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The Probabilistic Accident Consequence Evaluation (PACE) Software Methodology for version 3.3.2

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Public Health England
133–155 Waterloo Road
Wellington House
London SE1 8UG
T: 020 7654 8000

www.gov.uk/phe
Twitter: @PHE_uk
Facebook: www.facebook.com/PublicHealthEngland

Any enquiries regarding this publication should be sent to

Centre for Radiation, Chemical and Environmental Hazards
Public Health England
Chilton, Didcot, Oxfordshire OX11 0RQ
E: PACE@phe.gov.uk

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TW Charnock, AP Bexon, J Sherwood, N Higgins*, S Field, JG Smith and I Brown

*** Former employee of Public Health England**

ABSTRACT

The PACE™ (probabilistic accident consequence evaluation) software has been written to perform Level 3 probabilistic safety analysis (PSA) for nuclear power stations (or other facilities that may have short-term releases of radioactive material to atmosphere).

This report documents the methodology of version 3.3.2 of the Probabilistic Accident Consequence Evaluation code (PACE). It describes the calculations, data and assumptions behind the five steps of a PACE analysis; the definition of the source term, the specification of the calculation grid and the handling of input spatial data, the cyclic running of the NAME3 Lagrangian particle atmospheric dispersion model or alternatively a Gaussian model to generate a large set of possible dispersion patterns (or 'met' sequences), the calculation of the doses, health effects and costs with and without countermeasures (urgent and long term protective actions) for each met sequence, and the aggregation and summary of results across met sequences to gain an insight into the ranges of possible consequences.

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Centre for Radiation, Chemical and Environmental Hazards
Public Health England
Chilton, Didcot
Oxfordshire OX11 0RQ

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Report version 1.0

Contents

1 Introduction

The PACE™ (probabilistic accident consequence evaluation) software has been written to perform Level 3 probabilistic safety analysis (PSA) for nuclear power stations (or other facilities that may have short-term releases to atmosphere). PACE has been implemented as a set of tools within a Geographic Information System (GIS) called ArcGIS™. This document refers to version 3.3.2 of PACE and concentrates on the methodology of the models that comprise PACE and on the data that comprise the default inputs.

To keep the text short and clear and to allow users to access this methodology non-sequentially, terms, abbreviations and jargon, for example “met sequence”, “cloud shine” and “feature class”, are used without necessarily being defined first. Please refer to the glossary (Section 10) when unsure of a term. This methodology is accompanied by a user guide for PACE 3.3.3 (Field et al, 2020) which explains how to use the software and should be read in conjunction.

1.1 Purpose and history

PACE has been developed by Public Health England (PHE). PHE was formed from the merger of the Health Protection Agency (HPA) with other organisations in 2013 and HPA was formed from the merger of the National Radiological Protection Board with other organisations in 2005. NRPB was involved with the development of several level-3 PSA systems including; CONDOR (SRD et al, 1993), MARC (Hill et al, 1988; Jones et al, 1990) and Cosyma (KfK and NRPB, 1991).

Currently in the UK there are several new nuclear power plants being proposed for construction and Public Health England (PHE) has a role in providing advice on the potential health impacts of the new designs, both generically and in more detail for any specific site. The advice includes consideration of both normal operations and emergency conditions. Consideration of emergencies requires a probabilistic approach but the tools for Level 3 Probabilistic Safety Assessment (PSA) were last used in the UK in support of the Public Inquiries into the building of PWRs at Sizewell in Suffolk (Layfield, 1987) and Hinkley Point in Somerset (Barnes, 1990) in the 1980s and early 1990s.

As preparation for this proposed new build programme, HPA reviewed all the available PSA codes and found that there had been no significant development since the early 1990s and that they did not take into account advances in scientific knowledge (Bexon, 2008). The study also noted that since the early 1990s there have been major advances in computer technology including processing power, usability and data visualization capabilities. In addition, increasingly fine resolution electronic spatial datasets of demographic, agricultural, economic and environmental attributes are now compiled and maintained nationally and internationally. With these advances it is possible to perform much more sophisticated assessments on relatively inexpensive computers. As a result of the study a substantial development programme was undertaken to develop a new PSA tool built within a Geographic Information System (GIS).

1.2 PACE calculation overview

The level 3 analysis performed in PACE is conceptually simple, see Figure 1. The atmospheric dispersion of a given release is modelled for a large number of meteorological conditions or *met sequences* drawn from a meteorological database. Doses, health effects and economic consequences are calculated for each modelled release of contamination to build up data distributions about which statistical statements can be made. The effects of countermeasures (or protective actions) such as evacuation, sheltering, stable iodine prophylaxis, food restriction, relocation and clean-up can be accounted for as required by the user.

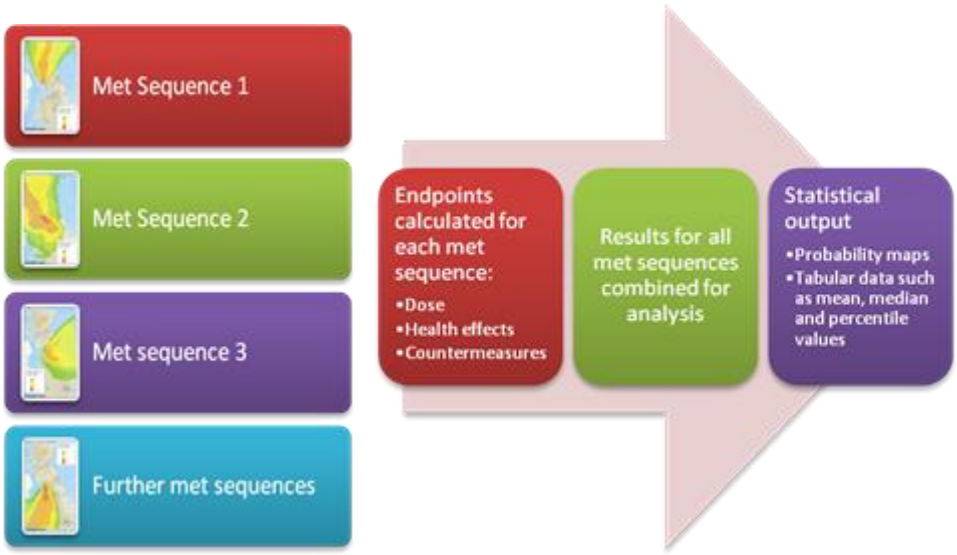


Figure 1 PACE calculation scheme

A PACE analysis consists of a number of steps which are performed by separate tools within the software.

The first step is to specify a source term. A source term is specified as an XML file with a specific format. It can be written by hand using a text editor or created and modified using the *source term* tool. The tool in PACE evaluates the source term specified to ascertain the most important radionuclides and to allow the user to remove less important radionuclides to speed up subsequent analysis.

The second step uses the *Preprocess* tool to specify the nested grid on which all PACE calculations are performed and then to resample the input spatial data to conform to that grid.

The third step is optional and uses the *NAME3run* tool. The tool uses the Met Office NAME (Jones et al, 2007b) atmospheric dispersion model to simulate the dispersion. The tool uses the grid specified in step two together with the user-entered source term, location for the release and other options required to set up a NAME input file. Alternatively, the user can omit this step and use the simple Gaussian plume model ADEPT to model dispersion that has been built into PACE.

The fourth step uses the *PACErun* tool. The main input is the nested grid set up in step two and optionally the NAME dispersion results generated in step three. The tool loops over the

each met sequence whether calculated by ADEPT or NAME and calculates all the required dose, health effects and economic end points either with or without countermeasures.

The fifth step uses the analysis tools, *Analyse* and *PercentileMap*, to aggregate the raw results calculated in step four into summary statistics or mapped output that describe the probabilities of outcomes requested by the user.

1.3 Endpoints

All the steps produce endpoints that may be of use to the user, but the fourth step is the principal calculation step and it is important to understand the range and structure of the outputs generated. For each grid square in each met sequence the PACE calculation produces endpoints in the following categories:

- EA (environmental activity) includes hourly estimates of the integrated activity concentration in air and deposition on the ground of each radionuclide.
- DS (dose) includes individual dose endpoints from various non-ingestion pathways assuming no countermeasures are applied.
- DSIngProd (ingestion dose) collective dose endpoints for ingestion pathways assuming no food restrictions are applied calculated from the total production.
- DSIngInd (ingestion dose) individual dose endpoints for ingestion pathways assuming no food restrictions are applied calculated from individual consumption data.
- PL (plume doses) gives hourly dose endpoints from cloud shine, inhalation and ground shine during the passage of the plume with no countermeasures applied.
- RC (recovery doses) gives long term doses from ground shine and resuspension after the passage of the plume with no countermeasures applied.
- HE (health effects) includes stochastic and deterministic risks and health effects assuming no countermeasures are applied.
- EC (economic costs) includes economic consequences of the accident assuming no countermeasures are applied. Because countermeasures are not applied the economic costs are restricted to the costs of health effects.
- CM (countermeasures) includes whether different types of countermeasures are applied and in some cases such as relocation how long they are applied for.
- DSCM (dose with countermeasures) includes dose endpoints from various pathways assuming countermeasures are applied if they are needed (as indicated by CM endpoints).
- DSCMIngProd (ingestion dose) collective dose endpoints for ingestion pathways assuming food restrictions are applied if they are needed (as indicated by CM endpoints) total food production.
- DSCMIngInd (ingestion dose) individual dose endpoints for ingestion pathways assuming food restrictions are applied if they are needed (as indicated by CM endpoints) total food production.

- RCCM (recovery doses) gives long term doses from ground shine and resuspension after the passage of the plume with countermeasures applied if they are needed (as indicated by CM endpoints).
- HECM (health effects with countermeasures) includes stochastic and deterministic risks and health effects assuming countermeasures are applied if they are needed (as indicated by CM endpoints).
- ECCM (economic costs with countermeasures) includes economic consequences of the accident assuming countermeasures are applied if they are needed (as indicated by CM endpoints). Because countermeasures may be applied the economic costs include the costs of health effects, and also disruption to industry and tourism and cost of food restrictions.

1.4 Temporal model

PACE has a simple temporal model, but it is important to have a clear understanding of how this is defined.

Time zero is when the accident starts; it is the start time of the first hour of data extracted from the meteorological database in each met-sequence. Typically, it will be the time when the release starts however a source term can be specified with a pause before material is released. Almost all other times used in PACE are given relative to time zero.

A source term in PACE consists of a number of phases of defined length (see Section 4). The sum of all the individual phase durations is the overall release length or duration.

The term *Emergency ends* is given to the user entered parameter that defines when the emergency ends from the point of view of implementing emergency countermeasures. It is used by PACE as the time when evacuation and sheltering are lifted and when relocation begins. It requires some judgement on the part of the user to set, particularly in the case of a long duration release. In most cases it should be longer than the release length duration to ensure it encompasses the significant impacts of the release. However, the release may have been specified with a long tail of relatively low-level releases of radionuclides and it is the decision of the user to consider whether this would be sufficient to extend the emergency phase. Also, the plume may reach distant locations at some time after the release has ended due to the time taken for dispersal of the material in the atmosphere. Therefore, the emergency end time might be extended to include these locations, but at some distance it will reach low activity concentrations that do not constitute an emergency that needs to be managed.

If the NAME model is used, the user is required to specify a temporal domain (Section 3.3.2) which is not the same as the *Emergency ends* time. NAME represents atmospheric dispersion as particles which will move around the spatial domain until they are deposited, leave the spatial domain or until the temporal domain as explicitly set by the user ends. Depending on the length of the temporal domain chosen, towards the end of that temporal domain contamination may be at a low level, widespread and approaching background levels as not to constitute an emergency.

By default, *Emergency ends* is set to 1 day.

The user should also consider whether the default cut-off times for skin and clothing contamination are appropriate especially when dealing with long duration releases (See Section 5.6).

1.5 Verification and validation

The PACE system has been developed under an ISO9001:2015 certificated quality management system that includes a range of verification methods. Specifically, this consists of project managing the development process by breaking down developments into discrete programming tasks which can be completed on a timescale of a few months. The project then moves into a testing cycle so that all development can be signed off as part of the next version before moving onto a further cycle of design review and development. The testing process is controlled using a comprehensive test matrix which must be signed off by the project manager before a version of the software is released for use. The testing itself comprises many forms, firstly a series of tests have been implemented as automated tests which must pass before further testing is carried out. The next round of testing focuses on the parts of the software that have been added or updated within that project development cycle. These tests include unit tests looking in isolation at specific parts of the code that have been developed, as well as more comprehensive testing looking at any implications for the whole PACE system or comparison against other software or reports.

The PACE system combines several models into one system that can be used to assess the impacts of accidental releases of radioactive material to the environment. These models have undergone their own verification and validation processes which are summarised below.

- NAME3 – The atmospheric dispersion model used within PACE is the Met Office NAME III model (Jones et al, 2007a). This model has been developed over a period of many years and has undergone several verification and validation exercises (for example Ryall and Maryon (1998) and Webster and Thomson (2002)).
- ADEPT – Is an implementation of the Gaussian atmospheric dispersion model described in Clarke (1979) and (Jones, 1981).
- FARMLAND – The food chain modelling within PACE is based on the FARMLAND model for which a description is provided in (Brown and Simmonds, 1995).
- COCO-2 – The economics model within PACE is the COCO-2 model as described in Higgins et al (2008). This report provides a description of the verification and comparison of the model against previous economics models used for nuclear accidents.
- Data: PACE uses extensive datasets in spatial and non-spatial formats. The default spatial datasets have been compiled from official or openly published sources of data, for example, UK population census data published by ONS, UK agricultural census data published by EDINA. The economic datasets used within PACE are summarised in Higgins et al (2008).
- RAD Quality System: The Radiation Assessments Department operates a quality management system that is certificated to ISO9001:2015 by Lloyd's Register (LR). The quality management system covers all project work that is undertaken within the department and consists of policies, processes and procedures which provide a

means of controlling the scientific work undertaken. The system is reviewed by means of a programme of internal audits throughout each year as well as the 6-monthly external audits undertaken by LR.

1.6 Changes from previous versions

The following significant changes have been made in developing PACE 3.2.1 from PACE 3.1:

- The stochastic risk factors have been updated as documented in Appendix E.
- Dose coefficients for ingestion and inhalation have been updated to be consistent with the ICRP dose coefficient database v3.0 (ICRP, 2012).
- Dose factors for external dose due to deposition onto skin and clothes have been recalculated using the methodology as described in Appendix F.11appendix e
- The way that users specify countermeasures has been refined to allow more flexibility and control. Users can force sheltering to be applied if the criteria indicate that stable iodine prophylaxis should be applied. A mandatory distance can be specified for sheltering and evacuation regardless of weather conditions to simulate automatic countermeasures. A maximum distance can be applied to evacuation and to stable iodine prophylaxis to recognise that there are practical constraints to these options.
- The Percentile Map tool has been adapted so that it can operate on the output of the analysis tool.
- Finally, for practical reasons some standard output feature classes have been split so that they are easier to access and to analyse.

The following significant changes have been made in developing PACE 3.3.2 from PACE 3.2.1:

- A methodology to estimate individual ingestion dose has been added to the code.
- Because individual ingestion dose calculations are available, stochastic health effects from the ingestion pathway do not need to be treated separately.
- An overall estimate of fatalities across all health effects has been added.
- Analysis tool has been further developed. For example, it can use the results of its own calculations within further calculations.
- The Percentile Map tool has been further developed. For example, it can calculate percentiles or probabilities on multiple fields during a run.
- An optional maximum distance can be placed on sheltering.
- A second Analysis tool calculation specification file has been developed specifically for generating results to be compared to the UK Safety Assessment Principles (SAPs), (ONR, 2014)
- NAME upgraded to version 6.5.

2 Geographic Information System Based Approach

2.1 Introduction

PACE has been embedded within a commercial GIS framework. This has allowed the developers to concentrate on functionality, modelling and data compilation, which is substantial given the range of models included, while PACE still benefits from powerful data handling and visualization capabilities, and provides the user with a flexible and modern user interface. Users also benefit from the ad hoc analysis capabilities provided by other tools within the ArcGIS environment.

PACE calculations are handled on a user specified nested grid, but input need not be gridded and can be provided as irregular polygons. The nested grid specification and the handling of spatial inputs are performed by the Preprocess tool which in turn utilises the spatial data handling capabilities of the GIS.

2.2 Nested grid arrangement

PACE uses a nested grid arrangement for calculations. The nested grid is specified by the user using the Preprocess tool.

A nested grid can be set up with 0 to 3 inner grids with the outer most termed nest 0. The nested grid is constrained such that each inner grid exactly aligns with the grid that contains it. Inner grids may touch the edges of outer grids but may not go beyond them. Grids may be rectangular and the nesting arrangement can be asymmetric. The individual grid elements are square and the terms grid element and grid square are used interchangeably. The parameters that describe a nested grid are illustrated in Figure 2 and listed below.

nests – the number of grid nests from one to four.

x0, y0 – map unit co-ordinates of the top left corner of nest 0.

res – resolution of nest 0 grid squares given in map units.

ncol – number of columns in nest 0.

nrow – number of rows in nest 0.

relx (1 to nests) – the x co-ordinate of nest i given in columns of nest i-1 from left of nest i-1.

rely (1 to nests) – the y co-ordinate of nest i given in rows of nest i-1 from top of nest i-1.

relwidth (1 to nests) – the overall width of nest i given in columns of nest i-1.

relheight (1 to nests) – the overall height of nest i given in rows of nest i-1.

nestfactor (1 to nest) – a whole number representing the number of times the resolution of nest i divides into nest i-1. As grid elements are square this is the same in both the x and y directions.

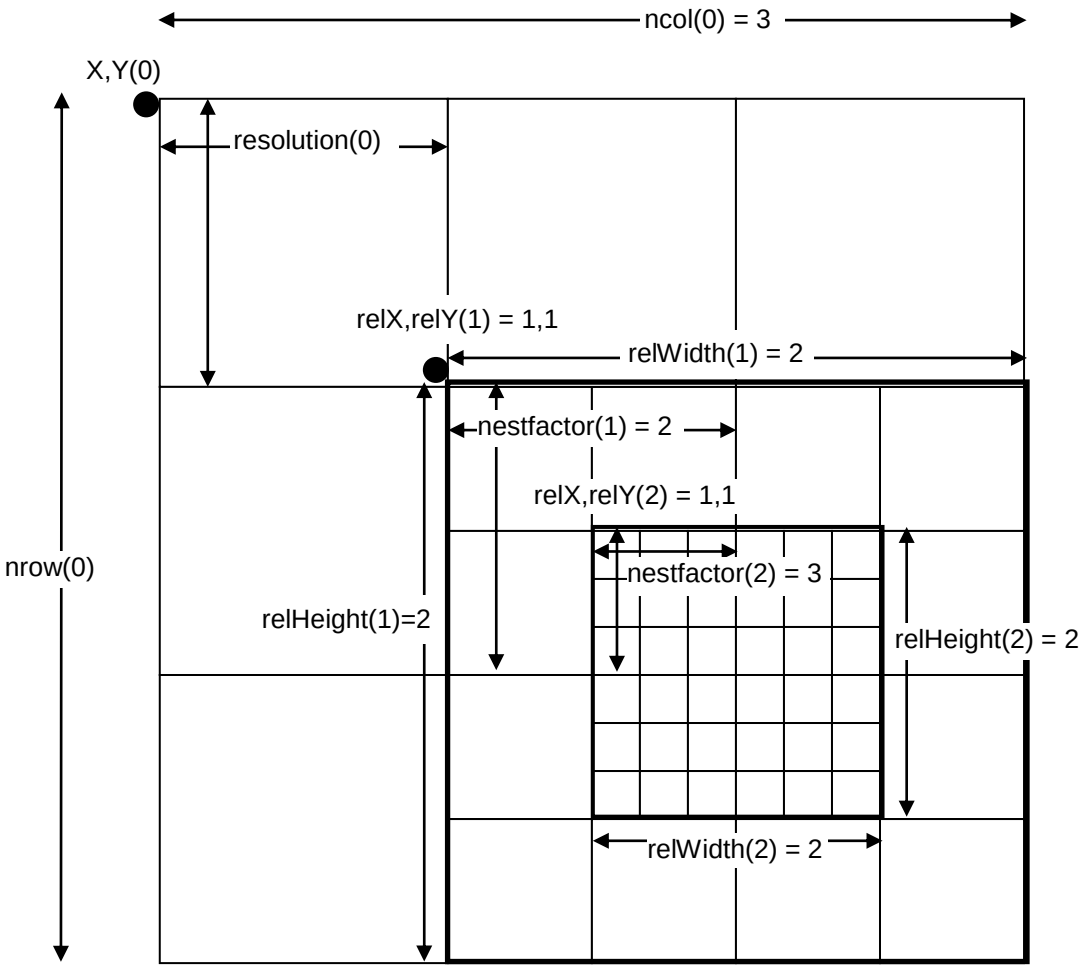


Figure 2 Specification of a PACE nested grid.

2.3 Co-ordinate systems

PACE currently allows the user to choose from two co-ordinate systems or spatial references; the British National Grid (BNG) and a geographic co-ordinate system based on the WGS1984 datum (termed lat-long in this document). The British national grid is a projected co-ordinate system and is suitable for use over or very near to the British Isles. For other locations and for very large areas encompassing the British Isles the geographic lat-long co-ordinate system should be used.

The choice of which spatial reference to use is made when defining the nested grid arrangement with the Preprocess tool, and this cannot be changed subsequently. If BNG is used, then the nested grid is specified in metres and grid elements within a nest will be the same size and will be square. Decimal degrees are used to specify the nested grid if lat-long is used. Because degrees in the east-west direction are only approximately the same distance as degrees in the north-south direction at the equator and become smaller as one moves further from the equator, so grid-elements in a lat-long grid are not necessarily square or the same size, though will appear so when plotted under certain co-ordinate systems.

PACE calculates the distance of each grid square from the point of release. This is a useful endpoint for the user if, for example, they wish to see how far countermeasures extend. The

calculation depends on the co-ordinate system chosen. For the BNG system the calculation uses Pythagoras' theorem.

$$D_g = \sqrt{(x_r - x_g)^2 + (y_r - y_g)^2}$$

Equation 1

Where:

D_g is the distance between the release point and the centre of the grid square in km.

x_r and y_r are the x and y co-ordinates of the point of release in km.

x_g and y_g are the x and y co-ordinates of the centre of the grid element in km.

For lat-long the calculation is more complex as it has to take into account that the earth is not flat. The calculation assumes that the earth is a perfect sphere that can be described by a single radius (in reality the shape is much more complex, but this approximation is sufficiently accurate for PACE).

$$D_g = E_r \times 2 \times arcsine(\sqrt{r})$$

$$r = sin^2\left(0.5 \times (y_r - y_g)\right) + \cos(y_r) \times cos(y_g) \times sin^2 0.5 \times (x_r - x_g)$$

Equation 2

Where:

D_g is the distance between the release point and the centre of the grid square in km along a great circle path.

E_r is the assumed earth radius of 6371.229 km

x_r and y_r are the longitude and latitude co-ordinates of the point of release in radians.

x_g and y_g are the longitude and latitude co-ordinates of the centre of the grid element in radians

When using the ADEPT Gaussian dispersion model in a lat-long project (Section 3.2) the plume centre line is assumed to follow a great circle line which is the shortest line between two points over the Earth's surface. However, it is not advisable to apply a Gaussian model over distances large enough such that the curvature this assumption produces becomes apparent when plotted on a geographic co-ordinate system. For each point that ADEPT estimates air concentration and deposition it requires both the downwind distance along the plume centre line and the crosswind distance from the plume centre line. These distances on the great circle are calculated using the following expressions.

$$CW_{dist} = arcsine\left(sin\left(\frac{D_g}{E_r}\right) \times sin(brng_g - brng_{pcl})\right) \times E_r$$

$$DW_{dist} = arccos\left(cos\left(\frac{D_g}{E_r}\right) \Big/ cos\left(\frac{CW_{dist}}{E_r}\right) \right) \times E_r$$

Equation 3

Where:

CW_{dist} is the off-track distance or cross wind distance in km. This is the distance of the centre of the grid square from the nearest point on the plume centre line which is following a great circle path.

DW_{dist} is the track distance or downwind distance in km. This is the distance along the plume centre line following a great circle path from the point of release to a point that is nearest to the grid square centre.

$brng_g$ is the forward bearing of the centre of the grid square from the point of release in radians, i.e. the bearing immediately leaving the point of release of a great circle path to the centre of the grid square. A forward bearing is given by this expression.

$$y_d = y_g - y_r$$

$$x_d = x_g - x_r$$

$$y = \sin(x_d) \times \cos(y_d)$$

$$x = \cos(y_r) \times \sin(y_g) - \sin(y_r) \times \cos(y_g) \times \cos(x_d)$$

$$brng_g = \arctan2(y, x)$$

Equation 4

Arctan2 is a function that returns the arctan of y/x and if x is 0 the function returns 0.

$Brng_{pcl}$ is the forward bearing of the plume centre line in radians. The forward bearing is the initial bearing at the point of release i.e. the direction the wind is going.

2.4 Handling of spatial input data

After a nested grid is specified, input data is translated onto this grid by the Preprocess tool. The input data is provided in one or more polygonal feature classes and data from these is transferred into a single feature class called “InputData” in which the polygons represent the grid elements in the nested grid. Figure 3 shows how this translation is done. On the left is a very simple grid comprised of just three squares and on the right is the input feature class comprised of two polygonal areas. The attributes of this feature class are “milk_kg”, the amount of milk produced annually in the area, and “original_area” the area of the polygon. So, for example the area ID13 has an annual milk production of 5000 kg and an area of 4000 m^2.

PACE requires the annual milk production in each grid square. To estimate this, the grid is superimposed on the input feature class to create 4 zones within the bounds of the grid. The milk production in a zone is estimated with the following expression.

milk_in_zone_kg = milk_kg × area of zone / original area

Equation 5

The estimate of milk production in a grid square is the sum of the milk production in the zones within the grid square.

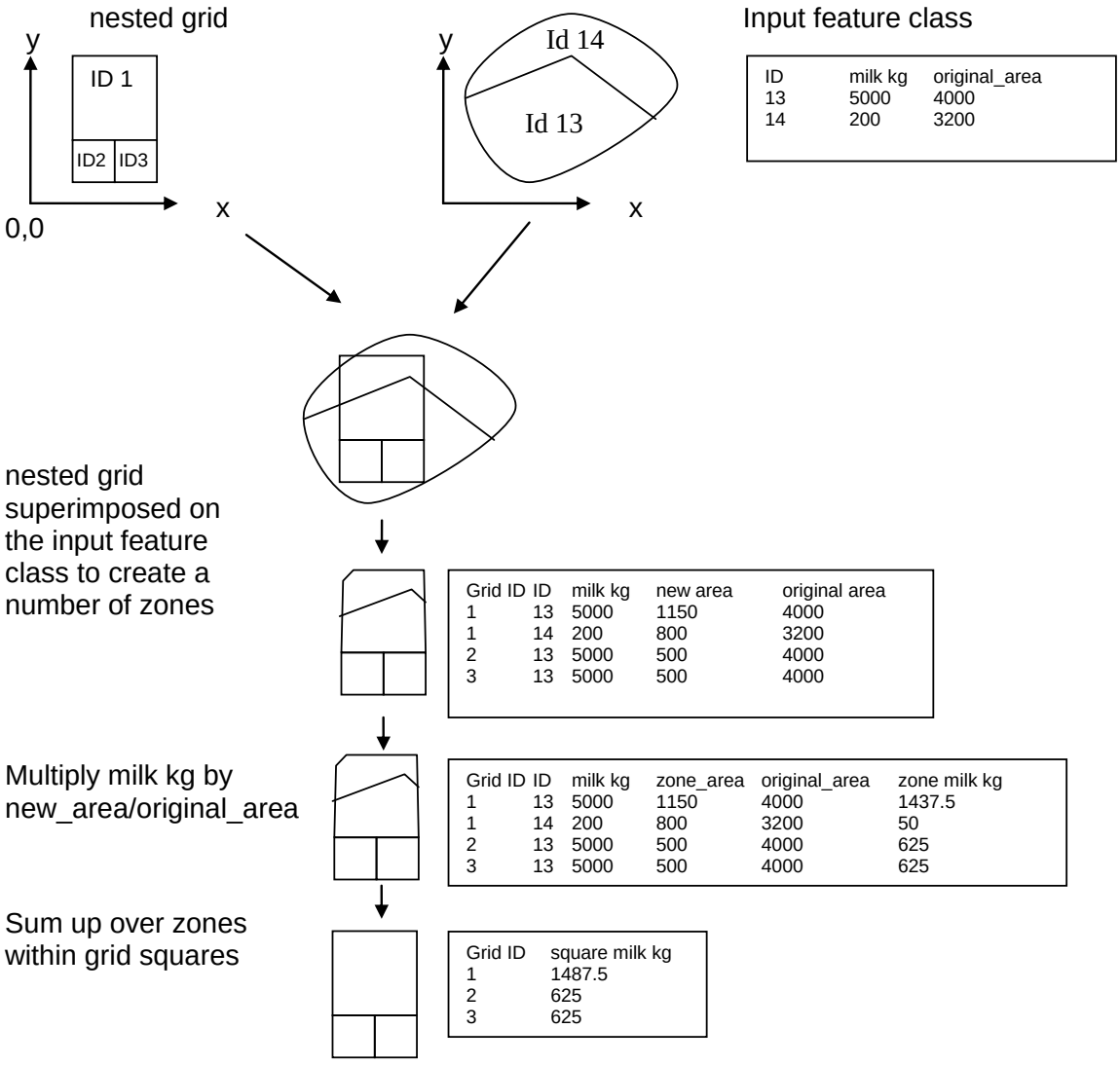


Figure 3 Resampling input spatial data to the PACE nested grid

The grid containing all the translated input data is stored as a feature class called input_data in the input geodatabase.

2.5 Spatial Input data

PACE requires a large number of spatial inputs to calculate the full range of endpoints. However, most of those inputs are for calculating ingestion dose and for economics endpoints. In order to calculate doses and health effects from non-ingestion pathways fewer inputs are required. The basic inputs, the inputs for ingestion and the inputs for the economics are

described in Table 1, Table 2 and Table 3 respectively. A full explanation of the inputs for economics are given in Higgins et al (2008).

