simmonds, 1995) for spike releases occurring in January and June and results are stored in datasets of time dependent activity concentrations in foods per unit deposition. These datasets are based on an implementation of FARMLAND that takes account of detailed agricultural practices. Consequently, the time of the year when the accident occurs will influence the activity concentrations in foods and, therefore, data is available for accidents occurring in both summer and winter. Datasets are also included for exposure to gamma emitters from material deposited on the ground and for inhalation of resuspended material. This data has been derived using the GRANIS and RESUS models (Kowe et al, 2007; Smith and Simmonds, 2009). Finally, the economic consequences of an accidental release are modelled using COCO-2 (Higgins et al, 2008). This model considers losses related to

business interruption and the displacement of affected populations, losses from restrictions on agriculture and the costs of health effects.

In order to estimate the effects of the modelled scenarios on the population in the affected region, population distribution data is required. The data used in the present study is night-time population data taken from the 2001 census and adjusted for land-use as provided in Smith et al (2005). The data was provided in the format of a GIS geodatabase with a resolution of 1 km^2.

1.5 NAME atmospheric dispersion model

NAME is part of the Met Office's real-time weather and dispersion prediction capability and is linked to the Met Office's Unified Model (UM), a unified Numerical Weather Prediction (NWP) meteorological model which is used for both weather prediction and long term climate modelling (Cullen, 1993; Staniforth and Wood, 2008).

The UK Met Office's Numerical Atmospheric-dispersion Modelling Environment, NAME, is a Lagrangian particle-trajectory model designed to predict the atmospheric dispersion and deposition of gases and particulates (Jones et al, 2007). The mean flow or advection of a particle is determined by the flow information, primarily the wind velocity, detailed in the required meteorological data. Diffusion is described by random walk (Monte Carlo) processes, determined by the turbulent velocity. Each particle carries a mass or activity of one or more pollutant species and evolves by various physical and chemical processes during its lifespan. A box-averaging scheme is used to derive activity concentrations in air from particle activities. The dry deposition scheme in NAME uses a deposition velocity, whereby the flux of a pollutant to the ground is proportional to the concentration and deposition velocity. The wet deposition scheme in NAME uses scavenging coefficients (a function of the precipitation rate, type of precipitation and type of deposition process). For radiological releases, NAME incorporates both radioactive decay processes and estimates of external dose from the radioactive plume (Bedwell et al, 2010).

The most comprehensive NAME validation study to date has been against the Kincaid data set, using a process based on the Model Validation Kit methodology developed under the Harmonisation initiative (Jones et al, 2017). The Kincaid dataset contains measurements of ground level air concentrations from an elevated, buoyant plume release from the Kincaid power plant in the US (Jones et al, 2005). The validation study used the puff scheme (in preference to the particle scheme which is used by NAME when run with PACE), as this is designed to be used for "short-range" applications. This study demonstrated that the performance of NAME was comparable with other leading short-range atmospheric dispersion models. The results showed a small over-prediction in the mean concentration, but the spread in the predicted concentrations was in good agreement with the observed spread. Another significant validation was published by the World Meteorological Organization in 2015. That related to atmospheric dispersion model estimates of activity concentration in air and on the ground compared to field measurements following the accident at the Fukushima Daiichi nuclear power plant (Draxler et al, 2015). NAME was one of five different atmospheric dispersion models taking part in the study. Time series of activity concentrations in air for ^{137}Cs and ^{131}I at a single location approximately 110 km from the plant were considered. When compared using statistical performance measures, NAME performed as well as, if not slightly

better than, the majority of the other models. Other validation studies include: modelling of consequences of the Windscale accident (Johnson et al, 2007; Nelson et al, 2006) and validation against the ETEX long-range tracer experiment (Ryall and Maryon, 1998). Non-radiological individual case studies are also regularly identified for qualitative, and sometimes quantitative, comparison against observational data, notably volcanic eruptions. Examples are Devenish et al (2012), Cooke et al (2014), Webster et al (2012), Heard et al (2012), Johnson et al (2012) and Marenco et al (2011).

Although NAME does include an option to consider a single isolated building when modelling atmospheric dispersion, the Met Office have cautioned about its use. Therefore, NAME as implemented in PACE does not account for building effects. There is a lot of uncertainty when considering building wake effects, but generally they draw the plume downwards and so they can be accounted for by specifying a lower effective height than the actual release.

1.6 Dose calculation in PACE and NAME

1.6.1 Internal exposure from the inhalation of material from the plume

The quantity of committed dose is used to describe the effect of radionuclides being incorporated in the human body and then irradiating the tissues over time. Therefore, where the dose to two days is discussed in this report, that includes the inhalation dose resulting from the initial two days of potential exposure, but which may be delivered over a longer period of time (over years in the case of some radionuclides). Values of inhalation dose coefficients are taken from ICRP Publication 119 (ICRP, 2012). The dose coefficients represent the committed dose to age 70 years. It is assumed that the particles inhaled are 1 µm in size. Assumed lung absorption types are in accordance with advice provided in NRPB (1999).

1.6.2 External exposure from material in the radioactive plume

NAME has the capability to calculate the effective dose arising from external exposure from material in the radioactive plume (cloud gamma dose) using a finite or semi-infinite cloud model. The finite cloud model involves simulating the plume by a series of model particles (point sources) and then integrating over these sources to estimate the dose at a point. The semi-infinite cloud model is much simpler and uses the activity concentration in air at the point of exposure to calculate dose. Implicit in this approach is the assumption that the activity concentration in air is uniform over the volume of the plume from which photons can reach the point at which the dose is delivered and that the cloud is in radiative equilibrium. The implications of using the approximation are that where the activity concentration in air is not uniform, doses may be over- or underestimated. An example of a scenario where dose would be underestimated is where the plume, which has been released at height, is overhead. In that situation, activity concentrations in the elevated plume would be greater than those on the ground where the dose is delivered. This is most likely to occur close to the release point. At downwind distances of more than about 10 km, greater dispersion occurs and differences between the two models will not be significant.

1.6.3 External exposure from material deposited on the ground

External gamma dose from deposited material is calculated by multiplying the amount of material deposited by a quantity, the dose per unit deposition, which is obtained from a data library. A suitable library, giving the dose per unit deposit at a series of times for each of many radionuclides, including the contribution from progeny products formed after deposition, is provided with the PACE system. This library was generated by combining information from different sources, and so includes doses calculated using three different models. The values for the radionuclides which typically make the most important contributions to deposited gamma dose from typical accidental releases from nuclear fission reactors (^{103}Ru, ^{106}Ru,^{131}I, ^{132}Te, ^{134}Cs, ^{137}Cs, and ^{140}Ba) were calculated using the NRPB model EXPURT (Crick and Brown, 1990). This considers the amounts of material deposited on different surfaces in residential areas, the movement of material between these surfaces and into the soil column, and the dose from material deposited on the different surfaces. The doses for other radionuclides were calculated using a simpler model which assumes that the dose in the area where people live can be represented by the dose received over an open field (Charles et al, 1982; Hill et al, 1988). The doses are calculated allowing for material to move into the soil column.

The ratio of doses in different body organs depends on the energy of the gamma radiation and the orientation of the body. Anterior-posterior (AP) irradiation geometry is used for calculating the ratio of organ doses to the effective dose, as this geometry was used for calculating effective dose from air dose. The ratios of doses in different organs do not differ significantly for photon energies above a few hundred keV. For simplicity, a single factor giving the ratio of organ dose to effective dose has been used and derived assuming AP irradiation and an energy of 0.5 MeV. The factors were derived from ICRP-74 (ICRP, 1996).

1.6.4 Internal exposure from ingested material

Underpinning the ingestion dose calculations in PACE are libraries of food contamination factors created using the terrestrial food chain model FARMLAND (Brown, 1995). Activity concentrations and integrated activities per unit mass of food for a unit deposition onto the ground (Bq kg^{-1} per Bq m^{-2} and Bq y kg^{-1} per Bq m^{-2}) have been calculated for the main terrestrial food groups that are important in the UK diet: cow meat, cow liver, cow milk, sheep meat, sheep liver, grain, root vegetables, potatoes, green vegetables, soft fruit and orchard fruit. In PACE these pre-calculated activity concentrations are combined with deposition estimates from the atmospheric dispersion model and production yields to determine the amount of activity that is consumed and hence the dose received across the considered population.

Corrections for delay times from harvest to consumption (for fresh and processed products) are included and doses are truncated to 100 years. The fraction of food consumed fresh and the fraction processed can be specified by the user in the PACE interface.

The calculation assumes that all deposition occurs at time zero.

The calculation accounts for food restrictions by removing the integrated activity up to the time of the end of the restriction from the calculation of activity consumed. If the restriction time does not correspond to an exact time in the food concentration factor library, then a linear adjustment is made.

In general, the PACE individual dose calculation is the sum of two components: the first representing local production, i.e. the consumption of food grown in the vicinity of the individual, and the second representing the consumption of food drawn from national production.

1.6.5 Dose from inhalation of resuspended material

PACE estimates doses arising from inhalation of resuspended material using a method based on resuspension factors and an adapted version of the Garland formula (Garland, 1979; Wellings et al, 2019).

2 Source Terms

In this example the source terms and the facility are hypothetical. The facility is located on the Norfolk coast, and two classes of incident have been defined that adequately represent the full range of hazards at the facility. They are given as two source terms, with probabilities of occurrence in Table 1.

Table 1: Representative source terms for hypothetical site

	Large Source Term	Small Source Term
Probability	1/100000	1/10000
Duration of release (hours)	4	4
Release height (m)	10	10
^{60}Co	2 10^{11} Bq	1 10^{9} Bq
^{134}Cs	2 10^{13} Bq	1 10^{11} Bq
^{137}Cs	1 10^{13} Bq	5 10^{10} Bq
^{137m}Ba	2 10^{10} Bq	1 10^{8} Bq
^{131}I (100% aerosol)	2 10^{14} Bq	1 10^{12} Bq
^{88}Kr	2 10^{13} Bq	1 10^{11} Bq
Location (British National Grid)	(632740.7, 335315.5)	

For the purposes of this study, it has been assumed that all particles are of a size that is respirable. In the atmospheric dispersion model, it is assumed that the particle size of all material in the source term is 1 µm, except for the noble gas. Iodine is assumed to be 100% in aerosol form.

2.1 Selection of radionuclides

The hypothetical source terms in this example are greatly simplified with fewer radionuclides than might be expected from a real facility. There may well be more radionuclides than the maximum of thirty that PACE can handle, and, though PACE can handle thirty, it will run more quickly and efficiently if the number can be reduced to a more manageable ten to fifteen.

The Source Term tool in PACE can be used to identify the most important radionuclides and exclude those that are not significant. The tool gives an approximate breakdown of the

proportion of the dose that is attributable to each radionuclide and can produce a ranked list. It also gives an indication of the relative importance of different pathways.

The Source Term tool uses a gaussian formulation (ADEPT) with a receptor at an assumed distance on the plume centre line, as well as other assumptions about the weather and integration periods. It is good practice to vary the assumptions to understand which radionuclides are contributing over which time periods and pathways, so that significant radionuclides are not prematurely excluded. Table 2 shows the ranking when the default settings are used and when the integration period is set at 2 days and ingestion dose is omitted. In both cases it would be defensible to omit ^{60}Co and ^{88}Kr, although, with so few radionuclides in this case, it is not necessary. Table 3 shows the contribution of pathways with default settings and when integration periods are set to 2 days and ingestion is omitted.

Table 2: Ranking of radionuclides by contribution using the Source Term tool with different assumptions (large source term).

Default settings, 1-year integration		2-day integration period, no ingestion	
Radionuclide	**Contribution (%)**	**Radionuclide**	**Contribution (%)**
^{134}Cs	50.6	^{131}I	87.7
^{131}I	34.3	^{134}Cs	8.8
^{137}Cs	14.5	^{137}Cs	2.9
^{60}Co	0.49	^{88}Kr	0.44
^{88}Kr	0.11	^{60}Co	0.13
^{137m}Ba[a]	0	^{137m}Ba	0

[a] ^{137m}Ba appears to make no contribution to dose. This is because the source term tool uses the ADEPT dispersion model which does not include ingrowth of progeny (^{137m}Ba is a progeny of ^{137}Cs).

Table 3: Relative contribution of different pathways using the Source Term tool with different assumptions (large source term).

Pathway	Contribution (%)	
	Default settings, 1-year integration	**2-day integration period, no ingestion**
Inhalation	23.5	94.7
External ground	40.2	3.6
External cloud	0.4	1.6
Ingestion	35.9	0.0

One could also argue for the exclusion of ^{137m}Ba, but it is important to understand that the NAME model treats progeny slightly differently from ADEPT. ^{137m}Ba is the daughter of ^{137}Cs and, with a very short half-life, it is generally in equilibrium with its parent and most of the dose comes from the decay of the progeny not the parent. If ^{137m}Ba is included in the source term, then the NAME model will correctly model the ingrowth and calculate the external cloud gamma exposure from it. However, if it is not included, there will be no external cloud gamma from ^{137}Cs/^{137m}Ba. In contrast, ADEPT does not model the ingrowth of progeny and for significant equilibrium pairs like ^{137}Cs/^{137m}Ba, it assumes that the dose rate is from the parent, hence ^{137m}Ba appears to make no contribution to dose in Table 2.

However, the inclusion or exclusion of ^{137m}Ba makes very little difference in practice and only for the external cloud gamma pathway. For the inhalation, ingestion, and external ground pathways, it makes no difference at all. This is because the ingrowth of ^{137m}Ba is built into the

^{137}Cs dose factors used in PACE for those pathways and there are no dose factors for ^{137m}Ba on its own. Little of any specified ^{137m}Ba in the source term will be deposited in the ground due to its short half-life of less than 3 minutes. Therefore, a release quantity of zero is acceptable.

The Source Term tool does not consider foetal doses and care must be taken when excluding radionuclides, such as isotopes of phosphorus, which can give higher doses to the foetus than adults, see Appendix C.

3 REPPIR Assessment Endpoints

The CAM specifies four groups of endpoints:

1 Doses by distance and pathway with no protective actions (projected doses) to 2 days and 1 year.

2 Distances for urgent protective actions.

3 Doses for comparison against reference levels (residual doses).

4 Optional additional results which the local authority might find helpful in planning.

3.1 Group 1, doses by distance and pathway with no protective actions

For each source term the CAM requires:

- the expectation (mean) value and the ninety-fifth percentile of effective dose, assuming no protective actions, at 1km, 3km, 5km, 10km, 30km, 50km – separately, from inhalation, external ground and external cloud, and the summed dose. To 2 days and 1 year.
- for sites which have the potential to release iodine: the expectation value and the ninety-fifth percentile of thyroid dose, assuming no protective actions, at 1km, 3km, 5km, 10km, 30km, 50km – from inhalation from iodine nuclides only. To 2 days and 1 year.

The CAM acknowledges that there may be a significant number of endpoints, but also notes that not all may be required for a given site and source term.

The CAM advises consideration of dose to three age groups (infants aged 1y, children aged 10y and adults aged 20y), and to foetuses and breast-fed for radionuclides that could be potentially limiting (the CAM lists the significant radionuclides for foetal doses and states that only the inhalation pathway is required).

The doses required should properly be interpreted as expected or 95th percentile *maximum* values, since many if not most of the locations at a given distance may well have zero dose depending on the wind direction. In PACE, distance banded results can be generated by extracting all the grid squares that intersect with a given distance band and then extracting the maximum value for each met sequence. This will give a set of maximum values (one for each met sequence) from which the mean and 95th percentile can be calculated.

A decision will need to be made about the built environment and the assumptions about the population placement within the environment. PACE offers three broad choices: time is spent indoors and outdoors within a brick house environment (Env1) or multi-storey building environment (Env2), or the individual could be continuously outside. For the short term two-day projected doses there is an argument for choosing outdoors. While it is a conservative assumption to place a person outdoors for the whole emergency period of two days, in many scenarios most of the dose is received during the passage of the plume which at any location is only likely to be a few hours in total. Even if the release is long, it is very unlikely the wind

will be in a constant direction over two days. For this illustration, outdoors will be assumed for the short-term doses. For outdoor locations, the CAM recommends a location factor of 1 for all pathways, i.e., no protection is given.

For doses over a year, it is unreasonable to assume that people are outside continuously and therefore dose estimates for either Env1 or Env2 should be used, unless the nearby buildings were very lightweight, for example, a static caravan park, in which case the outdoor dose might be the most appropriate. If required, it is possible to assume people are always outdoors for the calculation of the dose at 1km for example and then Env1 for further bands if the situation warranted. For this illustration, the Env1 environment is used at all distances. More information about the location factors chosen is given in Section 4.6.

For the 1-year doses it may be unnecessary to include the doses from external cloud and inhalation separately since they only accrue during the passage of the plume and so will be the same as the 2-day doses except for differences due to assumptions about the built environment. In this example they are not included separately but do contribute to the total 1-year dose.

3.2 Group 2, distances for urgent protective actions

For each source term, the CAM requires:

- the expectation value and the ninety-fifth percentile for the distance that sheltering is required at the lower and the upper ERL (inhalation and external pathways only).
- the expectation value and the ninety-fifth percentile for the distance that evacuation is required at the lower and the upper ERL (inhalation and external pathways only).
- for sites which have the potential to release iodine: the expectation value and the ninety fifth percentile for the distance that stable iodine prophylaxis is required at the lower and the upper ERL (inhalation from iodine isotopes only).
- the expectation value and the ninety-fifth percentile of the distance to which milk and green vegetable restrictions are placed based on the Maximum Permitted Levels in food currently applicable to the UK (MPLs)

In the UK, planning for protective actions is based on emergency reference levels (ERL) which are expressed as ranges of averted dose and relate to a single action not combinations of actions (Nisbet, 2019). However, PACE does not apply emergency protective actions by evaluating averted dose, but rather it uses a trigger dose; a total level of projected dose to trigger an action. Section 4.7 describes how these can be used to emulate an averted dose calculation. Since Group 2 results are required for both the higher and lower ERL, and PACE only has a single trigger dose for each action, two PACE runs are required for each endpoint.

As the CAM points out, ERLs are generally applied to the 10-year-old age group when assessing the potentially averted doses because of the assumed higher cancer risk of this group. Therefore, in most cases it will be justifiable to calculate these endpoints for only the 10-year-old endpoint. However, in this example they are calculated for all three age groups.

3.3 Group 3, doses for comparison against reference levels

For each source term, the CAM requires:

- The expectation value and the ninety-fifth percentile of the total effective residual dose in the first year assuming all protective actions are implemented at the lower ERL and the MPLs for food, separately from inhalation, external ground, external cloud, resuspension, food and summed total.
- The expectation value and the ninety-fifth percentile of the total effective residual dose in the first year assuming all protective actions are implemented at the upper ERL and the MPLs for food, separately from inhalation, external ground, external cloud, resuspension, food and summed total.