TABLE 1 Basic Spatial Inputs

Field name	Notes	Units
IsLand	Gives the area of land within the grid element. If there is no land within the grid element PACE will omit that element from the calculations.	m^2
Population	The resident night-time population of the grid element.	Person
Area_brick	The area of brick houses within the grid element.	m^2
Area_multi	The area of multi-storey residences within the grid element.	m^2

TABLE 2 Ingestion dose spatial inputs

attribute name	Notes	Units
D_Cow_Milk_Total	Milk produced each year in the grid element	kg y^{-1}
D_Cow_Meat	Cow meat produced each year in the grid element	kg y^{-1}
D_Cow_Liver	Cow liver produced each year in the grid element	kg y^{-1}
D_Sheep_Meat	Sheep meat produced each year in the grid element	kg y^{-1}
D_Sheep_Liver	Sheep liver produced each year in the grid element	kg y^{-1}
D_Grain	Grain produced each year in the grid element	kg y^{-1}
D_Potato	Potatoes produced each year in the grid element	kg y^{-1}
D_root_veg	Root vegetables produced each year in the grid element	kg y^{-1}
D_Green_Veg_and_Legume	Green vegetables and legumes produced each year in the grid element	kg y^{-1}
D_Soft_fruit	Soft fruit produced each year in the grid element [eg strawberries, raspberries, gooseberries etc]	kg y^{-1}
D_Hard_Fruit	Hard fruit produced each year in the grid element [eg apples, pears, plums etc]	kg y^{-1}

TABLE 3 Economic spatial inputs

attribute name	Notes	Units
P_Cow_Milk	Milk producing cows in the grid element	Cows
P_Cow_Meat	Meat producing cows in the grid element	Cows
P_Sheep_Meat	Meat producing sheep in the grid element	Sheep
P_Grain	Grain producing area in the grid element	hectares
P_Potato	Potato producing area in the grid element	hectares
P_Sugar_Beet	Sugar beet producing area in the grid element	hectares
P_root_veg	Root vegetable producing area in the grid element	hectares
P_Green_veg	Green vegetable producing area in the grid element	hectares
P_legume	Legume producing area in the grid element	hectares
P_Soft_Fruit	Soft fruit producing area in the grid element	hectares
P_Hard_Fruit	Hard fruit producing area in the grid element	hectares
Totalvalue	Total value of housing stock in the grid element	£M
NetHouseValue	Total value of housing stock buildings (ie total value less land value) in the grid element	£M
RentReturn	Total yearly residential rent return in the grid element	£M
AllHouses	Total number of houses of all types (classified as household spaces) in the grid element	Houses
Tourism	Gross value added from tourism in the grid element	£M
A, B, C, DA, DB, DC, DE, DF, DG, DH, DI, DJ, DK, DL, DM, DN, E, F, G, H, I, J, K, L, M, N, O	Gross value added from industry categories in grid element. Letters are Standard Industry Classification (SIC) codes (see Higgins et al (2008) for fuller explanation)	£M
CapValInd	Capital values of industry in the grid element	£M
CapValRet	Capital values of retail in the grid element	£M
CapValWare	Capital values of warehousing in the grid element	£M
CapValOff	Capital values of offices in the grid element	£M
Domestic	Area of domestic houses in grid element	m^2
Gardens	Area of gardens in grid element	m^2

3 Atmospheric Dispersion

3.1 Introduction

PACE incorporates two atmospheric dispersion models; a Gaussian plume model called ADEPT and a lagrangian particle model developed by the Met Office in the UK called NAME. NAME is a more sophisticated model and is run in a separate tool within PACE. The technical detail and methodology for the NAME model is available in other publications (Jones et al, 2007a), this section specifically describes how NAME has been implemented within PACE.

For each grid element in each met sequence, the PACE calculations that use the atmospheric dispersion model output require estimates of the hourly time integrated concentration of activity in air (TIAC) and deposition onto the ground. In addition, the NAME model provides hourly estimates of effective dose from external exposure to radioactive material in the plume or cloud shine.

3.2 ADEPT Gaussian Model

In the absence of a NAME run, atmospheric dispersion is modelled in PACE using a straight-line Gaussian plume model called ADEPT. The formulation is described in Clarke (1979) and Jones (1981).

ADEPT uses hourly single site met data only. The release is broken down into hours and the material in each hour of the release is assumed to travel through the air and be deposited within that hour regardless of the distance to the point of deposition. Therefore, if there is only one hour of release the plume will move in the wind direction for that hour and the plume centre line will be straight. If there are several hours of releases the total plume is a composite of several straight-line plumes that may be going in different directions.

The Gaussian formulation is a continuous function and the value of TIAC or ground deposition of a radionuclide given to any grid square is the value calculated for the centre of the grid element.

3.3 NAME Lagrangian Particle Model

PACE 3.3.2 uses the NAME3 (version 6.5) atmospheric dispersion model developed by the UK Met Office (Jones et al, 2007a). NAME is part of the Met Office's real-time weather and dispersion prediction capability. NAME uses a Lagrangian approach and simulates particles moving within a 3-dimensional grid.

NAME 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 real-time dispersion predictions of NAME in combination with the UM enable predictions to be made of the instantaneous and time integrated activity concentrations in air, and wet, dry and total ground depositions of radionuclides. NAME estimates external dose ('cloud gamma') from the radioactive plume.

NAME can use single site data or NWP data. The formats of NWP data allowed by PACE are given in Table 4.

NAME supports radioactive decay both in the air and after deposition. However, in PACE, NAME is run so that no radioactive decay occurs on the ground because such decay is implicit in the dose factors. NAME allows the in-growth of progeny radionuclides. Such progeny radionuclides can also have further progeny and so on however it is a restriction on NAME that each radionuclide can only have one progeny. Within PACE, in-growth will only be considered for a parent-progeny combination if both are explicitly included in the source term, and a progeny radionuclide may be included in the source term with zero release to allow such in-growth to be considered. If two progenies for a radionuclide are included in the source term, then only the in-growth of the progeny associated with the greatest branching ratio will be modelled. PACE allows iodine to have different forms, elemental, aerosol and organic. These are represented in NAME as separate species with the suffixes of E, A and O respectively. Any parent of an iodine isotope is assumed to decay into elemental iodine only.

TABLE 4 NWP formats supported by PACE

Met data type	Notes
MESUM5	Available from 7/8/2002 to 2/4/2009, a Mesoscale domain covering UK, Ireland and most of France with 12 by 12 km horizontal grid
REGUM5	Available from 01/11/2005 to present, a regional scale domain covering Europe and the North Atlantic with approximately 40 by 40 km horizontal grid
4KM50L_UM6	Available from 26/11/2007 to present. High resolution data on 4 by 4 km horizontal grid

NAME can be run on multiple threads (processors) to shorten run times however this can mean there are small differences between runs with identical inputs because threads may access the random number generator used for NAME calculations in a different order in different runs. If exact repeatability is required, then NAME should be run with a single thread only.

3.3.1 External exposure from radioactive material in the plume

NAME has the capability to calculate the effective dose arising from cloud gamma using a finite or semi-infinite cloud model. The finite cloud model involves simulating the plume by a series of model particles (point sources), estimating the contribution to dose at a point from each individual particle as it disperses through the environment and then integrating over these particles to estimate the total dose (Bedwell et al, 2010). 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. Application of the semi-infinite cloud model under non-uniform activity concentrations in air may result in an over or underestimate of dose. For example, when a plume has been released at height and has yet to descend to ground level. This is most likely to occur close to the release point. Further downwind, where there is greater dispersion, differences between the two models will be less pronounced.

Because the finite cloud model is much more computationally expensive it is only used for the inner most grid of the PACE nested grid arrangement where non-uniform activity concentrations are most likely to occur. Model comparisons and analysis indicate that beyond 7 km from the release the semi-infinite cloud approach will always be representative and therefore the inner most grid can be defined accordingly.

In PACE it is possible to select the type of environment where the exposure occurs. The environment accounts for the types of buildings and shielding they provide, see Section 5.1.4.

3.3.2 Temporal and spatial domains

Important inputs to NAME are the temporal and spatial domains in which the Lagrangian particles move. Large domains are more realistic because for real world particles the spatial domain is global and the temporal domain unlimited. In NAME when a particle leaves the spatial domain it is destroyed even if subsequent weather conditions might have moved it back into the domain and when NAME has run to the end of the temporal domain no further air concentrations are calculated and no further deposition occurs. However large spatial and temporal domains are associated with relatively long model run times and large temporal domains result in more data being generated.

The NAMErun tool sets the spatial domain automatically. For a BNG co-ordinate system the spatial domain is set to encompass the British Isles and is a box bounded between longitude 4°W to 10°E and 48°N to 62°N. For a lat-long co-ordinate system the spatial domain is set to be 2° of latitude or longitude larger than the largest grid specified by the user.

The temporal domain is set by the user and can have a profound effect on run times and the amount of data generated. Setting it is a matter of judgement. Certainly, the temporal domain should be larger than the release duration to allow time for the last particles released to travel sufficiently far to impinge on the population. This may be less crucial if the release tails off and more important if there is a spike at the end of the release. It should be large or larger than the *Emergency ends* parameter (see Section 1.4). If the main interest is focussed on areas close to the site of the release then the travel times from the point of release will be small and so the temporal domain can be small, for example a few hours longer than the release period. If the interest is in the impact on a national or international scale, then the travel times will be long and a temporal domain 24 to 48 hours (or more) beyond the end of the release may be appropriate.

3.4 Plume rise

When using the ADEPT model, the user must account for plume rise by including the effective release height in the source term specification. The classic approach to calculating plume rise and effective height is the Briggs model (Briggs, 1975).

The user can follow this approach when using the NAME model or, alternatively they can specify the parameters that allow NAME3 to estimate the plume rise. This is the preferred approach because plume rise depends on the meteorological conditions as well as the energy and momentum of the release. However, this is a complex calculation that will extend run times and require additional information from the user. The user must provide a stack diameter (the stack is assumed circular), a release temperature, and either an exit velocity or

a volume flow rate. These parameters are assumed to be constant for the whole release period. The correct use of the NAME plume rise calculation is documented in Jones (2015).

4 Source Term

For the calculations within PACE, a description of the material released is required. This description is called a source term and is a comprehensive specification of the quantity of radionuclides released to the atmosphere during a given accident. The source term gives the timing of different phases of the accident and the amounts of different radionuclides released in each phase. It includes other information such as the release height and the fraction of the different forms of iodine released.

This is not calculated by PACE but is an input. A source term is specified as an XML file with a certain structure. This file can be written manually or constructed using the source term tool. The source term tool also performs a basic analysis of the source term to allow the radionuclides that contribute most to dose to be identified and those that are less important to be eliminated. Elimination can reduce the calculation burden significantly.

4.1 Restrictions on the Source term

The source terms that PACE can handle can be very varied but there are restrictions. A source term is made of one or several phases and each phase must be a whole number of hours long. Each phase has a release height which is restricted to between 0 and 2000m.

PACE can handle a long release up to 30 days in total, however long releases are very resource intensive.

PACE can handle up to 30 different radionuclides over all releases including progeny. However, releases involving many radionuclides are very resource intensive.

4.2 Source term evaluation

The Sourceterm tool performs a simple dose assessment using the ADEPT dispersion model. The tool considers one receptor point on the plume centre line and assumes constant meteorological conditions, i.e. the whole release is carried towards the receptor. The tool considers outdoor doses, i.e. no location factors are applied. The tool uses the same dose calculations as the main tool, and considers cloud shine (Section 5.3), inhalation (Section 5.2), ground shine (Section 5.4), resuspension (Section 5.5) and individual ingestion dose (Section 5.7.2). The doses are presented to the user and can be ranked by percentage contribution, and any radionuclides contributing less than a specified percentage can be removed.

Table 5 gives the default values that the tool assumes but these can all be changed by the user.

TABLE 5 Default values for dose contribution evaluation in the Sourceterm tool

Input	Default value
Receptor location	3km downwind
Stability category	D
Windspeed	5 m s^{-1}
Rainfall	0 mm h^{-1}
Integration period	365 days (for external dose and resuspension)
Mixing layer	800m
Day of year	180 (i.e. a midsummer release when cattle and many crops are in the fields)
Location consumption	0.25 (the fraction the fraction of consumption that is local, only this fraction is assumed contaminated, the remaining fraction is assumed uncontaminated (this differs from the main PACE consequence calculation, see Section 5.7.2)

It should be noted that ADEPT is a simple model that does not account for the in-growth of progeny. If it is intended that the NAME model is used for the PSA then it may be important to include progeny even if they apparently do not contribute to the dose in this simple analysis.

5 Dose Calculation

5.1 Introduction

Dose calculations are performed on each grid square independently. Effective dose and doses to individual organs (Table 6) are calculated for several pathways (Table 7).

TABLE 6 Organs considered in PACE

Lung	Eye	Breast	Oesophagus	Remainder
Thyroid	Ovaries and uterus	Stomach	Gonads	
Bone marrow	Skin	Colon	Ovary	
GI-tract	Bone surface	Liver	Bladder	

TABLE 7 Pathways considered in PACE

Pathways	Label	Dose type	Notes
Internal exposure from radioactive material inhaled from the plume	Inhalation	Individual	
External exposure to radioactive material in the plume	Cloud shine	Individual	
External exposure to radioactive material deposited on the ground	Ground shine	Individual	
Internal exposure to inhaled resuspended radioactive material	Resuspension	Individual	
External exposure to radioactive material deposited on skin and clothes.	Skin deposition	Individual	Only doses to skin are calculated other organs and effective doses are omitted
Internal exposure to radioactive material ingested by consuming contaminated food	Food	Individual and collective	The collective dose in a grid square is dose to the whole population from consuming the food produced in the grid square and not to the population within the grid square. For the individual dose calculation, it is assumed an individual in a grid square consumes a proportion of his diet from crops grown locally and the remainder from national supplies. See Section 5.7.

PACE reports dose endpoints directly to the user (for example the DS, PL and RC categories, see Section 1.3) but it also uses various dose endpoints internally to calculate other endpoints including whether countermeasures are required (category CM) and what health effects can be expected in the population (category HE and HECM). The methodology for calculating all

these doses is the same and is given below in this section. However, the inputs to the calculations in different categories may be subtly different. This means the doses presented to the user may be different from the dose used internally by PACE to calculate other endpoints.

For example, the individual DS and DSCM doses presented to the user include complex time dependent location factors that account for time spent indoors and outdoors, different built environments and also the imposition of countermeasures in the case of DSCM endpoints. However, the CM calculations that ascertain whether emergency countermeasures are required use doses that are calculated with simple location factors which by default assume that the population is outdoors and that countermeasures have not been applied.

Another example is for deterministic health effects. The inhalation DS doses presented to the user are committed doses, i.e. they include the doses accrued over the whole lifetime of the individual because radionuclides once inhaled can be in the body for many years. However, the inhalation doses used to calculate deterministic health effects only include the doses in a short period following the inhalation as the dose-rate is required factor in estimating such effects.

The PL endpoints are hourly doses during the passage of the plume. The purpose of the PL doses is to enable specific movements by the individuals to be examined in an ad hoc way external to the PACE calculation. A dose in the PL output either assumes the individual is outdoors for one hour (i.e. a location factor of 1.0) or indoors for an hour, in which case the sheltering location factor is applied regardless of whether CM predicts that sheltering would be required.

PACE assumes that the whole population is adult, and for long term doses from deposited radionuclides it assumes that there is no population movement other than evacuation or relocation. The age group can be changed but this will give some inconsistent results when looking at long term doses and health effects.

5.1.1 Timing

Timing aspects need to be considered in the calculation of doses. In each grid square the passage of the plume is represented by hourly TIAC and deposition estimates. During the passage of the plume various countermeasures may be enacted such as sheltering, evacuation and stable iodine prophylaxis which may modify parts of the exposure and the relative timing of such measures are a required input to the dose estimation.

In the following discussion nH is the number of hours for which TIAC and deposition estimates are provided to the dose calculations.

5.1.2 Location factors

Location factors (LF) are used to modify a dose calculated for standard conditions (usually outdoors in the middle of a large grass surface) to account for environment, occupancy and countermeasures. Therefore, they can change during the passage of the plume and beyond.

PACE considers location factors in the short and long term. Long term location factors are applied to ground shine and resuspension which give doses over months and years and have a time dependency that accounts for weathering.

In the short-term PACE recognises 5 exposure situations for a population as given in Table 8.

TABLE 8 Short term exposure situations

Exposure situation	Shortened label	Notes
Default	Default	The normal situation in pre-accident situations and after the emergency has passed. The population spend time indoors and outdoors.
Countermeasures imminent	Pre-CM	The situation when an emergency has happened, but countermeasures have not been enacted
Sheltering	Sheltering	The situation for a population instructed to shelter.
Evacuated	Evacuated	The situation when a population is evacuated. The population is assumed to get no dose in this situation and so the location factor for all pathways is implicitly zero
Evacuating by car or other vehicle	Car	The situation when a population is in the process of being evacuated

PACE assumes that when the population is in a vehicle there is no protection, so all location factors are implicitly 1.0.

In the long-term there are only three exposure situations; the default, the population is relocated and the default but with clean-up applied. As with the evacuated situation, the relocated population is assumed to get no dose and the relocated location factor for all pathways is implicitly zero. LF for clean-up are not specified directly but are obtained by applying a dose reduction factor appropriate for the pathway and for the level of clean-up applied.

The location factors used in PACE account for both the protection that the building offers from the dose pathway and the relative amount of time the population spends in the building and outdoors. The default location factor values are described in Appendix A1.3.

To calculate doses to the public over a protracted period, PACE combines location factors according to the timing of different events which trigger different exposure situations. For example, in a grid square where sheltering is required there is an initial delay in which the pre-CM location factors are used (by default this delay is 2 hours), then sheltering location factors are used up to the ‘Emergency-ends’ time (see Section 1.4) and after that the default location factors are used. Similarly, if evacuation is required then there is an initial delay, followed by a period of sheltering while the population awaits transportation, followed by a period of driving, then the population is assumed evacuated until the end of the emergency (specified by the user via the ‘Emergency-ends’ parameter) and then again, the default location factors are used.

Table 9 gives the default timing for different events for different situations. A user can omit certain events by changing the default times. For example, the initial delay can be omitted by changing the default time of 2 hours to 0 hours. Relocation may also be applied after evacuation or sheltering.

TABLE 9 Default timing of events and how location factors are applied when different countermeasures or no countermeasures are enacted

Event	No countermeasures	Sheltering only	Evacuation only	Relocation
Initial Delay	Default LF applied throughout	Pre-CM LF for 2 hours	Pre-CM LF applied for 2 hours	Default LF applied unless sheltering or evacuation is enacted.
Duration of sheltering before evacuation			Sheltering LF applied for 2 hours	
Drive time during evacuation			Car LF applied for 1 hour	
Emergency countermeasure enacted		Sheltering LF applied until emergency ends	LF of zero applied until emergency ends	
Emergency countermeasure lifted, relocation enacted		Default LF applied from emergency end	Default LF applied from emergency end	LF of zero applied until relocation no longer required as calculated by PACE

The plume passage is represented by hourly TIAC estimates but LF periods can be arbitrary. Therefore, the LFs must be resampled to the TIAC hours before a dose calculation on exposure to TIAC can commence. The LF for an hour is given by the following expression in Equation 6 and illustrated in Figure 4.

$$LF_h = \sum_{p=1}^{nLF} LF_p \times Frac_{hp}$$

Equation 6

Where:

LF_h is the location factor in hour h.

nLF is the number of LF periods that intersect with hour h.

LF_p is the location factor in LF period p.

$Frac_{hp}$ is the fraction of hour h in LF period p.

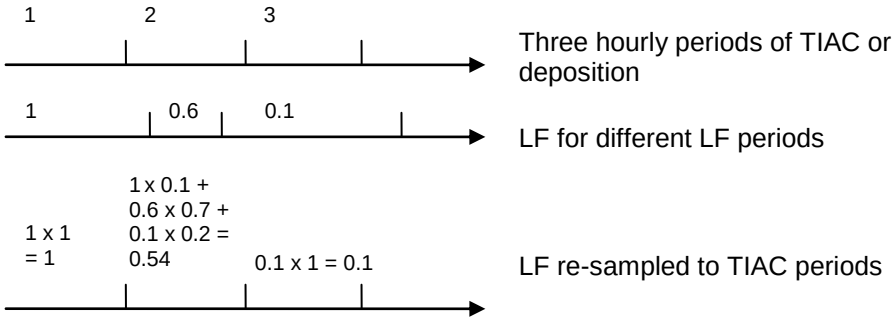


Figure 4 Resampling of location factors to hours

Exposure to deposited radionuclides continues beyond the hour in which they are deposited and beyond the end of the plume passage. In this case LF are not resampled to the hours of the plume passage but are applied to the output times for which dose calculations are required. However, output times and location factor periods do not necessarily match. Therefore, the calculation of exposure to deposited radionuclides joins the sets of output times to the set of location factor periods to produce a single set of times known as result times to which the LFs can be applied. The joining of Output times and LF periods is shown in Figure 5. Doses are calculated within Results periods and then summed to the Output times required.

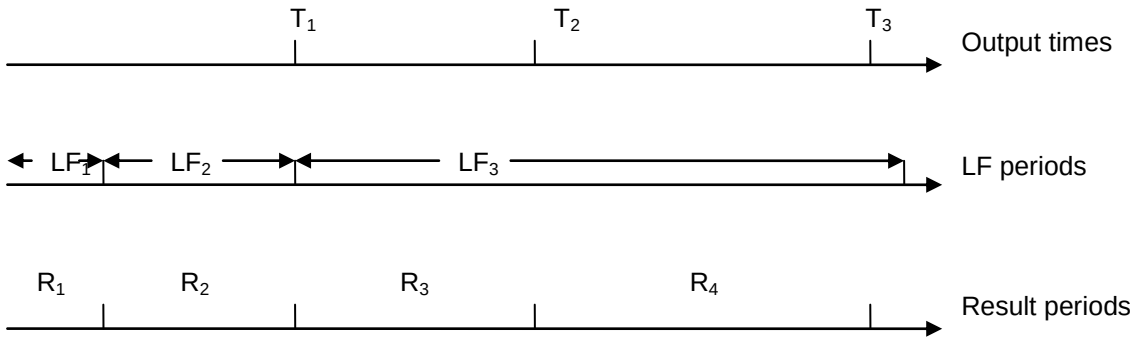


Figure 5 The joining of LF periods and output periods for the purposes of calculating external doses from deposited radionuclides

5.1.3 Radionuclide form

All radionuclides except iodine and noble gases are assumed to be in one physical form; a particle with an aerodynamic diameter of 1 µm. Dose coefficients are chosen appropriately and assumed lung absorption rates are in accordance with advice provided in NRPB (1999).

Iodine can be in aerosol, organic or elemental form. The fractions of the forms are specified in the source term. Dose coefficients are chosen appropriately and assumed lung absorption rates are in accordance with advice provided in NRPB (1999).

In the following discussion nF_n is the number of forms for a radionuclide n. It will be 3 for isotopes of iodine and 1 for all other radionuclides.

5.1.4 Built environment

The individual doses calculated in PACE can only be representative values of the grid square. Doses vary between individuals because of individual behaviour and heterogeneity in environment and contamination. It is impossible to capture all variability, but PACE goes a little further than previous PSA codes by allowing two built environments to be considered.

Different built environments give rise to different doses because of the shielding properties of buildings and proportions of surfaces with different retention properties. They also respond differently to clean-up countermeasures. The variations are captured by using environment specific sets of location factors, population densities, clean-up dose reduction factors and costs.

For all non-ingestion pathways PACE calculates doses in environment-1, doses in environment-2, weighted average doses based on an estimate of relative population dwelling in each environment in the grid square and the maximum dose. The average individual dose (D_{avg}) is given by Equation 7.

$$D_{avg} = \sum_{e=1}^{2} D_e \times \frac{PopDens_e \times Area_e}{TotalPop}$$

Equation 7

Where:

D_e is individual dose estimated for environment e

$PopDens_e$ is the population density of environment e

$Area_e$ is the area of environment e in the grid square.

TotalPop is the total estimated population of the grid square given by Equation 8.

$$TotalPop = \sum_{e=1}^{2} PopDen_e \times Area_e$$

Equation 8

The default data for environment-1 represents an environment in which the dwellings are brick houses. Default data for environment-2 represents one in which the dwellings are flats within multi-storey apartment buildings (Table 10). The location factors, dose reduction factors and clean-up costs were calculated using the ERMIN model (Jones et al, 2007c) assuming a unit deposition of ^{137}Cs to a grass surface in the two built environments.

TABLE 10 Default Built Environments considered in PACE

PACE Environment	Represents	ERMIN Environments used
1	Brick built houses	90% 'Street of semi-detached houses without basement', with 'default' parameter set 10% 'Large open space', with 'park' parameter set
2	Multi-storey blocks of flats	70% 'Multi-storey block of flats amongst other house blocks', with 'default' parameter set 20% 'Multi-storey block of flats opposite parkland', with 'default' parameter set 10% 'Large open space', with 'park' parameter set

It should be noted that with the default environments the maximum dose is almost always given by the brick house environment.

5.2 Internal exposure from the inhalation of material in the plume

In this document, this pathway is termed inhalation dose for brevity.

Values of inhalation dose coefficients are taken from ICRP (2012) Publication 119. The dose coefficients assume an adult member of the public and a particle size of 1 µm. The doses are committed to age 70 years, for the relevant organs and effective dose.

The dose from inhalation of material in the plume is given by Equation 9.

$$DI_{onet} = \sum_{h=1}^{nH} \sum_{f=1}^{nF_n} TIAC_{nhf} \times BR \times LF_{eh} \times SI_{nh} \times DCI_{onf} \times Frac_h$$

Equation 9

Where:

nH is the number of hours (which truncated by the total integration time for that is shorter than the plume passage)

nFn is the number of chemical forms that the radionuclide is present in (for most radionuclides a single form is assumed but for iodine it can be up to three).

DI_{onet} is the dose to organ o from internal exposure to radionuclide n in the plume in environment e from time 0 to time t, in Sv.

$TIAC_{nhf}$ is the time integrated air concentration of radionuclide n in form f in hour h, in Bq s m^{-3}.

BR is the breathing rate in m^3 s^{-1}.

LF_{eh} is the inhalation location factor for hour h in environment e, which accounts for environment, occupancy and sheltering or evacuation.

SI_{nh} is the dose reduction factor for radionuclide n in hour h due to stable iodine administration.

DCI_{onf} is the inhalation dose coefficient to organ o for radionuclide n in form f in Sv Bq^{-1}

$Frac_h$ is the fraction of the hour h that occurs in integration period 0 to t.

The factor SI is calculated for each hour and radionuclide to account for the effect of administering stable iodine prophylaxis. The factor SI is only relevant for the thyroid organ dose and is assumed to be 1 for all other organs. If the stable iodine tablets are taken 0.25 hours or more before inhalation, then the subsequent thyroid dose from iodine and tellurium is assumed to be 0. Once they have taken effect, stable iodine is considered to be effective for as long as the pathway is relevant (in practice, this translates to the affected population being advised to take multiple doses in the event of an extended release). For this calculation, the conservative assumption is made that all material in an hour is inhaled at the start of that hour.

$$SI_{nh} = 0 \qquad \text{if } t < 0.25 \text{ hours}$$

$$SI_{nh} = 1 - e^{\left(-0.693 \times \frac{t+0.25}{4}\right)} \qquad \text{if } t \geq 0.25 \text{ hours}$$

Equation 10

Where t is the time in hours between the start of the hour hstart and the time T, at which the tablets are taken, and is given by the following expression.

$$t = (T - hstart)$$

Equation 11

5.3 External exposure from radioactive material in the plume

In this document, this pathway is termed cloud gamma or cloud shine for brevity.

The method used for calculation of cloud gamma varies depending on whether NAME or ADEPT is used to calculate atmospheric dispersion.

NAME has the capability to calculate the hourly effective dose in each grid square arising from cloud gamma see Section 3.3.1. For other organs the effective dose is scaled using factors derived from ICRP publication 74 (ICRP, 1996), see Appendix A1.5.3.

ADEPT does not calculate cloud gamma, so PACE calculates an hourly cloud gamma dose to all organs using the hourly TIAC at the point of exposure and factors based on a semi-infinite cloud model. 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 this 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 where activity concentrations are greater at height than those on the ground where the dose is delivered. This is most likely to occur close to the release point. Further downwind, where there is greater dispersion, differences between the two models will be less pronounced.

To account for this, the user can choose to apply cloud gamma correction factors to ADEPT. PACE cloud gamma correction factors were calculated using a Monte Carlo approach for 2 roughness categories, 4 stability classes, 4 release heights, ten angles from the plume centre line and 8 distances from the point of release. These factors used at a given point for a given release, roughness category and stability class need to be interpolated horizontally and vertically. The cloud gamma correction factors were developed for PC Cosyma (Jones et al, 1995) and they cause a noticeable narrowing of the plume cloud shine out to 20km when viewed on a map.

The total cloud gamma dose accounting for environment, occupancy and countermeasure is given by the following expression

$$DCS_{onet} = \sum_{h=1}^{nH} \sum_{f=1}^{nF_n} DCS_{onh} \times LF_{eh} \times Frac_h$$

Equation 12

Where:

nH is the number of hours (which is truncated by the total integration time if that is shorter than the plume passage)

nFn is the number of chemical forms that the radionuclide is present in (for most radionuclide a single form is assumed but for iodine it can be up to three).

DCS_{onet} is the dose to organ o from external exposure to radionuclide n in the plume from time zero to t in environment e, in Sv,

DCS_{onh} is the dose to organ o from external exposure to radionuclide n in the plume in hour h in Sv,

LF_{eh} is the cloud gamma location factor for environment e in hour h, and

$Frac_h$ is the fraction of hour h that occurs in integration period 0 to t.

5.4 External gamma dose from deposited radioactive material

In this document, this pathway is sometimes called ground shine for brevity.

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 for the PC Cosyma software (Jones et al, 1995) 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 γ dose from typical accidental releases from nuclear fission reactors (Ru-103, Ru-106, I-131, Te-132, Cs-134, Cs-137, and Ba-140) were calculated using the NRPB model EXPURT (Crick and Brown, 1990). This considers the amounts of material deposited on different surfaces (e.g. walls, roofs, grass, soil) 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 γ 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 absorbed dose in air. 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. For example, the factors 0.97 and 0.73 for the lung and bone marrow, respectively, were derived from ICRP (1996) publication 74 and are applied in this study.

The ground shine dose from time zero to T to organ o from radionuclide n in environment e is given by the following expression.

$$DED_{oneT} = \sum_{R=1}^{nR} \sum_{h=1}^{nH} (DCED_{onhR} - DCED_{onhR-1}) \times LF_{eR} \times Dep_{nh}$$

Equation 13

Where:

nR is the number of result periods in T see Section 5.1.2 for a discussion on results periods.

nH is the number of hours.

Dep_{nh} is the deposition of a radionuclide n in hour h summed over all forms, Bq m^{-2}.

$DCED_{onhR}$ is the ground shine dose coefficient to organ o from time 0 to end of period R for deposition in hour h without taking into account location factors, Sv per Bq m^{-2}.

$DCED_{onhR-1}$ is the ground shine dose coefficient to organ o from time 0 to end of period R-1 for deposition in hour h without taking into account location factors, Sv per Bq m^{-2}.

LF_{eR} is the ground shine location factor applicable to period R in environment e.

The data library only provides dose per unit deposition coefficients from time 0 to a set of fixed times. These standard dose coefficients need to be modified to account for result periods that will not necessarily match dose coefficient times and that for hours after the first hour there is a delay in deposition. The modified dose coefficient is given by the following expression. The deposition is assumed to occur at the start of each hour.

$$DCED_{onhR} = (DCED_{ont} - DCED_{ont-1}) \times Frac_R + DCED_{ont-1}$$

Equation 14

Where:

$DCED_{ont}$ is the library ground shine dose coefficient to organ o from radionuclide n from time 0 to time t, Sv per Bq m^{-2}.