The CAM does not prescribe the distances at which the residual dose is required, but merely states:

> *Some analysis by distance for the above endpoints is likely to be required, but even results for a single distance, such as at 1km, will give some information for RL planning.*

In this illustration results are generated for 1km only.

As with Group 1 endpoints, the doses required should properly be interpreted as expected or 95th percentile *maximum* values, since many if not most of the locations at a given distance may well have zero dose depending on the wind direction.

The residual dose should include the effect of all protective actions, though the CAM requires inclusion of only urgent protective actions and food restrictions (not relocation or clean-up).

Since residual doses are required with protective actions implemented to both the lower and upper ERLs, PACE will need to be run twice. It is likely that the doses presented for the upper ERL will be the same as those for the lower ERL, especially for small release or at further distances, where projected dose are too low to trigger any protective action under either upper or lower ERL. This presents an interpretation problem for the reader that may need to be addressed.

The CAM does not require residual doses to foetuses and breast-fed infants

3.4 Group 4, optional additional useful results

For each source term, the CAM suggests the following endpoints might add value to the assessment:

- for each of the urgent protective actions of evacuation, sheltering and stable iodine, the expectation value and the ninety-fifth percentile of the numbers of people affected and the areas of land affected.
- for food restrictions, the expectation value and the ninety-fifth percentile of the total area and total volume of food affected.

PACE can calculate both these sets of endpoints and comes with sets of spatial data that describe the resident population and the production of crops in the UK. However, it should be noted that these sets are static and tied to particular times. In reality, neither population nor food production are static and there will vary depending on factors such as the time of day or

year for the population and long-term population trends and farmers' decisions about what to grow and where are made each year in response to climate and demand. So, these endpoints should be treated as indicative.

As with distances of protective actions (Group 2 endpoints) it may be justifiable to perform these calculations for just the 10-year-old child age group.

4 Adaptation of PACE and NAME for REPPIR Assessments

To conform to CAM, several of the default PACE options need to be considered and modified before continuing.

4.1 Grid specification

The PACE interface allows a grid to be specified with up to three interior grids of increasingly fine resolution to be nested within it. The PACE interface allows considerable flexibility in grid resolution and coverage, so the grid structure needs to be carefully designed so that it that will adequately support the subsequent CAM analysis that needs to be performed, but it does not have such a fine resolution and so many grid squares that the run times are intolerable long and output sizes are unwieldy.

One of the endpoints required by the CAM is dose by distance, and these results are generated in PACE by examining all the grid squares that intersect with each of the specified distances and extracting the maximum value. Because grid squares have a size, the doses are effectively extracted from a band around the given distance. If the grid squares are very large, then the band is large, and the results will not satisfy the CAM requirement. The CAM suggests a grid resolution of 500m close to the release, with a larger resolution further out. However, one of the dose distances is 1km from the release, and 500m is perhaps a little too coarse for this purpose, and a grid size of around 200-300m is more appropriate. It is also a sensible approach to ensure that distance bands fit within a single nest of the grid, otherwise grid squares will be different size at difference points on the circumference.

Food restrictions can extend considerable distances from the site, and whilst it is desirable to specify a grid that encompasses the largest possible restriction zone there may be practical constraints that mean this is not always possible. It is important when presenting the ranges of food restriction distances to ascertain whether they have been truncated by the size of the grid and, if so, to acknowledge that in the report. If this is not tolerable for a given analysis, then it may be preferable to use a larger but very much coarser grid and perform the analysis of food restriction separately from the other endpoints.

To reconcile these considerations when constructing a grid, it is a useful practice to perform some pilot runs to ensure that the grid is fit for purpose. An example pilot study is given in Appendix A and the grid used is illustrated in Figure 1.

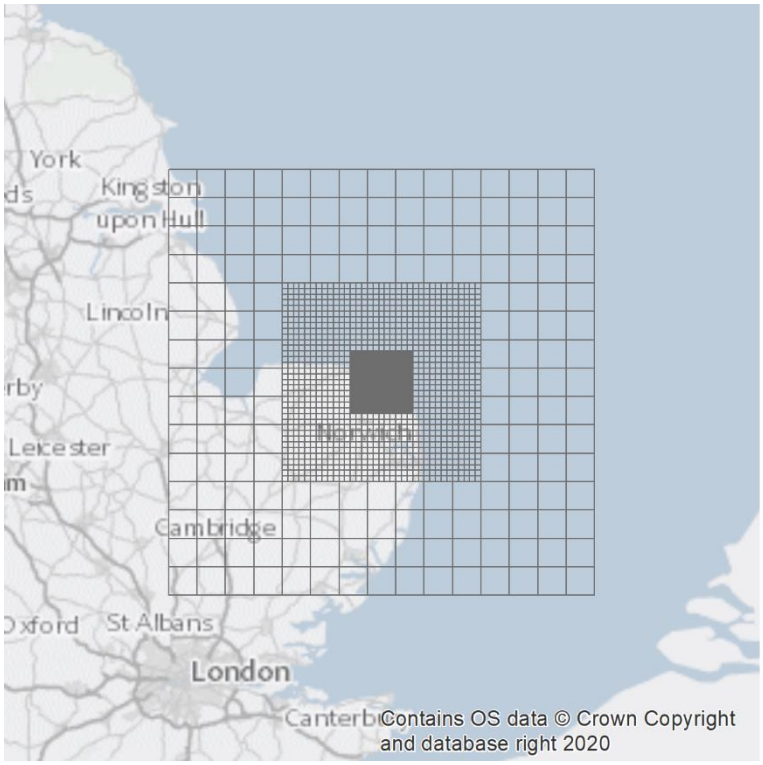

Figure 1 Calculation grid used, centred on the release with grid squares of 200m out to 1.5km, 600m to 14km, 3000m to 52km and 15000m to 112km, with 4697 individual grid squares.

4.2 Atmospheric dispersion modelling

When using NAME there are several choices the user must make:

- The meteorological data to use
- The number of met sequences to use
- The temporal domain
- The spatial domain
- The time-step
- The number of particles to use
- The approach to the external cloud calculation.
- Inclusion of plume rise.

Each choice has consequences for both the quality of the results and for the length of time both the NAME runs, and the subsequent PACE calculations and analysis take, as well as the physical disk space needed to store the inputs (principally the input meteorological data) and the outputs. Since the purpose here is illustration and, furthermore one that will be repeated for future versions of PACE, some of the inputs are chosen for speed and represent the minimum requirements for a successful analysis. To find appropriate values for some of these parameters, such as temporal domain and number of particles, further pilot studies are useful as illustrated in Appendix A2.

The minimum amount of meteorological data recommended is one year, so that the results are not biased towards a season, and ideally one would sample from several years so that an unusual year does not bias results. Since PACE uses historical met data, it cannot account for climate change. The dispersion scenarios considered in this study were derived using one year of meteorological data from 2004. For this period, 200 different meteorological sequences were sampled. A temporal domain of 24 hours was chosen and a sampling period of 43 hours, meaning the start-time of each met sequence was 43 hours later than the start-time of the previous met sequence. Ten thousand modelling particles were released per hour and because there are four hours of release there will be a total of 40000 particles in each met sequence.

Because the NAME finite cloud model is more computationally expensive and as external cloud generally makes only a small contribution to external dose it is usually appropriate to use the semi-infinite approximation.

The NAME model can calculate plume rise. However, this is for stack releases, and the NAME developers warn against use of plume rise model for non-stack releases, for example building fires. Plume rise is a time-consuming calculation in NAME and if plume rise is judged to be significant then users may prefer to directly adjust the effective height of the release in the source term file.

It should be noted that users should be wary of relying on results at very short distances, i.e. much less than 1km. Plume height and building entrainment effects, as well as the effect of averaging across large concentration gradients that will occur in the few grid squares around the release, are subject to large uncertainties.

4.3 Emergency period

The CAM advises the use of 2 days for the period of urgent protective actions in most cases, and since the release durations of both source terms is only 4 hours, this was used in this example as the PACE “emergency ends” parameter. This parameter is central to PACE calculations and should be chosen with care for longer duration events as it specifies how long protective actions of evacuation and sheltering last and when the long-term location factors take over from the short-term.

4.4 Age group

The CAM advises consideration of dose to three age groups (infants aged 1y, children aged 10y and adults aged 20y). While PACE can calculate doses for these groups, it can only calculate one group at a time and so separate runs are required. Changing age groups in PACE 3.3.4 only changes the inhalation and ingestion dose coefficients, and the default breathing rates. External dose factors do not change and neither do individual food consumption rates.

Given the complications of handling multiple ages, it may be worth doing a pilot study to ascertain how great the differences are likely to be and then selecting the group that tends to be the most conservative. The CAM points out that ERLs are generally applied to the 10-year-

old age group when assessing the potentially averted doses in recognition of their higher cancer risk.

For doses by distance and pathway with no protective actions (Group 1) endpoints, the CAM also requires consideration of doses to foetuses and breast-fed infants, for those radionuclides where these could be potentially limiting, for the inhalation pathway only. PACE cannot directly produce doses for foetuses and infants, but Appendix C demonstrates an approach to provide some indicative results.

4.5 Breathing rates

The CAM advises that for the calculation of doses from the inhalation of the plume and for short-term releases under 7 hours, a day-time active breathing rate is used, and, if the release is longer than 7 hours, then a daily average that includes a component of the breathing rate appropriate for sleeping is required. For the calculation of dose from inhalation of resuspended radioactivity that will occur over an extended period a daily average is recommended. However, PACE3.3.4 only allows a single breathing rate to be specified, which is applied to all inhalation dose calculations including resuspension. Generally, the CAM does not require dose from the inhalation of resuspended material, however it makes this statement:

> *For more unusual releases, the inhalation of material resuspended from the ground into the air may also need to be taken into account, although the contribution from this exposure pathway is generally small.*

Therefore, for PACE, choosing a single breathing rate based on the duration of the plume, whilst not conforming to the CAM completely, is adequate but it will be slightly conservative if doses from resuspended material are included.

For short releases, the CAM recommends a breathing rate representing one third of the time sitting and two thirds of the time with light exercises. The default breathing rates currently in PACE assume periods of activity, rest and sleep so are not consistent with the CAM for releases under 7-hours. ICRP publication 66 (ICRP, 1994) gives values for these activities that can be used to derived values need for PACE as shown in Table 4.

Table 4: Breathing rates from ICRP publication 66 used to derive values consistent with CAM recommendations for a release duration less than 7 hours.

	Sitting (m^3h^{-1})	Light exercise (m^3h^{-1})	Value derived for PACE (m^3h^{-1})	Value derived for PACE (m^3s^{-1})
1 year old (infant)	0.22	0.35	0.31	0.000086
10-year-old (child)	0.38	1.12	0.87	0.000242
Adult	0.54	1.50	1.18	0.000328

4.6 Location factors

The CAM distinguishes between and defines occupancy factor, location factor, shielding factor and fraction of time spent indoors and outdoors at a location. In PACE these factors are combined into a single set of pathway specific factors (also termed location factors) for two built environments, *env1* and *env2* which represent brick-houses and multi-storey flats respectively, and for different exposure situations (normal conditions, pre-implementation of

protective actions, active sheltering and driving)., Note that evacuation implicitly has a location factor of zero. In this example Env1 has been chosen as the environment to use for calculating the long-term 1 year projected doses (Set 1 endpoints, see Section 3.1) and the residual doses for comparison to reference levels (Set 3 endpoints, see Section 3.3).

PACE comes with a set of default location factors for both Env1 and Env2 and correspond reasonably well with the suggested values given in the CAM. For example, PACE assumes that individuals spend 90% of their time indoors. The CAM does not give a value for proportion of time spent indoors normally but suggests Lader et al (2006) as a suitable source for this. Lader et al does not give this information directly but provides information on the amount of time spent on different 'main activities', broken down by different groupings. If the activities that appear to be predominantly indoors (e.g., sleeping, resting, cooking, washing) are summed up, then approximately 90% of the time is spent indoors on average.

PACE defaults are based on shielding factors for external cloud of 0.2 and 0.07 for brick houses and multi-storey houses respectively. The CAM suggests values of 0.15 and 0.05 respectively.

PACE defaults are based on shielding factors for external ground of 0.18 and 0.035 for brick houses and multi-storey houses respectively. The CAM suggests values of 0.15 for brick houses but gives no value for multi-storey.

PACE assumes that buildings give no protection from inhalation of radioactive material except when active sheltering is implemented in which case the default factor is 0.5. Similarly, the CAM also suggests buildings offer no protection except when active sheltering is implemented, in which case a factor of 0.6 is suggested.

For long term doses beyond the emergency period, the CAM recommends that an occupancy factor is applied that accounts for time spent away from the contaminated area. The CAM does not give a value but, again, suggests Lader et al (2006) as a suitable source. Lader et al does not give this information directly but the sum of the home-based activities gives a result of 75% of time spent at home. This concept of absence can be accommodated in PACE because, in addition to short-term location factors, it has series of long-term location factors that apply to the pathways that persist beyond the passage of the plume: ground deposition and resuspension. The default PACE values for external ground for the two environments were calculated with the ERMIN model (Charnock et al, 2016) which accounts for both the shielding properties of the environment and the weathering of radionuclide at various rates on different urban surfaces. The default PACE values for resuspension assume no protection and are set at a value of 1. The CAM concept of occupancy can be easily incorporated into the PACE's long-term location factor by multiplying them by a suitable factor, e.g., multiplying the long-term location factor by 0.75, without affecting the location factor used for the short-term dose in the first two days (or whatever emergency period is specified). Since the CAM only requires doses to 1 year, the effect of weathering can be reasonably ignored.

For the example in this report, the suggested values from the CAM are adopted. However, the CAM makes clear that these are only suggested values and that the latest and most relevant values should be used.

Table 5: Location Factors adopted for Env1 adapted from recommendations in the CAM

	Default/Pre-CM	Sheltering	Driving in a car[c]	Long-term (for all times)
External cloud	0.235[a]	0.15	1	NA
Inhalation	1	0.6	1	NA
External ground	0.262[a]	0.18	1	0.197[b]
Resuspension	1	0.6	1	0.75[b]

a factors account for an assumed 10% of time spent outdoors

b factors account for an assumed 10% of time outdoors and an assumed 25% of time spent outside the region of contamination.

c PACE assumes no protection offered by vehicles so a location factor of 1 is given. The CAM gives no advice on vehicle protection. However, in this example doses do not include time evacuating in a vehicle as the travel time is set to zero, so the value chosen has no effect (see Section 4.8).

4.7 Emergency protective action criteria

A feature of PACE is that the protective actions are applied when a dose threshold is exceeded. This differs from the planning of protective actions, which in the UK are based on emergency reference levels (ERLs). The ERLs are expressed as ranges of averted dose and relate to a single action not combinations of actions. For example, in PACE the evacuation might be applied if the calculated dose without evacuation exceeds 300mSv. However, when planning for evacuation and comparing against the ERLs, the calculated dose *saved* by evacuation needs to exceed 300mSv.

If it is known or can be estimated by how much a protective action will reduce the dose, then a criterion, given as a dose received without protective action, can be set so that it reflects the averted dose that needs to be achieved. In PACE these dose criteria, the estimated dose without any protective actions that trigger protective actions, are termed trigger-doses.

The dose saving benefits of a protective action depend on several factors, for example the timeliness of application and the relative importance of different pathways (which in turn depends on the radionuclide mix). The CAM gives guidance on the effectiveness of the three principal protective actions, which is summarised in Table 6.

Table 6: Factors for the dose reduction of protective actions proposed by the CAM

	Sheltering	Evacuation	Stable iodine
Inhalation	0.6	0	0[b]
External cloud	0.15[a] brick house 0.05[a] for multi-storey	0	NA
External ground	0.18[a] brick house 0.035[a] for multi-storey	0	NA
Resuspension	0.6	0	NA

a The protection from external exposure comes from shielding provided to a person by the building. Typically, a person might spend 90% of the time indoors whether they are sheltering or not, so the additional protection of sheltering from external exposure only applies to that 10% of time spent a person would have spent outside if not sheltering. This differs from protection from internal exposure from inhalation, since being in the building is not sufficient to provide additional inhalation protection, the person must be actively sheltering, with windows, doors and ventilation systems shut.

b Only applies to the inhalation of iodine from the plume

The analysis of the source term (Section 2) demonstrates that the dose from inhalation was likely to be dominant in the first two days. Therefore, in this example, it is reasonable to

assume that sheltering will have an inhalation dose reduction factor of 0.6, i.e., the inhalation dose while sheltering is 40% less than it would have been if not sheltering.

If the trigger dose criteria in PACE is set to 7.5 mSv and a dose reduction factor of 0.6 is assumed, then the lower ERL for sheltering (3 mSv) will be met and at least this dose is averted if the action is applied (since 7.5 x (1-0.6) = 3). If applied in a timely fashion both evacuation and stable iodine prophylaxis (SI) can be assumed to be 100% effective and so the trigger dose criteria can be set to the lower ERL 30 mSv total effective and 30 mSv inhalation dose to thyroid from isotopes of iodine respectively i.e., unchanged in value from the ERLs. Table 7 gives the trigger dose criteria adopted in PACE for both lower and upper ERLs.

Table 7: Dose criteria adopted in PACE

Protective Action	Selected trigger doses to comply with the	
	upper ERL	lower ERL
Evacuation (mSv effective)	300 mSv	30 mSv
Sheltering (mSv effective)[a]	75 mSv	7.5 mSv
SI (thyroid dose from inhalation of iodine isotopes)	100 mSv	30 mSv

a Note that the ERLs for sheltering given in PHE's Public Health Protection in Radiation Emergencies (Nisbet, 2019) are 30 mSv and 3 mSv for upper and lower ERLs respectively but have been adapted for PACE for the reasons given in Section 4.7.

If there is reason to suspect that the doses saved might be very different from those in Table 6, for example because there may be difficulties in applying the protective action in a timely fashion or the relative contribution of pathways is different and inhalation is not dominant, it would be sensible to perform some pilot runs to ascertain what savings are achievable and adjust the dose criteria accordingly.

4.8 Emergency protective action considerations

PACE affords the user further options to specify the criteria for protective actions. For example, SI and sheltering can be linked, so that SI cannot be applied without also applying sheltering. Also, the maximum and minimum distances for protective actions can be specified. However, since the purpose is to explore what protective actions are needed it is appropriate to switch these options off.

The CAM excludes assessment of recovery actions of relocation and clean-up and so this option can also be switched off.

PACE allows some realism to be built into how protective actions are applied, for example for both sheltering and evacuation, an initial delay can be specified. The timing options should be evaluated given the expected size of accident and the population involved, as they may be very pessimistic for small accidents and overly optimistic for large accidents. For the example in this report, the protective actions are assumed to be able to be applied in a timely fashion as given in Table 8 and this is consistent with the corresponding trigger doses chosen (Section 4.7)

Table 8: Assumed protective action timings

	Evacuation	Sheltering	SI
Initial delay (hours)	0	0	0
Period of sheltering before evacuation (hours)	0	NA	NA
Drive time (hours)	0[c]	NA	NA
Hours between end of action[a] and removal of skin activity[b]	0	0	NA

a Emergency protective actions end when the emergency ends, in this example at two days.

b Generally skin contamination is an unimportant pathway and not considered further in this example.

c Clearly there is a finite drive time, but in expressing it as zero the assumption is made that the people can be removed completely before the plume arrives.