$DCED_{ont-1}$ is the library ground shine dose coefficient to organ o from radionuclide n from time 0 to time t-1, Sv per Bq m^{-2}.

t is the lowest library dose coefficient time that is equal to or greater than the time DT,

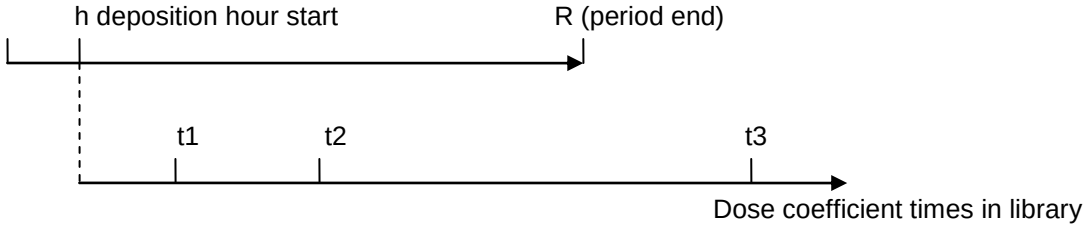
t-1 is the highest library dose coefficient time less than time DT,

h is the start time of the hour of deposition.

DT is the time the deposition has been on the ground and is end of results period R - h

$Frac_R$ is the fraction of the period from t-1 + h to t + h that overlaps with the results period 0 to R

An example of the resampling of dose coefficients is illustrated in Figure 6.



$DCED_{onhR} = DCED_{nt2} + (DCED_{nt3} - DCED_{nt2}) * Frac_R$

$Frac_R = (R - h - t_2) / (t_3 - t_2)$

Figure 6 Resampling library dose coefficients to results periods

5.5 Dose from inhalation of resuspended material

In this document, the dose from inhalation of resuspended radioactive material pathway is termed resuspension dose for brevity.

Values of time-integrated activity concentration in air per unit deposit are derived using an approach recommended by (Wellings et al, 2019) based on the estimation of resuspension factors. The approach is centered on the Garland formula (Garland, 1979) and adapted to include a long-term resuspension factor. This approach is empirical in nature and therefore takes account of removal processes (for example, uptake by plants and the infiltration and percolation in the soil system). The approach is based on a rural location and not an urban location, which would result in different 'sinks' of radioactivity, for example many hard surfaces retain material because of chemical fixing and the pitted nature of the surface.

The calculation is similar to the ground shine calculation as exposure to deposited radionuclides continues beyond the end of the plume passage and therefore location factors are not applied to hourly deposition periods but are applied to the output times as discussed in Section 5.1.2.

The resuspension dose from time zero to T to organ o from radionuclide n in environment e is given by the following expression.

$$DR_{oneT} = \sum_{R=1}^{nR} \sum_{h=1}^{nH} TIAC_{nhR} \times LF_{eR} \times BR \times DPUI_{on}$$

Equation 15

Where:

nR is the number of result periods in time T.

nH is the number of hours.

$TIAC_{nhR}$ is the time integrated concentration in air of radionuclide n summed over all forms from resuspension in hour h in period R in Bq s m^{-3}.

LF_{eR} is the resuspension location factor applicable to period R in environment e.

BR is the breathing rate in m^3 s^{-1}.

$DPUI_{on}$ is the dose per unit intake to organ o of radionuclide n.

Resuspension doses are generally low compared to other pathways and are only significant over months and years, therefore the effect of stable iodine prophylaxis on resuspension which is only effective in the first few hours and days of an accident is ignored.

PACE treats the resuspension factor calculation as comprising three components. The first component is resuspension over the first day. Over the first 24 hours the resuspension factor is assumed to be constant and resuspension only reduces as a function of radioactive decay and so this component can be integrated analytically. The second component is resuspension after the first day. After the first day, the resuspension factor reduces with time. This component must be integrated by an approximation and the approximation used is that given in Appendix C3 of (Wellings et al, 2019). The third component is a constant long-term resuspension factor that underlies the other two components, the long-term factor is small and only becomes significant at long times, it can be integrated analytically.

The resuspension calculation treats the three components separately and sums the integrated air concentration component from each at the end of the calculation. The calculation accounts for the delay in deposition for deposition that occurs hours after the first hour.

The first component, which accounts for the assumption that over the first day the resuspension factor K is constant, is given by the following expression:

$$TIAC_{1nh} = 82400 \times K \times {}^{1}/_{\lambda_n} \times \left[1 - e^{(-\lambda_n \times Frac_{day1})}\right] \times Dep_{nh}$$

Equation 16

Where:

$TIAC_{1nh}$ is the time integrated concentration in air of radionuclide n deposited in period h due to resuspension in the first 24 hours after deposition, Bq s m^{-3},

K is a constant resuspension factor of by default 1.2 10^{-6} m^{-1},

λ_n is the decay constant of radionuclide n, in day^{-1},

$Frac_{day1}$ is the fraction of the first 24 hours after deposition that intersect with the results period. For example, if the output time is one day and the deposition period started at 12 hours then the fraction is 0.5, and

Dep_{nh} is the deposition of radionuclide n in period h summed over all forms, Bq m^{-2}.

The second component accounts for the assumption that after the first day the resuspension factor K reduces according to Garland's formula. This cannot be integrated analytically and a polynomial approximation is used.

$$TIAC_{2nh} = 82400 \times Dep_{nh} \times \int_{1}^{time_h} Kt^{-1}e^{-\lambda_n t}dt \quad \text{if } time > 1day$$

Equation 17

Where:

$TIAC_{2nh}$ is the time integrated concentration in air of radionuclide n deposited in hour h due to resuspension after the first 24 hours after deposition, Bq s m^{-3},

K is a constant resuspension factor of by default 1.2 10^{-6} m^{-1}, and

$time_h$ is the time given by output time - the start time of the deposition hour h, in days.

The third component, which accounts for a smaller long-term component of resuspension, is given by the following expression

$$TIAC_{3nh} = 82400 \times KT \times {}^{1}/_{\lambda_n} \times \left[1 - e^{(-\lambda_n \times time_h)}\right] \times Dep_{nh}$$

Equation 18

Where:

$TIAC_{3nh}$ is the time integrated concentration in air of radionuclide n deposited in period h due to long term resuspension, Bq s m^{-3},

KT is a constant resuspension factor of 1 10^{-9} in m^{-1}, and

λ_n is the decay constant of radionuclide n, in day^{-1},

The total air concentration for a radionuclide and deposition period is the sum of the three components.

5.6 Skin dose from deposition on skin and clothing

In this document, this pathway is sometimes called skin deposition or skin deposition dose for brevity. In PACE only skin deposition doses to the skin organ are considered, doses to other organs are not. It should also be noted that other pathways also contribute doses to the skin organ.

Deposition on skin, hair and clothes and clearance from those surfaces involves a number of complex processes (Andersson et al, 2004; Fogh et al, 1999). Factors that affect deposition and clearance include weather, skin moisture, human activity, particle size and chemical properties.

PACE uses a simple model wherein deposition on to skin, hair and clothes is treated the same with the same parameters. Skin dose from deposition on skin and clothing is calculated by estimating the integrated amount of material deposited on skin and clothes. This is done by applying a deposition velocity to the hourly TIAC values and applying a retention half-life and a simple cut-off that accounts for removal of clothes and washing. The integrated activity is multiplied by a quantity, the dose rate per unit deposition, which is obtained from a data

library. A suitable library, giving the dose per second per unit deposit at a series of times for each of a large number of radionuclides, including the contribution from progeny products formed after deposition, is provided with the PACE system. The calculation of this library is described in Appendix F.

PACE applies different cut-offs to the general population and to the populations that have been subject to sheltering and evacuation. The sheltering and evacuation cut-offs cannot be longer than the general cut-off and PACE will truncate them if they are.

The calculation assumes that all deposition in an hour occurs instantaneously at the start of the hour. Environment specific location factors are first adjusted to TIAC periods as described in Section 5.1.2. The dose accounts for radioactive decay and skin retention half-life and cut-off. The dose to skin is given by the following expression

$$DSD_{net} = \sum_{h=1}^{nh}\sum_{f=1}^{nf} TIAC_{nhf} \times VD_{nf} \times SkinFrac \times LF_{eh} \times \frac{1}{(\lambda_n + \lambda_r)} \times \left[1 - e^{-(\lambda_n+\lambda_r)(t-h)}\right] \times 82400 \times Frac_h \times DCSD_n$$

Equation 19

Where:

DSD_{net} is the Dose to skin from deposition on skin of radionuclide n in environment e in time t, in Sv.

$TIAC_{nhf}$ is the time integrated concentration in air of radionuclide n of form f in hour h, Bq s m^{-3},

VD_{nf} is the deposition velocity that relates skin deposition to air concentration of radionuclide n in form f, in m s^{-1}.

SkinFrac is the fraction of skin contaminated,

LF_{eh} is the skin deposition location factor in environment e and hour h,

λ_n is the decay constant of radionuclide n in day^{-1},

λ_r is the decay constant of skin retention in day^{-1},

$DCSD_n$ is the dose coefficient for the skin for the radionuclide n in Sv s^{-1} per Bq m^{-2},

$Frac_h$ is the fraction of TIAC hour h that occurs in integration period 0 to t,

t is minimum of time in days of output time and the cut-off time:

$$t = \min(\text{output time}, \text{cut-off time})$$

Equation 20

h is start time of the TIAC hour in days.

5.6.1 Default skin deposition and retention parameters

The PACE default data for retention includes a 30-day half-life for retention on skin and clothes and a general cut-off period of 5 days. There are also specific cut-offs for people subject to evacuation and to sheltering which are equal to the Emergency ends time + 6 hours.

The 30 day half-life is the same as is the default used in Cosyma (Jones et al, 1995). Andersson et al (2004), building on the work of Fogh et al (1999), found a strong particle size dependency in retention. Their work suggests a 1.2day half-life for particles in the 2.5 μm AMAD range and about 0.16 days for larger particles of AMAD about 4.5 μm. They concluded that for particles in the 0.5 – 1 μm range, retention is governed by the shedding of the stratum corneum (the top layer of the epidermis) and suggest a half-life of a few weeks which is consistent with the default of 30 days.

Of course in PACE the half-life also accounts for retention on clothes. Andersson et al (2004), from experimental work and from reviewing earlier work, concluded that particles larger than a micrometre had a retention half-life of 0.3 days but for smaller particles retention is closely related to washing of clothes. This is compatible with a long half-life combined with a relatively short cut-off period. They also found the contamination of the underlying skin from contaminated clothes was negligible.

The default cut-offs are somewhat arbitrary. It is reasonable to assume that for short emergencies that the general population will wash and change their clothes much sooner than five days however there may be members of the population who do not, so 5 days is a conservative number for most of the population. If skin deposition is expected to be significant then it is reasonable to assume that special arrangements will be made or at least advice given for the sheltered and evacuated populations to wash and change clothes soon after the emergency is lifted. The user should consider whether these cut-offs are appropriate when dealing with long duration releases. PACE does not handle multiple washing and clothes changing during long releases.

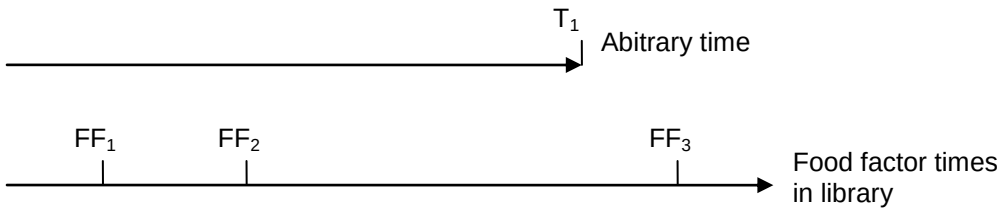
5.7 Ingestion dose

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 default values are described in Appendix A1.5.2.

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. For each food and each time T, the library contains two integrated activity factors the first giving the integrated activity concentration from time zero to T and the second from time T to infinity (but truncated by the code to 100 years). Figure 7 shows how the integrated activity factors are adjusted to a time T_1



$ZerotoT_1 = ZerotoT_{FF2} + Fraction \times (ZerotoT_{FF3} - ZerotoT_{FF2})$
$T_1toInf = TtoInf_{FF3} + (1\text{-}Fraction) \times (ZerotoT_{FF3} - ZerotoT_{FF2})$
Fraction is the fraction of the period FF_2 to FF_3 that intersects with the period 0 to T_1

Figure 7 Resampling food factors in the food production dose calculation.

In PACE 3.3.2 the user has the option to either calculate collective ingestion doses based on the food production data or individual ingestion doses that incorporate consumption data. The calculation in both cases is similar.

5.7.1 Collective ingestion dose

Collective ingestion dose uses food production data associated with each grid square. The underlying assumption is that the food is eaten by somebody somewhere. So, the dose given for a grid square should be interpreted as the collective dose from consumption that takes place elsewhere of the food produced in the grid square.

The collective dose to organ o from ingestion of radionuclide n in food fd truncated to 100 years (CDI_{onfd}) is given by Equation 21.

$$CDI_{onfd} = DCING_{on} \times TDep_n \times IntAct_{nfd} \times AnnualProd_{fd} \times \left[FracFresh_{fd} \times e^{-\lambda_n \times FreshDelay_{fd}} + \left(1 - FracFresh_{fd}\right) \times e^{-\lambda_n \times ProcDelay_{fd}}\right]$$

Equation 21

Where:

$DCING_{on}$ is the dose coefficient for ingestion for organ o and radionuclide n, in Sv Bq^{-1}.

$TDep_n$ is the total deposition of radionuclide n summed over all hours and forms and assumed to have occurred at time zero, in Bq m^{-2}.

$IntAct_{nfd}$ is the integrated activity concentration of radionuclide n in food fd accounting for food restrictions and truncated to 100 years in Bq y kg^{-1} per Bq m^{-2}.

$AnnualProd_{fd}$ is the annual production of the food fd in the grid square in kg y^{-1}.

$FracFresh_{fd}$ is the fraction of the food fd eaten fresh.

$FreshDelay_{fd}$ is the typical time between harvesting and consumption of fresh food fd in days.

$ProcDelay_{fd}$ is the typical time between harvesting and consumption of processed food fd in days.

λ_n is the decay constant of the radionuclide n in day^{-1},

$IntAct_{nfd}$ is calculated from the TtoInf factors from the library and truncated to 100 years. If food restriction has been applied to time T it is assumed to have been applied from time 0 and the approach illustrated in Figure 7 is used to adjust the TtoInf factors.

5.7.2 Individual Ingestion Dose

In PACE the 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, Equation 22 refers.

$$IDI_{onfd} = LIDI_{onfd} \times LCF_{fd} + NIDI_{\ onfd} \times \left(1 - LCF_{fd}\right)$$

Equation 22

Where:

IDI_{onfd} is the individual dose to organ o from ingestion of radionuclide n in food fd, in Sv.

$LIDI_{onfd}$ is the individual dose to organ o from ingestion of radionuclide n in food fd produced locally, in Sv.

$NIDI_{onfd}$ is the individual dose to organ o from ingestion of radionuclide n in food fd produced nationally, in Sv.

LCF_{fd} is a fraction that describes the proportion of food fd consumed that is grown locally.

In PACE the second component is represented by an average or per-caput dose calculated from the collective dose, Equation 23 refers.

$$NIDI_{onfd} = {CDI_{onfd}}/{Population}$$

Equation 23

The calculation of the per-caput dose depends on how the food production data has been formulated. In the default PACE run set, the data given is an estimate of the production in the grid square *that is consumed by the UK population*. Exports and the part of production that goes to animal feeds are not included. Therefore, in this case, regardless of the area covered by the grid, the calculation of a per-caput dose requires the total collective dose (the sum of all

the production doses from each grid square) to be divided by the total UK population as it is not correct to assume that the production within the area of the grid is only consumed by people living in the area. Of course, this ignores the contribution to collective dose of deposition beyond the area of the grid, so a grid must be specified in which the contribution to total collective dose is large compared to the area outside the grid. The contribution will be from the combined effect of deposition and production in the specified grid.

Using the individual ingestion dose regime, it is possible for the population to eat far in excess of the quantity of contaminated local food available. This is not a problem for the raw individual dose result but can lead to overestimates when calculating endpoints relating to the local population, for example the number of stochastic effects or collective dose. Users should take this into consideration when choosing how to model ingestion dose.

Another important point to note is that people living within the area of deposition will receive a total individual ingestion dose that is higher than the calculated national per-caput dose because they will receive an additional component from local production and conversely people living outside the area of deposition will receive only a fraction of the per-caput dose, that fraction being 1-LCF. This is as expected, however the average of all those sets of individual doses will not have the same numeric value as the originally calculated per-caput dose although they supposedly represent the same quantity. The calculated individual ingestion dose is likely to be less than the per-caput ingestion dose because of the greater number of people outside the area of deposition than inside it, although the calculated per-caput itself is likely to be too high because the local consumption of contaminated food was not subtracted before it was calculated. However, given all the uncertainties within the system this model is considered acceptable.

One further practical point to note, because individual doses occur outside of the area of deposition, there will be results in potentially all the grid squares (omitting only squares which there is no land) instead of just those grid squares in which there is deposition. This can detrimentally impact on both run times and on data storage resources.

A study of the food production for Oxford (Landshare, 2013) shows that around 1% of food is grown locally for a fairly typical UK city. Therefore, the default value of 25% is conservative though it is expected that the LCF would be much higher in rural areas.

The default individual consumption rates provided are taken from NRPB-W41 (Smith and Jones, 2003) for the mean consumer..

The expression for individual dose is similar to collective ingestion dose (Equation 21), except that the annual production of the grid square is replaced by an annual individual consumption rate as in Equation 24.

$$LIDI_{onfd} = DCING_{on} \times TDep_{n} \times IntAct_{nfd} \times IndConsumption_{fd}$$
$$\times \left[FracFresh_{fd} \times e^{-\lambda_n \times FreshDelay_{fd}} + \left(1 - FracFresh_{fd}\right) \times e^{-\lambda_n \times ProcDelay_{fd}}\right]$$

Equation 24

Where:

$IndConsumption_{fd}$ is the typical annual consumption of food fd in kg y^{-1}.

All other parameters are the same as Equation 21.

5.7.3 Activity concentrations in foods

The factors for activity concentrations in foods have been calculated using the terrestrial food chain model FARMLAND (Brown, 1995). The FARMLAND model is a dynamic compartmental model and input parameters can be chosen to reflect the physical and biological case under consideration. However, for reasons of practicability, the default FARMLAND output data on which PACE relies, are the results of fixed sets of parameters.

It is firstly important to note that FARMLAND is a generic model with parameters selected to be representative of conditions in the UK. The default FARMLAND data in FoodConcData.xml consist of runs performed for two nominal release dates chosen to give representative output for the two extremes of UK seasonal conditions: January 1st and June 1st. The choice of which set is used in the calculation is decided by the calendar days written in FoodConcData.xml: the June set if the release date is between April 16th and November 1st, else the January set for all other times. This approach does generalise the results somewhat for times between these two limits but for probabilistic analyses over different times of year it is envisaged that any effect will be reduced to acceptable levels.

The FARMLAND model output gives activity concentrations in the crop/animal standing in the field (known as “farm gate”) and the concentration following preparation for consumption (food in a “prepared” state). The activity concentration in prepared foods is reduced as a result of activities such as washing or removing elements of the crop, and for the purposes of dose calculation, it is assumed that foods are consumed in a prepared state.

A short breakdown of where each type of result is used is as follows: “farm gate” activity concentration for comparison with intervention levels (to make decision on food restrictions); “prepared” activity concentration for calculation of ingestion doses.

There are other parameters selected in the FARMLAND runs which can affect the results in various ways. In all cases, default parameters have been chosen which reflect the general conditions in the UK, but it is recognised that for specific sites, some of these parameters may be less appropriate. For example, the transfer factors chosen to represent root uptake from the soil are not associated with a single soil type but typically the result of averaging over a range of measurements of soil-to-plant concentration ratios for a range of soil types. This means the resulting model is broadly representative of most UK soil types, but in an instance of localised effects in upland areas, where peaty soil types are more dominant, the default assumption could lead to a significant underestimate of the activity concentrations in certain foods eg sheep meat.

6 Countermeasure Calculations

6.1 Introduction

PACE allows the user to consider the following protective actions or countermeasures:

Evacuation

Sheltering

Stable iodine prophylaxis

Relocation

Decontamination

Restrictions on foods

Countermeasure requirements are assessed in each grid square independently. For all countermeasures, except for food restriction, individual doses are calculated and tested against criteria to see if the countermeasure is required. For some actions the user can specify additional constraints or rules, for example that evacuation will always extend to 1km. The criteria include an assumption about the population location and the built environment (See Section 5.1.4) and the options available are:

The population are outdoors

Normal occupancy in environment 1

Normal occupancy in environment 2

A weighted average of normal occupancy environment 1 and 2

The maximum of normal occupancy in environment 1 or 2

6.2 Evacuation and sheltering

The procedures for evaluating evacuation or sheltering are the same. If both countermeasures are being considered, then evacuation is considered first and then if that is not required sheltering is considered.

The calculation can consider the cloud shine, inhalation and ground shine pathways. The doses are summed and compared with the dose criteria specified for the effective dose and for four organs of interest. The organs considered are lung, bone marrow, GI tract and thyroid. Averted dose is not explicitly calculated by PACE so the user will need to consider the dose criterion carefully if averted dose is planned to be incorporated. If any of the criteria are reached or exceeded then it is assumed that the countermeasure is applied in the grid square, if none of the criteria are reached the countermeasure is not applied.

The integration period used for the inhalation and cloud shine pathways is from time zero to the Emergency-ends time (see Section 1.4). Only radioactive material inhaled during this period is included in the inhalation dose calculation, but the dose is the committed dose, i.e. includes exposure over the assumed lifetime of the individual.

For the ground shine pathway, the integration period is from time zero to a user specified time.

To simulate automatic countermeasures, a mandatory distance can be set. For grid squares whose centres are less than the mandatory distance from the point of release, the countermeasure will be applied regardless of the radiological conditions. In the situation where the actual distance is less than the mandatory distance for both evacuation and sheltering, evacuation will be applied in preference to sheltering. Evacuation also has a maximum distance, set by the user, beyond which evacuation is not applied regardless of radiological conditions, this accounts for logistical limits to the extent of evacuation that can be achieved. For squares where evacuation would have been applied but are further than the maximum distance, sheltering will be applied.

The defaults for the evaluation are given in Table 11.

TABLE 11 Defaults for Evacuation and Sheltering evaluation

	Evacuation	Sheltering	Notes
Environment	Outdoor	Outdoor	
Effective dose criterion (Sv)	0.05	0.005	
Bone marrow dose criterion (Sv)	Not considered	Not considered	
Lung dose criterion (Sv)	0.5	0.5	
GI tract dose criterion (Sv)	Not considered	Not considered	
Thyroid dose criterion (Sv)	0.5	0.5	
Pathways included	Cloud shine Ground shine Inhalation	Cloud shine Ground shine Inhalation	
Cloud shine and inhalation integration period	Emergency ends	Emergency ends	
Ground shine Integration period	7 days	7 days	
Mandatory distance	none	none	
Maximum distances	none	none	
Implement sheltering where SI required	N/A	yes	Countermeasure will be applied if stable iodine criteria met

6.3 Stable iodine prophylaxis

Stable iodine prophylaxis protects against internal exposure to the thyroid from radioactive iodine inhaled from the plume. Therefore, there is one dose criterion; summed dose to the thyroid from inhaled radioactive iodine and tellurium (tellurium is included because tellurium-129, 131m and 132 decay to iodine-129, 131 and 132 respectively).

After the initial delay once stable iodine prophylaxis is taken, the effect is assumed to persist for as long as the pathway (radioactive material inhaled from the plume) is relevant.

By default, it is assumed the population are outdoors.

The calculation considers a secondary criterion of maximum distance. Stable iodine will only be applied if the centre of the grid square is within a maximum distance of the release. If the maximum distance is set to zero, this restriction is ignored.

Default values for the evaluation are given in Table 12.

TABLE 12 Defaults for stable iodine prophylaxis evaluation

Parameter	Default value	Notes
Environment	Outdoor	
Thyroid dose criterion (Sv) from inhalation of tellurium and iodine isotopes	0.2	
Integration period	Emergency Ends parameter	
Maximum distance of SI distribution	240 km	This is derived from the maximum default radius of polar grids in the Cosyma PSA code.

6.4 Relocation and clean-up

PACE can consider relocation on its own, clean-up on its own or relocation and clean-up together. When they are considered together, PACE first considers whether clean-up is required. If clean-up is required then PACE calculates whether relocation is required and for how long, after the doses have been reduced by that clean-up. If clean-up is not required, PACE considers whether relocation is required and for how long, without the doses being reduced by clean-up.

Relocation and clean-up occur after the end of the emergency given by the ‘Emergency Ends’ parameter (see Section 1.4). PACE only considers effective dose for relocation and clean-up criteria. The pathways considered are ground-shine and resuspension. The tests are performed after the time specified by ‘Emergency Ends’ and so the effect of emergency countermeasures is not included.

For the relocation calculation, a set of times at which to test the criterion are used. Imposition of relocation is only tested at the first of these times as it is assumed the doses at later times will be less. Relaxation is tested at each subsequent time in turn, relocation is assumed to end at the first time encountered when the calculated dose is less than the criterion level. For each test time the dose calculated is integrated over the period starting at the test time and continuing for the length of the criterion integration period. If the dose criteria are still exceeded during the final test period, then the value of relocation duration is set at a very large number which should be interpreted as indefinite.

The development of a clean-up strategy following an accident is a complex process involving many stakeholders and consideration of radiological, logistical, waste, economic and societal factors. It is not possible for PACE to replicate this decision-making process for each met sequence. PACE adopts a simple approach and considers two clean-up packages which are combinations of clean-up options. Packages are triggered if a measure of dose exceeds a given threshold. PACE considers package 2 and if that is not triggered, then PACE considers package 1. Therefore, package 2 should be a more costly and disruptive option but more

effective at reducing doses than package 1 and should have a higher trigger dose. The integration period for the dose starts at the 'Emergency Ends' time and finishes at 'Emergency Ends' plus the clean-up integration period.

Defaults for relocation and clean-up evaluation are given in Table 13 and the dose reduction factors following clean-up are given in Table 14. Default dose reduction factors for the clean-up were calculated using the ERMIN model (Charnock, 2010). Two plausible packages were developed, one to represent a relatively easy option with minimal disruption and one to represent an intensive option that is disruptive but more effective at reducing dose. The packages are summarised in Table 15.

TABLE 13 Defaults for relocation and clean-up

Parameter	Default value	Notes
Calculation	Relocation only	
Environment	Maximum normal occupancy	
Relocation effective dose criterion (Sv) from ground shine and resuspension	0.02	
Relocation integration period of (days)	365	For resuspension, this is the period of inhalation, the resuspension dose calculated is the committed dose which is integrated over the assumed lifetime of the individual
Test times	1, 2, 3, 5, 7, 14, 30, 45, 60, 75, 90 days ½, 1, 2, 5, 10, 20, 30, 40, 50, 70 years	Times cannot be altered by the user. 'Emergency Ends' time is also included and times before the 'Emergency Ends' time are omitted.
Package 1 effective dose criterion (Sv) from ground shine and resuspension	0.05	
Package 2 effective dose criterion (Sv) from ground shine and resuspension	0.5	
Relocation integration period (days)	365	

TABLE 14 Default clean-up reduction factors

Environment		Time (days)	0 – 1	7	14	30	90	1 year	2 years	10 years	50 years
1	Ground shine	Package 1	1	0.98	0.48	0.44	0.46	0.50	0.52	0.54	0.54
		Package 2	1	1	0.99	0.85	0.089	0.093	0.099	0.15	0.24
	Resuspension	Package 1	1	1	0.86	0.84	0.84	0.84	0.84	0.84	0.84
		Package 2	1	1	1	0.94	0.23	0.23	0.23	0.23	0.23
2	Ground shine	Package 1	1	0.99	0.45	0.39	0.41	0.46	0.5	0.52	0.53
		Package 2	1	1	0.99	0.79	0.11	0.11	0.1	0.15	0.25
	Resuspension	Package 1	1	1	0.88	0.86	0.86	0.86	0.86	0.86	0.86
		Package 2	1	1	1	0.94	0.24	0.24	0.24	0.24	0.24

TABLE 15 Countermeasure options assumed in default clean-up packages

Countermeasure package	ERMIN countermeasures applied	Timing
Package 1	Grass cutting large and small areas	At 7 days
	Vacuum sweeping all paved surfaces	At 7 days
Package 2	Tree removal/pruning	At 30 days
	Vacuuming indoors	At 15 days
	High pressure hosing roofs and walls	At 30 days
	High pressure hosing all paved areas	At 14 days
	Soil removal all grass, soil and plant areas	At 30 days

6.5 Food restrictions

Food restrictions are calculated by testing the activity concentrations in foods against criteria at a series of times. Criteria are based on radionuclide groups and food groups. For a given food at a given time, the activity concentration of radionuclides within a single radionuclide group are summed and tested against a corresponding activity level specified for the food group to which the food belongs. If the summed activity of any radionuclide group reaches or exceeds the corresponding activity level the food is considered restricted until at least the next time step. The calculation looks at all the time steps and considered that a food is restricted from time 0 until the last time beyond the time at which any radionuclide group activity exceeds the matching criterion.

The food concentration is calculated using factors obtained from the FARMLAND model see Section 5.7. The food factors used represent concentrations at the “farm gate” as this more closely represents the measurements expected at the point of crops being harvested or leaving the farm, and where restrictions would be applied.

All deposition is assumed to occur instantaneously at time zero. This is conservative in that the largest area is likely to be included in the restricted zone but for long duration releases the restriction duration estimated may be shorter than expected.

The default values are based on the Maximum Permitted Levels (MPLs) specified in (European Commission, 2016) and are given in Table 16. Radionuclides are assigned to groups in the internal PACE datafile “Nuclide physical data.xml”.

TABLE 16 Defaults for food restrictions

	Food group		Notes
Parameter	Milk (Bq/l)	Other foods (Bq/kg)	Milk includes products derived from milk. All other foods in PACE are considered as ‘other foods. The MPL regulations identify other groups such as baby foods, minor foods and liquid foods which are not considered by PACE.
Isotopes of strontium	125	750	
Isotopes of Iodine	500	2000	
Alpha –emitting isotopes of plutonium and transplutonium elements	20	80	
Radionuclides such as caesium 137 of half-life greater than 10 days	1000	1250	

7 Health Effects Calculation

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 due to 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. *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. These health effects 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. PACE considers both types of health effects due to radiation exposure.

For non-ingestion pathways, PACE estimates the number of effects in the resident population of each grid square. In previous versions of PACE, the ingestion pathway was considered separately from the other pathways because it was calculated as a collective dose. In PACE 3.3.2, the user has the option to estimate individual ingestion dose and therefore the ingestion pathway can be included with all the other pathways, although the option remains to treat it separately as a collective dose.

If treated separately, the health effects are not confined to the grid square where the food is produced but because they are due to the consumption of contaminated food produced in a grid square, they could appear anywhere in the consuming population. Consequently, the number is assigned to that grid square but may of course significantly exceed the resident population particularly as high food-producing rural grid squares generally have lower populations.

The presentation of risks of health effects is on the basis of the whole population, not only the affected group. To illustrate this, consider the case of an effect which affects only pregnant women, the risk is reported in terms of the chance of an individual representative of the entire population being affected. As such, allowance is made for the chance that any one member of the population is pregnant at the time of exposure by application of a scaling factor.

It is important to note that the number of health effects that PACE calculates is the mean or expected number given a level of exposure. If that level of exposure was applied to a real population of the same size, the actual number of health effects observed would be different and would of course be a whole number. However, because the calculated number of effects is an average it can be a fraction and it can be non-zero and less than one. It also means that when probabilistic statements are drawn from a set of met sequences, for example “the maximum number of health effects is less than 1”, that statement should really be interpreted as “the maximum mean number of health effects is less than 1”.