4.9 Food restriction

The CAM explicitly requires the calculation of food restriction distances for green vegetables and milk (Group 2 endpoints). It also suggests that areas and food volumes would be useful output (Group 4 endpoints) but is not explicit about which foods should be included for these endpoints. As these endpoints are essentially to inform planners about waste generation and economic consequences of restriction, it makes sense to choose foods that are significant locally. For the example in this report, only milk and green vegetables are analysed.

Residual ingestion dose for food is also a requested endpoint (Group 3 endpoints, see Section 4.10) and again the CAM is not prescriptive about which foods to include. This endpoint is mentioned in this Section because inclusion of foods in the residual dose calculation implies that the extent of restrictions on those food should also be calculated (even if not eventually included in the report).

The criteria PACE uses for evaluating restrictions is consistent with the recommendations of the CAM, it calculates concentration levels in food using data files generated with the FARMLAND model and compares them with the Maximum Permitted Levels (MPL) as defined by UK Parliament (2019) and given in Table 9. Therefore the PACE default values can be used for this set of endpoints.

Table 9: Maximum Permitted Levels (UK Parliament, 2019), used in PACE by default

Control	Description	Default (Bq kg^{-1})
Milk		
Strontium	sum of all strontium isotopes	125
Iodine	sum of all iodine isotopes	500
Alpha emitter	sum of all alpha emitting plutonium and transplutonium isotopes	20
Caesium	sum of all radionuclides with half-life greater than 10 days	1000
Other foods		
Strontium	sum of all strontium isotopes	750
Iodine	sum of all iodine isotopes	2000
Alpha emitter	sum of all alpha emitting plutonium and transplutonium isotopes	80
Caesium	sum of all radionuclides with half-life greater than 10 days	1250

4.10 Ingestion dose

The CAM requires calculation of ingestion dose (Group 3 endpoints). PACE has two ways of calculating dose from the ingestion of radionuclides in food, the production collective dose calculation and an individual ingestion dose calculation. For the purposes of calculating an ingestion dose to compare against a reference level, the individual ingestion dose calculation should be used.

The PACE individual ingestion dose calculation allows for a proportion of an individual's diet to be locally sourced, whilst the remainder of the diet is assumed to be contaminated at a national average. For green vegetables, the CAM specifically recommends that the consumption should be all local but it is less clear about other food stuffs. The CAM is not explicit about which foods should not be included in the ingestion dose endpoints, but it states that it is unlikely that individuals will source all their grain, beef and sheep meat from "specific and localised areas" and so, in most cases, the contribution to dose can be neglected. The CAM recommends including milk, but it does not currently give guidance as to what proportion is local. However, in terms of finding the maximum individual ingestion dose it is most appropriate to assume that the milk consumed is 100% local. For the example in this report, only green vegetables and milk are considered to contribute to the ingestion dose with 100% of production being local for both.

The default ingestion rates included with PACE are for adults. When considering other age groups, different ingestion rates are required to be entered manually. The CAM suggests Smith and Jones (2003) as a data source for ingestion rates and suitable rates have been extracted in Table 10. However, for the example in this report the ingestion rates for other foods are set to zero.

Table 10: Food consumption rates extracted from Smith and Jones (2003)

Food type	Individual consumption rate for adults (kg y^{-1})	Individual consumption rate for ten-year-old children (kg y^{-1})	Individual consumption rate for one-year-old infants (kg y^{-1})	Fraction local
Cow milk	115	125	145	1
Cow meat	15	15	3	1
Cow liver[a]	2.75	1.5	0.5	1
Sheep meat	8.0	4.0	0.8	1
Sheep liver[a]	2.75	1.5	0.5	1
Green vegetables	35	14	5	1
Root vegetables	10	6	5	1
Potatoes	50	45	10	1
Grain products	50	45	15	1
Soft fruit[b]	5	3.75	1	1
Orchard fruit[b]	15	11.2	8	1

a Offal has been split equally between sheep and cow liver
b Fruit has been divided roughly 25% - 75% between soft fruit and orchard fruit

4.11 PACE endpoint selection

PACE can generate many endpoints, some of which will not be required for a REPPIR assessment. Omitting endpoints can make run times shorter, but if an omitted endpoint is subsequently found to be required, then parts of PACE will need to be rerun. Figure 2, shows the endpoint selection in the PACE 3.3.4 interface and the options that were need for the example in this document. The justification for the choices is given below

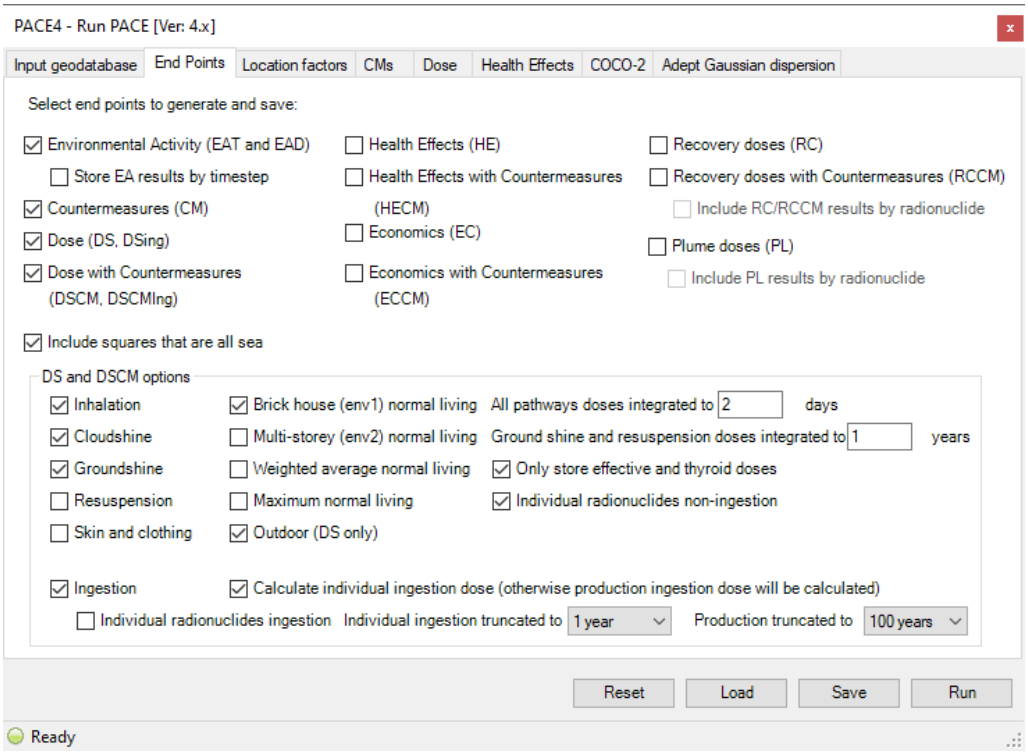

Figure 2 Endpoint selection tab in the PACE 3.3.4 interface.

The “Include squares that are all sea” option should be ticked because, the CAM is clear that grid squares that are entirely sea should be included in the calculations. Group 1 and Group 3 dose endpoints will be calculated for sea squares as though there were people present. Similarly, Group 2 endpoints, the extents of protective actions and food restriction, will be calculated for sea squares as though people are living there, or food produced there. However, for the calculation of Group 4 endpoints such as area affected, people evacuated or sheltered, or food yield lost, these grid squares will be treated as areas of no land and zero population or food production.

Health effects (HE, HECM), economics endpoints (EC, ECCM), hourly plume endpoints (PL) and recovery doses (RC, RCCM) can be omitted for REPPIR assessments. Resuspension and deposition on skin and clothing pathways can also usually be omitted if these pathways are small contributors. The environmental activity endpoints (EAT, EAD), that include total deposition and integrated concentration in air) can also be omitted but may be required if there is a need to map the plume, for example the ground deposition, for illustrative purposes.

For the example in this report, the only environments of interest are outdoors and “Env1”, therefore “Env2”, “Average dose” and Maximum dose” can be omitted. Only effective and thyroid doses are required and therefore other organs can be omitted.

The CAM requires thyroid doses from inhalation of isotopes of iodine, and therefore, when iodine is present, the “Individual radionuclides non-ingestion” option must be ticked, but the “Individual radionuclide ingestion” can be unticked.

5 Results

The CAM requirements produce many results, and these are presented in the following tables. To assist navigation, the tables are coloured to indicate their contents which is shown in Table 11.

Table 11: Colour coding of end points

External cloud doses
Cloud inhalation doses
External ground doses
Ingestion doses
Total doses (both with and without ingestion)
Other endpoints
Endpoint that may be truncated by grid extent

The CAM requires the mean and the 95th percentile values. In addition the median, maximum and minimum are also provided by PACE. Maximum and minimum values are generated automatically, and the median or 50th percentile is a useful result, as it is usually unaffected where a distance endpoint is truncated by the size of the grid.

For each dose end point, the maximum value is extracted from each met sequence to generate, for this example, a set of 200 maximum values, one for each met sequence. The mean, maximum, minimum, median and 95th percentile values are calculated from this set. Therefore, total doses are not usually the sum of the corresponding pathway values since the grid square where the maximum total dose occurs may not be the same grid square in which the maximum dose for any single pathway occurs.

Maximum extent/distance endpoints ignore the presence of sea, so it is the maximum extent of a protective action in all directions from the point of release, regardless of whether a person could live there, or a food could be produced there.

The area endpoints do account for sea and are the sum of the area of land in each grid square where the protective action is applied. However, they do not account for other factors that might preclude a population living there (e.g., lakes, industrial land etc). For food they are the area that would be banned if food was produced there and not the area of land given over to a particular food stuff.

The population impacted gives a broad indication of the magnitude of impact, but the results are based on the resident population. The actual number of people will depend on the time of day and year, and the resident population itself can be expected to change in future years. Similarly, the quantity of food restricted is indicative as the spatial pattern of agricultural production changes from season to season.

When considering endpoints together, it is important to be aware that the maximum or 95th percentile results for one endpoint is unlikely to occur in the same met sequence as for other endpoints. For example, it is unlikely that the maximum number of people affected will happen in the same met sequence as the maximum area of crops affected.

Complete sets of endpoints are given for each age group and source term. However, because of assumptions in the PACE calculations, external doses will be identical for different age groups with the same source term, and differences will only arise in internal doses from inhalation and ingestion. Extent of food restrictions will also be identical across age groups for the same source term as these are based on food concentration rather than doses.

To reduce the possibility of transcription errors, all endpoints in the tables are taken directly from PACE output. Doses are in Sv, distances in km, areas in m^2 and yields in kg or l and they are all given in scientific notation. For example, 7.5E-3 Sv is equivalent to 0.0075 Sv, 7.5 mSv or 7.5 10^{-3} Sv.

5.1 Tables

5.1.1 Adult, Large source term

5.1.1.1 *Adult, Large source term, group 1 endpoints*

Table 12: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.8E-05	1.3E-04	3.4E-06	4.1E-05	1.1E-04
3km	9.5E-06	3.0E-05	6.4E-07	8.2E-06	2.2E-05
5km	4.7E-06	1.4E-05	2.4E-07	3.9E-06	1.1E-05
10km	1.7E-06	5.2E-06	7.7E-08	1.3E-06	4.0E-06
30km	2.9E-07	9.5E-07	3.5E-09	2.1E-07	7.0E-07
50km	1.3E-07	4.7E-07	3.1E-09	9.6E-08	3.5E-07

Table 13: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.6E-03	5.6E-03	2.5E-04	2.6E-03	4.8E-03
3km	6.4E-04	1.7E-03	4.5E-05	5.8E-04	1.4E-03
5km	3.4E-04	8.8E-04	1.8E-05	3.0E-04	7.4E-04
10km	1.3E-04	3.6E-04	4.1E-06	9.7E-05	2.9E-04
30km	2.4E-05	8.1E-05	3.7E-07	1.8E-05	6.0E-05
50km	1.2E-05	4.3E-05	2.7E-07	8.4E-06	3.1E-05

Table 14: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	8.4E-05	5.0E-04	7.4E-06	6.3E-05	2.5E-04
3km	2.6E-05	2.0E-04	1.3E-06	1.9E-05	7.6E-05
5km	1.6E-05	1.6E-04	5.3E-07	1.1E-05	4.8E-05
10km	7.9E-06	9.3E-05	1.1E-07	5.1E-06	2.6E-05
30km	2.3E-06	2.2E-05	8.1E-09	1.3E-06	8.2E-06
50km	1.3E-06	1.7E-05	8.0E-09	6.5E-07	4.6E-06

Table 15: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances for all pathways excluding ingestion dose (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.7E-03	5.8E-03	2.6E-04	2.7E-03	5.0E-03
3km	6.8E-04	1.7E-03	4.7E-05	6.1E-04	1.4E-03
5km	3.6E-04	9.1E-04	1.9E-05	3.2E-04	7.7E-04
10km	1.4E-04	3.7E-04	4.3E-06	1.1E-04	3.1E-04
30km	2.7E-05	8.4E-05	3.8E-07	2.0E-05	6.5E-05
50km	1.3E-05	4.4E-05	3.5E-07	9.8E-06	3.2E-05

Table 16: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.7E-02	1.0E-01	4.6E-03	4.6E-02	8.7E-02
3km	1.2E-02	3.1E-02	8.1E-04	1.0E-02	2.5E-02
5km	6.2E-03	1.6E-02	3.3E-04	5.5E-03	1.3E-02
10km	2.3E-03	6.5E-03	7.4E-05	1.8E-03	5.3E-03
30km	4.4E-04	1.5E-03	6.6E-06	3.2E-04	1.1E-03
50km	2.2E-04	7.8E-04	4.9E-06	1.5E-04	5.7E-04

Table 17: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
3km	2.3E-04	1.8E-03	1.2E-05	1.7E-04	6.7E-04
5km	1.5E-04	1.4E-03	4.7E-06	1.0E-04	4.3E-04
10km	7.0E-05	8.3E-04	1.1E-06	4.6E-05	2.3E-04
30km	2.1E-05	2.0E-04	8.6E-08	1.2E-05	7.3E-05
50km	1.2E-05	1.6E-04	8.6E-08	6.0E-06	4.6E-05

Table 18: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances, all pathways excluding ingestion dose (Adult, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.3E-03	7.6E-03	3.2E-04	3.4E-03	5.7E-03
3km	8.7E-04	2.0E-03	5.7E-05	8.2E-04	1.7E-03
5km	4.9E-04	1.5E-03	2.3E-05	4.6E-04	9.5E-04
10km	2.0E-04	8.6E-04	5.2E-06	1.7E-04	4.1E-04
30km	4.4E-05	2.1E-04	4.5E-07	3.7E-05	9.6E-05
50km	2.3E-05	1.6E-04	4.2E-07	1.8E-05	5.3E-05

5.1.1.2 *Adult, Large source term, group 2 endpoints*

Table 19: Maximum extent of protective actions (Adult, Large source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	1.8E-01	6.3E-01	0.0E+00	2.0E-01	5.1E-01
Evacuation	2.3E-05	4.6E-03	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	1.3E+00	2.7E+00	4.6E-03	1.3E+00	2.2E+00
Upper ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	3.0E-01	9.0E-01	0.0E+00	2.8E-01	7.2E-01
Food restriction					
Green vegetables	6.4E+01	1.5E+02	4.6E+00	5.3E+01	1.3E+02
Milk	2.9E+01	1.5E+02	0.0E+00	1.3E+01	1.2E+02

5.1.1.3 *Adult, Large source term, group 3 endpoints*

Table 20: Maximum residual normal-living effective dose (Sv) over first year at 1 km, all pathways (Adult, Large source term, upper and lower ERL[a])

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	1.1E-05	3.2E-05	8.0E-07	9.5E-06	2.5E-05
Inhalation	2.6E-03	5.6E-03	2.5E-04	2.6E-03	4.8E-03
External ground	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
Ingestion	5.6E-04	1.3E-03	5.0E-05	6.6E-04	9.6E-04
Total	3.5E-03	7.6E-03	5.1E-04	3.6E-03	5.9E-03

a In this case both the upper and lower ERL calculation give the same maximum residual doses at 1km

5.1.1.4 *Adult, Large source term, group 4 endpoints*

Table 21: Consequences of predicted protective actions (Adult, Large source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	1.9E+00	1.3E+01	0.0E+00	3.1E-01	7.4E+00
Area sheltered m^2	3.9E+04	2.0E+05	0.0E+00	6.7E+03	1.5E+05
People evacuated	9.2E-03	1.8E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	2.0E+02	4.0E+04	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	5.1E+01	1.3E+03	1.8E+00	6.0E+00	2.4E+02
Area of prophylaxis advice m^2	3.2E+05	2.3E+06	4.0E+04	1.2E+05	1.2E+06
Upper ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	3.4E+00	2.2E+01	0.0E+00	2.2E+00	1.1E+01
Area of prophylaxis advice m^2	6.8E+04	3.6E+05	0.0E+00	4.7E+04	1.9E+05
Food restriction					
Area of green vegetables restricted m^2	3.2E+08	5.6E+09	8.3E+04	3.0E+06	2.1E+09
Yield of green vegetables lost kg	2.9E+05	1.4E+07	7.5E+01	1.1E+03	1.5E+06
Area of milk restricted m^2	1.1E+08	4.0E+09	0.0E+00	1.1E+05	5.3E+08
Yield of milk lost L	1.5E+05	4.2E+06	0.0E+00	1.8E+02	5.8E+05

5.1.2 Child, Large source term

5.1.2.1 *Child, Large source term, group 1 endpoints*

Table 22: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.8E-05	1.3E-04	3.4E-06	4.1E-05	1.1E-04
3km	9.5E-06	3.0E-05	6.4E-07	8.2E-06	2.2E-05
5km	4.7E-06	1.4E-05	2.4E-07	3.9E-06	1.1E-05
10km	1.7E-06	5.2E-06	7.7E-08	1.3E-06	4.0E-06
30km	2.9E-07	9.5E-07	3.5E-09	2.1E-07	7.0E-07
50km	1.3E-07	4.7E-07	3.1E-09	9.6E-08	3.5E-07

Table 23: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.5E-03	9.8E-03	4.4E-04	4.5E-03	8.4E-03
3km	1.1E-03	2.9E-03	7.8E-05	1.0E-03	2.4E-03
5km	6.0E-04	1.5E-03	3.2E-05	5.3E-04	1.3E-03
10km	2.2E-04	6.3E-04	7.2E-06	1.7E-04	5.1E-04
30km	4.3E-05	1.4E-04	6.4E-07	3.1E-05	1.1E-04
50km	2.1E-05	7.5E-05	4.7E-07	1.5E-05	5.5E-05