PACE treats the population simplistically. It assumes that there is a resident adult population that lives in the grid square continuously. Double counting of deaths is possible because it does not assume that one health effect will reduce the population who could succumb to another. Therefore, it is possible that the total number of deaths summed over all deterministic and stochastic effects in a grid square or an area exceeds the resident population in the area. This will only be significant when the mean number of effects is large compared with resident population, a situation that is likely to be unacceptable in any case. PACE calculates aggregated results which combine numbers of health effects to produce overall summary results. These are described in Section 7.4.

Given the wide range of scenarios that the PACE software could be applied to, careful consideration should always be given to the method of presentation of the results. For example, the calculation of the numbers of health effects could be based on the summation of very low doses over large population numbers that would not be considered an appropriate use of the concept of collective dose (ICRP, 2007). In such situations, further analysis of the results from PACE may be required to help understand the characterisation of the doses that have been used to estimate the numbers of health effects.

7.1 Deterministic health effects

There is a threshold dose below which the risk of deterministic health effects is essentially zero, which varies with the effect considered and with the dose rate. As doses increase above that threshold, both the percentage of the exposed population group that will exhibit the effect and the severity of the effect increase rapidly. This section briefly describes the types of deterministic health effects, and the times at which they manifest themselves in the exposed population.

Deterministic health effects arise from tissue damage, which prevents the proper functioning of one or more organs in the body and can lead to organ failure. If the organ is vital then its failure will lead to death. Those organs which are sensitive to high doses of radiation and for which failure could be fatal are the bone marrow, the lungs, the central nervous system and the gastrointestinal tract. The failure of other organs may be less critical, such as the thyroid and the lens of the eye. Health effects resulting from damage to these organs are categorised as non-fatal health effects, as are the lesser symptoms of lung fibrosis, prodromal vomiting and prodromal diarrhoea. Irradiation of the skin can lead to burns, which may lead to fatalities in a proportion of the people affected. Terminology used in this report includes acute doses that cause effects in 50% of the population (LD_{50}, for Lethal Dose (mortality), or ED_{50}, for Effect Dose (morbidity)) and threshold doses below which no health effects are expected.

The LD_{50} and the threshold value are dose-rate dependent. The dose-rate in different body organs changes as a function of time after material is inhaled or ingested, or in the case of external exposure, as the organ is irradiated. For internal exposure, material may be transported around the body, so altering the activity concentration in each organ as a function of time. Therefore, the dose received in several short time periods following incorporation, rather than the committed dose, must be calculated. The dose is presented in units of grays (Gy).

7.1.1 Calculation of risks and numbers

PACE uses the approach specified in NRPB (1996). Advice on deterministic health effects was issued by the International Commission on Radiological Protection (ICRP, 2007) and indicated that there were no changes which would significantly alter the methodology.

Doses are calculated using the methodology in Section 5. The internal dose from alpha emitting radionuclides is converted from Sv to Gy by dividing by 20 and then multiplied by the effect-specific relative biological effectiveness (RBE) to account for the high linear energy transfer (LET) of alpha particles.

The risk that deterministic health effects will occur for a given exposure increases rapidly as the dose increases above a threshold value. This is modelled using a “hazard function”, in which the probability of the effect occurring, risk r, is given by

$$r = 1 - e^{-H}$$

Equation 25

$$H = \ln(2) \times \left[\frac{D}{D_{50}}\right]^{V}$$

Equation 26

Where:

D is the dose received in the appropriate period.

D_{50} is the dose which causes the effect in 50% of the exposed population called LD_{50} and ED_{50} for lethal and non-lethal effects.

V is the shape parameter, which characterises the slope of the dose-risk relationship.

Equation 26 assumes that the dose rate is constant over the period of the exposure. The dose rate from activity in the body changes over time as the radioactive material is transferred between body organs or decays. D_{50} is dose-rate dependent and therefore its value and the risk from increments of dose also changes with time after intake. This is incorporated into the model by considering doses received in a series of time periods, calculating the appropriate value of D_{50} and hence the risk for each of those time periods, and summing the risks. This involves replacing the term D/D_{50} in Equation 26 by a term $\Sigma\, D^i/D^i_{50}$ where D^i and D^i_{50} refer to the value for the i^{th} time period. The equation therefore becomes

$$H = \ln(2) \times \sum_i \left[\frac{D^i}{D^i_{50}}\right]^V$$

Equation 27

In using this equation to calculate risks from inhalation or ingestion, D^i refers to the dose received in the period, rather than the committed dose from intakes during the time period. The intervals used are 1, 2, 3, 4, 5, 6, 7 days and 2, 3, 4 weeks.

Doses which are accumulated at a low dose rate are much less likely to cause deterministic health effects than doses delivered at a high dose rate.

The variation of D_{50} with dose rate is given by

$$D^i_{50} = \theta_\infty + \frac{\theta_1}{DR^i}$$

Equation 28

Where:

Θ_∞ is the value of D_{50} at high dose rate (Gy).

DR^i is the dose rate averaged over the period considered (Gy h^{-1}).

Θ_1 is a parameter to modify D_{50} with dose rate (Gy^2 h^{-1}).

The first term in this equation is the D_{50} at high dose rate, while the second term describes the increase in D_{50} as the dose rate is reduced.

The model described here predicts that there is a non-zero risk of early health effects for any dose, however small. Experience shows that there is a threshold dose below which deterministic effects are not observed. This is incorporated by setting the risk to zero if it is less than a small value that the user can specify (the default value is given in

).

The expected or mean number of people who are affected by a given effect is estimated by multiplying the population of the grid square by the risk.

$$n_e = r_e \times pop$$

Equation 29

Where:

n_e is the expected or mean number of fatalities or incidents of an effect.

r_e is the risk of fatality or incident of an effect.

pop is the population.

The pre-natal/neo-natal death and mental retardation effects can only affect a proportion of the population and to account for this a factor is used to represent the vulnerable proportion of the population.

Skin burns are treated differently, in that PACE calculates numbers of fatal and non-fatal effects. Fatal skin burns are estimated to be a fraction of the number of total calculated skin burn morbidities.

7.1.2 Dose delivery

The delivery of dose assumed in NRPB (1996) is rather simplified compared to an emergency situation. In this situation, the calculation needs to account for scenarios where acute doses may be delivered in a fluctuating manner over periods of greater than 24 hours and for the longer-term protraction of dose. This accounts for commitment of dose due to radioactive material inhaled and any additional external irradiation exposure over the specified periods, see Table 17.

TABLE 17 Time periods used for deterministic health effects calculations

1st day	6th day
2nd day	7th day
3rd day	2nd week
4th day	3rd week
5th day	4th week

For inhalation, the normalised dose (D/D_{50}) is calculated and summed for the time periods as illustrated for an example scenario in Figure 8.

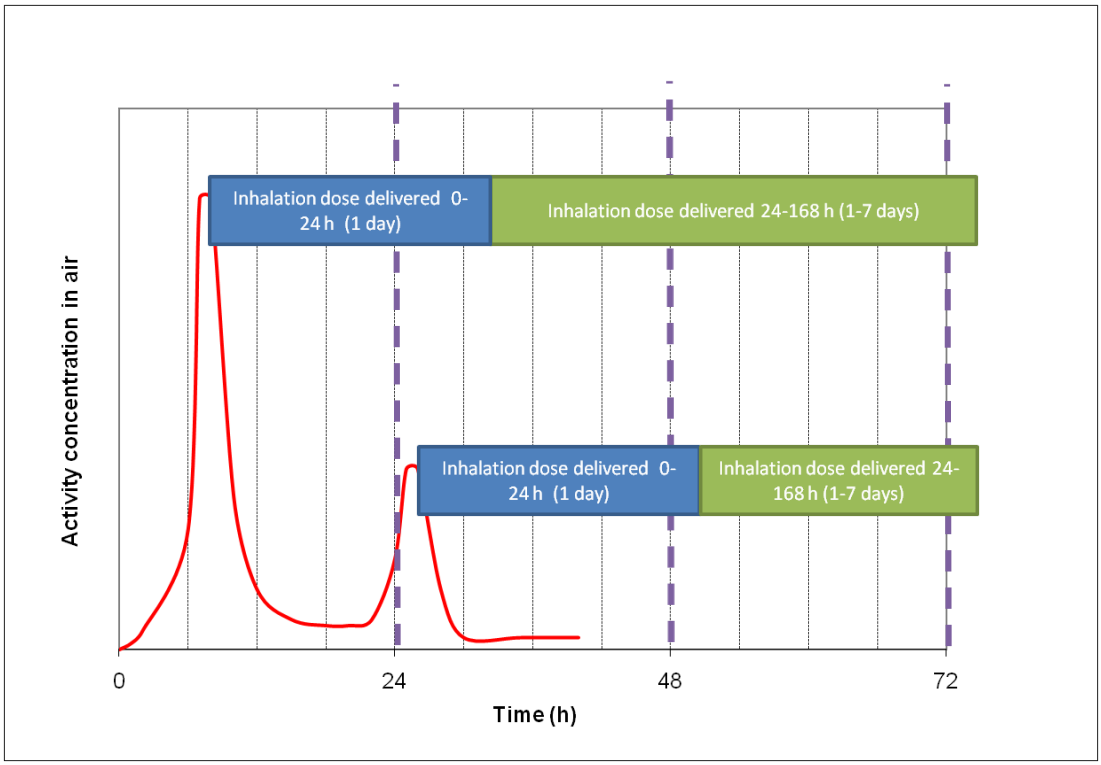


Figure 8 The calculation of protracted inhalation doses for deterministic effects determination during the passage of the plume.

Dose coefficients for inhalation are available for time periods from time 0. The dose coefficient for radionuclide n for other periods is calculated using:

$$DC_{noT1-2} = DC_{noT2} - DC_{noT1}$$

Equation 30

Where:

$DC_{nT1\text{-}2}$ is the derived inhalation dose coefficient for the period T_1 to T_2 days for radionuclide n for organ o (Sv Bq^{-1})

DC_{noTx} is the inhalation dose coefficient for radionuclide n for organ o integrated from 0 to x days (Sv Bq^{-1})

A dose for all radionuclides is estimated using the derived dose coefficient. However as discussed above, for calculating the risk of a particular deterministic effect the dose needs to be converted from Sieverts (Sv) to Grays (Gy). Gamma and beta radiation have a radiation weighting factor of one for both deterministic and stochastic effects and therefore Grays and Sieverts are equivalent. For alpha radiation was a radiation weighting factor of 20 for stochastic risk, and organ specific radiation weighting factors (known as relative biological effectiveness or RBE) for deterministic effects.

$$DI_{oT1-2} = \sum_n Q_n \times DC_{noT1-2} \times {}^{RBE_{no}}/_{WRF_n}$$

Equation 31

$$DRI_{oT2-T1} = \frac{DI_{T1-2}}{T2 - T1 \times 24}$$

Equation 32

Where:

$DI_{oT1\text{-}2}$ is the total inhalation dose for organ o in the period T_1 to T_2 days (Gy)

$DRI_{oT1\text{-}2}$ is the total inhalation dose rate for organ o in the period T_1 to T_2 days (Gy h^{-1})

Q_n is the intake of radionuclide n (Bq)

RBE_{no} is the organ and effect specific relative biological effectiveness for deterministic effects. For gamma and beta emitting radionuclides this value is 1, for alpha emitting radionuclides the value is given in Table A20.

WRF_n is the radiation weighting factor for stochastic effects. For gamma and beta emitting radionuclides this value is 1, for alpha emitting radionuclides the value is 20.

For practical implementation, the simplifying assumption is made that inhalation doses are delivered in a constant manner in the time periods being considered. Thus, doses are fitted into the fixed time periods as defined in Table 17. Doses due to external irradiation are combined with doses due to inhalation to estimate the overall risk.

To simplify the calculation the continuous intakes of both inhalation of the passing plume and inhalation of resuspended material are represented by series of discrete instantaneous intakes. However, there is a difference between the two; the inhalation of a period of the plume passage occurs during that period, whereas the inhalation of a period of deposition and resuspension occurs during that period and continues afterwards. Therefore, inhalation of the plume is represented as a sequence of discrete instantaneous intakes that occur at the start of each dispersion modelling period. Inhalation of resuspension is modelled as a sequence of discrete instantaneous intakes that occur at the middle of each of the intervals in Table 17 (i.e. 12, 36, 60 hours etc) and are the sum of resuspended material from all deposition before and during the interval. In both cases the sets of dose coefficients are calculated using Equation 30 that apportions the dose from the intake to each of the fixed periods in Table 17. Therefore, if the intake occurs after a particular fixed period the dose coefficient for that intake and period combination will be zero.

Cloud irradiation only occurs in periods when material is present in the atmosphere of the area in question. However, the dose from all pathways is required in each fixed time period and so the contributions from cloud irradiation are summed to produce the total dose in each fixed time period.

For irradiation from the ground, the same time periods used for the inhalation component are used to estimate dose and dose rate. The contribution from ground deposits will be summed with doses from other pathways.

Contributions to dose from deposition of material on skin and inhalation of resuspended material from deposition on the ground are also included in the calculation of total dose and total dose rate. However, in the time period of interest for deterministic health effects their relative contributions are typically very small.

The summation over contributions from all pathways is performed prior to the calculation of the normalised dose, thus the last term in Equation 27 becomes:

$$\left(\frac{D}{D_{50}}\right)_{T1-2} = \frac{DI_{T1-2} + DCS_{T1-2} + DGS_{T1-2} + DIR_{T1-2} + DSD_{T1-2}}{\left[\theta_{\infty} + {\theta_1}/{(DRI_{T1-2} + DRCS_{T1-2} + DRGS_{T1-2} + DRIR_{T1-2} + DRSD_{T1-2})}\right]}$$

Equation 33

Where:

DI_{T1-2} is the dose from inhalation of the plume, Equation 31, (Gy).

DIR_{T1-2} is the dose from inhalation of resuspended material which is delivered and therefore calculated in a similar way to inhalation from the plume, (Gy)

DCS_{T1-2}, DGS_{T1-2} and DSD_{T1-2} are the total cloud shine dose, total ground shine dose and total skin deposition dose respectively, for the period T_1 to T_2 days for radionuclide n (Gy)

DRI_{T1-2}, $DRCS_{T1-2}$, $DRGS_{T1-2}$, $DRIR_{T1-2}$ and $DRSD_{T1-2}$ are the total dose rates from cloud inhalation, cloud shine, ground shine, inhalation of resuspended material and deposition on skin, respectively, for the period T_1 to T_2 days for radionuclide n (Gy h^{-1})

The normalised doses, as calculated for each fixed time period using Equation 33, are summed over all of the fixed time periods to produce a single normalised dose quantity, which is used in the hazard function in the calculation of risks of deterministic effects (see Equation 27). Therefore, the normalised dose over the total time of interest (first 28 days) is given by:

$$\left(\frac{D}{D_{50}}\right)_C = \left(\frac{D}{D_{50}}\right)_1 + \left(\frac{D}{D_{50}}\right)_2 + \ldots$$

Equation 34

Where:

subscripts 1, 2, etc apply to the different time periods specified in Table 17 (1 day, 2 days etc.) and include the contributions from different exposure pathways.

7.1.3 Fatal deterministic effect considerations

The relative importance of the different health effects depends on the situation in which the exposure is received. PACE considers atmospheric releases, in such scenarios, people are exposed due to inhalation (both from direct inhalation of material that has dispersed from the release point and from material that has deposited on the ground and subsequently

resuspended into the air) and external exposure (both from material dispersed in the air and deposited on the ground).

7.1.3.1 Haematopoietic or bone marrow syndrome

This syndrome results from the killing of stem cells in the bone marrow, potentially leading to death a few weeks after the exposure. White cells in the blood or lymphatic system die naturally and are normally replaced by dividing stem cells. However, this process cannot take place once the stem cells have been killed. As a result, the body's immune system is impaired and this, without medical intervention, can lead to overwhelming infection. Low platelet counts lead to internal haemorrhaging. Without any medical treatment, except perhaps on-the-spot first aid, an acute radiation dose to the whole body or to the bone marrow of about 3 Gy is the mean lethal dose, LD_{50}. The threshold fatal acute dose is about 1.5 Gy. If standard hospital treatment is available these values increase to about 5 and 2 Gy, respectively. With advanced medical procedures, such as growth factors and stem cell transplants, it may be possible to rescue bone marrow such that, if death occurs in the patient, it is due to pneumonitis (see below) rather than due to the direct bone marrow effects. Hence, under circumstances when the number of patients needing such support is small enough for the treatment to be delivered by available resources, bone marrow syndrome may not in itself be a fatal consequence. However, such radical treatment may not be feasible for significant and simultaneous numbers of patients.

7.1.3.2 Pulmonary or pneumonitis syndrome

This syndrome is caused by inflammation of the lung which may prevent the transfer of gases to and from the blood. An affected person will die of lung failure within about 3 months of exposure. The LD_{50} for this effect due to acute exposure is in the region of 10 Gy, with a threshold of about 5 Gy.

7.1.3.3 Gastro-intestinal (GI) syndrome

This syndrome is caused by irradiation of the crypt cells in the GI tract which can induce vomiting, diarrhoea and infection. Haemorrhages and bacteraemia may occur which aggravate injury and contribute to death.

7.1.3.4 Neo-natal and pre-natal or embryonic death

Irradiation of the uterus can lead to embryonic or foetal death. Although evidence for this in humans is limited it has been observed in animals with doses of low LET radiation as low as 0.1 Gy given on the first day of gestation.

The PACE default deterministic calculation parameters are described in Appendix A1.5.5.

7.2 Stochastic health effects

The main longer-term health effects that are expected to occur in exposed populations following exposure to ionising radiation are increases in cancer incidence in those exposed

and hereditary disease in their descendants. For both effects, the probability of their occurrence depends on the radiation dose that an individual is exposed to. As these effects are related to a probability of an event occurring, they are termed stochastic health effects.

Based on the assumption of a linear no-threshold relationship between dose and risk, the risk that a stochastic health effect will occur can be determined from the dose, i.e. there will be a specific percentage risk of getting cancer per unit of dose received. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has regularly reviewed information on radiation risks, most recently in a report published in 2008 (UNSCEAR, 2008). This estimation is largely based on epidemiological studies of the Japanese atomic bomb survivors (Preston et al, 2007), many of whom received medium to high doses of ionising radiation, and is supported by studies of other populations such as patients given medical exposures and workers receiving exposures whilst at work (occupational exposures). ICRP (2007) used the available UNSCEAR estimates of radiation risk, together with data from Preston et al (2007), as the basis for the risk estimates used in their radiation protection system. ICRP made adjustments to allow for lower doses and lower dose rates, in order to make estimates of the risks of various cancers following exposure to ionising radiation from typical situations such as medical diagnostic, occupational or environmental exposures. ICRP estimated the risks for different types of cancers per unit dose received for males and females separately, and for adults and children at different ages and then combined them to provide one overall estimate of the risk of cancer per unit dose received. They also made adjustments to allow for the fact that the total risk of cancer depends on the underlying average risk of cancer and that differs from country to country. The ICRP risk estimates are therefore designed to give the likelihood of cancer occurring in an exposed population, for health protection purposes, rather than giving the risk to a specific individual. One of the reasons for combining the risks for females and males and for adults and children was so that the risk estimates do not appear to be more accurate than they are. Another important point is that control of exposure is applied to all workers irrespective of gender and all members of the public from infants to adults. Hence the risk factors are essentially estimates for a ‘reference’ person.

The basis for the ICRP risk factors was reviewed and generally supported by the independent UK CERRIE report (CERRIE, 2004). CERRIE also concluded that advances in understanding the detailed interactions of radiation with tissue may ultimately provide a complementary approach and called for further research. UK specific risks for leukaemia were developed by the UK Advisory Group on Ionising Radiation (AGIR, 2003) and similar risk calculations for solid tumours have been developed (AGIR, 2011).

Current ICRP recommendations (ICRP, 2007) for radiation protection indicate an approximated overall fatal cancer risk from ionising radiation of 5% per Sv for a population of all ages. Other views do exist however, particularly regarding the validity of the adjustments made when taking risk estimates that are based on exposures to high doses of external irradiation and then applying them to low doses or to internal exposure. PHE has confidence that the ICRP risk factors are suitable for radiation protection purposes because they are supported by other studies that do consider low doses and internal exposure (Mobbs et al, 2009). Equally, other reports claim much lower risks at low doses and even no risk at all because of an assumed low-dose threshold for the process of cancer induction (Tubiana et al, 2005). PHE believes that there is not enough evidence to support these views.

7.2.1 Reasons for confidence in the current radiation risk factors

The studies of the Japanese atomic-bomb (A-bomb) survivors, on which estimates of radiation risk factors are primarily based, include many features of good epidemiological studies. They cover a large population, of both sexes, and a wide range of ages. Because the population was not selected on the basis of disease, or other similar factors, there is little potential for the population studied to be biased towards a particular type of person. There has been a long period of follow up, during which the population has been assessed for both mortality and cancer incidence. In addition, individuals received a wide range of doses, and because of the extensive effort spent in the decades since the bombings to develop estimates of radiation doses (Cullings et al, 2006) there is confidence in the accuracy of the estimated doses.

Studies of other populations exposed occupationally, medically or environmentally give reasonable agreement with the A-bomb studies, providing reassurance that the risk factors are appropriate. Examples are populations exposed to the naturally occurring radioactive gas, radon (both domestic exposure and uranium miners) and workers in the nuclear industry (UNSCEAR, 2008). Some of these studies involved populations who received relatively low dose or dose rate radiation, or internal exposure, or alpha emitters, thus giving reassurance that the risk factors may be applied to a range of exposure situations. One of the studies is based on the actual (low) doses received by workers in the UK over the last 50-60 years, and provides good consistency with risk factors derived from high doses (Muirhead et al, 2009) . This study also shows a decrease in the risk of cancers with a decrease in dose.

The reliability of the estimates of radiation risk factors depends on the level of dose being considered because the level of dose determines whether it is possible to see any health effects in an epidemiology study. Uncertainties are lowest at the levels of dose at which health effects have been observed (doses of about 10 mSv or greater) (Mobbs et al, 2009). At lower doses where the actual risk is very low and has not been detected in epidemiological studies, the proportional level of uncertainty is greater. However, it is possible to estimate an upper bound on the uncertainty at these low doses because otherwise some health effects would actually have been detected. People typically receive average doses of a few mSv from natural background radiation, but the estimated cancer risk associated with such exposures cannot be demonstrated by epidemiological studies.

Despite the many uncertainties involved in estimates of radiation risks, it is possible to estimate the accuracy of the radiation risk models from the evidence provided by the epidemiology studies. PHE's view is that, when considering the risk of all cancers in a population of all ages, it is reasonable to assume that the estimates of risk provided by these models are accurate to within a factor of 3 either way for some radionuclides and for external exposure. For certain radionuclides, the evidence suggests that the accuracy of the risk estimates is likely to be around a factor of 10 either way. For example, for external irradiation and all cancers they are accurate to within a factor of 4 or less (Muirhead et al, 2009); for certain internal exposures and specific cancers they are within a factor of 10 (Harrison and Day, 2008).

7.2.2 Calculation of risks and numbers

Doses from individual pathways are calculated according to the methodology in Section 5.

For non-ingestion pathways, and for the ingestion pathway if individual ingestion doses are calculated, the individual doses are summed for each organ associated with a particular stochastic effect. The calculation uses a risk of fatality per Sv value for each effect to calculate the risk of fatality.

$$r_{fe} = R_{fe} \times D_o$$

Equation 35

Where:

r_{fe} is the risk of a fatal effect.

R_{fe} is the risk of a fatal effect per Sv in Sv^{-1}.

D_o is the dose to organ o associated with the effect in Sv.

The total incidence is calculated by applying a mortality fraction.

$$r_{ie} = \frac{r_{fe}}{m_e}$$

Equation 36

Where:

r_{ie} is the risk of an incident of the effect.

m_e is the fraction of effects that are fatal.

Where the effect is not fatal (e.g. hereditary effects) the risk of mortality is set to zero and the risk of incidence is calculated by multiplying the total dose for the organ by the risk per Sv.

For high doses a calculated risk of mortality or incidence could be greater than 1, these risks are truncated within PACE to be 1.

The absolute numbers are calculated by multiplying the risks by the population in the grid

$$n_e = r_e \times pop$$

Equation 37

Where:

n_e is the expected or mean number of fatalities or incidents of an effect.

r_e is the risk of fatality or incident of an effect.

pop is the population.

When collective ingestion dose to the whole population from food produced in the grid square is calculated as an alternative to individual ingestion dose, the application of a risk of fatality per Sv factor gives the mortality numbers rather than the risk of mortality

$$n_{ife} = R_{fe} \times Dcol_o$$

Equation 38

Where:

n_{ife} is the expected or mean number of fatal effects from ingestion of food produced in the grid square.

$Dcol_o$ is the collective dose to organ o in person Sv. The dose calculated is based on the 'prepared' food radioactivity concentration factors see Section 5.7.

Similarly, the application of a mortality fraction gives the number of incidences.

$$n_{iie} = \frac{n_{ife}}{m_e}$$

Equation 39

Where:

n_{iie} is the expected or mean number of incidents from ingestion of food produced in the grid square.

The PACE default values are described in Appendix A1.5.6.

7.3 Health effects and effective dose

Effective dose is a convenient surrogate of the aggregated risk people are exposed to following a radiological accident. However, it is difficult for such a quantity to represent consistently the consequences of very different types of exposures (eg external gamma, inhalation, ingestion etc.).

PACE calculates the expected number of cancers associated with an organ, directly from the estimated organ dose. However, for the purposes of applying countermeasures and giving a more readily understood scale to the event PACE also calculates the effective dose. It is to be expected that under the complex and mixed exposures of an accidental release, the relationship between the effective dose and the consequences in terms of numbers of cancers would be influenced by the nature of the exposure. If the estimated numbers of cancers in each grid square (excluding ingestion) are plotted against the estimated effective doses (excluding those from ingestion) in each respective grid square for a particular met-sequence then a clear linear relationship with only a small amount of scatter will result. The particular slope and scatter about the linear regression fit of the plotted points is a result of the difference in the relative contributions of the various exposure pathways contributing to the organ doses. The contributions will vary as a function of distance, direction and environment

and can therefore only be approximately summarised by the effective dose formed as a simple weighted aggregate.

Thus, it is important to note that a consequence of directly relating cancer occurrence to the sum of the respective organ doses received by the exposed population and the associated risks is that the number of fatal cancers predicted by PACE is not related to the effective dose by the simple risk relationship, quoted for ease of estimation by ICRP, of 5% per Sv (ICRP, 2007).

7.4 Aggregated health effect results

PACE calculates incidents and fatalities of individual deterministic and stochastic health effects in each grid square. Each individual calculation does not account for the reduction in population by deaths from other health effects. This double counting means that the sum of individual health effects within a grid square (ignoring health effects from collective ingestion doses which may occur outside of the grid square) may exceed the population within the grid square. It is important to note:

This double counting will only be significant when the mean number of effects is large compared with resident population, a situation that is likely to be unacceptable in any case.

This applies to the grossly simplified assumption of a static adult population that does not move around and is not replaced.

PACE calculates several aggregated end points which are summarised in Table 18.

TABLE 18 Summary of aggregate results in HE and HECM output

Field name	Variants indicated by suffix	Notes
EstimatedFatalities_…	"Env1", "Env2" and "total". Optional "noIng"	Total number of expected fatalities over all stochastic and deterministic fatal effects, excluding pre/neonatal and hereditary effects. See Equation 40 to Equation 44. "noIng" suffix indicates ingestion pathway not included
EstimatedFatalities_risk_…	"Env1", "Env2" and "total". Optional "noIng"	Cumulative risk of fatality from all stochastic and deterministic fatal effects. Optional "noIng" suffix indicates ingestion pathway not included.
Total_deterministic_...	"Incidence" and "mortality"	This is the value passed to the EC module to calculate costs of health effects. It is the sum of all deterministic effects calculated within the grid square. Double counting of fatalities is possible; however, the sum of fatalities from the non-ingestion doses and individual ingestion doses can be truncated to be no more than population of the grid square. If collective ingestion doses are used these are added subsequent to truncation so the final amount can exceed the population of the grid square.
Total_Solid_Cancer_...	"Incidence" and "mortality"	This is the value passed to the EC module to calculate costs of health effects Sum of all stochastic health effects excluding leukaemia (bone marrow) and hereditary effects calculated within the grid square. Double counting of fatalities is possible; however, the sum of fatalities from the non-ingestion doses and individual ingestion doses are truncated to be no more than population of the grid square. If collective ingestion doses are used these are added subsequent to truncation so the final amount can exceed the population of the grid square.
Total_leukaemia_...	"Incidence" and "mortality"	This is the value passed to the EC module to calculate costs of health effects Number of leukaemia (stochastic effect in bone marrow) health effects in the grid square. The number of fatalities does not take into account the reduction in the population due to other fatal health effects. However, the numbers from non-ingestion doses and individual ingestion doses can be truncated to be no more than population of the grid square. If collective ingestion doses are used these are added subsequent to truncation so the final amount can exceed the population of the grid square.
Hereditary_...	"FirstGen" and "SecondGen"	This is the value passed to the EC module to calculate costs of health effects The number of first- and second-generation hereditary effects in the grid square. Numbers of health effects from non-ingestion doses and individual ingestion doses cannot be truncated to the resident population because effects occur in subsequent generations also if collective ingestion doses are used these are added so the final amount can exceed the population of the grid square.

The estimated risk of fatality is the risk that an individual living as part of the resident population in given environment, in a grid square, dies of any health effect either deterministic

or stochastic. Pre/neonatal death and deaths from hereditary effects are excluded as these do not occur in the resident population as such. It only includes ingestion doses if these have been calculated as individual doses as in Section 5.7.2.

The risk of fatality is calculated by first calculating the chance of survival. The chance of survival of a given health effect is 1 - [the risk of fatality from that health effect]; survival of different health effects are treated as independent events and can be combined using the rule of multiplication (Equation 40). The overall risk of fatality is calculated by subtracting from 1 (Equation 49).

$$Chance\ of\ survival_e = \prod 1 - r_{fhe,e}$$

Equation 40

$$r_{f,e} = 1 - chance\ of\ survival_e$$

Equation 41

Where:

$r_{f,e}$ is the aggregated risk of fatality from any fatal health effect (fhe) for an individual in environment e.

$r_{fhe,e}$ is the risk of fatality from a particular stochastic or deterministic fatal health effect (fhe) for an individual in environment e.

The expected numbers of fatalities among a group of individuals living in an environment in a given grid square is given by Equation 42.

$$n_{f,e} = r_{f,e} \times pop_e$$

Equation 42

Where:

$n_{f,e}$ is the expected number of fatalities in environment e

pop_e is the population in environment e.

The expected total number of fatalities is the sum over all environments, as in Equation 43.

$$n_f = \sum_{e=1}^{e=2} n_{f,e}$$

Equation 43

Where:

n_f is the expected number of fatalities.

The aggregated risk over all environments can be calculated from the expected overall number, but it is also the average of the environment risks weighted by the numbers of people in each environment, Equation 44.

$$r_f = \sum_{e=1}^{e=2} r_{f,e} \times \frac{pop_e}{pop}$$

Equation 44

Where:

pop is the population in the grid square in all environments.