Table 24: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	8.4E-05	5.0E-04	7.4E-06	6.3E-05	2.5E-04
3km	2.6E-05	2.0E-04	1.3E-06	1.9E-05	7.6E-05
5km	1.6E-05	1.6E-04	5.3E-07	1.1E-05	4.8E-05
10km	7.9E-06	9.3E-05	1.1E-07	5.1E-06	2.6E-05
30km	2.3E-06	2.2E-05	8.1E-09	1.3E-06	8.2E-06
50km	1.3E-06	1.7E-05	8.0E-09	6.5E-07	4.6E-06

Table 25: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances, all pathways excluding ingestion dose (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.6E-03	1.0E-02	4.5E-04	4.6E-03	8.6E-03
3km	1.2E-03	3.0E-03	8.0E-05	1.0E-03	2.4E-03
5km	6.2E-04	1.6E-03	3.3E-05	5.5E-04	1.3E-03
10km	2.3E-04	6.4E-04	7.4E-06	1.8E-04	5.3E-04
30km	4.5E-05	1.5E-04	6.5E-07	3.4E-05	1.1E-04
50km	2.2E-05	7.6E-05	6.0E-07	1.6E-05	5.6E-05

Table 26: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	8.4E-02	1.8E-01	8.3E-03	8.4E-02	1.6E-01
3km	2.1E-02	5.5E-02	1.5E-03	1.9E-02	4.5E-02
5km	1.1E-02	2.9E-02	6.1E-04	1.0E-02	2.4E-02
10km	4.2E-03	1.2E-02	1.3E-04	3.2E-03	9.6E-03
30km	8.1E-04	2.7E-03	1.2E-05	5.9E-04	2.0E-03
50km	3.9E-04	1.4E-03	8.8E-06	2.8E-04	1.0E-03

Table 27: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
3km	2.3E-04	1.8E-03	1.2E-05	1.7E-04	6.7E-04
5km	1.5E-04	1.4E-03	4.7E-06	1.0E-04	4.3E-04
10km	7.0E-05	8.3E-04	1.1E-06	4.6E-05	2.3E-04
30km	2.1E-05	2.0E-04	8.6E-08	1.2E-05	7.3E-05
50km	1.2E-05	1.6E-04	8.6E-08	6.0E-06	4.6E-05

Table 28: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances, all pathways excluding ingestion dose (Child, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	5.2E-03	1.1E-02	5.1E-04	5.2E-03	9.3E-03
3km	1.4E-03	3.3E-03	9.1E-05	1.3E-03	2.6E-03
5km	7.4E-04	1.7E-03	3.7E-05	7.0E-04	1.5E-03
10km	2.9E-04	8.8E-04	8.3E-06	2.5E-04	6.4E-04
30km	6.2E-05	2.2E-04	7.2E-07	5.3E-05	1.4E-04
50km	3.2E-05	1.7E-04	6.8E-07	2.7E-05	7.4E-05

5.1.2.2 *Child, Large source term, group 2 endpoints*

Table 29: Maximum extent of protective actions (Child, Large source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	4.9E-01	1.1E+00	0.0E+00	4.5E-01	1.0E+00
Evacuation	5.2E-03	2.0E-01	0.0E+00	0.0E+00	4.6E-03
SI prophylaxis	2.0E+00	4.6E+00	2.0E-01	1.9E+00	3.8E+00
Upper ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	7.3E-01	1.6E+00	0.0E+00	7.2E-01	1.5E+00
Food restriction					
Green vegetables	6.4E+01	1.5E+02	4.6E+00	5.3E+01	1.3E+02
Milk	2.9E+01	1.5E+02	0.0E+00	1.3E+01	1.2E+02

5.1.2.3 *Child, Large source term, group 3 endpoints*

Table 30: Maximum residual normal-living effective dose (Sv) over 1st year at 1km, all pathways (Child, Large source term, lower ERL)

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	1.0E-05	2.5E-05	8.0E-07	9.5E-06	2.1E-05
Inhalation	4.3E-03	7.3E-03	4.4E-04	4.5E-03	7.1E-03
External ground	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
Ingestion	4.5E-04	1.0E-03	3.8E-05	5.3E-04	7.7E-04
Total	5.1E-03	1.0E-02	6.6E-04	5.4E-03	8.0E-03

Table 31: Maximum residual normal-living effective dose (Sv) over 1st year at 1km, all pathways (Child, Large source term, upper ERL)

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	1.1E-05	3.2E-05	8.0E-07	9.5E-06	2.5E-05
Inhalation	4.5E-03	9.8E-03	4.4E-04	4.5E-03	8.4E-03
External ground	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
Ingestion	4.5E-04	1.0E-03	3.8E-05	5.3E-04	7.7E-04
Total	5.4E-03	1.1E-02	6.6E-04	5.4E-03	9.4E-03

5.1.2.4 *Child, Large source term, group 4 endpoints*

Table 32: Consequences of predicted protective actions (Child, Large source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	6.0E+00	8.7E+01	0.0E+00	3.8E+00	2.2E+01
Area sheltered m^2	1.0E+05	5.6E+05	0.0E+00	8.0E+04	3.2E+05
People evacuated	1.1E-01	3.5E+00	0.0E+00	0.0E+00	1.7E+00
Area evacuated m^2	2.4E+03	7.6E+04	0.0E+00	0.0E+00	3.7E+04
People advised to take SI prophylaxis	1.4E+02	2.6E+03	2.2E+00	1.1E+01	7.7E+02
Area of prophylaxis advice m^2	6.9E+05	5.7E+06	4.7E+04	2.0E+05	3.5E+06
Upper ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	1.3E+01	3.5E+02	0.0E+00	4.8E+00	4.9E+01
Area of prophylaxis advice m^2	1.5E+05	8.0E+05	0.0E+00	9.2E+04	5.0E+05
Food restriction					
Area of green vegetables restricted m^2	3.2E+08	5.6E+09	8.3E+04	3.0E+06	2.1E+09
Yield of green vegetables lost kg	2.9E+05	1.4E+07	7.5E+01	1.1E+03	1.5E+06
Area of milk restricted m^2	1.1E+08	4.0E+09	0.0E+00	1.1E+05	5.3E+08
Yield of milk lost L	1.5E+05	4.2E+06	0.0E+00	1.8E+02	5.8E+05

5.1.3 Infant, Large source term

5.1.3.1 *Infant, Large source term, group 1 endpoints*

Table 33: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.8E-05	1.3E-04	3.4E-06	4.1E-05	1.1E-04
3km	9.5E-06	3.0E-05	6.4E-07	8.2E-06	2.2E-05
5km	4.7E-06	1.4E-05	2.4E-07	3.9E-06	1.1E-05
10km	1.7E-06	5.2E-06	7.7E-08	1.3E-06	4.0E-06
30km	2.9E-07	9.5E-07	3.5E-09	2.1E-07	7.0E-07
50km	1.3E-07	4.7E-07	3.1E-09	9.6E-08	3.5E-07

Table 34: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	5.9E-03	1.3E-02	5.8E-04	5.9E-03	1.1E-02
3km	1.5E-03	3.9E-03	1.0E-04	1.3E-03	3.1E-03
5km	7.9E-04	2.0E-03	4.2E-05	7.0E-04	1.7E-03
10km	2.9E-04	8.3E-04	9.4E-06	2.2E-04	6.8E-04
30km	5.6E-05	1.9E-04	8.4E-07	4.1E-05	1.4E-04
50km	2.7E-05	9.8E-05	6.2E-07	1.9E-05	7.2E-05

Table 35: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	8.4E-05	5.0E-04	7.4E-06	6.3E-05	2.5E-04
3km	2.6E-05	2.0E-04	1.3E-06	1.9E-05	7.6E-05
5km	1.6E-05	1.6E-04	5.3E-07	1.1E-05	4.8E-05
10km	7.9E-06	9.3E-05	1.1E-07	5.1E-06	2.6E-05
30km	2.3E-06	2.2E-05	8.1E-09	1.3E-06	8.2E-06
50km	1.3E-06	1.7E-05	8.0E-09	6.5E-07	4.6E-06

Table 36: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances, all pathways excluding ingestion dose (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	6.0E-03	1.3E-02	5.9E-04	6.0E-03	1.1E-02
3km	1.5E-03	3.9E-03	1.0E-04	1.4E-03	3.2E-03
5km	8.1E-04	2.1E-03	4.3E-05	7.2E-04	1.7E-03
10km	3.0E-04	8.4E-04	9.6E-06	2.3E-04	7.0E-04
30km	5.9E-05	1.9E-04	8.5E-07	4.5E-05	1.4E-04
50km	2.9E-05	1.0E-04	7.9E-07	2.1E-05	7.3E-05

Table 37: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	1.1E-01	2.5E-01	1.1E-02	1.1E-01	2.1E-01
3km	2.8E-02	7.4E-02	2.0E-03	2.5E-02	6.0E-02
5km	1.5E-02	3.9E-02	8.1E-04	1.3E-02	3.3E-02
10km	5.6E-03	1.6E-02	1.8E-04	4.3E-03	1.3E-02
30km	1.1E-03	3.6E-03	1.6E-05	7.9E-04	2.7E-03
50km	5.2E-04	1.9E-03	1.2E-05	3.7E-04	1.4E-03

Table 38: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
3km	2.3E-04	1.8E-03	1.2E-05	1.7E-04	6.7E-04
5km	1.5E-04	1.4E-03	4.7E-06	1.0E-04	4.3E-04
10km	7.0E-05	8.3E-04	1.1E-06	4.6E-05	2.3E-04
30km	2.1E-05	2.0E-04	8.6E-08	1.2E-05	7.3E-05
50km	1.2E-05	1.6E-04	8.6E-08	6.0E-06	4.6E-05

Table 39: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances (Infant, Large source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	6.6E-03	1.4E-02	6.5E-04	6.6E-03	1.2E-02
3km	1.7E-03	4.2E-03	1.2E-04	1.6E-03	3.4E-03
5km	9.3E-04	2.2E-03	4.7E-05	8.8E-04	1.9E-03
10km	3.6E-04	9.2E-04	1.1E-05	3.1E-04	7.9E-04
30km	7.6E-05	2.3E-04	9.2E-07	6.7E-05	1.8E-04
50km	3.8E-05	1.7E-04	8.6E-07	3.2E-05	9.2E-05

5.1.3.2 *Infant, Large source term, group 2 endpoints*

Table 40: Maximum extent of protective actions (Infant, Large source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	6.8E-01	1.5E+00	0.0E+00	7.2E-01	1.4E+00
Evacuation	2.3E-02	2.9E-01	0.0E+00	0.0E+00	2.0E-01
SI prophylaxis	2.6E+00	5.5E+00	4.4E-01	2.3E+00	5.0E+00
Upper ERL					
Sheltering	2.3E-05	4.6E-03	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	9.6E-01	2.0E+00	0.0E+00	1.0E+00	1.7E+00
Food restriction					
Green vegetables	6.4E+01	1.5E+02	4.6E+00	5.3E+01	1.3E+02
Milk	2.9E+01	1.5E+02	0.0E+00	1.3E+01	1.2E+02

5.1.3.3 *Infant, Large source term, group 3 endpoints*

Table 41: Maximum residual normal-living effective dose (Sv) over 1st year at 1km, all pathways (Infant, Large source term, lower ERL)

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	9.2E-06	2.0E-05	8.0E-07	9.5E-06	1.8E-05
Inhalation	5.0E-03	7.8E-03	5.8E-04	5.9E-03	7.3E-03
External ground	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
Ingestion	6.2E-04	1.4E-03	4.9E-05	7.2E-04	1.0E-03
Total	5.9E-03	1.0E-02	8.6E-04	6.7E-03	8.2E-03

Table 42: Maximum residual normal-living effective dose (Sv) over 1st year at 1km, all pathways (Infant, Large source term, upper ERL)

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	1.1E-05	3.2E-05	8.0E-07	9.5E-06	2.5E-05
Inhalation	5.9E-03	1.3E-02	5.8E-04	5.9E-03	1.1E-02
External ground	7.4E-04	4.4E-03	6.6E-05	5.6E-04	2.2E-03
Ingestion	6.2E-04	1.4E-03	4.9E-05	7.2E-04	1.0E-03
Total	6.9E-03	1.4E-02	8.6E-04	6.8E-03	1.2E-02

5.1.3.4 *Infant, Large source term, group 4 endpoints*

Table 43: Consequences of predicted protective actions (Infant, Large source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	1.1E+01	2.4E+02	0.0E+00	4.1E+00	4.3E+01
Area sheltered m^2	1.4E+05	6.8E+05	0.0E+00	8.6E+04	4.6E+05
People evacuated	3.8E-01	5.3E+00	0.0E+00	0.0E+00	3.5E+00
Area evacuated m^2	8.0E+03	1.2E+05	0.0E+00	0.0E+00	7.6E+04
People advised to take SI prophylaxis	1.9E+02	2.9E+03	2.2E+00	1.3E+01	1.0E+03
Area of prophylaxis advice m2	1.0E+06	9.9E+06	4.7E+04	2.1E+05	5.7E+06
Upper ERL					
People sheltered	9.2E-03	1.8E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	2.0E+02	4.0E+04	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	2.6E+01	7.3E+02	0.0E+00	5.2E+00	8.4E+01
Area of prophylaxis advice m^2	2.2E+05	1.4E+06	0.0E+00	9.9E+04	7.4E+05
Food restriction					
Area of green vegetables restricted m^2	3.2E+08	5.6E+09	8.3E+04	3.0E+06	2.1E+09
Yield of green vegetables lost kg	2.9E+05	1.4E+07	7.5E+01	1.1E+03	1.5E+06
Area of milk restricted m^2	1.1E+08	4.0E+09	0.0E+00	1.1E+05	5.3E+08
Yield of milk lost L	1.5E+05	4.2E+06	0.0E+00	1.8E+02	5.8E+05

5.1.4 Adult, Small source term

5.1.4.1 *Adult, Small source term, group 1 endpoints*

Table 44: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.4E-07	6.7E-07	1.7E-08	2.0E-07	5.4E-07
3km	4.8E-08	1.5E-07	3.2E-09	4.1E-08	1.1E-07
5km	2.3E-08	6.9E-08	1.2E-09	1.9E-08	5.3E-08
10km	8.5E-09	2.6E-08	3.9E-10	6.7E-09	2.0E-08
30km	1.4E-09	4.8E-09	1.8E-11	1.0E-09	3.5E-09
50km	6.7E-10	2.4E-09	1.6E-11	4.8E-10	1.8E-09

Table 45: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	1.3E-05	2.8E-05	1.3E-06	1.3E-05	2.4E-05
3km	3.2E-06	8.4E-06	2.2E-07	2.9E-06	6.8E-06
5km	1.7E-06	4.4E-06	9.2E-08	1.5E-06	3.7E-06
10km	6.4E-07	1.8E-06	2.0E-08	4.8E-07	1.5E-06
30km	1.2E-07	4.1E-07	1.8E-09	8.9E-08	3.0E-07
50km	5.9E-08	2.1E-07	1.3E-09	4.2E-08	1.6E-07

Table 46: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.2E-07	2.5E-06	3.7E-08	3.1E-07	1.2E-06
3km	1.3E-07	9.9E-07	6.7E-09	9.6E-08	3.8E-07
5km	8.1E-08	7.9E-07	2.6E-09	5.7E-08	2.4E-07
10km	3.9E-08	4.6E-07	5.7E-10	2.6E-08	1.3E-07
30km	1.1E-08	1.1E-07	4.1E-11	6.4E-09	4.1E-08
50km	6.6E-09	8.7E-08	4.0E-11	3.2E-09	2.3E-08

Table 47: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances, not including ingestion dose (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	1.3E-05	2.9E-05	1.3E-06	1.3E-05	2.5E-05
3km	3.4E-06	8.7E-06	2.3E-07	3.0E-06	7.0E-06
5km	1.8E-06	4.5E-06	9.6E-08	1.6E-06	3.8E-06
10km	6.8E-07	1.9E-06	2.1E-08	5.5E-07	1.6E-06
30km	1.3E-07	4.2E-07	1.9E-09	1.0E-07	3.2E-07
50km	6.6E-08	2.2E-07	1.7E-09	4.9E-08	1.6E-07

Table 48: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.3E-04	5.1E-04	2.3E-05	2.3E-04	4.3E-04
3km	5.8E-05	1.5E-04	4.1E-06	5.2E-05	1.2E-04
5km	3.1E-05	8.0E-05	1.7E-06	2.7E-05	6.7E-05
10km	1.2E-05	3.3E-05	3.7E-07	8.8E-06	2.7E-05
30km	2.2E-06	7.4E-06	3.3E-08	1.6E-06	5.5E-06
50km	1.1E-06	3.9E-06	2.4E-08	7.7E-07	2.8E-06

Table 49: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.7E-06	2.2E-05	3.3E-07	2.8E-06	1.1E-05
3km	1.1E-06	8.9E-06	6.1E-08	8.6E-07	3.4E-06
5km	7.3E-07	7.1E-06	2.4E-08	5.1E-07	2.2E-06
10km	3.5E-07	4.2E-06	5.3E-09	2.3E-07	1.1E-06
30km	1.1E-07	1.0E-06	4.3E-10	6.1E-08	3.7E-07
50km	6.2E-08	7.9E-07	4.3E-10	3.0E-08	2.3E-07

Table 50: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances, all pathways excluding ingestion (Adult, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	1.7E-05	3.8E-05	1.6E-06	1.7E-05	2.8E-05
3km	4.3E-06	1.0E-05	2.8E-07	4.1E-06	8.4E-06
5km	2.4E-06	7.5E-06	1.2E-07	2.3E-06	4.8E-06
10km	9.8E-07	4.3E-06	2.6E-08	8.4E-07	2.1E-06
30km	2.2E-07	1.0E-06	2.2E-09	1.8E-07	4.8E-07
50km	1.2E-07	8.1E-07	2.1E-09	9.1E-08	2.6E-07

5.1.4.2 *Adult, Small source term, group 2 endpoints*

Table 51: Maximum extent of protective actions (Adult, Large source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Green vegetables	5.8E-01	7.3E+00	0.0E+00	4.0E-01	1.8E+00
Milk	1.9E-01	3.8E+00	0.0E+00	0.0E+00	1.2E+00

5.1.4.3 *Adult, Small source term, group 3 endpoints*

Table 52: Maximum residual normal-living effective dose (Sv) over 1st year at 1km, all pathways (Adult, Small source term, lower and upper ERL[a])

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	5.6E-08	1.6E-07	4.0E-09	4.8E-08	1.3E-07
Inhalation	1.3E-05	2.8E-05	1.3E-06	1.3E-05	2.4E-05
External ground	3.7E-06	2.2E-05	3.3E-07	2.8E-06	1.1E-05
Ingestion	1.7E-05	6.3E-05	1.5E-06	1.1E-05	5.2E-05
Total	3.3E-05	1.0E-04	4.4E-06	2.7E-05	7.1E-05

a In this case both the upper and lower ERL calculation give the same maximum residual doses at 1km