8 Economic Consequences Calculation

8.1 Introduction

PACE models the economic consequences of accidents based on the framework established by COCO-2 (Higgins et al, 2008): a model for assessing the off-site economic costs likely to arise following an accident at a nuclear reactor. The consequences calculated by the model include direct costs (for example, from the loss of use of property) and indirect costs from the temporary loss of business from customers forced to cease operating as a result of the accident. Consequences can also be split into two types: tangible (can be valued through the market) and intangible (cannot be valued through the market), both of which are dealt with in the model where possible.

In PACE, as in COCO-2, the losses incurred are broken down into three main categories. *Agriculture losses* arise through contamination of crops and livestock products such that the product is then unsuitable for its intended use. This not only includes an immediate loss in the value of agricultural production at the time of the accident but also the future value of production that is no longer viable due to continuing soil contamination. *Health losses* cover the costs of treatment and the losses of health and productivity of those affected. *Built environment losses* include the production losses of industry including tourism and the lost use of capital assets such as accommodation and capital goods.

The COCO-2 model was developed to analyse accident consequence costs in the UK specifically, although the principles of the model are valid for other countries and regions of the world. The default cost data (both spatial and non-spatial) that is provided with PACE is for the UK. A detailed description of the economics model can be found in the COCO-2 report but an overview of the elements considered is given for each of the three categories below. The calculations followed in implementing the model in PACE are given in Appendix C of this methodology.

8.2 Agriculture costs

An economic loss to agriculture may follow where areas used for farming are contaminated with radioactive material. A direct loss is likely to occur when restrictions are placed on the

sale of products for human consumption, for example, where radionuclide concentrations in foodstuffs exceed food intervention levels. The calculation of direct losses depends on the ability to estimate the radionuclide activity concentrations in the foodstuffs, which is done in the PACE countermeasures module (which by default relies on the FARMLAND food-chain model).

The foodstuffs considered in the economics module are leafy green vegetables, cereals, root vegetables, potatoes, sugar beet, legumes, orchard fruit, soft fruit, sheep meat, cow meat and cow milk.

The calculation of what is restricted from sale and for how long (i.e. the restriction length) is described in Section 6.5; the results as described in Table 19 then feed in to the calculation of costs.

TABLE 19 Countermeasures summary endpoints used for economic calculations

Endpoint	Notes
Duration of restriction (for each foodstuff)	The number of days from the start of restrictions until the restrictions are lifted (restrictions, if in place, are assumed to start on the day of the accident).

For a given accident scenario the amount of annual production lost can be estimated for each of the product types; agricultural production data are among the spatial data that form the overall input for a PACE run and are required for these endpoints. Unlike most losses in other, non-agriculture sectors, the amount lost is likely to be strongly dependent on the season. An accident occurring in the late spring has greater consequences for food production systems than one occurring in the late autumn and the model accounts for this.

In COCO-2, agricultural production can be modelled as either a periodic or continuous process, depending on the crop or animal husbandry in question. Periodic production represents the case where harvest or collection is done at a particular time of year, whereas continuous production represents crops or animal products which are collected throughout the year, at least to a close approximation. The type of production for each crop and animal product and the specific calculations are described in Appendix C1.

8.2.1 Model data

The calculation of agriculture losses requires site-specific production data which varies from region to region, and crop value data. The default input fields are described in Table 20.

TABLE 20 Other inputs used for agricultural calculations

Endpoint	Notes
Spatial agricultural production (for each foodstuff)	The agricultural production in the grid square in terms of area used in hectares (for crops) or animals (for livestock) from EDINA study and other sources (see Appendix C).
Crop output	The economic output of the crop £ per hectare (for each crop type) in table C2 of the COCO-2 report (COCO data.xml).
Crop GVA	The GVA (gross value added) £ per hectare (for each crop type) in table C3 of the COCO-2 report (COCO data.xml).
Animal output	The economic output £ per animal (for each animal type) in table C2 of the COCO-2 report (COCO data.xml).
Animal GVA	The GVA (gross value added) £ per animal (for each animal type) in table C3 of the COCO-2 report (COCO data.xml).
Average animal values	The average capital value £ of an animal (for each animal type) in Section 9.4 of the COCO-2 report (COCO data.xml).
Seasonal adjustment factor	The seasonal adjustment factor to account for the relative costs incurred at different times of the year (for each periodically produced foodstuff) in the COCO-2 report tables C5, C7a, C9, C11, C13, C15, C17 (COCO data.xml).
Harvest date	The approximate mean harvest date (for each periodically produced foodstuff) in the COCO-2 report tables C5, C7a, C9, C11, C13, C15, C17 (COCO data.xml).
Agricultural multiplier	The specific industry multiplier for agriculture in table 21 of the COCO-2 report (COCO data.xml).

8.2.2 Model assumptions and limitations

An assumption adopted for COCO-2 is that the output of the agricultural economy could fully recover within two years to allow the production to return to pre-accident levels in the third year through changes in the pattern of production nationally and locally. Therefore, whilst the effect of restrictions remaining in place for an extended period would certainly impact agricultural production in an affected area, it is considered that the Gross Value Added (GVA) lost could be recouped by production elsewhere in the country within a relatively short period (a few years) through the release of land from set-aside or the build-up of overall capacity. However, if, for example, instead of relocating production, clean feed was imported into an affected area as a countermeasure to allow milk production to continue, the continued higher cost of this production would, as with all active countermeasures, have to be accounted for separately.

In addition to the costs from the loss of production, there are many diverse additional costs that may arise from the implementation of restrictions following an accident, not least the problem of waste disposal. For example, crops could be ploughed in or harvested and composted. Some options could lead to reduced fertility of soils and reduced yields in subsequent years. Costs incurred by the various disposal routes and countermeasures that can be implemented to reduce the update of radioactivity into crops and animals are collected in the UK Recovery Handbook (Nisbet et al, 2015). These practices and their additional costs

are discussed in the COCO-2 report but are not included in the economics cost model implemented in PACE.

8.3 Health effects costs

The costs to the economy from any health effects resulting from an accident are diverse and the calculation of these is complex. The COCO-2 model incorporates the calculation of costs of the following: the direct loss of labour from people who are ill; the cost of treatment; the personal loss (direct but intangible) of those suffering radiation-induced morbidity or death. This approach necessitates the concept of valuing a statistical life, which in COCO-2 is derived from the literature related to the Compensating Variation (CV) required to match the personal losses estimated to be inflicted as a result of morbidity or death[1]. It should be noted that the model does not assume that costs of this type are realised as a financial loss to the economy, but rather are included to provide a measure of the loss appropriate for policy and planning decisions.

The numbers of health effects are calculated according to the methodology in Section 7. The numbers are summarised before being used to calculate the costs, as explained in Table 21.

TABLE 21 Health effects summary endpoints used for economic calculations

Endpoint	Notes
Total number of non-fatal deterministic effects	The sum of lung impairments, hypothyroidism, cataracts, mental retardation, and non-fatal skin burns.
Total deaths from deterministic health effects	The sum of deaths from pulmonary syndrome, haematopoietic syndrome, gastro-intestinal syndrome, pre-natal and neo-deaths and fatal skin burns.
Total incidence of solid cancers	This is the sum of all cancers from all stochastic effects other than cancers of bone marrow.
Total deaths from solid cancers	This is the sum of fatal cancers from all stochastic effects other than cancers of bone marrow.
Total incidence of leukaemia	This is incidence of cancers of bone marrow.
Total deaths from leukaemia	This is the deaths from cancers of bone marrow.
1st generation hereditary effects	The calculation of 1st and 2nd generation hereditary effects is discussed in Appendix D.
2nd generation hereditary effects	The calculation of 1st and 2nd generation hereditary effects is discussed in Appendix D.

8.3.1 Model data

The costs of individual health effects are estimated based on the COCO-2 methodology, and passed into PACE as input parameters in the form described in Table 22.

[1] Sample groups are surveyed in complex ways to assess their response to small changes in risk which are then scaled.

TABLE 22 Other inputs used for health effects calculations

Input	Notes
Cost of health effects	Cost of deterministic effects (£) and hereditary effects (£) in COCO-2 report table 16; cost of cancer fatalities (£) (table 18) and cancer incidence (£) (table 19) also in COCO-2 report (COCO data.xml).

8.3.2 Model assumptions and limitations

In the COCO-2 model, the economic cost of cancer cases consists of several contributing factors, but the model results are presented as the cost of cancer incidence and cost of cancer fatalities. The cost of cancer incidence represents the cost of morbidity and care for all cancer cases, including a contribution for those cases which ultimately result in a fatality. The cost of cancer fatalities represents the additional costs arising from terminal illness. PACE provides a morbidity cost which is the cost of cancer incidence for those that survive and a cancer mortality cost which is the sum of the incidence and fatalities costs for those that do not survive.

8.4 Industry, tourism and other built-up area costs

Economic costs to inhabited areas can arise from several different effects on both residential and industrial areas. To estimate the direct economic effects on people and industry of an accident, information on the area affected and the length of time any restrictions are in force is used. The application of COCO-2 relies on matching the affected area against relevant features on the ground, such as industrial estates, schools, houses etc as discussed in the specific sections.

The methodology for calculating countermeasures is described in Section 6. These countermeasure durations are then interpreted as situations which result in economic impact, as described in Table 23.

TABLE 23 Countermeasure summary endpoints used for economic calculations

Endpoint	Notes
Sheltering period	The total duration (in days) of the sheltering countermeasure.
Evacuation period	The total duration (in days) of the evacuation countermeasure.
Relocation period	The total duration (in days) of the relocation countermeasure.
Disruption	Disruption is a measure (in days) of the time during which the situation does not reflect "business as usual" and is the net duration of the following countermeasures: sheltering, evacuation and/or relocation.
Time out of homes	Time out of the home is a measure (in days) of the time that the population are required to be away from their usual place of residence according to countermeasure criteria and is the net duration of evacuation and/or relocation.

8.4.1 Production losses

The model assumes GVA to be lost for the length of time a business is closed because of the workforce being subject to disruption due to the accident. Disruption to business as usual occurs when one or more of the countermeasures of sheltering, evacuation or relocation are applied. Economic loss is assumed to be proportional to the length of time that a business is closed, which assumes that GVA is uniformly produced throughout the year. Although not true in all cases, this assumption is unlikely to significantly distort estimated costs (the obvious exceptions – agriculture and tourism – are dealt with separately). Lost GVA is calculated separately across all industry types, or SICs (Standard Industrial Classifications), and then summed to arrive at a total amount of lost GVA.

8.4.2 Nuclear site power production

The contribution to the economy of power production at the site of the accident is accounted for in the economics module by default. An estimate of loss is made from the product of the portion of site power generated by the damaged reactor, the time for which the reactor is damaged and the GVA from the plant (in spatial input data) when running normally. To estimate this, lost GVA in the SIC (Standard Industrial Classification) which covers electricity generation is calculated separately, as described in Appendix C.

For prospective probabilistic safety assessments or similar assessments where there is not already power production at the selected site, this economic loss from suspended power production will not be accounted for since the GVA will not be included in the spatial input data. This will have the greatest effect for smaller accidents where the site will generate much more value per year than the affected general activities nearby. Users may choose to modify the input data in the relevant grid square - introducing an estimate of future power production GVA - so that this source of economic loss is accounted for in the assessment.

8.4.3 Model data

TABLE 24 Other inputs used for built environment calculations

Input	Notes
Spatial GVA and building capital data	The GVA (gross value added) (£ millions per grid square) generated annually and the capital value of commercial and industrial buildings (£ millions per grid square), as described in Appendix B of the COCO-2 report.
Spatial house data	Total value of housing stock (£ millions per grid square), rental return (£ millions per grid square) and numbers of houses (per grid square), as described in Appendix B of the COCO-2 report.
Spatial land use data	The areas of land occupied by different uses (1000 m^2 per grid square), as described in Appendix B of the COCO-2 report.
Number of houses, UK	The total number of houses in the UK, input by the user in the PACE user interface.
Industry multipliers for indirect effects	Multipliers for each SIC (Standard Industrial Classification) sector to estimate indirect effects on suppliers, as described in Section 11 (table 21) of the COCO-2 report (COCO data.xml).
Tourism multiplier of indirect effects	Multiplier for tourism to estimate indirect effects on suppliers (COCO data.xml).
Tourism seasonal adjustment factors	Expenditure weighted seasonal adjustment factors for variation in tourism GVA, as described in Section 11 (table 23) of the COCO-2 report (COCO data.xml).
Capital consumption and value of assets	Annual household consumption of capital assets (£ million) excluding cars and motorcycles; value of household capital assets (£ million) including cars and motorcycles, as described in Section 8 (table 9) of the COCO-2 report (COCO data.xml).
Capital assets per sector	Net capital stock by sector as fraction of GVA, as described in Section 11 (table 24) of the COCO-2 report (COCO data.xml).

8.4.4 Model assumptions and limitations

In the COCO-2 model, it is considered that regardless of ongoing relocation and remediation, the economy on a national scale would adjust to recover within a period of two years (730 days), and so any periods of "disruption" and "time out of homes" that exceed this length of time, are not considered to incur any further cost (i.e. these are truncated at 730 days for calculation purposes). This principle is discussed in Section 8 of the COCO-2 report and is supported by official data from Japan[2] which indicates that the 2011 shock to the overall economy of both the Tsunami and nuclear accident at Fukushima has been absorbed and the economy is now back on trend to recover from the Lehman Brothers collapse. This is illustrated in Figure 9.

2 The data are the Jul.-Sep. 2014 (The 2nd preliminary) figures from the Japanese Real Gross Domestic Product (seasonally adjusted series) available at the Cabinet Office Website http://www.esri.cao.go.jp/en/sna/data/sokuhou/files/2014/toukei_2014.html .

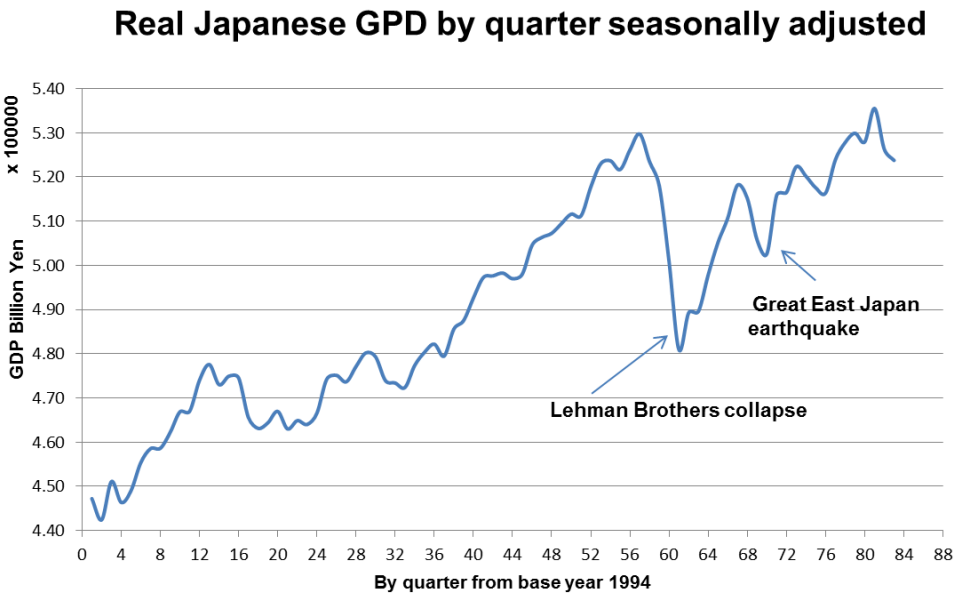


Figure 9 The real Japanese GDP as a function of time with the major dip of the Lehman brothers collapse in 2008 and the smaller dip following the Tsunami and Fukushima accident of 2011

The estimates of costs to businesses and industry are reliant on assumptions around what criteria are used to make certain decisions after an accident. For example, the PACE implementation of COCO-2 assumes that "disruption" means businesses will be closed, while if "time out of homes" becomes long term (i.e. exceeds "maximum delay for those returning", selected by the user) then local businesses will be relocated with associated costs. The exact conditions set in PACE for certain costs being incurred are detailed in Appendix C, where the calculations are also given, and it is recognised that input parameters affecting these conditions can have a significant effect on the results.

The effect on regional tourism can be a significant result for decision makers, and it is therefore included as an economic endpoint of the COCO-2 model. However, it should be recognised that the separate tourism endpoint is a regional quantity only and should not be summed with the overall business losses when estimating the national loss estimate, which includes the loss to tourism already as an industry like any other.

The model is designed to calculate losses to the economy as a whole and not to account for local variations where they do not contribute to a loss or gain to the overall economy.

Specific exclusions further to those already discussed are covered in Section 8.4 of the COCO-2 report.

8.5 Exclusions

The economic considerations of COCO-2 are not all-encompassing and are designed to consider those costs which would be incumbent on the state rather than corporate liabilities,

for example. Some notable economic consequences that are not included are discussed briefly in this section.

8.5.1 On-site costs

The COCO-2 model is concerned with off-site consequences and as such does not include costs incurred to equipment and facilities on-site.

In a majority of significant accidents at nuclear power plants, it is foreseeable that one or more reactors would be damaged beyond repair. Any costs associated with this are not considered in the COCO-2 model.

8.5.2 Loss of power production

The COCO-2 model does consider the loss of power generation from the site in question as discussed in Section 8.3.2.

However, in the event of a severe accident, it is likely that electricity production not only at the affected plant would cease, but that other plants in the country or region may also temporarily cease to produce electricity as a result of precautionary shutdowns. This has been observed after the accident at the Fukushima Dai-ichi Nuclear Power Plant where the incident resulted in many of the other reactors in Japan being taken offline (Inajima and Okada, 2011). This is of course a decision that would be based on a multitude of political and economic factors and highly dependent on both the location of the reactor and circumstances around the event. Wider loss of electricity production, beyond the site directly affected, is not considered in the economics model implemented in PACE.

8.5.3 Regional image

Although the direct effect on tourism is considered, the broader issue of the effect on the public image of the region as a result of an accident is not. As well as a decrease in demand for travel to the affected region, there would be an expected decrease in demand for local produce as a consequence of negative connotations (health or otherwise) in the eyes of the consumer. Local produce that is idiosyncratic to the area, for example food or drink associated with a particular region, could be particularly affected. It may be noted however, that tourism to Japan as a whole following the tsunami recovered in approximately two years as generally assumed in COCO-2 (Wu and Hayashi, 2014; Wu and Hayashi, 2013).

8.5.4 Other societal costs

The psychological burden of a nuclear accident on the affected population is well recognised. Although COCO-2 deals with a variety of health effects of an accident, it does not attempt to put a cost on the psychological trauma incurred which is not only difficult to assess but likely to be heavily dependent on the details of the on the day response.

9 Statistical Analysis

9.1 Introduction

The PACE probabilistic approach is straightforward to describe. A typical PACE run will generate many results for each grid square in each of the met sequences. The met sequences are drawn cyclically so each corresponding endpoint in each met sequence has an equal probability. For this reason, it is important to use many met sequences to ensure that PACE captures extreme, low probability events. Typically, a few hundred met sequences taken from at least one year of meteorological data is appropriate but preferably three or more years. Each endpoint has a large set of possible values and will approximate the distributions from which they are drawn as illustrated in Figure 10.

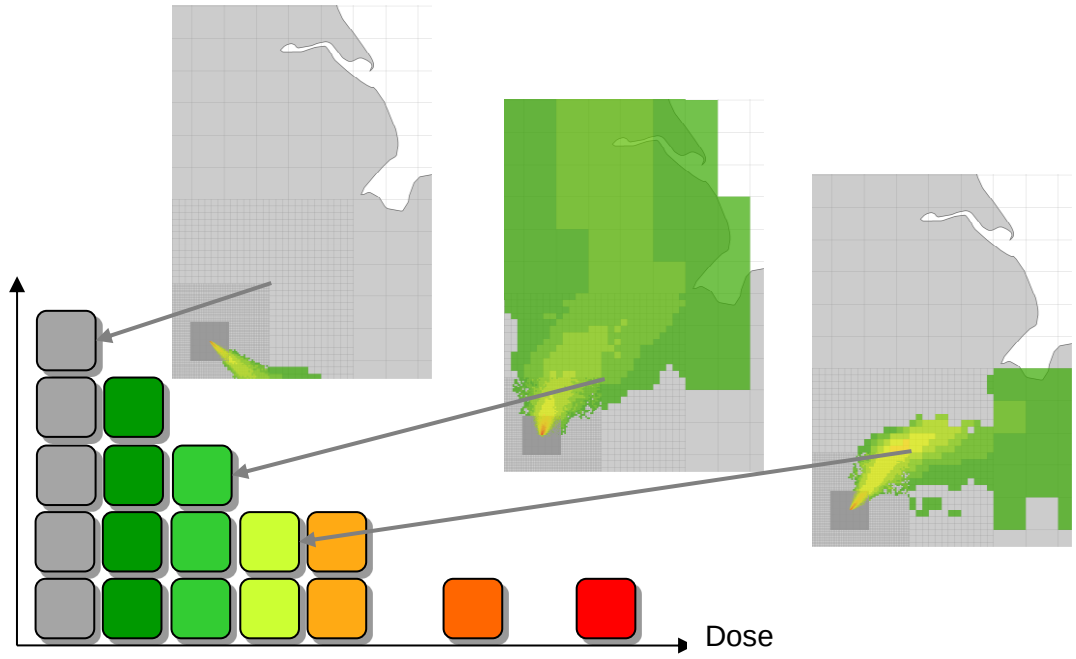


Figure 10 Illustration of the probabilistic approach in PACE. A given endpoint, in this case the dose in a certain grid square has a different value in each met sequence (here three met sequences are shown for clarity but ideally there would be a few hundred). This set of possible values can be used to construct a histogram that approximates that distribution from which they were drawn. In this case we can see the doses in the grid square which is some distance from the release point are skewed towards low values with high values being rather improbable.

PACE provides two tools to aggregate and summarise the vast number of results generated in a typical run; the Analysis tool and the PercentileMap Tool. Both tools present percentiles and other summary statistics to the user but in different ways.

A percentile is a value below which a given percentage of results will fall. Given a large enough number of results this will approximate the corresponding probability. There is no standard procedure for calculating a percentile value, though all methods converge when the number of results is large. PACE supports two approaches; a standard method and one like that implemented in the Microsoft Excel® Spreadsheet.

9.2 Standard percentile calculation

The standard approach for calculating percentiles is as follows. Given N values v_1, v_2 ... v_n sorted into ascending order. The rank of the nth value is given by the expression:

$$P_n = \left({}^{100}/_{N}\right) \times \left(n - \frac{1}{2}\right)$$

Equation 45

To find the value that corresponds to percentile p, find the value v_k such that the rank of v_k is just below or equal to p and the rank of v_{k+1} is just above, i.e. the ranks of v_k and v_{k+1} straddle the required percentile p. The actual value corresponding to the percentile is then found by linear interpolation.

$$v_p = v_k + \left[\frac{(p - p_k)}{(p_{pk+1)} - p_k}\right] \times (v_{k+1} - v_k)$$

Equation 46

If p is below the rank of the lowest observation then $v_p = v_1$, if p is above the rank of the highest observation then $v_p = v_n$.

The standard approach can be generalised to allow the observations to be weighted. This is useful when different PACE runs need to be aggregated together. For example, there may be several PACE runs that represent different releases with different probabilities of occurrence. To account for this the observations in the geodatabases are weighted.

Given N values v_1, v_2 ... v_n sorted in ascending order and N corresponding weights w_1, w_2 ... w_n etc. Then the rank of the nth observation is given by the expression

$$P_n = \left({}^{100}/_{S_N}\right) \times \left(S_n - \frac{W_n}{2}\right)$$

Equation 47

Where S_N is the sum of all weights and S_n is the sum of weights up to and including n. To find the value that corresponds to percentile p Equation 46 is applied.

It should be noted that there is potential for a small ambiguity that can occur if two or more observations have the same value but different weights. It can happen that observations are assigned to either v_k or v_{k+1}, depending on the arbitrary ordering given to the equally ranked but differently weighted observations. The expression above will give slightly different results because of the different weights. This effect is localised and should be small when the number of observations is sufficiently large.

Weights for individual observations are calculated by dividing the overall weight given to a geodatabase by the number of met sequences in the geodatabase (taking into account met sequences that have been explicitly excluded).

9.3 Excel percentiles

This approach is used by Microsoft Excel® 2007 and is included to be compatible with Excel and with earlier versions of the Analysis tool.

Given N values v_1, v_2 ... v_n sorted in ascending order. To estimate the value v_p of the Pth percentile, then the rank of the percentile is calculated as

$$n = \left({}^{P}/_{100}\right)(N-1)+1$$

Equation 48

The rank is split into its integer component k and decimal component d, such that n=k+d.

If n=1 then $v_p=v_1$

If n=N then $v_p=v_N$

If n is between 1 and N then $v_p = v_k + d \times (v_{k+1} - v_k)$

Equation 49

The Excel approach does not allow for weighting so cannot be applied to multiple geodatabases.

9.4 Probabilities

Probabilities can be estimated from the percentiles and indeed the percentile map tool (Section 9.6) does this explicitly. For example, if 3mSv is at the 25th percentile of all the values for all the met sequences at a grid square then the probability of a met sequence having a value less than or equal to 3mSv at that grid square is estimated as 25% and the probability of it having more than that value is estimated as 75%.

The probabilities calculated this way are strictly estimates of the conditional probability, i.e. a probability of specified level of an endpoint given that the accident described by the source term has happened. To calculate the unconditional probability the conditional probability must be multiplied by the probability of the accident.

Where weights are used for several accidents, then the conditional probability calculated is the probability that any one of the accidents has happened and the unconditional probability is calculated by multiplying by the combined probability of any of the accidents happening.

9.5 Analyse tool

The Analyse tool performs a three-step operation. In the first step, mathematical operations are applied to the values in the fields relating to a grid square within each met sequence producing a new result for each grid square in each met sequence. In the second step these new results are aggregated over the whole grid within a met sequence so that there is one value per met sequence. For example, it may find the average, total or maximum value. In the third step the tool will calculate the percentiles and other statistics of the aggregated values across all met sequences.

The operations to be applied are specified in an xml file which can be modified by the user. Table 25 gives all the operations that the Analyse tool supports. The tool supports standard and excel percentiles and can operate over multiple geodatabases when using the standard percentile formulation.

TABLE 25 Analyse tool operations that can be applied to the results within met sequences.

Code[a]	Name	Notes
"POPGT0" (1)	Population where value greater than zero	Calculates the population where the value for any of a given list of input fields is greater than 0. For a grid square, if any value in a given list of fields is greater than 0 then the result is the population (from "InputData") of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares. Additional criteria can be supplied to exclude grid squares.
"POP" (6)	Population where value meets criteria	Calculates the population where the value for any of a given list of input fields is between or equal to the specified criteria. For a grid square, if any value in a given list of fields is between or equal to the specified criteria then the result is the population (from "InputData") of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares.
"POPSUM" (8)	Population where sum of values meets criteria	Calculates the population where the sum of the values for a given list of input fields is between or equal to specified criteria. For a grid square, if the sum of values for a given list of fields is between or equal to the specified criteria then the result is the population (from "InputData") of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares.
"SUMTRUNCPOP" (2)	Sum of values truncated by population	Calculates the sum of the values for a given list of input fields, truncated by the population. For a grid square, the result is the lower value from i) the population (from "InputData") and ii) the sum of the values in a given list of fields. The aggregated result for the met sequence is the sum of the results in all the grid squares. Additional criteria can be supplied to exclude grid squares. This calculation should only be used on field where the units are people; it would make no sense to apply it to dose field for example.
"SUM" (3)	Sum	Calculates the sum of the values for a given list of input fields. For a grid square, the result is the sum of the values for a given list of input fields, where each field may be multiplied by a scaling factor (if applied eg to account for differences in units). By default the scaling factor is 1. The aggregated result for the met sequence is the sum of the results in all the grid squares. Additional criteria can be supplied to exclude grid squares.
"AREAGT0" (4)	Area where value greater than zero	Calculates the area where the value for any of a given list of input fields is greater than 0. For a grid square, if any value in a given list of fields is greater than 0 then the result is the area of land (from "InputData") of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares. Additional criteria can be supplied to exclude grid squares.
"AREA" (5)	Area where value meets criteria	Calculates the area where the value for any of a given list of input fields is between or equal to the specified criteria. For a grid square, if any value in a given list of fields is between or equal to the specified criteria then the result is the area of land (from "InputData") of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares.

“AREASUM” (7)	Area where sum of values meets criteria	Calculates the area where the sum of the values for a given list of input fields is between or equal to specified criteria. For a grid square, if the sum of values for a given list of fields is between or equal to the specified criteria then the result is the area of land (from “InputData”) of the grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares.
“MAXVALUE” (9)	Maximum value	Calculates the maximum (in each met sequence) of the sum of the values for a given list of input fields. For a grid square, if the sum of values for a given list of input fields is greater than or equal to the maximum from all the grid squares, then the result is the sum value in that grid square (otherwise 0). The aggregated result for the met sequence is the sum of the results in all the grid squares divided by the number of grid squares which share the maximum value. Additional criteria can be supplied to exclude grid squares.
“YIELD” (10)	Total yield with criteria	Calculates the food yield (mass/volume as appropriate) of food restricted based on the number of years’ production restricted. For a grid square, if the value of a given input field (restriction duration) is greater than the criteria, the result is the length of the restriction on that food in years multiplied by the yield in one year (from “InputData”) in that grid square. So, for example, a 731-day restriction results in 2 times the annual yield being restricted. The aggregated result for the met sequence is the sum of the results in all the grid squares.

[a] originally the calculation type were referred to by an integer code (given in brackets) in the xml file, these have been replaced by character codes to make the file more readable. The integer codes can still be used and may be seen in older files, there is no significance in the value which were assigned in order of when the operation was added to the tool functionality during development.

9.6 Percentile map tool

Percentile map tool aggregates output from a PACE run over met sequences to create a feature class that can be used to visualise the spatial characteristics of the PACE output.

The user selects a field from a feature class in an output geodatabase generated during a PACE run and can then choose to estimate for each grid square either; percentiles of that field, the probability of that field exceeding a given amount, or counts of the number of met sequences that meet user specified criteria in that grid square.

During a PACE run if no radioactivity reaches the particular grid square in a particular met sequence then that grid square is not generated in any of the output feature classes for that met sequence. This behaviour was included in order to reduce the output geodatabase size. The percentile map tool assumes that if a grid square is missing the values of all the fields that would have been in that grid square are zero. These notational zeros are included in the calculation of percentiles and in the counts. In every feature class produced, the tool adds an additional field called “count” and for each grid square this gives the number of met sequences that have output at that grid square. The values of count will be some number between 0 and the total number of met sequences. Subtracting count from the total number of met sequences will give the number of met sequences in which radioactivity does not reach the grid square.

The percentile map can also operate on the output of an Analysis tool (Section 9.5), and in this way can operate over multiple PACE runs. If weights are applied in the Analysis tool these can be used by the Percentile map to modify the percentile and probability outputs.

9.6.1 Percentile output

When generating percentile output the user must specify a percentile interval, for example 5 percentiles. The tool then calculates for each grid square the 0^{th} percentile to the 100^{th} percentile in 5 percentile intervals and stores them as fields in a new feature class within the existing output geodatabase. Percentiles are calculated using the Excel formulation, see Section 9.3.

The values of percentile can be plotted on a map using the standard plotting functionality of ArcGIS.

9.6.2 Probabilities output

The probability output is the reverse of the percentile output. When generating probabilities output the user must enter one or more threshold values. They must also indicate whether they want an estimate of the probability of a grid square exceeding the threshold or being less than or equal to the threshold.

The probability of a met sequence giving a value less than or equal to the threshold in each grid square is estimated as the percentile of the threshold and the probability of having a value greater than the threshold is estimated as 1 – the percentile. All probabilities calculated are conditional, see Section 9.6.2.

9.6.3 Count output

The count output is simply the count of the number of met sequences that satisfy numerical criteria in each grid square. The user must enter threshold values for the criteria and also specify whether they require counts of met sequences that exceed the thresholds, that exceed or are equal to the threshold, that are equal to the threshold, that are equal to or less than the threshold, or are less than the threshold.

10 Glossary

ADEPT – an implementation of the R91 atmospheric dispersion model.

Aerodynamic Diameter – is a value used to describe irregular shaped aerosols. It is the diameter of a spherical particle with a density of 1000 kg m^{-2} that has the same settling velocity as the irregular particle.

Aerosol – a small solid particle or liquid droplet particle that is airborne.

Analyse results tool – a tool in PACE that applies calculations to met sequences and aggregates the results of those calculations over met sequences in order to calculate percentiles and other statistics.

ArcGIS™ – a commercial GIS package in which PACE is embedded and developed by ESRI see http://www.esri.com/.

BNG – British National Grid, a projected co-ordinate system for the British Isles.

Capital goods – goods, other than material inputs and fuel, used for the production of other goods and/or services. They include factory buildings, machinery, locomotives, lorries and tractors. Land is not usually regarded as a capital good.

Capital services – the productive inputs, per period, that flow to production from a capital asset. The value of capital services is the quantity of services provided by the asset multiplied by the price of those services.

Clean-up – a recovery countermeasure that tackles environmental radioactive contamination after an accident. In PACE clean-up is used broadly to include decontamination operations that remove contamination and other operations such as ploughing, shielding and fixing that do not remove radioactivity but reduce the doses from that activity.

Cloud gamma – external exposure to radiation from radioactive material in the plume

Cloud shine – synonymous with cloud gamma.

CM – a grouping of calculations and results in PACE that describe the implementation of countermeasures.

COCO-2 – model implemented in PACE for assessing the potential economic costs arising off-site following an accident at a nuclear reactor.

Compensating Variation (CV) – For a ‘proposed welfare gain’ due to the provision of a public good, the compensating variation refers to the amount of money that would be given up by the consumer to attain the increased level of utility (ie, WTP measure).

CONDOR – A UK level-3 PSA code developed in the late 1980’s.

Co-ordinate systems – a system for defining points on the earth’s surface. There are geographic and projected co-ordinate systems.

Costs – Section 56 of the Environment Act (1995) defines costs as including 'costs to any person and costs to the environment’. Costs include any environmental, human health or other social impacts, which are detrimental in nature, any capital and recurrent expenditure, administrative costs, monitoring and enforcement costs, and research and development costs.

COSYMA – a level 3 PSA code developed for the European Community by National Radiological Protection Board and Forschungszentrum Karlsruhe.

Countermeasure – a protective action taken to ameliorate the consequences of an accident. The countermeasures considered by PACE are Evacuation, Sheltering, Stable Iodine Prophylaxis, Relocation, Clean-up and food restrictions.

Cut-off time for skin and clothes – a time specified by the PACE user which PACE uses to truncate doses from radioactivity deposited on the skin and clothes. It can be thought of as the time at which an individual changes clothes and washes.

Cyclic Sampling - Cyclic sampling is the name given to the procedure of extracting meteorological data at regular intervals (typically of length a few hours) from a dataset. The extracted data is termed a met sequence and may or may not overlap with subsequent met sequences.

Deposition – Radionuclides deposited on the ground.

Deterministic Health Effects – health effects which have a threshold dose below which the risk is essentially zero and above which the severity is directly related to the dose received. They generally occur when high doses are received over short time periods; and include fatal and non-fatal effects. They result from damage to a significant number of cells within tissues. See also stochastic health effects.

Discounting - A method used to convert future costs or benefits to present values using a discount rate.

Disruption - as defined in Section 8.3 is the length of time that "business as usual" is interrupted as a result of countermeasures. Disruption is considered to last as long as sheltering, evacuation or relocation is in place.

DS – a grouping of calculations and results in PACE that describe individual doses from various pathways without countermeasures. May include the individual ingestion pathway of that option has been chosen by the User.

DSCM – a grouping of calculations and results in PACE that that describe individual doses from various pathways assuming that countermeasures are applied if the criteria for countermeasures are met. May include the individual ingestion pathway of that option has been chosen by the User.

DSIng – a grouping of calculations and results in PACE that describe collective ingestion doses without food restrictions.

DSIngCM – a grouping of calculations and results in PACE that describe collective ingestion doses assuming that food restrictions are applied if the criteria for restrictions are met.

EA – a grouping of calculations and results in PACE that describe environmental activity. Either deposited activity or integrated concentration of radioactivity in air.

EC – a grouping of calculations and results in PACE that describe economic consequences of the accident assuming no countermeasures are applied. In this case the consequences are the costs of health effects.

ECCM – a grouping of calculations and results in PACE that describe economic consequences of the accident assuming countermeasures are applied if the criteria for countermeasures are met.

Emergency Countermeasure – an urgent protective action used during the emergency phase of an accident, the emergency countermeasures considered by PACE are evacuation, sheltering and stable iodine prophylaxis.

Emergency Ends – is a time parameter specified by the user that defines when the emergency ends from the point of view of implementing emergency countermeasures. It is used by PACE as the time when evacuation and sheltering are lifted and when relocation begins.

Emergency phase – a term used in emergency response to describe the phase in which a release is imminent, ongoing or has not yet definitely ended and countermeasures are being applied to protect the public, see also recovery phase.

ESRI – the company that develops and supports the ArcGIS™ desktop products.

Evacuation – an emergency countermeasure that involves removing people from an area during the emergency phase.

Features – a term used in ArcGIS to mean distinct items on the earth's surface such as trees, roads, fields, administrative units or grid squares that can be represented in the database by points, lines or polygons.

Feature class – a term used in ArcGIS to mean a dataset within a geodatabase, containing features of a particular type. Each feature has the same set of attributes though the values of the attributes will be different. For example, a feature class may contain roads represented as lines and each road has attributes length, name, speed limit but the values of those attributes are different for different roads. Features may be represented as lines, polygons or points.

Food group – for the purposes of applying food restriction criteria food are divided into several groups. PACE considers two groups milk and other foods.

Food intervention levels – criteria for restricting the marketing of food contaminated following an accident. Typically based on dividing radionuclides and foods into a number of groups and setting appropriate criteria for each group. European maximum permitted levels (MPLs) are an example of this.

Food restriction – a countermeasure that involves preventing food being sold.

Gaussian model – a simple form of atmospheric dispersion model that represents the spread of the plume down wide as increasingly broad normal distributions in the horizontal and vertical directions.

GDP – Gross Domestic Product at market prices is a measure of the value of goods and services produced in a country before providing for capital consumption. It is equal to gross value added at basic prices plus taxes (less subsidies) on products. Alternatively, it is equal to the sum of total final domestic consumption expenditures less imports of goods and services.

Geodatabase – a database format used by ArcGIS to store data. PACE creates and uses a number of geodatabases during operation.

Geographic co-ordinate system – a coordinate system that uses a three-dimensional spherical or spheroid surface to define locations on the earth surface. The point on a surface is given by

its longitude and latitude. Latitude is the angle between the point and the equator and longitude is the angle between the point and the prime meridian.

Geographic Information System – a computer program designed for storing, handling, displaying, analysing and manipulating spatial data.

GIS – Geographic Information System.

GI tract – gastrointestinal tract, for RP purposes an organ for which doses and health effects can be calculated.

Great circle – a line on the earth surface formed by the intersection of a sphere representing the earth and a plane that passes through the sphere's centre. It has the property that it represents the shortest distance travelling over the earth's surface between two points.

Grid element – synonymous with grid square.

Grid square – a single element within a nested grid, PACE calculations are generally performed at the grid square level.

Gross Value Added (GVA) – Gross Domestic Product excluding taxes (less subsidies) on products; the headline measure of regional economic activity.

Ground shine - external dose from deposited radioactive material

GVA – Gross Value Added.

HE – a grouping of calculations and results in PACE that describes the expected numbers of different kinds of health effects from the accident assuming no countermeasures are applied.

Health Effects – the health consequences of the accident; PACE considers stochastic and deterministic health effects.

Health Protection Agency – a UK body which was merged into PHE in 2013.

HECM – a grouping of calculations and results in PACE that describes the expected numbers of different kinds of health effects from the accident assuming countermeasures are applied if the criteria for countermeasures are met.

Hereditary effects – Germ-line mutations induced by radiation that are transmitted to the subsequent generations and may result in congenital anomalies or increased risk of common multifactorial diseases.

HPA – Health Protection Agency.

Inhalation dose – internal exposure from the inhalation of radioactive material from the plume.

Input geodatabase – the name given to the geodatabase created by the PACE preprocess tool.

"Inputdata" feature class – the name of a feature class containing the spatial input data superimposed on the PACE calculation grid.

Lagrangian model – a sophisticated form of atmospheric dispersion model in which the pollutants are simulated as a large number of Lagrangian particles that move through a 4-dimensional weather field.

Lagrangian particle – a simulated particle in a Lagrangian model.

Lat-long – in this document this abbreviation refers to a geographic co-ordinate system based on the WGS1984 datum.

Leukaemia – a disease in bone marrow in which more abnormal leucocytes are produced which inhibit the production of normal blood cells causing among other symptoms anaemia.

Level 1 PSA – PSA concerned with evaluating the risk of core damage in a nuclear reactor.

Level 2 PSA – PSA concerned with evaluating the risk of radioactivity escaping containment in the event of core damage.

Level 3 PSA – concerns evaluating the probabilities of offsite consequences given a release of radioactive material to the atmosphere.

LF – location factor.

Lloyd's Register– an independent provider of Business Assurance and Quality Certification.

Location factor - a factor applied to a generic dose to include location specific effects. Typically, a dose calculated (or measured) in a simple outdoor location such as on a lawn away from buildings, trees and paved surface will be converted to an indoor dose that accounts for shielding and different geometries of contaminated surface. In PACE a location factor might include occupancy so that it accounts for time spent indoors and outdoors.

LR – Lloyd's Register

MARC – a level-3 PRA code developed by NRPB in the early 1980s.

Met data – historical data describing meteorological conditions.

Met Office – the UK's national weather service that provides global weather predictions and other services.

Met sequence – meteorological data drawn from a database of meteorological data for a particular period defined by a start date and time, and duration.

MPL – Maximum Permitted Levels; European criteria for restricting the marketing of food contaminated following an accident (European Commission, 2016). MPLs are based on categorising radionuclides and foods into a number of groups. For each radionuclide and food group combination, maximum activity concentrations are specified in Bq kg^{-1} and Bq l^{-1}.

Multiplier – The second-round effects on the level of economic activity (output, income or employment) associated with a policy intervention (e.g. where the employees of a new project spend their earnings and so increase consumer demand). Several types of multiplier (income, local, long run, short run and supply) are often estimated. The size of the multiplier depends on the period over which it is measured, and the geographical area considered.

NACE - General Industrial Classification of Economic Activities with the European Communities, the industrial classification adopted by countries in the EU

NAME – a model for atmospheric dispersion developed by the Met Office. It uses the lagrangian model approach that simulates a large number of particles to represent a pollutant that moves in a complex weather field.

NAME3tool - a tool in PACE that sets up, runs and imports results from the NAME model for each met sequence required. Imported results are placed in a geodatabase that is used as an input to the PACErun tool.

NAME3 – synonymous with NAME.

NAMEIII – synonymous with NAME.

National Radiological Protection Board - a UK body which was merged into Health Protection Agency in 2005 which was then merged into Public Health England in 2013.

Nested grid – a structure of grids of different resolution with the finest resolution grid embedded within a coarser resolution grid which in turn is embedded in a still coarser grid and so forth.

Net - The term net is a common means of referring to values after deducting consumption of fixed capital (for example, net capital stock or net domestic product).

NRPB – National Radiological Protection Board.

NWP – Numerical Weather Prediction.

NWP data – meteorological data generated by NWP models. Contents of NWP data depends on the model but typically it contains many atmospheric parameters on a 4-dimensional grid. Typically, the generation of NWP data will involve data assimilation of real world observations.

Nuclide group – a grouping of radionuclides of similar properties for the purposes of specifying radioactivity-concentration based criteria for restricting food.

Organ – a structural unit in the body that fulfils a function or functions, for RP purposes an organ is a component of the body for which risk factors for radiation induced health effects have been defined.

PACE – PSA code whose methodology is being described in this document. PACE stands for Probabilistic Accident Consequence Evaluation.

PACErun Tool – a tool in PACE that performs consequence calculations on a large number of dispersion patterns and calculates countermeasure requirements and doses, health effects and economic consequences with and without countermeasures.

Particles – small solid or liquid objects that can be dispersed in the atmosphere.

Phase – a distinct period within the whole accident release, see source term.

PHE – Public Health England.

PL – a grouping of calculations and results in PACE that describe hourly individual doses from various pathways during the passage of the plume.

Polygon feature class – a feature class where spatial data are represented as polygons on the earth’s surface.

PRA – Probabilistic Risk Analysis (synonymous with PSA)

Preprocess tool – a tool in PACE that allows the user to specify a nested grid and converts spatial input to that grid.

Projected co-ordinate system – uses a two-dimensional flat surface to define points on the earth surfaces. A mathematical transformation is used to map or project points on a 3-dimensional sphere or spheroid surface to the flat surface. The process of projection causes different kinds of distortion. For a given purpose one kind of distortion may be either more or

less tolerable than others. Different kinds of projection are used to minimise different kinds of distortion.

Projection – synonymous with projected co-ordinate system.

Protective Action – synonymous with countermeasure.

PSA – Probabilistic Safety Analysis (synonymous with PRA)

Public Health England - an executive agency of the UK Department of Health and Social Care with responsibility for protecting and improving the nation's health and wellbeing, reducing health inequalities and preparing for public health emergencies.

PWR – Pressurised water reactor, a type of nuclear reactor.

R91 – a particular formulation of a Gaussian dispersion model as described in the NRPB-R91 report (Clarke, 1979).

Radiological protection – a discipline involving the application of scientific principles for accessing the risks of radiation and developing appropriate protection strategies.

Recovery countermeasure – a protective action used in the recovery phase of an accident, recovery countermeasures considered in PACE are relocation and clean-up.

Recovery phase – recovery phase is a term used in emergency response to describe the phase after the emergency phase when the release has ended, and countermeasures are being applied to return activity in the area to normal.

Release – synonymous with source term.

Release duration – the total period that material is released according to the source term, it is the sum of all the phases in the source term.

Relocation – a recovery countermeasure that involves removing the population from an area and restricting access to that area.

Remainder – for RP purposes a surrogate tissue allowing the occurrence of 'other solid cancers' not included in the cancers of named tissues to be accounted for.

Resuspension – the process in which radioactive material that has been deposited on the ground or other surfaces is returned to being suspended in the atmosphere.

RL – a grouping of calculations and results in PACE that describe long term doses for periods after the plume passage from various pathways without countermeasures.

RLCM – a grouping of calculations and results in PACE that describe long terms doses for periods after the plume passage from various pathways assuming countermeasures are applied if the criteria for countermeasures are met.

RP – radiological protection.

Shelter – see sheltering

Sheltering – an emergency countermeasure under which the population are advised to go indoors and remain there with windows and doors shut and all ventilation minimised.

SI – stable iodine.

SAPs – UK nuclear regulation Safety Assessment Principles (ONR, 2014).

Single site met data – a simple set of met data based on observations from a single site or point.

Solid cancers – defined for the purposes of PACE as all cancers except leukaemia. Therefore, all stochastic health effects except cancer in bone marrow (leukaemia) and hereditary effects are grouped together as solid cancers.

Source term – the quantity of radionuclides released to the atmosphere during a given accident. The source term gives the timing of different phases of release during the accident and the amounts of different radionuclides released in each phase. It includes other information such as the release height and the fraction of the different forms of iodine released.

Source term tool – a PACE for creating and editing source term XML files.

Spatial reference – synonymous with co-ordinate system

Stable Iodine Prophylaxis – an emergency countermeasure which involves ingesting stable iodine in tablet form. The stable iodine floods the thyroid organ and a consequence of that is that any radioactive iodine that is ingested is much more likely to be quickly excreted from the body rather than remain in the thyroid for a prolonged period thus minimising the dose from the iodine. SI prophylaxis will also protect from ingested radioactive iodine however it is considered that restricting contaminated foods is a better approach. SI prophylaxis provides no protection from internal or external exposure from other radionuclides and provides no protection from external exposure to radioactive iodine in the plume or on the ground.

Standard Industrial Classifications (SICs) – The industrial classification applied to the collection and publication of a wide range of economic and industrial statistics. The current version, SIC (2003), is consistent with NACE Rev. 1.1. (SIC 1992 is equivalent to NACE except at the most detailed level).

Start time – synonymous with time zero.

Stochastic health effects – health effects that may not appear in the exposed population until many years after exposure and include fatal and non-fatal cancers. These health effects 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 below which the risk is zero. See also deterministic health effects.

Temporal domain – a term used in the NAME model to describe the period in which the movement of the lagrangian particles in the atmosphere is simulated.

TIAC – Time-Integrated Activity Concentration, a measure of radioactivity in air in Bq s m^{-3}.

Time out of homes - is the length of time a population is required to spend out of their usual place of residence as a result of evacuation and/or relocation.

Time zero – Time zero is the start time of the accident. For any given met-sequence it is the time and date of the start of the first period of met data extracted from the database and the first phase of the release is assumed to begin at time zero. All other times are given relative to time zero.

XML – Extensible Markup Language is a set of rules for encoding documents in a format that is both human and machine readable. Many of the PACE input files use an XML structure.

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APPENDIX A PACE default interface data

A1 PACE run tool

The user interface to the PACE tool contains many default values. Some of them are scientific values such as risk factors or location factors while others represent user choices such as criteria for imposing countermeasures. When developing PACE, the default inputs were based on the PC COSYMA program and a great many of the user inputs particularly those that represent user choices will be familiar to COSYMA users. For ease of reference this appendix gives the default data by the tabs available in the PACE tool user interface, referring to the main text where necessary. More details on the application of COCO2 parameters are given in Appendix C.

A1.1 Input Geodatabase Tab

The input geodatabase tab contains only one model parameter: “Emergency Ends”. “Emergency Ends” is a crucial parameter for understanding PACE output and is described in detail in Section 1.4 and in Table A1.

TABLE A1 Default parameters on the Input Geodatabase tab

PACE parameter	Description	Value
Emergency Ends	The parameter that defines when the emergency ends from the point of view of implementing emergency countermeasures. It is used by PACE as the time when evacuation and sheltering are lifted and when relocation begins	1 day

A1.2 End Points tab

The End Points tab contains two model input parameters as described in Table A2

TABLE A2 Default parameters on the End Points tab

PACE parameter	Description	Value
All pathway doses integrated to …	Individual dose endpoints (DS) will be integrated to the time given for all pathways and summed over pathways. NB doses from short term pathways will also integrated over the passage of the plume and long-term pathways will be integrated to the “Ground shine and resuspension doses integrated to” time below.	1 day
Groundshine and resuspension dose integrated to…	Individual doses from long term pathways (i.e. groundshine and resuspension) endpoints (DS) will be integrated to this time in addition to the “All pathways integrated to” time above	50 years

A1.3 Location factors tab

The Location factor tab is where the factors are set that modify doses to account for shielding of buildings in the given environment, occupancy and countermeasures. The protection

offered by buildings depends on the construction, materials and spatial relationship to other buildings, as well as the radiation energy and the pathway. Location factors attempt to capture this complexity in a single representative figure that can never be perfect for every situation. Brown (1988) and (Brown and Jones, 1993) have summarised a large number of studies and suggested values suitable for different classes of buildings.

The expression for including occupancy is

$$LF_{occ} = LF_i p_i + LF_o p_o$$

Equation A1

Where

LF_{occ} is the location factor including occupancy,

LF_i is the location factor for indoors,

p_i is the proportion of time spent indoors

LF_o is the location factor for outdoors, and

p_o is the proportion of time spent outdoors.

In the derivation of the default location factors it was assumed that the population spends 90% of the time indoors in all situations except sheltering in which case they spend 100% of the sheltering period indoors. For the default location factors, regardless of the environment it was assumed the outdoor location factor LF_o is always 1 and so Equation A1 becomes

$$LF_{occ} = 0.9LF_i + 0.1$$

Equation A2

Table A3 gives the short-term location factors for these situations for the default built environments (see Section 5.1.4).

TABLE A3 Default location factors short term

	Environment 1				Environment 2			
Exposure situation	Default[a]	Pre-CM[a]	Sheltering[b]	Car	Default[a]	Pre-CM[a]	Sheltering[b]	Car
Cloud Shine	0.28[c]	0.28[c]	0.2[c]	1	0.163[d]	0.163[d]	0.07[d]	1
Inhalation[e]	1	1	0.5	1	1	1	0.5	1
Skin Deposition[f]	1	1	0.5	1	1	1	0.5	1
Ground shine	0.26	0.26	0.18	1	0.13	0.13	0.035	1
Resuspension[f]	1	1	0.5	1	1	1	0.5	1

a the location factors account for the assumption that the population spend 90% of their time indoors, for the default location factors there is no difference between the default situation and the Pre-CM situation

b for the sheltering situation indoor occupancy is assumed to be 100%

c assuming an indoor location factor of 0.2 as a reasonable value for a typical brick house (Brown and Jones, 1993).

d assuming an indoor location factor of 0.07 as a reasonable value for a multiple storey building (Brown and Jones, 1993).

e buildings are assumed not to provide any protection from inhalation unless active sheltering is occurring in which case a factor of 0.5 is applied, (Brown, 1988).

f location factors for skin deposition and resuspension pathways assumed to be the same as inhalation.

Default long term relocation factors are given in Table A4 these were calculated using the ERMIN model (Jones et al, 2007); more information is given in Section 5.1.4.

TABLE A4 Default[a] long term location factors. Location factors are assumed constant for the period in which they applied, for example 0 to 1 days, 1 to 7 days etc

	Time (days)	0 – 1	7	14	30	90	1 year	2 years	10 years	50 years
Environment 1	Ground shine	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.22	0.19
	Resuspension	1	1	1	1	1	1	1	1	1
Environment 2	Ground shine	0.13	0.13	0.13	0.13	0.13	0.12	0.11	0.11	0.11
	Resuspension	1	1	1	1	1	1	1	1	1

a the location factors account for the assumption that population spend 90% of their time indoors

PACE3.3.2 has two environments; environment 1 representing a residential area of brick houses and environment 2 representing a residential area of multi-storey buildings. The environments are described in Section 5.1.4. The environments are made up of proportions of the idealised environments from the ERMIN model (Jones et al, 2007) see Table A5.

TABLE A5 Default Built Environments considered in PACE

PACE Environment	Represents	ERMIN Environments used
1	Brick built houses	90% 'Street of semi-detached houses without basement', with 'default' parameter set 10% 'Large open space', with 'park' parameter set
2	Multi-storey blocks of flats	70% 'Multi-storey block of flats amongst other house blocks', with 'default' parameter set 20% 'Multi-storey block of flats opposite parkland', with 'default' parameter set 10% 'Large open space', with 'park' parameter set

Default environment population densities are given in Table A6. These are calculated by combining the population densities of the separate ERMIN environments in each PACE environment. The ERMIN environment densities are a little high as they represent fully occupied environments but this is not important as they are only used for weighting average doses and so it is the relative density between environments that is used, see Section 5.1.4.

TABLE A6 Default environment population density

Environment	Density people km^{-2}
Environment 1	14076
Environment 2	41666

A1.4 The Countermeasures (CMs) tab

The countermeasures tab is where the user can set the criteria that allow PACE to decide where countermeasures are applied. It is split into several sub-tabs that represent the different countermeasures that PACE can consider.

A1.4.1 Evacuation and sheltering tabs

The algorithm that PACE employs to decide whether evacuation or sheltering is required in each location is described in Section 6.2. Default evacuation parameters are given in Table A7 and sheltering parameters are given in Table A8.

TABLE A7 Default evacuation criteria and parameters. Defaults are the same as Cosyma (Jones et al, 2000).

PACE parameter	Description	Value
Lung	The dose criteria in Sv for the corresponding organs.	0.5 Sv
Bone Marrow		0.0 Sv
GI tract		0.0 Sv
Thyroid		0.5 Sv
Effective		0.05 Sv
Ground shine period	The period ground shine is integrated over when comparing to evacuation criteria	7 days
Mandatory distance	The distance from the point of release within which evacuation will be applied regardless of radiological conditions	0 km
Maximum distance	The maximum distance from the point of release that evacuation can be applied regardless of radiological conditions	0km (a zero means that no maximum is applied)
Initial delay	Initial delay in applying evacuation in hours.	2 hours
Drive time	The time the population take to drive out of the region in hours.	1 hour
Hours between end of evacuation and removal of skin activity	The delay in removing skin activity following evacuation.	6 hours
Duration of sheltering before evacuation	Defined as the period of time after the initial delay but before people are actually moved out of their houses.	2 hours

TABLE A8 Default sheltering criteria and parameters. Defaults are the same as Cosyma (Jones et al, 2000).

PACE parameter	Description	Value
Lung	The dose criteria in Sv for the corresponding organs.	0.05 Sv
Bone Marrow		0.0 Sv
GI tract		0.0 Sv
Thyroid		0.05 Sv
Effective		0.005 Sv
Ground shine period	The period ground shine is integrated over when comparing to sheltering criteria	7 days
Mandatory distance	The distance from the point of release within which sheltering will be applied regardless of radiological conditions	0 km
Maximum distance	The maximum distance from the point of release that sheltering can be applied regardless of radiological conditions	0km (a zero means that no maximum is applied)
Initial delay	Initial delay in applying sheltering in hours.	2 hours
Hours between end of sheltering and removal of skin activity	The delay in removing skin activity following sheltering.	6 hours

A1.4.2 Stable iodine tab

The algorithm that PACE employs to decide whether stable iodine prophylaxis is required is described in Section 6.3. The default parameters are given in Table A9.

TABLE A9 Default stable iodine prophylaxis criteria and parameters. Defaults are the same as PC Cosyma (Jones et al, 2000).

PACE parameter	Description	Value
Inhalation dose intervention level	The committed dose from inhalation of the plume up to the 'Emergency Ends' time defined on the "input Geodatabase tab" see Section A1.1.	0.2 Sv
Maximum distance	The maximum distance from the point of release that SI can be applied.	240km (a zero means that no maximum is applied)
Mandatory implementation distance	The distance from the point of release within which SI will be applied regardless of radiological conditions	0km
Time taken after the accident	The time in hours after the start of the accident at which stable iodine is taken. NB it is assumed there is always an additional ¼ hour delay.	4 hours

A1.4.3 Food tab

The algorithm that PACE employs to decide whether food is restricted is required in each location is described in Section 6.5. The default parameters are given in Table A10.

TABLE A10 Default food restriction criteria, based on European maximum permitted levels (European Commission, 2016).

Restriction group	Description	Value
Strontium – Milk Iodine - Milk Alpha emitter - Milk Caesium – Milk	The milk activity concentration restriction criteria for the sum of activity concentration of the strontium isotopes, iodine isotopes, alpha emitting radionuclides and radionuclides with half-life greater than 10 days such as caesium.	125 Bq l^{-1} 500 Bq l^{-1} 20 Bq l^{-1} 1000 Bq l^{-1}
Strontium – Other Iodine - Other Alpha emitter – Other Caesium – Other	The other food activity concentration restriction criteria for the sum of activity concentration of the strontium isotopes, iodine isotopes, alpha emitting radionuclides and radionuclides with half-life greater than 10 days such as caesium.	750 Bq kg^{-1} 2000 Bq kg^{-1} 80 Bq kg^{-1} 1250 Bq kg^{-1}

A1.4.4 Relocation and clean-up tab

The algorithm that PACE employs to decide whether relocation and clean-up are required in each location is described in Section 6.4. The default parameters are given in Table A11. The default factors for calculating the costs of each clean-up package in each environment are calculated by multiplying the cost of each countermeasure in the package (£ per m^2 of surface) by the ratio of the surface that the countermeasure is applied, to ground area and finally summing over countermeasures in the package. The ratios of surface area to ground area of the ERMIN environments are given in Jones et al (2007) Section 6.4, and have been extracted into Table A12 and Table A13. The individual ratios for ERMIN environments are combined together in to give overall ratios for PACE environment.

TABLE A11 Default relocation and clean-up criteria and parameters Countermeasure relocation and clean up tab default data

Control	Description	Value
Integration period	The period over which ground shine and resuspension are integrated. NB the criteria are tested for imposition from the Short Integration Time for this period. The criteria are tested for relaxation at a number of different times following the short integration time for this period. The default of one year is consistent with UK advice for recovery (NRPB, 1997).	365 days
Relocation criteria	The effective dose at and above which relocation is imposed and below which it is relaxed. Defaults are the same as Cosyma (Jones et al, 2000).	0.05 Sv
Package 1 trigger	Total dose at which package 1 clean-up is triggered. Chosen to be consistent with relocation criterion.	0.05 Sv
Package 2 trigger	Total dose at which package 2 clean-up is triggered. Chosen as a suitable value greater than the relocation criterion.	0.5 Sv
Trigger integration period	The period over which trigger doses are integrated from Short Integration Time. Chosen to be consistent with relocation.	365 days

TABLE A12 Surface ratios of the ERMIN environments that make up the PACE Environment 1

	ERMIN environment "open area"	ERMIN environment "brick house"	Combined
Proportion of ERMIN environment in PACE environment	0.1	0.9	
Ratio of roof to total area	0	0.398	0.3582
Ratio of wall to total area	0	0.657	0.5913
Ratio of internal surfaces to total cell area	0	0.732	0.6588
Ratio of road to total area	0.02	0.132	0.1208
Ratio of pavement to total area	0.005	0.088	0.0797
Ratio of other paved to total area	0.075	0.134	0.1281
Ratio small grass to total area	0	0.224	0.2016
Ratio large grass to total area	0.8	0	0.08
Ratio small plant to total area	0	0.028	0.0252
Ratio large plant to total area	0.05	0	0.005
Ratio small bare soil to total area	0	0.028	0.0252
Ratio large bare soil to total area	0.05	0	0.005
Ratio trees to total area	0.1	0.063	0.0667

TABLE A13 Surface ratios of the ERMIN environments that make up the PACE Environment 2

	ERMIN environment "open area"	ERMIN environment "multi-storey"	ERMIN environment "multi-storey next to park"	Combined
Proportion of environment	0.1	0.7	0.2	
Ratio of roof to total area	0	0.458	0.229	0.3664
Ratio of wall to total area	0	1.146	0.573	0.9168
Ratio of internal surfaces to total area	0	2.75	1.375	2.2
Ratio of road to total area	0.02	0.195	0.158	0.1701
Ratio of pavement to total area	0.005	0.061	0.053	0.0538
Ratio of other paved to total area	0.075	0.143	0.155	0.1386
Ratio small grass to total area	0	0.114	0	0.0798
Ratio large grass to total area	0.8	0	0.324	0.1448
Ratio small plant to total area	0	0.014	0	0.0098
Ratio large plant to total area	0.05	0	0.04	0.013
Ratio small bare soil to total area	0	0.014	0	0.0098
Ratio large bare soil to total area	0.05	0	0.04	0.013
Ratio trees to total cell area	0.1	0.038	0.038	0.0442

The basic costs of countermeasures are taken from the 2nd version of the Radiation Recovery Hand Book (Nisbet et al, 2008b) as the current version does not give such costs. There are a lot of factors that affect the cost of clean-up which is why the 3rd Handbook moved away from giving explicit values. These factors are captured in the second handbook as different values depended on the situation (e.g. the cost might be different if the surface is dry or wet). For this

work, just one of situations is selected to come up with a representative default figure for PACE. The costs and the assumptions made for each option on each package are given in Table A14.