5.1.4.4 *Adult, Small source term, group 4 endpoints*

Table 53: Consequences of predicted protective actions (Adult, Small source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Area of green vegetables restricted m^2	1.1E+05	1.2E+06	0.0E+00	7.9E+04	4.2E+05
Yield of green vegetables lost kg	6.5E+00	6.9E+01	0.0E+00	2.2E+00	2.6E+01
Area of milk restricted m^2	3.5E+04	6.4E+05	0.0E+00	0.0E+00	1.5E+05
Yield of milk lost L	3.5E+00	5.4E+01	0.0E+00	0.0E+00	1.9E+01

5.1.5 Child, Small source term

5.1.5.1 *Child, Small source term, group 1 endpoints*

Table 54: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.4E-07	6.7E-07	1.7E-08	2.0E-07	5.4E-07
3km	4.8E-08	1.5E-07	3.2E-09	4.1E-08	1.1E-07
5km	2.3E-08	6.9E-08	1.2E-09	1.9E-08	5.3E-08
10km	8.5E-09	2.6E-08	3.9E-10	6.7E-09	2.0E-08
30km	1.4E-09	4.8E-09	1.8E-11	1.0E-09	3.5E-09
50km	6.7E-10	2.4E-09	1.6E-11	4.8E-10	1.8E-09

Table 55: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.2E-05	4.9E-05	2.2E-06	2.2E-05	4.2E-05
3km	5.6E-06	1.5E-05	3.9E-07	5.1E-06	1.2E-05
5km	3.0E-06	7.7E-06	1.6E-07	2.7E-06	6.4E-06
10km	1.1E-06	3.1E-06	3.6E-08	8.5E-07	2.6E-06
30km	2.1E-07	7.1E-07	3.2E-09	1.6E-07	5.3E-07
50km	1.0E-07	3.7E-07	2.4E-09	7.4E-08	2.7E-07

Table 56: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.2E-07	2.5E-06	3.7E-08	3.1E-07	1.2E-06
3km	1.3E-07	9.9E-07	6.7E-09	9.6E-08	3.8E-07
5km	8.1E-08	7.9E-07	2.6E-09	5.7E-08	2.4E-07
10km	3.9E-08	4.6E-07	5.7E-10	2.6E-08	1.3E-07
30km	1.1E-08	1.1E-07	4.1E-11	6.4E-09	4.1E-08
50km	6.6E-09	8.7E-08	4.0E-11	3.2E-09	2.3E-08

Table 57: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances, all pathways excluding ingestion dose (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.3E-05	5.0E-05	2.3E-06	2.3E-05	4.3E-05
3km	5.8E-06	1.5E-05	4.0E-07	5.2E-06	1.2E-05
5km	3.1E-06	7.9E-06	1.6E-07	2.7E-06	6.6E-06
10km	1.2E-06	3.2E-06	3.7E-08	8.9E-07	2.7E-06
30km	2.3E-07	7.3E-07	3.3E-09	1.7E-07	5.5E-07
50km	1.1E-07	3.8E-07	3.0E-09	8.1E-08	2.8E-07

Table 58: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.2E-04	9.2E-04	4.1E-05	4.2E-04	7.9E-04
3km	1.1E-04	2.8E-04	7.3E-06	9.5E-05	2.2E-04
5km	5.6E-05	1.4E-04	3.0E-06	5.0E-05	1.2E-04
10km	2.1E-05	5.9E-05	6.7E-07	1.6E-05	4.8E-05
30km	4.0E-06	1.3E-05	6.0E-08	2.9E-06	9.9E-06
50km	2.0E-06	7.0E-06	4.4E-08	1.4E-06	5.1E-06

Table 59: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.7E-06	2.2E-05	3.3E-07	2.8E-06	1.1E-05
3km	1.1E-06	8.9E-06	6.1E-08	8.6E-07	3.4E-06
5km	7.3E-07	7.1E-06	2.4E-08	5.1E-07	2.2E-06
10km	3.5E-07	4.2E-06	5.3E-09	2.3E-07	1.1E-06
30km	1.1E-07	1.0E-06	4.3E-10	6.1E-08	3.7E-07
50km	6.2E-08	7.9E-07	4.3E-10	3.0E-08	2.3E-07

Table 60: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances, all pathways excluding ingestion (Child, small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.6E-05	5.4E-05	2.5E-06	2.6E-05	4.7E-05
3km	6.8E-06	1.6E-05	4.5E-07	6.4E-06	1.3E-05
5km	3.7E-06	8.4E-06	1.9E-07	3.5E-06	7.6E-06
10km	1.5E-06	4.4E-06	4.1E-08	1.2E-06	3.2E-06
30km	3.1E-07	1.1E-06	3.6E-09	2.7E-07	7.1E-07
50km	1.6E-07	8.3E-07	3.4E-09	1.3E-07	3.7E-07

5.1.5.2 *Child, Small source term, group 2 endpoints*

Table 61: Maximum extent of protective actions (Child, small source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Green vegetables	5.8E-01	7.3E+00	0.0E+00	4.0E-01	1.8E+00
Milk	1.9E-01	3.8E+00	0.0E+00	0.0E+00	1.2E+00

5.1.5.3 *Child, Small source term, group 3 endpoints*

Table 62: Maximum residual normal-living effective dose (Sv) over 1st year at 1km (Child, small source term, lower and upper ERL[a])

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	5.6E-08	1.6E-07	4.0E-09	4.8E-08	1.3E-07
Inhalation	2.2E-05	4.9E-05	2.2E-06	2.2E-05	4.2E-05
External ground	3.7E-06	2.2E-05	3.3E-07	2.8E-06	1.1E-05
Ingestion	2.2E-05	8.2E-05	1.1E-06	1.2E-05	7.6E-05
Total	4.7E-05	1.2E-04	6.4E-06	3.7E-05	1.0E-04

a In this case both the upper and lower ERL calculation give the same maximum residual doses at 1km

5.1.5.4 *Child, Small source term, group 4 endpoints*

Table 63: Consequences of predicted protective actions (Child, small source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Area of green vegetables restricted m^2	1.1E+05	1.2E+06	0.0E+00	7.9E+04	4.2E+05
Yield of green vegetables lost kg	6.5E+00	6.9E+01	0.0E+00	2.2E+00	2.6E+01
Area of milk restricted m^2	3.5E+04	6.4E+05	0.0E+00	0.0E+00	1.5E+05
Yield of milk lost L	3.5E+00	5.4E+01	0.0E+00	0.0E+00	1.9E+01

5.1.6 Infant, Small source term

5.1.6.1 *Infant, Small source term, group 1 endpoints*

Table 64: Maximum projected outdoor effective dose (Sv) from external cloud to two days at a range of distances (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	2.4E-07	6.7E-07	1.7E-08	2.0E-07	5.4E-07
3km	4.8E-08	1.5E-07	3.2E-09	4.1E-08	1.1E-07
5km	2.3E-08	6.9E-08	1.2E-09	1.9E-08	5.3E-08
10km	8.5E-09	2.6E-08	3.9E-10	6.7E-09	2.0E-08
30km	1.4E-09	4.8E-09	1.8E-11	1.0E-09	3.5E-09
50km	6.7E-10	2.4E-09	1.6E-11	4.8E-10	1.8E-09

Table 65: Maximum projected outdoor effective dose (Sv) from inhalation to two days at a range of distances (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.0E-05	6.5E-05	2.9E-06	2.9E-05	5.5E-05
3km	7.4E-06	1.9E-05	5.1E-07	6.6E-06	1.6E-05
5km	3.9E-06	1.0E-05	2.1E-07	3.5E-06	8.5E-06
10km	1.5E-06	4.1E-06	4.7E-08	1.1E-06	3.4E-06
30km	2.8E-07	9.4E-07	4.2E-09	2.0E-07	7.0E-07
50km	1.4E-07	4.9E-07	3.1E-09	9.7E-08	3.6E-07

Table 66: Maximum projected outdoor effective dose (Sv) from external ground to two days at a range of distances (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	4.2E-07	2.5E-06	3.7E-08	3.1E-07	1.2E-06
3km	1.3E-07	9.9E-07	6.7E-09	9.6E-08	3.8E-07
5km	8.1E-08	7.9E-07	2.6E-09	5.7E-08	2.4E-07
10km	3.9E-08	4.6E-07	5.7E-10	2.6E-08	1.3E-07
30km	1.1E-08	1.1E-07	4.1E-11	6.4E-09	4.1E-08
50km	6.6E-09	8.7E-08	4.0E-11	3.2E-09	2.3E-08

Table 67: Maximum projected outdoor total effective dose (Sv) to two days at a range of distances, all pathways excluding ingestion dose (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.0E-05	6.6E-05	2.9E-06	3.0E-05	5.6E-05
3km	7.6E-06	2.0E-05	5.2E-07	6.8E-06	1.6E-05
5km	4.0E-06	1.0E-05	2.2E-07	3.6E-06	8.6E-06
10km	1.5E-06	4.2E-06	4.8E-08	1.2E-06	3.5E-06
30km	2.9E-07	9.5E-07	4.3E-09	2.2E-07	7.1E-07
50km	1.4E-07	5.0E-07	3.9E-09	1.0E-07	3.7E-07

Table 68: Maximum projected outdoor thyroid dose (Sv) from inhalation to two days at a range of distances (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	5.7E-04	1.2E-03	5.6E-05	5.7E-04	1.1E-03
3km	1.4E-04	3.7E-04	9.9E-06	1.3E-04	3.0E-04
5km	7.6E-05	1.9E-04	4.1E-06	6.7E-05	1.6E-04
10km	2.8E-05	7.9E-05	9.1E-07	2.1E-05	6.5E-05
30km	5.4E-06	1.8E-05	8.1E-08	3.9E-06	1.3E-05
50km	2.6E-06	9.4E-06	5.9E-08	1.9E-06	6.9E-06

Table 69: Maximum projected normal-living effective dose (Sv) from external ground to one year at a range of distances (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.7E-06	2.2E-05	3.3E-07	2.8E-06	1.1E-05
3km	1.1E-06	8.9E-06	6.1E-08	8.6E-07	3.4E-06
5km	7.3E-07	7.1E-06	2.4E-08	5.1E-07	2.2E-06
10km	3.5E-07	4.2E-06	5.3E-09	2.3E-07	1.1E-06
30km	1.1E-07	1.0E-06	4.3E-10	6.1E-08	3.7E-07
50km	6.2E-08	7.9E-07	4.3E-10	3.0E-08	2.3E-07

Table 70: Maximum projected total normal-living effective dose (Sv) to one year at a range of distances, all pathways (Infant, Small source term)

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
1km	3.3E-05	6.9E-05	3.2E-06	3.3E-05	6.0E-05
3km	8.5E-06	2.1E-05	5.8E-07	8.1E-06	1.7E-05
5km	4.7E-06	1.1E-05	2.4E-07	4.4E-06	9.4E-06
10km	1.8E-06	4.6E-06	5.3E-08	1.5E-06	3.9E-06
30km	3.8E-07	1.1E-06	4.6E-09	3.3E-07	8.9E-07
50km	1.9E-07	8.4E-07	4.3E-09	1.6E-07	4.6E-07

5.1.6.2 *Infant, Small source term, group 2 endpoints*

Table 71: Maximum extent of protective actions (Infant, Small source term) km

Distance	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
Sheltering	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Evacuation	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Green vegetables	5.8E-01	7.3E+00	0.0E+00	4.0E-01	1.8E+00
Milk	1.9E-01	3.8E+00	0.0E+00	0.0E+00	1.2E+00

5.1.6.3 *Infant, Small source term, group 3 endpoints*

Table 72: Maximum residual normal-living effective dose (Sv) over 1st year at 1km (Infant, Small source term, lower and upper ERL[a])

Pathway	Mean	Maximum	Minimum	50th Percentile	95th Percentile
External cloud	5.6E-08	1.6E-07	4.0E-09	4.8E-08	1.3E-07
Inhalation	3.0E-05	6.5E-05	2.9E-06	2.9E-05	5.5E-05
External ground	3.3E-06	2.0E-05	3.0E-07	2.5E-06	9.8E-06
Ingestion	6.4E-05	2.5E-04	1.3E-06	3.5E-05	2.3E-04
Total	9.6E-05	3.0E-04	8.0E-06	5.9E-05	2.6E-04

a In this case both the upper and lower ERL calculation give the same maximum residual doses at 1km

5.1.6.4 *Infant, Small source term, group 4 endpoints*

Table 73: Consequences of predicted protective actions (Infant, Small source term)

	Mean	Maximum	Minimum	50th Percentile	95th Percentile
Lower ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Upper ERL					
People sheltered	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area sheltered m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People evacuated	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area evacuated m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
People advised to take SI prophylaxis	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Area of prophylaxis advice m^2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Food restriction					
Area of green vegetables restricted m^2	1.1E+05	1.2E+06	0.0E+00	7.9E+04	4.2E+05
Yield of green vegetables lost kg	6.5E+00	6.9E+01	0.0E+00	2.2E+00	2.6E+01
Area of milk restricted m^2	3.5E+04	6.4E+05	0.0E+00	0.0E+00	1.5E+05
Yield of milk lost L	3.5E+00	5.4E+01	0.0E+00	0.0E+00	1.9E+01

6 Analysis

The final section of a REPPIR consequence assessment will generally be an analysis of the results, to summarise the findings and to direct the reader to salient features. As the CAM makes clear, the assessments inform rather than prescribe emergency planning decisions. It is at this point that associated likelihood of the occurrence of different source terms is brought into the discussion.

An important main feature is that for the Small source term there is no predicted requirement for protective emergency actions. The largest dose identified was about 0.05mSv (Maximum Child 2-day total outdoor dose at 1km, Table 57). However, there may well be requirements for local food restrictions for both milk and green vegetables, in both cases the maximum predicted distance was 7.3km and the mean less than 1km (Table 51).

It is also noteworthy that evacuation is only required in very few of the met sequences for even the Large source term with the distances being so short as to be very uncertain given the grid size of 200m used. Sheltering too is less than 1km in almost all cases. It is for the planners to decide whether the Large source term is sufficiently likely as to be considered for detailed emergency planning but if so then the definition of the detailed planning zone is likely be driven by the need to ensure the effective distribution of stable iodine to the local population. For the child group with the Large source term the 95th Percentile SI distance at the lower ERL reaches almost 4km (Table 29) and includes a resident population of approximately 800 people (Table 32).

Only the Child and Infant age-groups, with the large source term, show different residual doses at 1km depending on whether upper or lower ERLs are considered (compare Table 30 with Table 31, or Table 41 with Table 42).

6.1 Geographical distribution of protective actions

The CAM does not require generation of maps, although the aim of a REPPIR assessment is to assist in the delineation of planning zones. Therefore, maps of the distribution of dose, or the extent of protective actions, can clearly assist in this process especially when combined with other information such as road networks, settlements, or infrastructure. It is not possible or desirable to plot every endpoint for every met sequence, but the production of a few illustrative examples will add valuable context.

PACE also provides the possibility of generating aggregated plots. One example is to use the PACE Percentile Map tool to generate the percentile values for a given endpoint in each grid square, for example the 95th percentile dose in each grid square, the dose which is predicted to be exceeded by only 5% of the met sequences and to fall short by 95% of the met sequences, shown in Figure 3.

The percentile map tool can also estimate the conditional probability of an endpoint exceeding a given value, for example the probability of requiring stable iodine prophylaxis in each grid square is shown in Figure 4. Such plots are attractive but should be included with care as they can be misinterpreted, and experience has shown that they need to be supported with plots from individual met sequences to provide context. For example, met sequence 78 was

identified as having a maximum distance of SI prophylaxis that just exceeded the 95th percentile value and is shown in Figure 5 and included to give context to Figure 4

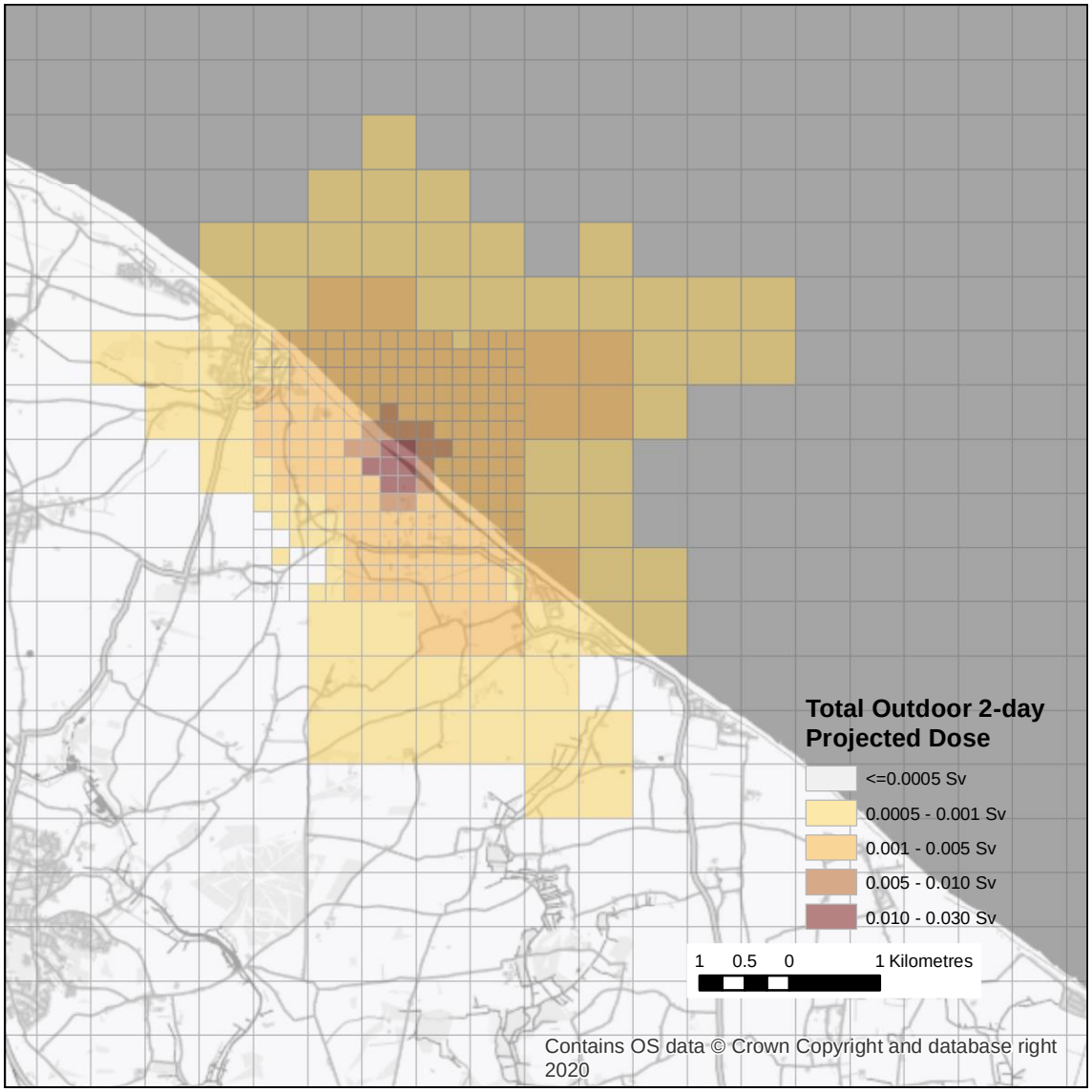

Figure 3 Example of a plot showing the 95th percentile total outdoor 2-day 10-year-old projected effective dose in each grid square. i.e., only 5% of the met sequences predicted a dose higher than the dose shown.