TABLE A14 Clean-up option costs rates (£m^{-2}) extracted from UK Recovery handbook for Radiation Incidents: 2008 (Nisbet et al, 2008a)

	Data sheet	Equipment cost (£m^{-2})	Material Cost (£m^{-2})	Labour cost (£m^{-2})	Total (£m^{-2})	Notes
Package 1						
Grass cutting small areas	32	0.0008	0	0.1	0.1008	
Grass cutting large areas	32	0.007	0	0.002	0.009	
Vacuum sweeping small paved areas[a]	24	0.001	0	0.005	0.006	Assuming dry surface and waste collected
Vacuum sweeping large paved areas[b]	24	0.0008	0	0.001	0.0018	Assuming dry surface and waste collected
Package 2						
Tree removal	43	0.2	0	1	1.2	Felling only
Vacuuming indoors	3	0.004	0	0.04	0.044	Using costs for rugs and carpet
High pressure hosing roofs and walls	10	0.4	0.	2	2.4	Assuming a large area and waste filtered
High pressure hosing paved areas[c]	27	0.2	0	1	1.2	Assuming waste filtered
Removal of soil and grass small areas	35	0.6	0	2	2.6	
Removal of soil and grass large areas	35	0.06	0	0.1	0.16	

a Taken to apply to pavements and other paved areas but not roads

b Taken to apply to roads

c Taken to apply to all paved areas

The derived default costs used in PACE are given in Table A15.

TABLE A15 Default clean-up costs

Cost factors £/m^2	Package 1	Package 2
Environment 1	0.023	3.5
Environment 2	0.011	4.0

A1.5 The Dose tab

The dose tab contains various parameters that control how doses are calculated in PACE. It is split into three sub tabs; Miscellaneous, Ingestion and Cloudshine.

A1.5.1 Miscellaneous tab

The miscellaneous tab includes breathing rates, resuspension and skin deposition parameters. Resuspension is discussed in Section 5.5 and skin and clothes deposition is discussed in Section 5.6. The default values are given in Table A16.

TABLE A16 Default miscellaneous dose parameters.

PACE parameter	Description	Value
Breathing rate	The breathing rate used for all plume inhalation and resuspension calculations (dependent on the age group selected: adult, 10-year-old or 1-year-old). Derived from Smith and Jones (2003).	2.57e-4 m^3/s (adult) 1.77e-4 m^3/s (10-year-old) 6.02e-5 m^3/s (1-year-old)
Resuspension factor K	The resuspension factor used in the calculation of resuspended material (Wellings et al, 2019)	1.2e-6 m^{-1}
Resuspension factor Kt	The long-term resuspension factor used in the calculation of resuspended material (Wellings et al, 2019)	1e-9 m^{-1}
Resuspension multiplier	A multiplier used in the calculation of resuspended material. By default it is set to 1.0 (rural conditions) but it can be used to simulate other conditions (Wellings et al, 2019)	1.0
Half-life of activity on skin	The half-life of activity on skin. Taken from Cosyma (Jones et al, 2000).	30 days
Fraction of skin contaminated	Fraction of total skin surface area contaminated. Taken from Cosyma (Jones et al, 2000).	0.1
Removal of skin activity	Cut-off time at which it is assumed that all activity on the skin is removed. See the discussion in Section 5.6.1.	5 days
Ratio of activity on the skin to integrated activity concentration in air	Ratio of activity on the skin to integrated activity concentration in air (dependent on radionuclide form: aerosol, elemental iodine or organically bound iodine)	0.001 (aerosols) 0.01 (elemental iodine) 0.0005 (organically bound iodine)

A1.5.2 Ingestion tab

The Ingestion tab includes the parameters for the ingestion dose pathway. This pathway is discussed in Section 5.7 and the default parameters are given in Table A17.

TABLE A17 Default ingestion dose parameters

Control	Description	Value	
Fresh fraction	The fraction of foodstuff that is consumed fresh for the purposes of applying a "delay time" for radioactive decay calculations	1.0 with the exceptions:	
		Cow's milk	0.5
		Soft fruit	0.65
		Orchard fruit	0.65
Fresh/process delay	The length of delay between farm gate and ingestion by the final consumer for fresh and processed foodstuffs, respectively	Cow's milk	2 days / 30 days
		Cow's meat	10 days / N/A
		Cow's liver	7 days / N/A
		Sheep's meat	10 days / N/A
		Sheep's liver	7 days / N/A
		Green vegetables	2 days / N/A
		Root vegetables	14 days / N/A
		Potatoes	14 days / N/A
		Grain products	60 days / N/A
		Soft fruit	4 days / 180 days
		Orchard fruit	90 days / 180 days
Individual Consumption	These are values for a UK mean adult consumer taken from NRPB-W41 (Smith and Jones, 2003).	Cow's milk	115 kg y^{-1}
		Cow's meat	15 kg y^{-1}
		Cow's liver	2.75 kg y^{-1}
		Sheep's meat	8 kg y^{-1}
		Sheep's liver	2.75 kg y^{-1}
		Green vegetables	35 kg y^{-1}
		Root vegetables	10 kg y^{-1}
		Potatoes	50 kg y^{-1}
		Grain products	50 kg y^{-1}
		Soft fruit	18 kg y^{-1}
		Orchard fruit	2 kg y^{-1}
Fraction of local produce in diet	An arbitrary conservative value	0.25 for all foods	

A1.5.3 Cloudshine tab

If the Cloudshine component of dose is calculated by the NAME model, PACE will need to scale the effective dose calculated to dose to the other organs as described in Section 5.3. The factors are taken from ICRP (2010) assuming 0.5 MeV energy and ISO geometry as in Table A18. Male and female factors were averaged.

TABLE A18 Default cloud gamma scaling factors

PACE organ	ICRP 116 Female	ICRP 116 Male	ICRP 116 Average	ICRP 116 scaling factor	Notes
Effective			0.687	1.000	
Lung	0.717	0.68	0.6985	1.017	
Thyroid	0.747	0.717	0.732	1.066	
Bone Marrow	0.679	0.652	0.6655	0.969	
GI tract	0.655	0.637	0.646	0.940	Using colon value as GI-tract unavailable
Eye	0.857	0.857	0.857	1.247	
Ovary	0.611	NA	0.611	0.889	Using female value only
Skin	0.81	0.806	0.808	1.176	
Bone surface	0.75	0.741	0.7455	1.085	
Breast	0.805	0.796	0.8005	1.165	
Stomach	0.667	0.626	0.6465	0.941	
Colon	0.655	0.637	0.646	0.940	
Liver	0.666	0.627	0.6465	0.941	
Gonads	0.611	0.706	0.6585	0.959	
oesophagus	0.63	0.64	0.635	0.924	
Bladder	0.641	0.594	0.6175	0.899	
Brain	0.791	0.778	0.7845	1.142	
Remainder	0.684	0.649	0.6665	0.970	

A1.5.4 Health Effects tab

The Health Effects tab is divided into two sub-tabs; Deterministic and Stochastic.

A1.5.5 Deterministic tab

The calculation of deterministic health effects is described in Section 7.1. The PACE default values for the risk calculation are given in Table A20 and Table A21. Parameters are taken from both NRPB (1996) Table 1 and from PC-Cosyma, Jones et al (1995a) Table 2. It should be noted that different symbols for the same values in these references and in PACE as tabulated in Table A19.

TABLE A19 Explanation of symbols of quantities in various references and PACE interface.

NRPB (1996)	PC Cosyma (Jones et al, 1995b)	PACE	Meaning
Θ_∞	D_∞	D-infinity	The value of D_{50}[a] at very high dose rates.
Θ_1	D_0	D-0	Describes the increase in D_{50}[a] with decrease in dose rate.
V	S	Shape	Describes the sigmoid shape of the risk function (must be greater than 1).
RBE	RBE	RBE	Relative biological effectiveness of alpha particles.

a D50 is the dose at which the effect is seen in half the population

The most appropriate values for the parameters for some effects depend on the medical treatment provided.

TABLE A20 Default parameters for risk of deterministic health effect calculation, consistent with Cosyma (Jones et al, 2000).

Symptom	Organ	Θ_∞	Θ_1	V	RBE (alpha)	Notes
Bone marrow (haematopoietic) syndrome	Red bone marrow	4.5	0.1	6	2	(NRPB, 1996) assuming adequate medical care
Pneumonitis (pulmonary syndrome)	Lung	10	30	7	7	(NRPB, 1996)
Gastro-intestinal syndrome (external)	Small intestine	15	0	10	0	(NRPB, 1996) taking the lower external value
Embryonic / foetal death	Uterus	1.5	0	3	2	PC Cosyma (Jones et al, 1995a)
Hypothyroidism	Thyroid	60	30	1.3	0	(NRPB, 1996)
Lung function impairment	Lung	5	15	5	7	(NRPB, 1996)
Skin burns	Skin	20	5	5	0	(NRPB, 1996)
Mental retardation	Uterus	1.5	0	1	0	Cosyma
Cataracts	Eye lens	3	0.01	5	0	(NRPB, 1996)

TABLE A21 Default values for deterministic health effects calculation

Parameter	Default value	Notes
Individual risk threshold	0.01	
Fraction of population vulnerable to pre-natal and neo-natal death	0.01	A conservative estimate of the proportion of the population who are pregnant
Fraction vulnerable to mental retardation	0.002	A conservative estimate of the proportion of the population who are pregnant and within the vulnerable gestational period.
Fraction of skin effects that are fatal	0.05	

A1.5.6 Stochastic tab

The calculation of stochastic health effects is described in Section 7.2. The derivation and assumptions for the chosen risk factors for organs is described in Appendix E and for hereditary effects in Appendix D, the risk factors used are summarised in Table A22 Other default parameters are given in Table A23.

TABLE A22 Default parameters for calculation of risk of stochastic health effects

Effect		Risk of mortality per Sv	Mortality as a fraction of incident
Cancer in	Oesophagus	0.0014	0.93
	Stomach	0.00655	0.83
	Colon	0.00313	0.48
	Liver	0.00289	0.95
	Lung	0.01015	0.89
	Bone surface	0.00032	0.46
	Skin	0.0002	0.002
	Breast	0.0033	0.29
	Ovary	0.0006	0.57
	Bladder	0.0012	0.28
	Thyroid	0.00022	0.07
	Bone Marrow	0.0028	0.67
	Remainder	0.00705	0.49
Hereditary effects	1st Generation	0.0015	0.8
	2nd Generation	0.0009	0.8

TABLE A23 Default values for health effects calculation

Parameter	Default value	Notes
Long term dose integration period	50 years	

A1.6 COCO-2 tabs

TABLE A24 Default parameters for calculation of economic costs

Parameter	Description	Value
Harvest delay tolerance	The length of delay of the harvest at which an economic loss is likely to materialise. Figures based on table 18 of COCO-2 report.	7 days (root vegetables) 0 days (leafy green vegetables)
Growth period	The length of time from sowing/planting of crop to harvest. Figures based on FARMLAND model.	120 days (root vegetables) 120 days (leafy green vegetables)
Sheep production	Sheep production may be classified as either periodic (default) or continuous and will be modelled as such	Periodically produced
Cull delay	The delay from the start of the accident to the time any cull is carried out.	365 days (beef herd) 365 days (dairy herd) 365 days (sheep flock)
Tourism days from start of year	The time of year at which restrictions are implemented, counted from 1st January	365 days
Number of tourism seasons	The number of equal partitions of the year which are considered as separate seasons for the purposes of modelling	2
Maximum length of short term accommodation	The maximum length of time for which short term relocated people are housed in temporary accommodation	730 days
Short term component of long term relocation	The length of time for which long-term relocated people are housed in temporary accommodation before being moved to new permanent accommodation	730 days
Number of houses in the UK	The number of houses in the UK	24729634
Portion of site power generated by damaged reactor	The percentage of site power generation lost due to shut-down/damaged reactors (accident specific)	50%
Time for which reactor not operational	The length of time after the start of the accident for which shut down/damaged reactors not producing power	365 days
Site perimeter radius	The approximate radius of the site perimeter (assuming a roughly circular equivalent site)	1000 metres

A1.7 Adept Gaussian dispersion tab

TABLE A25 Default parameters for ADEPT Gaussian dispersion model

Parameter	Description	Value
Default washout coefficients		0.00008 (A) 0.8 (B) 0.6 (B elemental iodine)
Wind direction (from north)		0 degrees
Wind speed		5 m/s
Mixing layer height		800 m
Stability category (Pasquill)		D
Rainfall rate		0 mm/h

A2 References

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APPENDIX B Default spatial data

The PACE run set contains a geodatabase called “PACE Input Data.gdb” which contains several polygon feature-classes that can be used as default input to the PACE calculation. The polygons in these feature classes are resampled onto the calculation grid to create the “InputData” feature class as described in Section 2.4. The field names and units before and after the mapping process are the same and are as given in the tables in Section 2.5.

The data have slightly different coverage, but all include most of the United Kingdom. The feature classes contain several fields, only those fields that are by default used by PACE are described below. Each feature class contains a field called “Shape_area” which gives the area of each polygon in m^2.

B1 Population feature class

The “population” feature class is based on the 2001 UK census data and converted to a 1km grid with a coastal outline. This data covers the United Kingdom including Northern Ireland and Isle of Man. It includes the Channel Islands, but these areas are not gridded and give only the population for each island.

From this feature class PACE uses the “Population” field giving the resident population of the polygon. However, PACE also uses the “Shape_area” field to generate the “IsLand” field that indicates which squares in the calculation grid contain land. PACE ignores grid squares without land. The “Population” and “IsLand” fields are described in Table 1.

B2 EDINA

The EDINA data is based on agricultural information compiled by the EDINA National Data Centre at Edinburgh University (http://edina.ac.uk/). It describes agricultural production. The data is based on the year 2003 and has been manipulated and converted to a 2km grid. EDINA have agreed that PACE users can use this data within PACE only and it should not be used other than as an input to the PACE calculation. The EDINA data does not include Northern Ireland, Isle of Man, but it does include the Channel Islands.

There are two sets of fields, those that begin with the prefix “P_” for primary and those that begin with the prefix “D_” for derived. Primary fields are closest to the original EDINA supplied data and give the production as hectares of crops or head of cattle. The primary fields are used principally in the economics calculations and are described in Table 3. The derived fields have been manipulated to estimate the production as kilograms of meat, milk, grain, vegetables and fruit. The derived fields are used for collective ingestion dose calculations and are described in Table 2.

B3 GLUD_UK

The “GLUD_UK” feature class covers Scotland, England and Wales but excludes Northern Ireland, Isle of Man and the Channel Islands. GLUD stands for Generalised Land Use Data.

The data in the “GLUD_UK” feature class is given on a 1km grid, each polygon gives the estimated area of different surface types. The fields “Domestic” and “Gardens” are used by PACE for economics calculations. “Domestic” is the area of domestic housing and “Gardens” is the area of gardens both given as m^2 in each polygon see Table 3. The data in the GLUD feature class was developed for the COCO2 model and its derivation is described in Higgins et al (2008).

B4 GVACAP

The “GVACAP” feature class holds economic data, it covers Scotland, England and Wales but excludes Northern Ireland, Isle of Man and the Channel Islands. The data was prepared on a regular 1km grid by HSL with units of £(m) per km^2 for the COCO2 model (Higgins et al, 2008).

GVA stands for Gross Value Added and is a measure of the contribution made to GDP by a given sector of the economy. In GVACAP the GVA for tourism is given in the “Tourism” field and the GVA of different sectors of industry are given in different fields named using the Standard Industry Classification (SIC) codes, so for example field “C” is GVA for “Mining and Quarrying”. The “Tourism” and SIC Industrial fields are described in Table 3. The derivation of the GVA values and the meaning of all the SIC codes is given in Higgins et al (2008).

“CAP” is an abbreviation of capital value. PACE uses four capital value fields from the “GVACAP” feature class. “CAPVALIND”, “CAPVALRET”, “CAPVALWARE” and “CAPVALOFF” which are the capital values in each grid square of industrial premises, retail premises, warehouses and offices respectively, see in Table 3.

B5 House

The “House” feature class holds economic data, it covers Scotland, England and Wales but excludes Northern Ireland, Isle of Man and the Channel Islands. The data was prepared on a regular 1km grid by HSL for the COCO2 model (Higgins et al, 2008). PACE uses four fields from “House”. The field “TotalValue” is the total value in £m of housing stock in the grid square. The field “NetHouseValue” is the value in £m of housing stock buildings in the grid square and does not include the land value. The field “RentReturn” is residential rent return in £m in the grid square. The field “AllHouses” is the number of houses in the grid square. For more information about the meaning of these values see Higgins et al (2008).

B6 References

Higgins NA, Jones C, Munday M, Balmforth H, Holmes W, Pfuderer S, Mountford L, Harvey MP and Charnock TW (2008). *COCO2: A Model to Assess the Economic Impact of an Accident.* Health Protection Agency, Chilton, HPA-RPD-046.

APPENDIX C Economic consequences equations

The COCO-2 report describes the way in which economic costs can be calculated, and where appropriate presents the equations, but the specific formulae and conditions coded in the PACE implementation of the COCO-2 model are included here for clarity. The derivation of the formulae and the sources of information used to produce the parameters involved are described in detail in the COCO-2 report. The report is therefore referenced where appropriate in order to simplify the presentation and avoid unnecessary duplication.

C1 Agriculture costs

The loss to agriculture is split into direct and indirect loss categories. Agricultural products are also divided into those which are harvested continuously (eg green vegetables) and those that are harvested periodically (eg cereal crops). The formulae used in the COCO-2 model to calculate these different losses are discussed in Section 9 of the report. The PACE implementation of these calculations follows the report closely and is as follows.

C1.1 Periodic production

As discussed in Section C3 of the COCO-2 report, periodic production describes agricultural production that follows an annual cycle, which in the PACE implementation includes the crop categories: cereals, potatoes, sugar beet, legumes, orchard fruit and soft fruit. It also includes sheep products (sheep meat and sheep liver).

C1.1.1 Crops

When considering foods which are the result of periodic production, the time of year of the accident is of consequence when estimating the cost incurred. In COCO-2, the variability in severity throughout the year is represented by different fractions lost (of output-GVA) for each crop as displayed in tables C5, C7a, C9, C11, C13 and C15 of the COCO-2 report. PACE uses the quarterly fractions ("standard quarters" column) from these tables. For periodic crops, PACE considers the whole year's crop to be lost if it is predicted that the MPL would be exceeded at the default time of harvest, where the harvest dates are the first of the month (from the same fractions lost tables in the COCO-2 report listed above).

The following equations describe agricultural loss for periodically produced crops in the order: direct loss in year 1; direct loss in year 2; indirect loss in year 1; indirect loss in year 2.

$$DL_{Y1} = Area(QF \times (Output - GVA) + GVA)$$

Equation C1

$$DL_{Y2} = Area \times GVA$$

Equation C2

$$IL_{Y1} = (M_A - 1)(Area(Output - GVA) - DL_{Y1})$$

Equation C3

$$IL_{Y2} = (M_A - 1)(Area(Output - GVA) - DL_{Y2})$$

Equation C4

Where $Area$ is the number of hectares of this crop restricted; QF is the mean of the quarterly loss fractions for this crop; $Output$ is the output value of this crop in £ per hectare; GVA is the gross value added for this crop in £ per hectare; M_A is the agricultural multiplier for indirect effects (as discussed in Section 4 of the COCO-2 report).

C1.1.2 Animals

Production of sheep meat and sheep liver is modelled as being periodic. The different fractions lost (of output-GVA) and end of sale season for sheep products are as displayed in table C17 of the COCO-2 report.

The following equations describe direct losses for periodically produced sheep products.

$$DL_{Y1} = Area(QF(Output - GVA) + GVA)$$

Equation C5

$$DL_{Y2} = \begin{cases} (Area \times GVA) & \forall\ \Delta T\ >\ (365 + H) \\ 0 & \forall\ \Delta T\ \leq\ (365 + H) \end{cases}$$

Equation C6

Where ΔT is the estimated length of the restriction in days (to a maximum of 730 days); H is the number of days after the incident to the end of sale season for the product; $Area$ is the number of animals restricted; QF is the mean of the quarterly loss fractions for this animal product; $Output$ is the output value of this product in £ per animal; GVA is the gross value added for this product in £ per animal.

The indirect losses are calculated in exactly the same way as for periodically produced crops, as described in Equation C3 and Equation C4 for the first and second years, respectively.

C1.2 Continuous production

The term *continuous production* is used to describe agricultural production, which is active throughout the year, at least to a reasonable approximation, and is discussed in Section C4 of the COCO-2 report. In PACE, all cow products (meat, liver and milk), root vegetables and leafy green vegetables are classified as the result of continuous production and as such assumed to be produced continuously and uniformly throughout the year.

C1.2.1 Crops

The calculation of when continuously grown crops are considered to be lost is different to that for those grown periodically. In the case of continuous production, there is considered to be an economic loss only if the estimated duration of restrictions exceeds what is known as the

"harvest delay tolerance" of the crop (otherwise losses are set to zero). The "harvest delay tolerance" is set by the user and the concept is described in Section C4.1 of the COCO-2 report. In simple terms, it is the length of time that the typical harvest date can be delayed before an economic loss is incurred.

The following equations describe direct and indirect agricultural losses, respectively, for continuously produced crops.

$$DL = \begin{cases} \frac{Area(\Delta T - H)}{365}\left(\left((2 \times G) + 1 - (\Delta T - H)\right)\left(\frac{Output - GVA}{2G}\right) + GVA\right) & \forall\, \Delta T < G + H \\ \frac{Area}{365}\left((G + 1)\left(\frac{Output - GVA}{2}\right) + GVA(\Delta T - H)\right) & \forall\, \Delta T \geq G + H \end{cases}$$

Equation C7

$$IL = (M_A - 1)\left(\frac{Area(\Delta T - H)}{365}(Output - GVA) - DL\right)$$

Equation C8

Where ΔT is the estimated length of the restriction in days (to a maximum of 730 days); G is the growing period of the crop in days; H is the harvest delay tolerance of the crop in days; $Area$ is the number of hectares of this crop restricted; $Output$ is the output value of this crop in £ per hectare; GVA is the gross value added for this crop in £ per hectare; M_A is the agricultural multiplier for indirect effects (as discussed in Section 4 of the COCO-2 report).

C1.2.2 Animals

Cow products - meat, liver and milk - are the result of continuous production throughout the year. The following equations describe direct and indirect losses, respectively, for continuously produced animal products.

$$DL = \begin{cases} \frac{Area}{365}\left(\left(Output \times T_C + GVA(\Delta T - T_C)\right)\right) & \forall\, T_C > 0 \\ \frac{Area \times Output}{365}(\Delta T - T_C) & \forall\, T_C \leq 0 \end{cases}$$

Equation C9

$$IL = (M_A - 1)DL$$

Equation C10

Where T_C is the number of days after the incident that culling begins; ΔT is the estimated length of the restriction in days (to a maximum of 730 days); $Area$ is the number of animals restricted; $Output$ is the output value of this product in £ per animal; GVA is the gross value added for this product in £ per animal; M_A is the agricultural multiplier for indirect effects (as discussed in Section 4 of the COCO-2 report).

C1.3 Culling animals

The culling of livestock is a drastic measure and an option that is unlikely to be chosen in the event. However, culling and the associated economic costs are discussed in the COCO-2 report and are implemented in this version of PACE.

It is very likely that animals would be able to return to normal production following an introduction to clean feed or transportation to an uncontaminated area, but this too has associated costs. It is only foreseeable that culling would be implemented as a policy where there is severe contamination over a large area, such that it is not cost effective to move the animals or import such quantities of clean feed.

In the current version of PACE, the user has the option to choose whether culling is considered as a countermeasure and also when (up to 730 days after the accident) at which it would be carried out should animal products still be restricted at that time. The costs as calculated by PACE simply include the lost capital of culled animals and do not account for the cost of the process and disposal of carcasses, for example.

$$C = N \times V$$

Equation C11

Where C is the capital loss; N is the number of animals of a given type (beef herd, dairy herd, sheep flock) culled; V is the capital value, in £ per animal, for the given animal type.

C2 Health effects costs

The economic cost of health effects includes contributions from deterministic health effects, cancers and hereditary effects, the calculation of which is discussed in more detail in Section 10 of the COCO-2 report. The simple overall formula, applied to different variables, and used to calculate each of the contributions is as follows.

$$C = N \times V$$

Equation C12

Where, in general terms, C is the cost of the health effect, to be calculated; N is the number of cases of the given type of health effect; V is the cost per effect, of the given type of health effect.

C2.1 Deterministic effects

The costs of deterministic effects are calculated by multiplying the number of effects, calculated by PACE, by a "cost per effect" factor, derived for COCO-2, which is discussed in Section 10 of the COCO-2 report. Equation C12 describes this calculation where N is the number of deterministic fatalities or non-fatalities, respectively, as calculated by PACE; V is the cost of deterministic fatalities or non-fatalities, respectively, in £ per effect.

C2.2 Hereditary effects

The costs of hereditary effects are calculated by multiplying the number of effects, calculated by PACE, by a "cost per effect" factor, derived for COCO-2, which is discussed in Section 10 of the COCO-2 report. Equation C12 describes this calculation where N is the number of first- or second-generation hereditary effects, respectively, as calculated by PACE; V is the cost of first- or second-generation hereditary effects, respectively, in £ per effect.

C2.3 Cancers

The costs of cancers are calculated by multiplying the number of effects, calculated by PACE, by a "cost per effect" factor, derived for COCO-2, which are discussed in Section 10 of the COCO-2 report. Equation C12 describes this calculation where N is the number of fatal cancers or cancer incidence, respectively, as calculated by PACE; V is the cost of cancer fatalities or cancer incidence, respectively, in £ per effect. In PACE, numbers of solid cancers and leukaemia, and therefore the associated costs, are calculated separately.

C3 Industry, tourism and other built-up area costs

The cost in urban areas includes a range of losses from various sources: business, tourism, accommodation, household goods, infrastructure and others and this is discussed in more detail in Section 8 of the COCO-2 report. The formulae used in COCO-2 to calculate these are as follows. Note: although many input variables to the built-up area cost calculations are given in units of £ million, all PACE results are converted to units of £.

C3.1 Business

In the model, it is assumed GVA is lost for the period that the workforce might be required to shelter, evacuate or relocate from the area. Therefore, the GVA lost is proportional to the net length of any relevant countermeasures implemented. Different types of business are dealt with separately, broken down by their Standard Industrial Classifications (SICs). The following equations describe direct and indirect business losses, respectively.

$$DL = \frac{1}{365}\sum_{SIC} GVA_{SIC} \times \Delta T \; \forall \; SIC \neq E$$

Equation C13

$$IL = \frac{1}{365}\sum_{SIC} (M_{SIC} - 1) GVA_{SIC} \times \Delta T$$

Equation C14

Where GVA_{SIC} is the GVA generated by the industry type in question, in £ million per annum; ΔT is the total length of any relevant countermeasures in days (to a maximum of 730 days), or "disruption", as calculated by PACE; M_{SIC} is the industry multiplier for the industry in question for indirect effects (as given in table 21 of the COCO-2 report).

The direct loss as a result of electricity generation following a plant shutdown or damage to plant reactor(s) is calculated separately from the other classifications and is described by the following equation. Note: this reduces to the standard form in Equation C13 for any grid square that does not include the reactor.

$$DL_E = \frac{1}{365}\big((1 - F_{SIC})T_E + F_E \times \Delta T\big)GVA_E \;\forall\; SIC = E$$

Equation C15

Where $F_E$is the fraction of GVA generated in the E classification by sources *other than* shut reactors (input through user interface); T_E is the length of time for which any reactors are shut, in days (input through user interface); ΔT is the total length of any relevant countermeasures in days (to a maximum of 730 days), ie "disruption", as calculated by PACE; GVA_E is the GVA generated by the industry type E, in £ million per annum.

In PACE, indirect losses are calculated in the same way for all SICs. Thus, it is calculated in the same way for classification E as for other SICs.

C3.2 Tourism

Overall tourism losses are included under the relevant industry for business losses. However, COCO-2 also considers regional tourism losses separately, calculating a measure of lost GVA from all tourism related enterprises taking account of seasonal variations. The following equations describe direct and indirect tourism losses, respectively.

$$DL_{TGVA} = \frac{TGVA}{365}\left\{\begin{array}{l}(L_s - T_s)\times sf_I + (L_s \times \sum_{J=1}^{J=N_s-2} sf_{I+J})\times\theta(N_s-2)+ \\ sf_{I+N_s-1}\times(\Delta T - (L_s - T_S) - Ls\times(N_s-2)\times\theta(N_s-2))\end{array}\right\}$$

$$\textit{where}\quad \theta(x) = \begin{cases} 1\;\forall x > 1 \\ 0\;\forall x \le 0 \end{cases}$$

Equation C16

$$IL = (M_T - 1)DL$$

Equation C17

Where $TGVA$ is the GVA generated by tourism, in £ million per annum; L_S is the length of the tourist season in days; T_S is the number of days from the 1st January to the start of restrictions (≤ 365); sf are the seasonal adjustment factors (sum to 1); ΔT is the total length of any relevant countermeasures in days (to a maximum of 730 days), ie "disruption", as calculated by PACE; T_S is the number of seasons that are at least partially restricted; M_T is the industry multiplier for tourism for indirect effects.

The calculation of direct losses from tourism is complex, as described in Equation C16, in order to take into account the effect of the seasonal adjustment factor, which is included to

model the seasonal variation in tourism. This formulation is adapted from equation 8.4 of the COCO-2 report, as the version described here better handles the three possible selections of the number of tourist seasons in PACE: 1, 2 or 4. As a default, PACE calculates losses based on 2 tourism seasons (broadly reflecting "on-" and "off-season" in the UK), but this can be adjusted in the user interface (to 1 or 4). There are four default seasonal adjustment factors in the PACE data library, which represent the four quarters of the financial year (April-April), which are used in the PACE calculation.

C3.3 Accommodation

Accommodation costs are incurred when people are forced to evacuate or relocate from affected areas. There are two components to this, short and long term, which are calculated separately.

Short term accommodation costs only include the direct tangible cost of accommodation where the evacuated population are not expected to be away from their homes for very long, as described by the following equation.

$$A_S = \frac{R_i \times \Delta T}{365}$$

Equation C18

Where R_i is the imputed rent, in £ million per annum; ΔT is the length of relevant countermeasures in days (up to 730 days), ie "time out of homes", as calculated by PACE, up to a maximum length of the "maximum delay for those returning" set by the user in the user interface (default value 90 days).