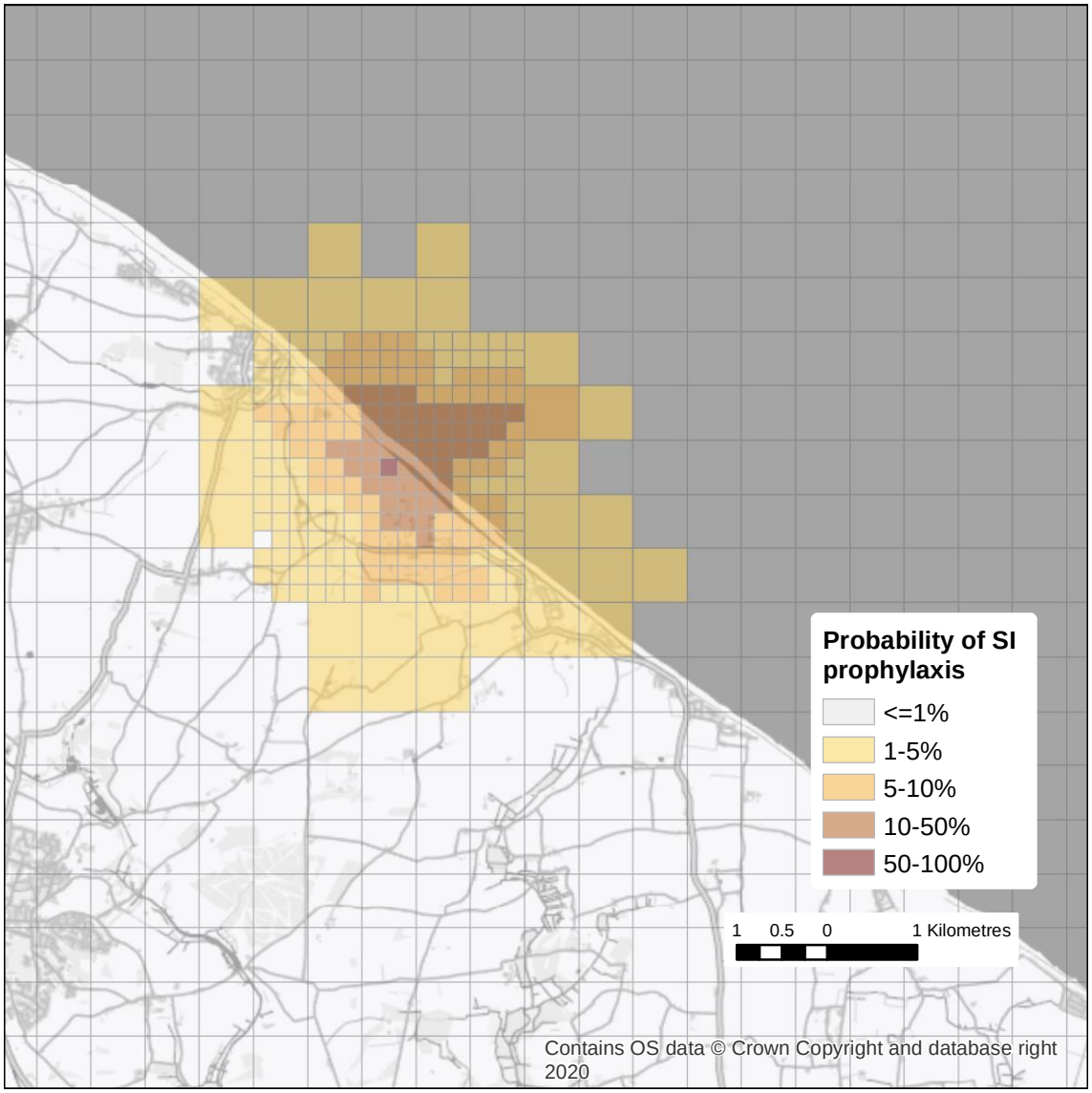

Figure 4 Estimated probability of dose exceeding the criteria for SI prophylaxis in each grid square, based on 10-year doses. NB should be viewed as the likelihood of requiring SI in each grid square separately, and not the probability of requiring SI in the whole of a coloured region. For context Figure 5 shows the zone of SI prophylaxis for a single met sequence with roughly the 95th percentile maximum distance

Figure 5 The zone where SI prophylaxis is predicted to be required in the 78th met sequence, which is the first sequence to exceed the 95th percentile maximum distance for SI prophylaxis.

6.2 Results for foetus

A short analysis was performed to evaluate the importance of foetus doses for emergency planning. A met sequence which gave a total outdoor 2-day adult projected dose at 1km at approximately the 95th percentile was selected. For the large source term, adult doses were extracted from the grid square giving the maximum outdoor 2-day total dose at 1km and were scaled in a conservative manner to estimate 2-day projected doses to the foetus (see appendix C for more detail). The foetus doses along with the corresponding adult doses are given in results are given in Table 74.

Table 74: Estimates of representative foetus doses calculated for the met-sequence and grid-square that give approximately the 95th percentile of the projected adult outdoor 2-day dose.

	2-day outdoor projected doses	
	Foetus	Adult
External cloud	1.03E-04	1.03E-04
Inhalation	1.22E-02	4.81E-03
External ground	9.29E-05	9.29E-05
Total	1.24E-02	5.01E-03

The estimated foetus doses, whilst larger by around a factor of 2 than the corresponding adult dose and child dose due to the presence of ^{131}I, are very similar to the corresponding maximum infant dose, see Table 36, and so for this example scenario no further exploration is warranted.

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Appendix A Example pilot study

A1 Grid dimensions

Defining a grid is a balance between achieving adequate extent and resolution to produce the endpoints required and minimising the number of grid squares so that the run-times and the amount of hard disk space required for the output are manageable. As a rule-of-thumb, there should be no more than a few thousand grid squares in total.

The CAM explicitly requires dose endpoints at a 50km band for large releases, so a minimum starting size for the grid is over 50km from the release point to the edge. However, food restrictions zones are known to extend large distances, so a larger grid may be required. Ideally one would have a single calculation grid for all endpoints, but it can be difficult to achieve this because food restriction zones can be much larger than emergency protective action zones, and it may be necessary to perform a separate set of runs with a larger coarser grid.

Distance banded endpoints are a feature of the CAM requirements. These are calculated from PACE results by extracting values from grid squares that intersect with a given distance (see Appendix A3). It is a sensible approach to ensure that distance bands fit within a single nest of the grid, otherwise grid squares will be different sizes at different points on the circumference.

For many endpoints such as mean-maximum dose by distance, the CAM requires that all directions from the site are included, even if that includes directions that are out to sea. It is therefore preferable if the grid is symmetrical about the release point. As a technical point, it is also preferable that the release point is central within the central most grid square and this leads to an odd number of rows and columns in the nests.

As a first step, a PACE consequence calculation run was undertaken using the large source term and the gaussian dispersion model with constant meteorological conditions. A trial grid was specified for this as given in Figure A1.

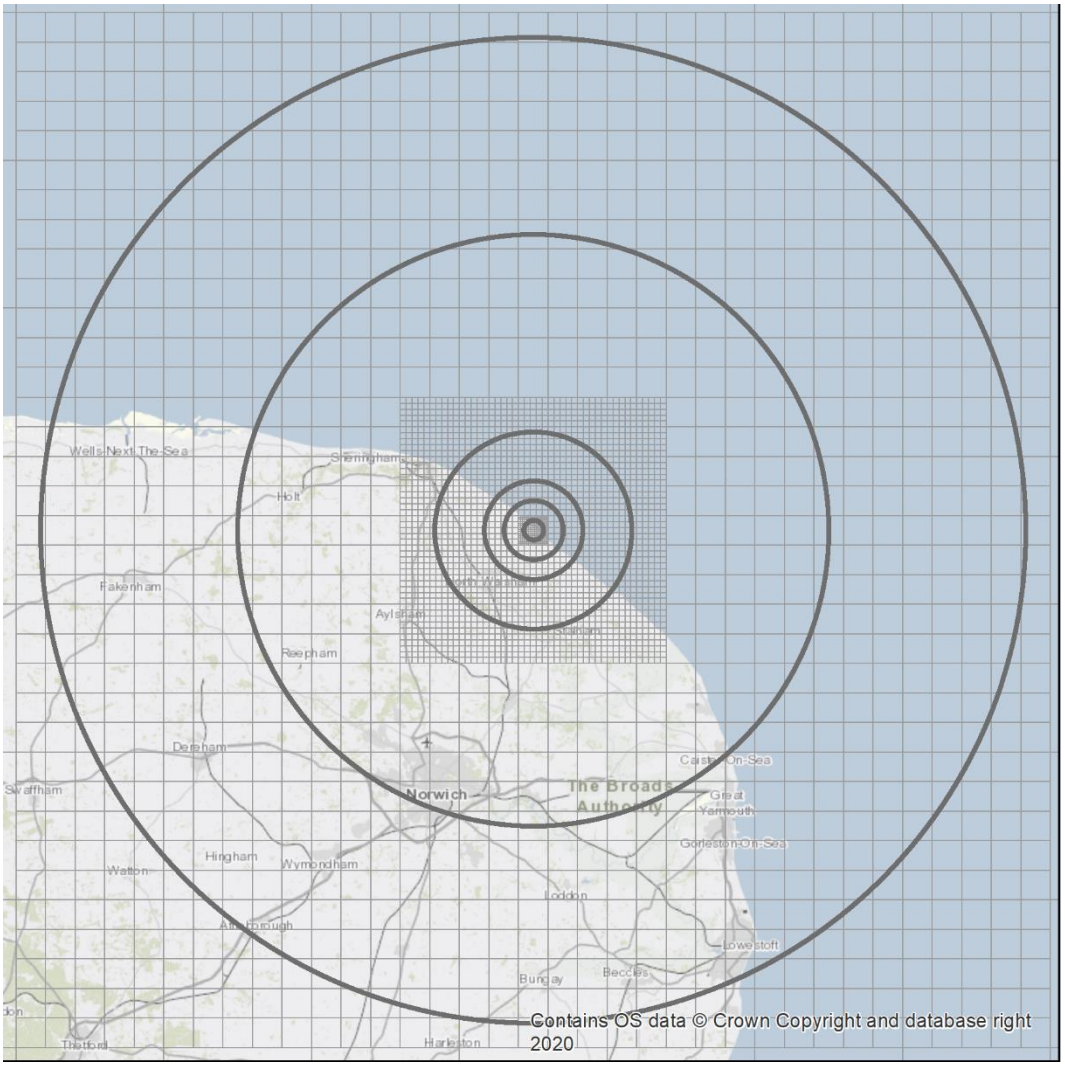

Figure A1: Calculation grid used for analysis, centred on the release with grid squares of 200m out to 1.5km, 600m to 14km, 3000m to 52km and 15000m to 112km, with 4697 individual grid squares. The standard CAM distance bands of 1, 3, 5, 10, 30 and 50km have been drawn to ensure that each one fits within a single nest.

For the pilot run, the criteria for Evacuation, Sheltering and SI prophylaxis were based on the lower ERL to maximise the extent and the food restrictions based on the maximum permitted levels. The meteorology was assumed to be a constant category D, 5ms^{-1} windspeed, 800m mixing layer depth, with no rain and with wind blowing from 55 degrees. The release date was set at 1st July to maximise the likely extent of food restrictions. Figure A2 show the predicted extent of protective actions.

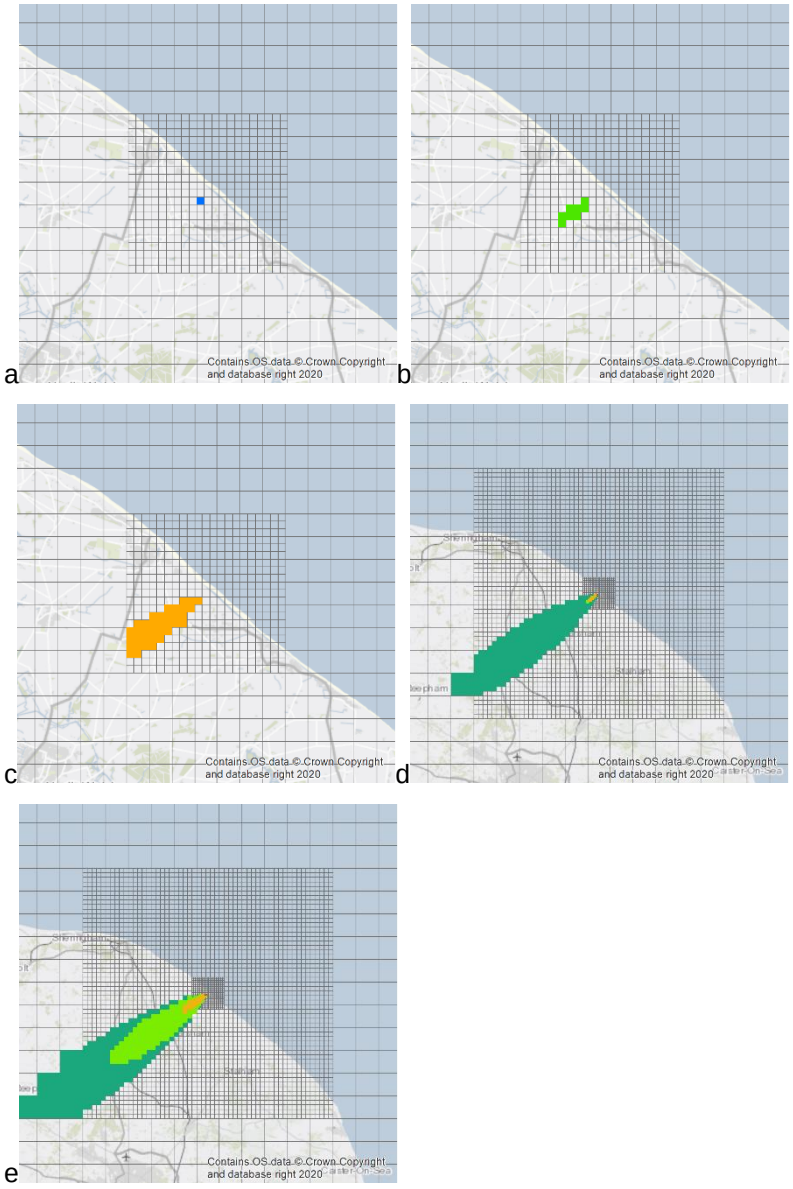

Figure A2: Predicted extent of protective actions: a) evacuation, b) sheltering c) SI prophylaxis, d) milk restriction and e) green vegetable restriction.

Under these conditions the green vegetable restriction extends the furthest, about 30km, which is well within the 112km minimum distance to the edge of the grid and does not reach the largest grid squares. Therefore it seems safe to assume that the grid is large enough to accommodate all but the most extreme conditions and it may be possible to reduce its size if necessary. However, it is worth considering the extent required under different conditions. As a further analysis, a NAME run was performed with the Large source term, for ten met sequences extracted evenly across 2004. The consequences of these for the extent of green vegetable restriction were analysed and Figure A3 shows the results.

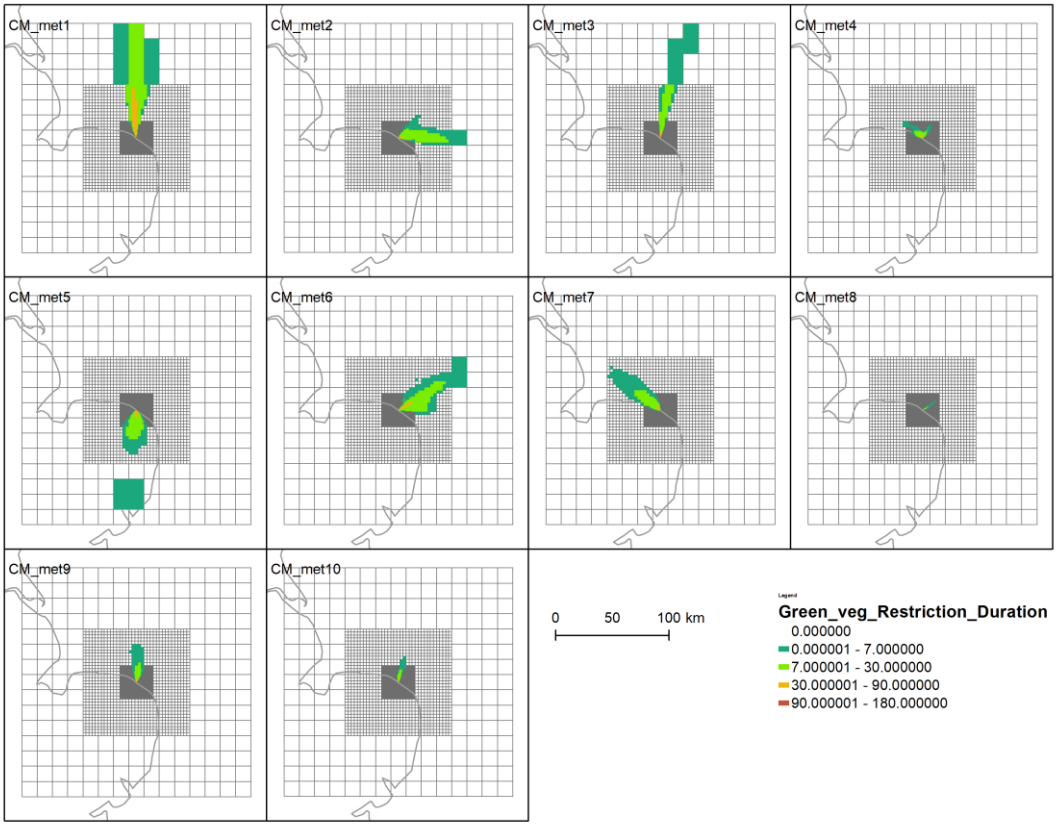

Figure A3: Predicted extent green vegetable restriction for 10 met sequences at different times of the year 2004.

Two of the sequences, 1 and 3, do reach the edge of the grid. Therefore, it might be advisable to increase the size of the grid. However, this will impact on run times and for most endpoints is not necessary. The choice depends on whether it is judged that the impact on green vegetables is an important endpoint. In this example, the grid was not enlarged though the impact of the restricted spatial domain was noted in the results for green vegetables.

A2 Temporal domain

A second decision is the length of the temporal domain. In the NAME model, computational particles are generated and move around within the spatial domain until either all the radioactivity on the particle has been deposited or decayed away, or the particle leaves the spatial domain, or the temporal domain ends. Any activity on the particle when it leaves the spatial domain or, when the temporal domain ends, is lost and does not contribute to dose. Therefore, it is important that the temporal domain is sufficiently long that most of the particles have a chance to either deposit most of their radioactivity or leave the spatial domain. However, having a long temporal domain will increase the run times and the sizes of the output.

As an aside, it is for this reason that long duration releases are challenging because a large temporal domain is needed and consequently run times can be very long, particularly for large releases when the spatial domain also needs to be large. In this case, the use of a timestep larger than the usual 1 hour (e.g. 2, 3 or 6 hours) might be needed but the effects should be

investigated before commencing. An alternative is to compress the duration but again this should be investigated with pilot runs before commencing.

Further pilot runs can be used to understand the effects of different temporal domains. As an example, a NAME run was performed for ten met sequences, extracted evenly across the year 2004. Figure A4 give plots of the time integrated air concentration of ^{137}Cs in the twelfth hour. In most of the met sequences the plume has completely left the grid, but in three, most notably number 5 and 7, there is still radioactivity in the plume. By the 24th hour only met sequence 5 has any radioactivity remaining, Figure A5. Therefore, in this example, 24 hours was selected as a suitable temporal domain.

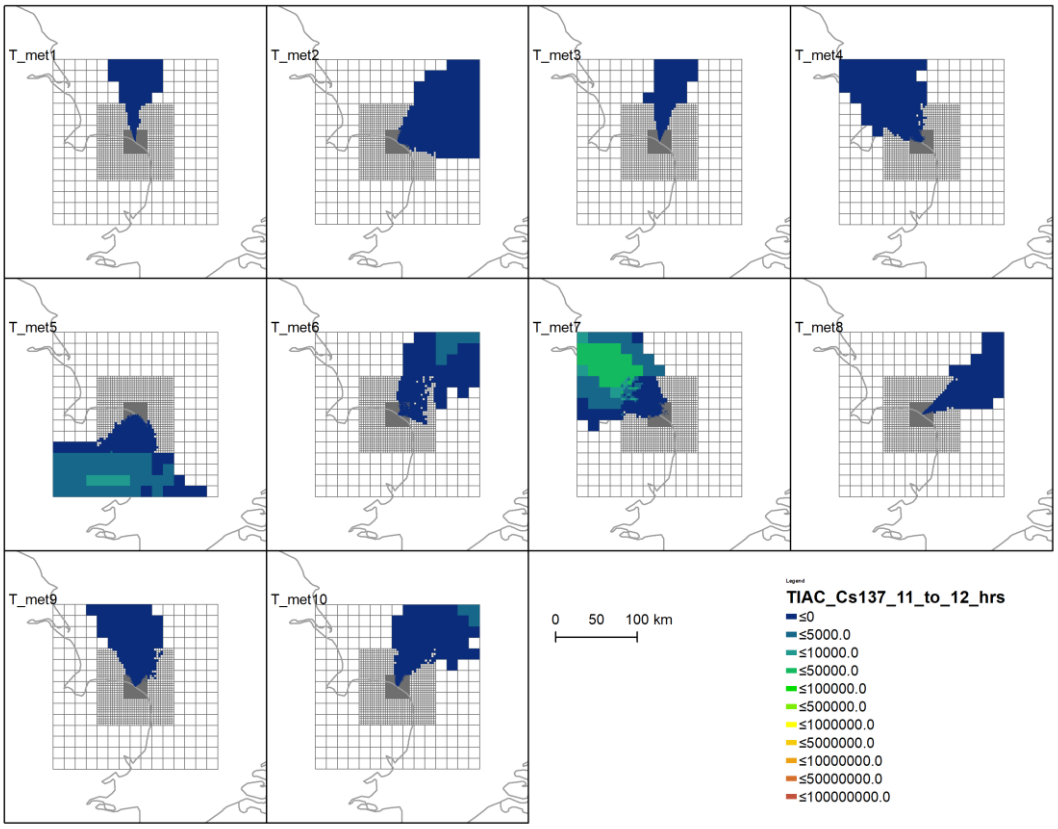

Figure A4: Time integrated air concentration TIAC of ^{137}Cs in the 12th hour since the start of the release.

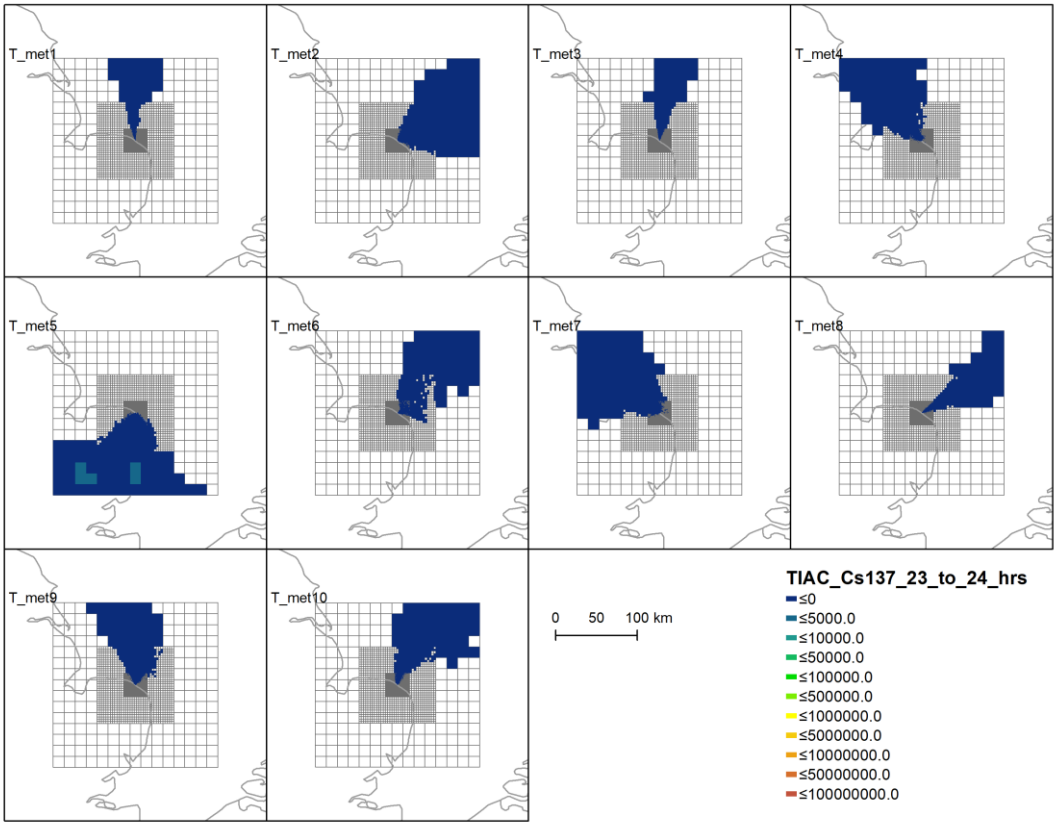

Figure A5: Time integrated air concentration TIAC of ^{137}Cs in the 24th hour since the start of the release.

A3 Numbers of particles

NAME is a Lagrangian model and works by representing the plume as particles that move around within the spatial domain. Each particle carries a fraction of the source term which it loses to deposition and to radioactive decay. The more particles that are represented, the smoother and less noisy the output will be, but this comes at a cost of run time. PACE allows the user to either specify a constant number of particles or to allow the number of particles released in each hour to vary between a maximum and minimum value depending on how much of the source term is released in the hour. This second option is most useful for long duration releases where there is considerable variability in the release rate.

For a short uniform release, a constant particle rate is appropriate. The number of particles needed to produce an adequately smooth output depends on the size of the domain, the size of the grid squares and time steps. Large grid squares and time steps will tend to smooth the results. Table A1 gives run times for four runs performed using one met sequence with different numbers of particles. It shows that the impact on run time is not necessarily linear.

Table A1: Example run times for one met-sequence with variable numbers of particles h^{-1}, performed on a typical laptop computer

Particles h^{-1}	Example time for one run
100	17secs

1000	21secs
10000	44secs
100000	7min 46 secs

Figure A6 illustrates the noise in the output by plotting the TIAC of ^{137}Cs in the 4th hour for each of the met sequences in Table A1. For this example and considering the run times, around 10000 particles per hour appears appropriate.

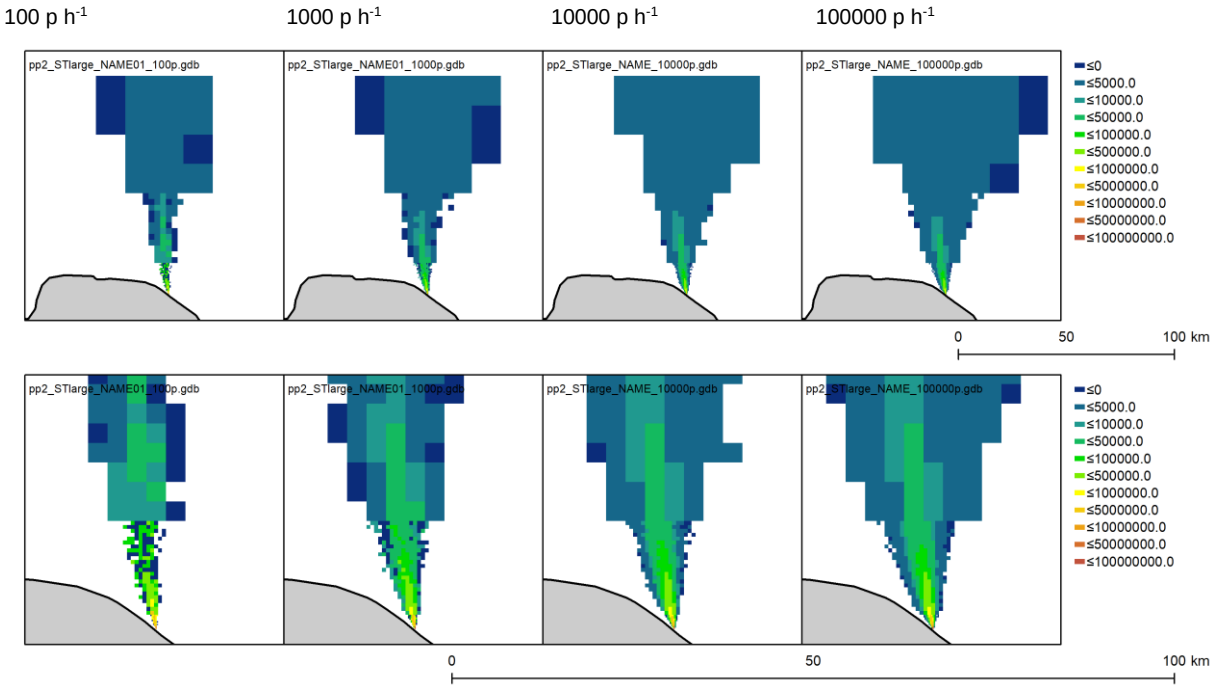

Figure A6: Illustration of the impact of numbers of particles on output noise. The bottom row is a larger scale view of the top row

A4 Defining distance bands

The CAM requires several endpoints at different distances, which are often referred to as radial bands. PACE uses a regular grid, and it is not possible to calculate the value at each point on a circle drawn around the site at any given distance, but it is possible to emulate this by selecting only the grid squares that intersect with this circle. This is done by using the Analyse tool in PACE and specifying criteria based on the distance of the grid square from the release (see section B1). It should be noted that the distance of each grid square is the distance of the centre of the grid square from the point of release. No grid square is exactly 1km from the release and some tolerance in the criteria is needed. This is illustrated in Figure A7

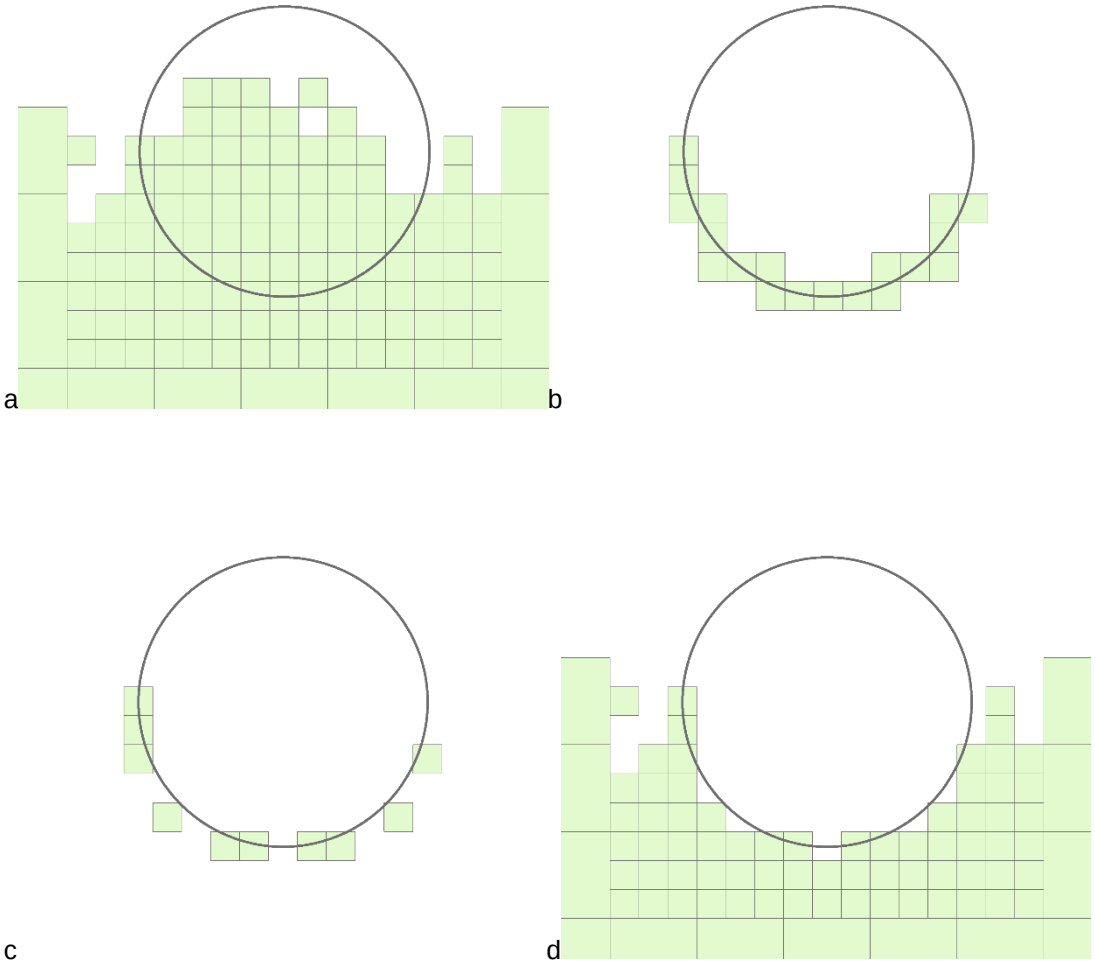

Figure A7. Selecting grid squares by distance criteria a) no criteria b) grid squares whose centres are between 0.86 and 1.14km from release c) grid squares between 1 and 1.14km and d) grid squares with distance equal to or greater than 1km.

Figure A7a shows all the grid squares in a met sequence with a non-zero value and with no distance criteria applied, the circle represents the 1km radius distance around the point of release, the grid squares are 200x200m. To get the maximum dose at 1km, criteria are used to restrict the grid-squares. Figure A5b shows the set of grid squares with criteria limiting distances to between 0.86km and 1.14km, the buffer distance of 280m is roughly the diagonal distance of a grid square which ensures that every grid square which touches the line is included, this is slightly conservative because it includes grid squares closer than 1km. In Figure A5c the criteria restrict the set to those with distances in the range of 1.0 - 1.14km, a tighter tolerance and consequently there are gaps in the selected grid squares. d) a single criterion is used to select all grid squares at a distance equal to or greater than 1km. This is slightly different to the CAM requirements since it includes all grid squares greater than a given distance rather than at a given distance. However, it is likely to be more robust in situations where perhaps the resolution chosen is a little too coarse. Whatever criteria are chosen it should be properly documented. In the example in this report, the approach in Figure A7d is used.

Tolerances should be consistent at all distances but account for larger grid squares in outer nests where appropriate.

Appendix B Analyse specification

The Analyse tool extracts the REPPIR results from the large amount of data produced by PACE. Before they can be used, the endpoints need to be specified in an xml file. This appendix provides a description of how the xml is structured, and examples of suitable endpoints for a REPPIR assessment.

The basic structure is given below:

```
<Results name="REPPIR endpoints">
<Percentiles>50,95</Percentiles>

<Endpoint [Attributes relating to endpoint] >
        <Field [attributes relating to field]/>
        <Field [attributes relating to field]/>
      [further fields]
</Endpoint>

<Endpoint [Attributes relating to endpoint] >
        <Field [attributes relating to field]/>
        <Field [attributes relating to field]/>
      [further fields]
</Endpoint>

[further endpoints]
</Results>
```

An xml file defines a tree structure. In an endpoint definition the root of the tree is the <results> node, which has a single attribute name which describes the purpose of the endpoints.

Within the results node are any number of <endpoint> nodes. Each <Endpoint> node is a calculation that is performed on all the met sequences using the values of the fields as specified in the <field> nodes that the <Endpoint> node contains.

The <percentiles> node should appear just once and gives the percentiles that are produced. In the example in this report, the 50th percentile or median and the 95th percentile are required. In addition, means, maximums and minimums are always generated.

The basic attributes of an endpoint node are:

name – the name of the endpoint stored in the ArcGIS geodatabase. This name must obey the rules of field naming in ArcGIS; it must start with a letter and can only contain letters, numbers and underscore characters and no spaces. It must be unique among all the endpoints in the file.

long name – is the name of the endpoint as displayed by the tool and can be any text.

calc – is a label indicating the kind of calculation to be applied. Some examples of calculation labels are given below.

fc (optional) – is the label of the feature class from which fields are drawn by default.

Crit1 (optional) – a value for a lower boundary of a criterion

Crit2 (optional) – a value for an upper boundary of a criterion

critfield (optional) – a field from which to take a value to test against the criterion if specified

critfc (optional) – a feature class from which to take the criterion field (if not specified the value of fc will be used instead).

There are only two attributes for a field node

name – the name of the field in the feature class from which to take a value for the calculation

fc (optional) – the feature class from which to extract the field, if omitted the fc attribute of the endpoint will be assumed.

The feature classes that maybe specified are those that relate to met sequences in the PACE geodatabase e.g.: EAT, EAT, DS, DSCM, CM, DSIngInd, DSIngIndCM, DSIngProd, DSIngProdCM, HE, HECM, EC, ECCM and PL. Additionally, the value “THIS” may be used and indicates the field that refers to an endpoint calculated in the specification. This previous endpoint must be specified as a separate node before it can be referred to in another endpoint.

B1 Distance band example

```
<Endpoint name="Max_Eff_Adult_Outdoor_Cloud_Shine_2days_Dose_1km"
 longname="Maximum effective adult cloud shine 2 day dose outdoor (Sv) 1km"
calc="MAXVALUE" fc="DS" critfield="DistanceFromReleaseKm" crit1="0.86"
crit2="1.14">
  <Field name="Cloud_shine_2days_Effective_Adult_Outdoor_Total" />
</Endpoint>
```

The endpoint specification above uses the “MAXVALUE” calculation to find the maximum value from the field “Cloud_shine_2days_Effective_Adult_Outdoor_Total”, contained in the set of DS featureclasses (e.g. DS_met1, DS_met2 etc). A criterion is specified that limits the calculation to grid squares that are roughly 1km from the release. The criterion field is “DistanceFromReleaseKm”, and only grid squares with a value for this field greater than or equal to 0.86km and less than or equal to 1.14 km are considered. This endpoint can be copied and used for other distance bands by altering the values of crit1 and crit2.

B2 Maximum extent example

```
<Endpoint name="MaxDistSheltered"
```

```
longname="Furthest distance sheltering implemented (km)"
calc="MAXVALUE" fc="CM" critfield="Sheltering" crit1="0.99">
       <Field name="DistanceFromReleaseKm" />
</Endpoint>
```

The endpoint specification above also uses the “MAXVALUE” calculation. Its purpose is to find the maximum extent of sheltering. In this case the criterion is the “Sheltering” field in the set of CM feature classes (E.g. CM_met1, CM_met2 etc). This field can take either a value of 0 (no sheltering) or 1 (sheltering), therefore a criterion value of 0.99 is specified as any grid square with a value greater than or equal to 0.99 is sheltered. Within this subset of grid squares, the calculation looks for the maximum value of the “DistanceFromReleasekm” field.

B3 Number of people affected example

```
<Endpoint name="NumberSheltered"
longname="Total number of people sheltered"
calc="POPGT0" fc="CM" >
       <Field name="Sheltering" />
</Endpoint>
```

In this example the “POPGT0” calculation is used. This calculation sums up the population for grid squares where the value of any of the fields is greater than zero. The population is taken from the “Population” field of the feature class called “InputData” which is created during the preprocessing step of PACE.

B4 Area affected example

```
<Endpoint name="AreaGreenVegRestr"
longname="Total area for which green vegetables restricted (m2)"
calc="AREAGT0" fc="CM" >
       <Field name="Green_veg_Restriction_Duration" />
</Endpoint>
```

The “AREAGT0” calculation can be used to calculate the sum of land affected. This calculation sums up the area of land for grid squares where the value of any of the fields is greater than one. The area of land is taken from the “IsLand” field of the feature class called “InputData” which is created during the preprocessing step of PACE.

B5 Intermediate calculation example

Sometimes it is not possible to calculate the endpoint required with a single specification. For example, PACE provides predictions of dose from ingestion of individual foods but not from several foods together.

```
<Endpoint name="SumTotalEffDose1yIng"
longname="Sum total effective adult 1year dose ingestion only 1st year (Sv)"
```

```
calc="SUM" fc="DSCMIngInd" >
       <Field name="Ingestion_Ind_Effective_Adult_Milk_Total" />
       <Field name="Ingestion_Ind_Effective_Adult_Green_veg_Total" />
</Endpoint>

<Endpoint name="Max_Res_Eff_Adult_1year_Dose_over_1km"
longname="Maximum residual effective adult total dose 1st year NL (Sv) 1km"
calc="MAXVALUE" fc="DSCM" critfield="DistanceFromReleaseKm" crit1="0.86">
  <Field name="Sum_ind_no_ing_1years_Effective_Adult_Env1_Total" />
  <Field name="SumTotalEffDose1yIng" fc="THIS" />
</Endpoint>
```

The “SUM” calculation is used to sum the doses from ingestion of green vegetables and milk. Then the “MAXVALUE” calculation sums the resulting field “SumTotalEffDose1yIng” with the total non-ingestion dose and then the maximum value is identified from grid squares that meet the distance criterion given.

Appendix C Foetus doses

PACE 3.3.4 does not include the capability to directly calculate doses to the foetus. However, it is possible to estimate such doses from adult doses produced by PACE by using conversion factors. This appendix describes how it can be done in a simplified but robust manner. The CAM requires consideration of foetuses if certain specified radionuclides are included in the release. The CAM only requires projected doses and only the inhalation pathway is required. The methodology below goes beyond this as it provides information for other pathways including ingestion and can be applied to residual dose estimates as well.

In general, it will not be practical to perform a full set of probabilistic calculations outside of PACE, but in in most cases, it should be sufficient to select individual representative met sequences (e.g., the one closest to the 95th percentile 2-day adult dose at a given distance close to the release).

(HPA, 2008) gives guidance on estimating doses to the foetus (Guidance on the Application of Dose Coefficients for the Embryo, Foetus and Breastfed Infant in Dose Assessments for Members of the Public) and identifies a number of radionuclides that may be important to consider for acute *in utero* exposures for which there is potential for the dose to the offspring to be greater than that for the mother (table 6.1 of HPA, 2008). Section 6.3.1 of the guidance also notes that, for such radionuclides, although the dose to the foetus may be greater than that to the adult, it is still likely to be less than that to a child (or infant), and so may not be limiting.

For the calculation, internal dose coefficient ratios of foetus to adult, for the relevant radionuclides should be calculated from the dose coefficients given in ICRP (ICRP (2001) Publication 88 for foetus dose coefficients, and ICRP (2012) Publication 119 for adult dose coefficients). Dose coefficient ratios are not required for external dose pathways as the ratio is assumed to be 1. Example internal effective dose coefficient ratios for the radionuclides in the example source terms are provided in table C1 (for all radionuclides the chemical form assumed is aerosol and the uptake rate assumed is “M” except iodine, for which it is “F”).

Table C1. Ratio of effective dose coefficients (foetus:adult) by intake type. The Bold numbers are those with ratios much larger than one.

	Inh (acute[a])	Ing (acute[a])	Inh (chronic)	Ing (chronic)
^{60}Co	0.16	0.68	0.12	0.56
^{131}I	**2.84**	**2.73**	1.09	1.05
^{134}Cs	0.15	0.58	0.11	0.46
^{137}Cs	0.09	0.55	0.06	0.44
^{137m}Ba[b]	NA	NA	NA	NA
^{88}Kr	NA	NA	NA	NA

a Acute intakes are assumed to occur at the point prior to or during pregnancy at which the dose coefficient is highest. This could be different for different radionuclides, so there is some inconsistency, but the results will be conservative.

b ^{137m}Ba is very short lived and in equilibrium with its parent ^{137}Cs, the ^{137}Cs dose coefficients include the ingrowth of ^{137m}Ba and separate dose coefficients are not provided.

c ^{88}Kr and other noble gases do not contribute to internal dose from inhalation or ingestion.

Foetus dose coefficients are only available for a subset of radionuclides. For radionuclides where foetus dose coefficients are not available, it should in most cases be conservative to

assume the ratio with adult dose coefficients is 1:1. However, caution should be used in applying this assumption, especially if the radionuclide in question contributes significantly to the overall dose for adult, child or infant age groups.

Foetus dose coefficients vary significantly depending on whether an acute or chronic intake is considered. The acute intake dose coefficients vary significantly depending on the exact timing of the intake with respect to conception/stage of pregnancy. For these calculations, different assumptions should be made for the dose calculation depending on the timescale being considered:

- For the dose to two days, the intake (inhalation of the plume and resuspended material if included) should be treated as acute and assumed to occur at the point at which the dose coefficient is highest (this point varies for different radionuclides).
- For the dose to one year, the inhalation of the plume should still be considered to be an acute intake (occurs over a duration < 48 hours), but the inhalation of resuspended material and ingestion should be considered to be chronic intakes (occur over the course of a year).

In both cases, the approach is likely to be conservative.

The calculations of total dose to the foetus for each radionuclide are as follows:

$$D_{2day} = dCS_{2day} + (dCI_{2day} \times r_{acute}^{inh}) + dGS_{2day} + (dR_{2day} \times r_{acute}^{inh})$$

(equation C1)

$$D_{1year} = dCS_{2day} + (dCI_{2day} \times r_{acute}^{inh}) + dGS_{1year} + (dR_{1year} \times r_{chronic}^{inh}) + (dIng_{1year} \times r_{chronic}^{ing})$$

(equation C2)

Where D is the total dose to the foetus (Sv)
dCS is dose to an adult from external gamma irradiation from material in the plume (Sv)
dCI is dose to an adult from inhalation of material in the plume (Sv)
dGS is dose to an adult from external gamma irradiation from material deposited on the ground (Sv)
dR is to an adult dose from inhalation of resuspended material (Sv)
dIng is to an adult dose from ingestion of contaminated foodstuffs (Sv)
r^{inh} is the inhalation dose coefficient ratio foetus:adult (acute or chronic)
r^{ing} is the ingestion dose coefficient ratio foetus:adult (acute or chronic)

Other considerations:

- Ingrowth of progeny following deposition on the ground is not modelled in PACE and therefore are not included in this approach. While it could be significant in some cases (for example, the dose from ^{241}Am relative to the parent ^{241}Pu), it is unlikely to be significant compared to the resuspension doses received from other radionuclides in the source term.
- Breast fed infants are not explicitly considered in this approach. The recommendations in HPA (2008) suggest that in general, for chronic exposures, using the foetal dose coefficient and assuming annual intake rates for the mother throughout pregnancy should be sufficiently cautious.

- The exposure pathway resulting from inadvertent ingestion of contaminated material is not considered in this approach. It is not included in PACE, but it is possible that in some cases, it could be significant (for example, for actinides, and for infants).
- The assumption that exposures are either acute or chronic is imperfect but is the most practical way to implement the calculation. For example, this approach assumes that the rate of ingestion is steady over the course of a year and so the exposure is chronic in nature. In reality, an ingestion exposure for an individual could be acute and occur at a particularly sensitive time for the foetus development (where the dose coefficient is maximised), but this is unlikely, and it would be incorrect to apply the annual average intake of the given food to a single intake event.

C1.1 Example dose calculation

In the illustrative scenario in this document, only ^{131}I is a significant radionuclide for foetus doses according to the CAM, and Table C1 shows that it has the potential to exceed the corresponding adult acute doses. Therefore, it is necessary to estimate acute foetus dose values for the consequence report. It would also be possible to calculate 1-year doses but, since the inhalation component of those doses is delivered acutely and resuspension is not being considered, it will not provide much more information.

To generate some representative foetus dose values for the CAM the following methodology was used.

For the large source term, the met sequence that gives a representative '95th percentile' result for the total outdoor adult dose over 2 days at 1km was identified. This was done by first examining the "Analyse_metsummary" table in the analyse output geodatabase. This table lists all the results of the analyse tool calculations by met sequence number. The result of interest is the maximum total projected outdoor dose at 1km which is labelled as "Max_Eff_Adult_Outdoor_2days_Dose_1km_no_ing". If the table is sorted on this field, then the 191st result in the table is the first met sequence that exceeds the 95th percentile value for this endpoint (because there are 200 met sequences in total). In this example this corresponds to met sequence number 10, see Figure C1

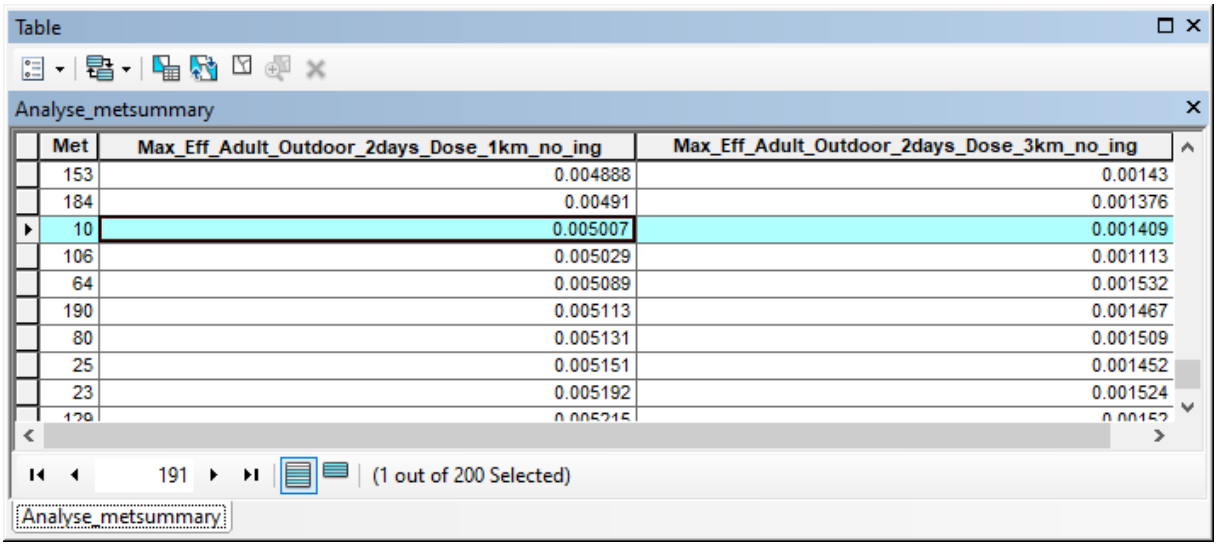

Figure C1 the "Analyse_metsummary" table giving Analyse tool results by met sequence.

Having identified the met sequence, the grid square which holds the maximum value can be identified by examining the corresponding Analyse tool feature class which in this case is called “Analyse_met10”. The user should open the attribute table of the feature class and sort the corresponding field in descending order. Only the grid-square or grid-squares which contain the maximum value have a non-zero value and are therefore placed at the top of the list. In this example as shown in Figure C2, the grid square with the maximum value has the “PgridsquareID” value 3495.

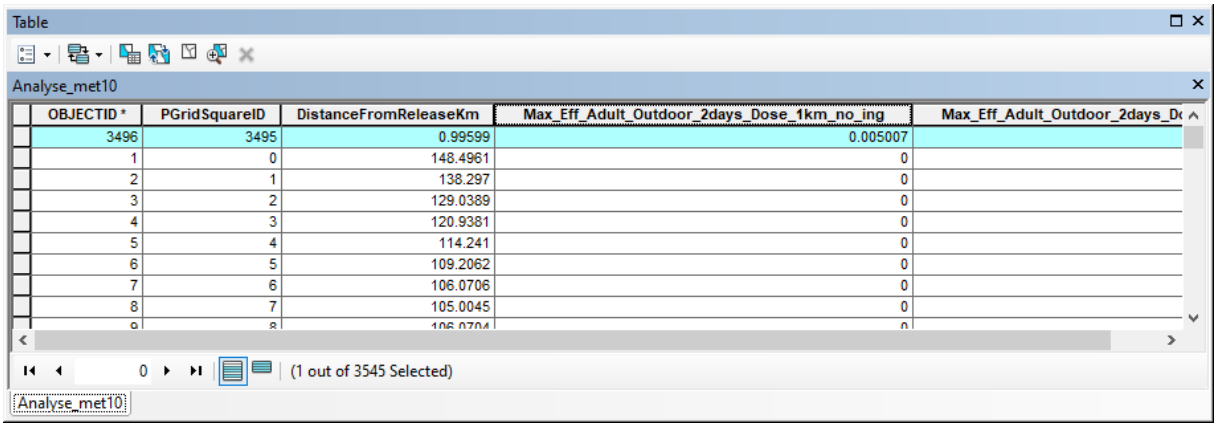

Figure C2 the attribute table for the “Analyse_met10” feature class giving Analyse tool results by grid square.

To estimate the foetus doses, the adult doses by radionuclide are required for grid square 3495 (as given by the “PgridSquareID” field), in met sequence 10. It may be necessary to repeat the consequence calculation for the chosen met sequence but changing the endpoints required to include ingestion and non-ingestion doses by radionuclide (which for the full analysis of 200 met sequences was omitted to reduce run times). When this is completed, the doses from met-sequence 10, grid-square 3495 can be copied from the feature class DS_met10 to a spread sheet and equations C1 and C2 applied, as illustrated in Table C2, the totals at the bottom were used to populate Table 74.

Table C2 Foetus calculation steps (shaded totals copied into Table 74)

Step 1 Effective dose ratios calculated

	Foetus (F) inhalation acute effective DC	Adult (A) effective DC	Ratio inhalation DC F:A acute
60Co	1.60E-09	1.00E-08	1.60E-01
131I	2.10E-08	7.40E-09	2.84E+00
134Cs	1.40E-09	9.10E-09	1.54E-01
137Cs	8.50E-10	9.70E-09	8.76E-02

Step2 Adult effective doses extracted for a grid square in a met sequence from PACE

	External cloud gamma field names and values	Cloud inhalation field names and values	External ground gamma field names and values	Total
60Co	Cloud_shine_2days_Effective_Adult_Outdoor_Co60 0.00E+00	Cloud_inh_2days_Effective_Adult_Outdoor_Co60 5.80E-06	Ground_shine_2days_Effective_Adult_Outdoor_Co60 3.47E-07	6.15E-06
131I	Cloud_shine_2days_Effective_Adult_Outdoor_I131 5.01E-05	Cloud_inh_2days_Effective_Adult_Outdoor_I131 4.29E-03	Ground_shine_2days_Effective_Adult_Outdoor_I131 6.31E-05	4.40E-03
134Cs	Cloud_shine_2days_Effective_Adult_Outdoor_Cs134 2.11E-05	Cloud_inh_2days_Effective_Adult_Outdoor_Cs134 3.83E-04	Ground_shine_2days_Effective_Adult_Outdoor_Cs134 2.49E-05	4.29E-04
137Cs	Cloud_shine_2days_Effective_Adult_Outdoor_Cs137 0.00E+00	Cloud_inh_2days_Effective_Adult_Outdoor_Cs137 1.33E-04	Ground_shine_2days_Effective_Adult_Outdoor_Cs137 4.59E-06	1.38E-04
^{137m}Ba	Cloud_shine_2days_Effective_Adult_Outdoor_Ba137m 3.04E-06			
88Kr	Cloud_shine_2days_Effective_Adult_Outdoor_Kr88 2.86E-05			
Total	1.03E-04	4.81E-03	9.29E-05	5.01E-03

Step 3 Foetus effective doses calculated by multiplying adult dose by the appropriate ratio

	External cloud gamma (using F:A=1)	Inhalation (using F:A acute)	External ground gamma (using F:A=1)	Total
60Co	0.00E+00	9.28E-07	3.47E-07	1.27E-06
131I	5.01E-05	1.22E-02	6.31E-05	1.23E-02
134Cs	2.11E-05	5.89E-05	2.49E-05	1.05E-04
137Cs	0.00E+00	1.17E-05	4.59E-06	1.63E-05
137m Ba	3.04E-06			3.04E-06
88Kr	2.86-05			2.86E-05
Totals	1.03E-04	1.22E-02	9.29E-05	1.24E-02

C1.2 References

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