Long term accommodation costs apply to the population that requires permanent resettlement, consisting of the short-term relocation cost, and the value of the lost capital asset (i.e. house value less land value). The following equations describe losses from long term accommodation.

$$A_P = \frac{R_i \times \Delta T}{365} + P_H - V_L$$

Equation C19

Where R_i is the imputed rent, in £ million per annum; ΔT is the length of relevant countermeasures in days (up to 730 days), ie "time out of homes", as calculated by PACE, up to a maximum length of the "duration of short term accommodation for those not returning" set by the user in the user interface (default value 730 days); $P_H$is the total price of houses, in £ million; V_L is the value of land, in £ million.

The actual calculation in PACE has been adapted due to limitations in the available source data for the UK, which resulted in rare instances where land value exceeded the total price of houses. In the adapted form, net house value is computed for each region before the pre-processing stage, and replaces the $P_H - V_L$ term in Equation C19.

C3.4 Capital services

Capital services represent the benefits gained from infrastructure, which in this context could be temporarily lost because of the accident. Capital assets of business are covered in a separate calculation (C3.6), and housing stock in the calculation of long term accommodation costs (C3.3), so this quantity is focused on lost services in household goods (excluding cars and motorcycles), as described by the following equation.

$$C_S = \frac{C_A \times N_i \times \Delta T}{365 \times N_{UK}}$$

Equation C20

Where C_A is the total consumption of capital assets by households in the UK, in £ million per annum; N_i is the number of houses in the area in question; ΔT is the length of relevant countermeasures in days (to a maximum of 730 days), ie "time out of homes", as calculated by PACE; N_{UK} is the number of houses in the UK.

C3.5 Household assets

Loss of household assets represents the minimum loss in the unlikely case that such assets are permanently lost, for example because of contamination. The value of cars and motorcycles is included in this quantity. The loss of household assets is only calculated in the case where the population are out of their homes for longer than the "maximum delay for those returning" set by the user in the user interface (default value 90 days), i.e. they are permanently relocated. The calculation is described by the following equation.

$$C_{HA} = \frac{V_A \times N_i}{N_{UK}}$$

Equation C21

Where V_A is the total value of household assets in the UK, in £ million; N_i is the number of houses in the area in question; N_{UK} is the number of houses in the UK.

C3.6 Business buildings

Capital assets of businesses are lost in the situation where the business is forced to relocate if, for example, it is considered impractical to decontaminate the area. In PACE, this is assumed to be the case where the population are required to be "out of their homes" for longer than the "maximum delay for those returning" set by the user in the user interface (default value 90 days), eg they are permanently relocated. If this condition is met, the loss of business buildings is simply the total capital value of industrial, warehouse, retail and office buildings, in £ million.

C3.7 Capital plant, machinery and transport

Where industrial and commercial buildings are vacated, as in Section C3.6, there is a chance that the contents are also lost. In PACE, this is again assumed to be the case where the

population are required to spend "time out of homes" greater than the "maximum delay for those returning" set by the user in the user interface (default value 90 days). This quantity also includes the loss of transport equipment. Where the vacated premises condition is met, total loss of capital equipment (plant, machinery and transport) is described by the following equation.

$$C_E = \sum_{SIC} GVA_{SIC} \left(F_{PM,SIC} + F_{T,SIC}\right)$$

Equation C22

Where GVA_{SIC} is the GVA generated by the industry type in question, in £ million per annum; $F_{PM,SIC}$ and $F_{T,SIC}$ are the plant and machinery fraction and transport fraction, respectively, of the industry type in question, as given in table 24 of the COCO-2 report.

APPENDIX D First- and second-generation health effects

D1 Introduction

There are two distinct aspects to the costing of hereditary health effects in PACE both of which require several modelling assumptions to be made. The first involves establishing a cost for a hereditary health effect and the second a method for estimating the likely number of such effects that is practical to calculate and consistent with the operation of PACE. The first problem was tackled by the COCO-2 report (Higgins et al, 2008) and this approach will be followed. The method taken from the COCO-2 report is repeated in Section D2 for convenience. The methodology for estimating the number of effects is then considered in Section D3. Section D4 describes how doses are currently calculated in PACE and includes recommendations about how it should be calculated in future versions.

D2 Hereditary Costs

It is assumed for simplicity that the costs of hereditary effects are adequately represented by Equation 10.3 (Higgins et al, 2008) based on the provision in the COCO-2 report that it is reasonable to assume, for costing purposes, that all hereditary effects are fatal while from a radiation effects perspective ICRP 103 (ICRP, 2007) assumes that 20% of hereditary effects are non-fatal. It is further assumed that the relative years of life lost from hereditary effects compared to the average for all cancers, used by ICRP to assess detriment, can be used in the estimation of an aggregate cost. Thus, as the average number of years lost from all cancers is ~13 (Burnet et al, 2005), the ratio of relative years of life lost suggests that on average approximately 17 years of life are lost to those that die from their radiation induced hereditary burden. In reality, some hereditary diseases will have only a minor effect on the lives of those affected while others suffering from a different range of diseases will require a high level of care before succumbing to an early death. It could be argued in the latter case that the cost is being underestimated. However, severe effects acting from birth will be rare in comparison to more minor or late onset conditions. Similarly, if a chronic condition were assumed, the total cost, estimated by a slight variation of Equation 10.4 that allows the annually accruing VOLY costs to be discounted over the life of the patient, will be similar to that estimated for premature death[3]. Thus, assuming that all those suffering from hereditary effects die early should more than account for the cost of those needing care over an extended period. In addition to this assumption, there is no discounting of the cost to account for the delay between the accident happening and the gradual appearance of the next generation. The subsequent generation is, for simplicity, also assumed to appear at a single time in the future.

D2.1 Summary cost components

Table D1 (Table 15 in the COCO-2 report) summarises the health costs to be used in Equations 10.3 and 10.4 of the COCO-2 report.

[3]Equation 10.4 discounts costs to the time in the future when a subject first becomes ill. As treatment is only assumed to last a few years, no further discounting is applied. For a chronic condition, discounting should be applied to the costs accruing every year.

TABLE D1 Summary of health cost parameters (Table 15 from COCO-2 report)

Illness	WTP / VOLY £(000)	Net Output loss £	Medical £(000)
Cancer (fatal) Equation (10.3)	1,296	90,000	12
Cancer (non-fatal) Equation (10.4)	30	18,336	12
Deterministic (fatal) Equation (10.3)[1]	1,296	90,000	47
Deterministic (non-fatal) Equation (10.4) [1]	30	18,336	47
Hereditary Equation (10.3)[2]	1,296	90,000	12

[1]Acute Radiation Syndrome (ARS) acts as a surrogate cost for all deterministic effects

[2]The assumption is made that all the children affected are born within a year of the accident, and die ~17 years premature.

Hereditary effects, as shown in Table D2 (Table 16 in the COCO-2 report), are discounted, but the result is a simple cost factor applicable without any further calculation. To calculate the cost of hereditary effects life tables[4] are used to predict the age of death of males and females born in 2004. Equation 10.3 is then applied assuming that the average years of life lost from cancer is 12.5 (Burnet et al, 2005) and the relative loss of life due to hereditary effects is 1.32 with respect to all cancers. The resulting male and female costs are then simply averaged to give a cost of £549,000 per hereditary effect in the first generation. In calculating the cost for the second generation, the average age of a mother at the birth of a child (29) is used as an additional discounting offset with all other parameters as before (ONS, 2007). The resulting averaged cost is £357,000 per hereditary effect in the second generation. If the detriment estimate of ICRP, which is the source of the relative loss of life estimate, is soundly based then these values are likely to be conservative estimates of the cost.

TABLE D2 Cost of Deterministic Injuries and Hereditary effects (Table 16 from COCO-2 report)

Effect	Cost per effect £
Deterministic (fatal)	1,433,000
Deterministic (non-fatal)[1]	80,336
Hereditary 1st generation[2]	549,000
Hereditary 2nd generation[3]	357,000

[1]Treatment in 1 year

[2]No delay assumed for production of next generation

[3]29 year delay assumed in the production of the second generation

D3 Risk of Hereditary Effects

ICRP 103 follows UNSCEAR (2001) in the estimation of the risk of hereditary effects and the discussions of those references outlining the methodology will be not be repeated in detail. However, the resulting estimated risks generated by ICRP are not directly applicable to post-accident exposure and the minor change required to the standard assumptions is discussed below. It should also be noted that there is no direct epidemiological evidence of hereditary health effects in human populations and estimates of risk are based on animal studies.

ICRP 103 considers two options or exposure situations and gives estimates of risk for those options. Neither option satisfactorily resembles the characteristics of dose delivery during the

[4] Interim Life Tables, England & Wales, 1980-82 to 2004-06 ONS http://www.statistics.gov.uk/

accident and in the years after. Option 1 assumes that the parents of both the first and second generations are exposed to radiation and each receives the same radiation dose delivered uniformly before the next generation is born. The risk values of Table D3 (Table A6.3 in ICRP 103) will then apply with conventionally a factor of 0.4 applied to convert the risks from the reproductive population to those for the whole population. Alternatively, option 2 as shown in Table D4 (Table 6.4 in ICRP 103) assumes that only the initial reproductive population is exposed and not the subsequent generations.

TABLE D3 (Table A.6.3. in ICRP 103) Current estimates of genetic risks from continuing exposure to low-LET, low-dose or chronic irradiation (UNSCEAR, 2001) with assumed doubling dose of 1 Gy.

Disease class	Baseline frequency (per million live births)	Risk per Gy per million progenies: 1st generation	2nd generation
Mendelian Autosomal dominant & X-linked	16,500	~750 to 1500[a]	~1300 to 2500
Autosomal recessive	7500	0	0
Chromosomal	4000	[b]	[b]
Multifactorial Chronic	650,000[c]	~250 to 1,200	~250 to 1,200
Congenital abnormalities	60,000	~2000[d]	~2400 to 3000[e]
Total	738,000	~3000 to 4700	~3950 to 6700
Total per Gy expressed as per cent of baseline		~0.41 to 0.64	~0.53 to 0.91

[a] The ranges reflect biological and not statistical uncertainties.

[b] Assumed to be subsumed in part under autosomal dominant and X-linked diseases and in part under congenital abnormalities.

[c] Frequency in the population.

[d] Estimated from mouse data without using the DD method.

[e] Newly induced damage of pre-existing damage (It is assumed that 20–50% of the progeny affected in the first generation will transmit the damage to the next generation resulting in 400 to 1000 cases.)

TABLE D4 (Table A.6.4. in ICRP 103) Current estimates of genetic risks from one-generation exposure to low-LET, low-dose or chronic irradiation (UNSCEAR, 2001) with assumed doubling dose of 1 Gy.

Disease class	Baseline frequency (per million live births)	Risk per Gy per million progenies: 1st generation	2nd generation
Mendelian Autosomal dominant & X-linked	16,500	~750 to 1500[a]	~500 to 1000
Autosomal recessive	7500	0	0
Chromosomal	4000	[b]	[b]
Multifactorial Chronic	650,000[c]	~250 to 1200	~250 to 1200
Congenital abnormalities	60,000	~2000[d]	~ 400 to 1000[e]
Total	738,000	~3000 to 4700	~1150 to 3200
Total per Gy expressed as per cent of baseline		~0.41 to 0.64	~0.16 to 0.43

[a] The ranges reflect biological and not statistical uncertainties.

[b] Assumed to be subsumed in part under autosomal dominant and X-linked diseases and in part under congenital abnormalities.

[c] Frequency in the population.

[d] Estimated from mouse data without using the DD method.

[e] Newly induced damage of pre-existing damage (It is assumed that 20–50% of the progeny affected in the first generation will transmit the damage to the next generation resulting in 400 to 1000 cases.)

In ICRP Tables 6.3 and 6.4 (reproduced as Table D3 and Table D4 above) the risk to the first generation is the same while the second generation either experiences the residual consequences of the irradiation of their grandparents or those consequences plus the effect of the parent's exposure i.e. the first generation effect. Previously (ICRP 60) the calculation of the risks had continued until equilibrium had been reached and it was this extrapolation of the risk over many generations that had resulted in the much higher estimate of hereditary risk in ICRP 60. The reasoning behind the limitation of the risks to the first two generations can be found in ICRP 103 and UNSCEAR (2001).

ICRP 103 constructs averages from the Tables A6.3 and A6.4 reproduced above which are reported as Tables A6.6 and A6.7 respectively and are repeated below for simplicity in Table D5 and Table D6.

TABLE D5 (Table A.6.6 in ICRP 103) Risk coefficients for the reproductive and the total population obtained up to two generations when the population sustains radiation exposure generation after generation (all values expressed in per cent per Gy).

Disease class	Reproductive population		Total population Average[b]
	Range	Average[a]	
(a) Mendelian diseases	0.13 to 0.25	0.19	0.08
(b) Chronic diseases	0.03 to 0.12	0.08	0.03
(c) Congenital abnormalities	0.24 to 0.30	0.27	0.11
Total for all classes		0.54	0.22

[a] Average of the limits of the indicated ranges.
[b] 40% of that for the reproductive population.

TABLE D6 (Table A.6.7 in ICRP103) Risk coefficients for the reproductive population and the total population for the first post-irradiation generation (all values are expressed as per cent per Gy).

Disease class	Reproductive population		Total population Average[b]
	Range	Average[a]	
(a) Mendelian diseases	0.075 to 0.150	0.11	0.05
(b) Chronic diseases	0.025 to 0.120	0.07	0.03
(c) Congenital abnormalities	–	0.20	0.08
Total for all classes		0.38	0.16

[a] Average of the limits of the indicated ranges.
[b] 40% of that for the reproductive population.

ICRP consider that there are two options for the second-generation risks that depend on whether the exposure continues for subsequent generations or is instead limited to the primarily exposed generation. The latter option might seem to be the more realistic in most accident circumstances with a long exposure tail that might require the chronic exposure of the next generation to be considered. However, this would greatly complicate the analysis as the ICRP second generation risk estimate implicitly assumes chronic uniform exposure over all generations whereas the doses from an accident are heavily skewed towards the first year and the first generation. Unfortunately, the information required for more detailed calculations is not available. If it were the risk to the next generation of exposing a particular age cohort for a given length of time combined with information on the reproductive rate of different age cohorts would when appropriately integrated over time yield an estimate of the number of

radiation-induced hereditary effects expected. Although clearly more complex this calculation would be easier to understand and adjust in an appropriate way to fit the circumstances of an exposure than the simple estimation procedures that must be used instead.

Following the procedure of ICRP 103 Tables 6.3 and 6.4 can be processed to yield the risk to the first post irradiation generation of hereditary effects as approximately 0.15 % per Gy while the risk to the second post irradiation generation is 0.09 % per Gy. Alternatively, if the exposure is assumed to continue so that the first generation is also exposed then there is a cumulative risk of hereditary effects by the second generations of 0.21 % per Gy. This latter number is equivalent to the values quoted in ICRP 103 of 0.20 % per Gy (Tables 1, A.4.1, A.4.2 of ICRP 103, although it should be noted that Table 1 quotes the detriment as 0.2 % per Gy instead of 0.193 % per Gy as given in Table A4.1) and in Table A6.6 (ICRP 103) as 0.22 % per Gy.

The result is shown in detail in Table D7 and Table D8 which are respectively slight variations on Tables A6.3 and A6.4 of ICRP 103.

TABLE D7 an expansion of Table A.6.3. in ICRP 103. Averaged in each generation in % per Gy.

Disease class	Baseline frequency (per million live births)	Risk % per Gy			
		1st generation	Average population risk (0.4)	2nd generation	Average population risk (0.4)
Mendelian Autosomal dominant & X-linked	16,500	0.11	0.05	0.19	0.08
Autosomal recessive	7500	0.00	0.00	0.00	
Chromosomal	4000	[b]	0.00	[b]	
Multifactorial Chronic	650,000[c]	0.07	0.03	0.07	0.03
Congenital abnormalities	60,000	0.20	0.08	0.27	0.11
Total	738,000	0.39	**0.15**	0.53	**0.21**
Total per Gy expressed as per cent of baseline		0.53	0.21	0.72	0.29

b Assumed to be subsumed in part under autosomal dominant and X-linked diseases and in part under congenital abnormalities.
c Frequency in the population.

TABLE D8 an expansion of Table A.6.4. Averaged in each generation in % per Gy.

Disease class	Baseline frequency (per million live births)	Risk % per Gy			
		1st generation	Average population risk (0.4)	2nd generation	Average population risk (0.4)
Mendelian Autosomal dominant & X-linked	16,500	0.11	0.05	0.08	0.03
Autosomal recessive	7500	0.00		0.00	
Chromosomal	4000	b		b	
Multifactorial Chronic	650,000[c]	0.07	0.03	0.07	0.03
Congenital abnormalities	60,000	0.20	0.08	0.07	0.03
Total	738,000	0.39	**0.15**	0.22	**0.09**
Total per Gy expressed as per cent of baseline		0.53	0.21	0.30	0.12

b Assumed to be subsumed in part under autosomal dominant and X-linked diseases and in part under congenital abnormalities.
c Frequency in the population.

The numbers quoted above are considered applicable to the whole population by ICRP and use a multiplier of 0.4 to convert the risk originally calculated for the reproductive population to whole population. This conversion assumes that the life expectancy at birth is of the order of 75 years and implicitly assumes uniform exposure over a lifetime so that the dose received by the age of 30 (the mean reproductive age) is 40% of the total dose received (30/75=0.4).

It will be noted that the use of a 30-year reproductive time is in agreement with the approach used in the COCO-2 cost estimation procedure. However, as noted the inherent assumption is that the population is being uniformly exposed for 75 years whereas following an accident it would be reasonable to expect the majority of the exposure to occur in the years immediately following the event and that those exposed would receive almost all their lifetime dose within this 30 year window.

The ICRP 103 approach to estimating the overall population risk is therefore not appropriate to PACE as the post-accident doses received by the population are likely to decline quite rapidly with time. Thus, although also approximate it is more appropriate in the context of PACE to assume that the entire dose from the accident is received in a short period of time and that everyone of reproductive age is equally affected (the risk estimates are age at exposure time independent provided the recipient is in the reproductive target group). This should be a conservative assumption with the proviso that an appropriate reproductive age can be set. The simplest option is to follow the ICRP and COCO-2 lead and determine the proportion of the population under thirty and assume that is equivalent to the reproductive population. Data from ONS for the years 2002 until 2005 consistently indicate that the population less than 30 is approximately 37% of the UK population.

It will be noted that 37% is very similar to 40% and although not based on the same approach it is proposed that the 40% value is used. This will reduce the risk of potential confusion over the source of the risks used by PACE while providing a mildly conservative result. However, if age specific population data are subsequently used by PACE it should be possible to elaborate the calculation to some extent to take into account the exposure of different age cohorts and their expected future reproductive rates.

Thus, in summary it is assumed that ~40% of the population is under 30 years of age which is the mean age of mothers giving birth and all the exposure is received within 30 years of the accident. Clearly even within these artificial constraints a 25-year-old could be exposed for 5 years and then have a child that is exposed for a further 25 years before that person in turn has a child. However, the inherent uncertainty in the parameters is likely to make such a complex calculation over ambitious.

If such complications are considered the only tractable approach is to assume that the risk is directly proportional to the dose received before the age of thirty. In the example above that would mean that the risk of generation zero who were 25 years old at the time of the event giving birth to a child with hereditary effects would be 5/30 of risk of someone exposed from year 0 assuming that the dose was uniformly delivered over the thirty year period. This scheme could be used to adjust the effective risk-taking account of exposures in generation zero and generation 1 assuming either that a generic dose profile was used or that PACE calculated the dose profile for each cell or area.

D4 Application in PACE

PACE calculates the risk in a grid element by multiplying the risk per Gy from ICRP 103 by the total dose received over 50 years in that grid element. It is therefore straightforward to apply the costs and risks (Sections D2 and D3) in PACE which currently uses a static population with no age differentiation if the difference between the cumulative dose to 30 years is approximately the same as the dose to 50 years.

The error introduced by using a longer integration period (50 years instead of 30 years) is likely to be smaller than the other sources of error. In particular, the assumption in the derivation above that the dose is delivered relatively rapidly means that the parents of the second generation are not directly exposed. In reality, as noted in Section D3, the children of the first affected generation will also be exposed but to lesser doses and for shorter times[5]. The risk in the second generation will therefore be between those calculated for continuous exposure and short-term exposure but weighted towards the short-term result.

Table D9 summarises results for a calculation based on the above argument that explicitly handles first and second-generation effects.

TABLE D9 The cost of first- and second-generation hereditary health effects

	First generation % Risk per Gy R_f	Second generation % Risk per Gy R_s	Population burden first generation PB_f	Population burden second generation PB_s	Cost first generation HC1	Cost second generation HC2	Total cost
Primary population P exposed only	**R_f = 0.15**	**R_s = 0.09**	**$PB_f = P \times R_f \times D$**	**$PB_s = P \times R_s \times D$**	**549,000 x PB_f**	**357,000 x PB_s**	**HC1 + HC2**
Continuous exposure population P	R_f = 0.15	R_s = 0.21	$PB_f = P \times R_f \times D$	$PB_s = P \times R_s \times D$	549,000 x PB_f	357,000 x PB_s	HC1 + HC2

Recommended result in Bold

The important feature of these results is that the constant population acts as both the initial (zeroth) population and the first-generation population. The first of the above results, where only the primary (zeroth) population is exposed, is currently used in PACE as it is the most coherent simple approximation to apply. If a more realistic approximation is required it is recommended that the first result is modified to take account of the number of people in each age group, the attenuation of the exposure with time after the event and the change in future reproductive potential with time (at a given age how many future children are expected) . The first-generation result can then be applied to the zeroth generation and the first generation with the latter combining with the second-generation risk from the exposure of the zeroth population to form the cumulative second-generation risk. If there were no attenuation factors the cumulative second-generation risk calculated this way would be slightly higher than the continuous exposure estimate (i.e. 0.24).

[5] Exposure of the parents must take place before conception but could be from any age while they remain in the reproductive population.

Note ICRP publication 103 states that the lethality fraction of genetic disease is explicitly designated to be 80%. This assumption is designed to encompass the increased range of severity and lethality considered in ICRP publication 103. This assumption is applied by PACE to estimate the number of fatalities expected for both first- and second-generation effects. However, COCO-2 assumes for costing purposes that all hereditary effects are fatal i.e. there is no difference in the cost of a fatal or non-fatal hereditary effect when averaged over all hereditary effects. The consequences of this assumption are difficult to demonstrate but as argued in Section D2 should err on the conservative side due to the discounting otherwise imposed on the cost of non-fatal effects.

D5 References

Burnet NG, Jefferies SJ, Benson RJ, Hunt DP and Treasure FP (2005). Years of life lost (YLL) from cancer is an important measure of population burden – and should be considered when allocating research funds. *British Journal of Cancer* **92**(2), 241-245.

Higgins NA, Jones C, Munday M, Balmforth H, Holmes W, Pfuderer S, Mountford L, Harvey MP and Charnock TW (2008). *COCO2: A Model to Assess the Economic Impact of an Accident.* Health Protection Agency, Chilton, HPA-RPD-046.

ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. Publication 103. *Annals of the ICRP* **37**(2-4).

UNSCEAR (2001). *Hereditary Effects of Radiation, UNSCEAR 2001 Report to the General Assembly, with scientific annex.* United Nations, ISBN 92-1-142244-2.

APPENDIX E Stochastic health effect risk factors

PACE 3.1 and earlier versions used a mixture of mortality risks and mortality fractions sourced from COSYMA which are mostly from ICRP 60 (ICRP, 1991) but include some risks and fractions of unknown origin. The files in PACE after 3.1 have been updated to be more coherent and fully sourced.

Table E1 summarises the current risks and mortality fractions reported in ICRP 103 (ICRP, 2007) together with those used in COSYMA (and in PACE 3.1 and earlier versions). The problem that is immediately apparent is that ICRP 103, while including additional organs to those in COSYMA, does not include the pancreas. The pancreas is considered a remainder organ in both the ICRP 60 and 103 definitions of effective dose indicating that it is not thought a major source of radiation induced cancers. The AGIR (AGIR, 2011) report notes that although pancreatic cancer has a very high mortality rate it is a rare cancer and there is a dearth of evidence linking radiation to pancreatic cancer. The largest studies (the LSS and cervical cancer patients given radiotherapy) suggest there is no association although particularly in the case of the LSS this may be the result of attribution errors as the cancer is difficult to diagnose.

TABLE E1 Mortality risks and fractions

		Risk of mortality per Sv (Incidence(I) derived value more likely to be more accurate than mortality (M))					Mortality as a fraction of incidence				
	Organ	**COSYMA**	**60 (1990)**	**60 (2007)**	**103 (M)**	**103 (I)**	**COSYMA**	**60 (1990)**	**60 (2007)**	**103 (M)**	**103 (I)**
Cancer of the:	Oesophagus	NA	0.003	0.00248	0.0027	0.0014	NA	0.95	0.93	0.93	0.93
	[Stomach]	0.011	0.011	0.00466	0.00597	0.00655	0.85	0.90	0.83	0.83	0.83
	[Colon]	0.0085	0.0085	0.01172	0.00343	0.00313	0.55	0.55	0.48	0.48	0.48
	[Liver]	0.0015	0.0015	0.0015	0.00644	0.00289	1	0.95	0.95	0.95	0.95
	[Lung]	0.0085	0.0085	0.00625	0.00986	0.01015	0.75	0.95	0.89	0.89	0.89
	[Bone surface]	0.0005	0.0005	0.00032	0.00032	0.00032	1	0.72	0.46	0.46	0.46
	[Skin]	0.0002	0.0002	0.0002	0.0002	0.0002	0.01	0.002	0.002	0.002	0.002
	[Breast]	0.002	0.002	0.0014	0.00166	0.0033	0.4	0.50	0.29	0.29	0.29
	Ovary	NA	0.001	0.00133	0.0012	0.0006	NA	0.70	0.57	0.57	0.57
	Bladder	NA	0.003	0.0029	0.002	0.0012	NA	0.50	0.29	0.28	0.28
	[Thyroid]	0.0008	0.0008	0.0008	0.00016	0.00022	0.1	0.10	0.07	0.07	0.07
	[Bone marrow]	0.005	0.005	0.00314	0.00363	0.0028	1	0.99	0.67	0.67	0.67
	[Remainder]	0.0093	0.005	0.00963	0.0111	0.00705	0.6	0.71	0.49	0.49	0.49
	[Pancreas]	0.0026					0.9				
Sum risk of fatal cancer		0.050	0.050	0.046	0.049	0.040					
Hereditary effects[a]		0.01	0.01	0.0016	0.0016	0.0016	NA	1	0.8	0.8	0.8
Total risk		0.060	0.060	0.048	0.050	0.041					

Organs in square brackets used in PACE 3.1 and earlier versions

[a] PACE uses alternative risk factors for hereditary effects that allow first and second generation to be estimated as described in Appendix D.

As a concomitant to the presence of the pancreas, the 'remainder' organ in COSYMA cannot represent the same mix of organs as either the ICRP 60 or ICRP 103 effective dose remainder. However, it is important to note that the ICRP remainder data given in Table E1 strictly represents 'other solid cancers' and is therefore not exactly the same as the remainder as a composite organ weighted to calculate the effective dose but it will encompass the risk of cancer in all the identified 'remainder' organs. Viewing the remainder category as a catch all and not the risk associated with a prescribed group of organs would seem sensible but it should be borne in mind that in calculating the dose per unit intake to the remainder the result is based on the dose to those named organs.

Dose per unit intake values based on voxel phantom calculations are not yet available for ICRP 103 definitions. Therefore, since PACE 3.1, PACE takes the pragmatic approach of adopting the ICRP 103 risk and mortality fractions (columns labelled 103(I) in Table E1) but still using the ICRP 60 dose per unit intake values. The organs included in PACE were updated to remove the pancreas and to add the Oesophagus, Ovary and Bladder. The organs with ICRP dose per unit intake data are shown in Table E2 where the 'remainder organ' is the effective combination organ dose per unit intakes for the ICRP 60 mix of organs. The effective dose is similarly for the ICRP 60 mix. The error introduced by using ICRP 60 definitions but with ICRP 103 risks and mortality fractions is not likely to be particularly significant for PACE as the risks are epidemiological and effective dose is not directly used to assess consequences and generally loses its meaning when the exposure is not uniform.

The risk estimates could be localised using either the euro-north American data quoted in ICRP 103 or the results of AGIR (AGIR, 2011) for the UK. However, this would require significant work to generate the correct summary form as the data are presented by age and sex and often on the basis of different model assumptions. Other changes may be thought more relevant to future uses of PACE and easier to implement for example applying age dependent risks estimates or, although not officially sanctioned by ICRP, using the separate risks and mortality fractions available in ICRP 103 for males and females.

TABLE E2 ICRP 60 organ data for calculated dose per unit intake

Organ	Data available for risk estimate from ICRP 103	ICRP 60 remainder	ICRP 103 remainder
Adrenals		*	*
Bladder Wall	Bladder		
Bone Surface	Bone surface		
Brain		*	
Breast	Breast		
Oesophagus	Oesophagus		
St Wall	Stomach		
SI Wall		*	*
ULI Wall		*	
LLI Wall			
Colon	Colon		
Kidneys		*	*
Liver	Liver		
Muscle		*	*
Ovaries	Ovary		
Pancreas		*	*
Red Marrow	Bone marrow		
ET Airways			*
Lungs	Lung		
Skin	Skin		
Spleen		*	*
Testes			
Thymus		*	*
Thyroid	Thyroid		
Uterus		*	*
Remainder	Remainder		
Effective dose			

In addition to the organs shown the ICRP 103 remainder includes: Gall bladder, heart, lymphatic nodes, oral mucosa and prostate. In addition, organs considered explicitly when creating the effective dose in ICRP 103 include in addition to those specifically listed for ICRP 60 are the brain and salivary glands and gonads.

E1 References

AGIR (2011). *Risk of Solids Cancers following Radiation Exposure: estimates for the UK population. Report of the independent Advisory Group on Ionising Radiation.* Chilton, RCE-19.

ICRP (1991). 1990 Recommendations of the International Commission on Radiological Protection. ICRP publication 60. *Annals of the ICRP* **21**(1-3).

ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. Publication 103. *Annals of the ICRP* **37**(2-4).

APPENDIX F Derivation of skin deposition dose factors

Factors for calculating dose from deposition to skin and clothes were calculated using a methodology based on the GSF Report 14/89 (Jacobi et al, 1989) and the prior GSF-Report 7/85 (Henrichs et al, 1985). Previous versions of PACE only calculated the beta dose from deposition on skin to the skin organ. The application of this methodology also allows the calculation of factors for doses to other organs from deposition on skin although currently in PACE these factors are not used.

Alpha, Beta and Gamma skin doses have been calculated separately.

Information about radionuclide half-lives and emissions were taken from ICRP38 (ICRP, 1983) and the connected files ICRP38.IDX, ICRP38.RAD and ICRP38.BET described in (Eckerman et al, 1993).

F1 Gamma Radiation

The gamma equivalent dose rate to organ T (in Sv/s) is calculated by:

$$\dot{D}_i(T) = 1.6 \cdot 10^{-10} \cdot A \cdot \sum_i f_i E_i SAF_i(T)$$

Equation F1

Where:

i is the index for the radiation type and energy

A is activity of the surface of the body (Bq or Bq/cm^2) (=1 in this methodology)

E_i is the mean energy of the radiation (MeV)

f_i the intensity of the decay (per decay)

$SAF_i(T)$ is the specific absorbed fraction for the radiation in organ T (1/g or cm^2/g)

The energies and intensities of the radiations for a given radionuclide are taken from ICRP 38 and the associated ICRP38.RAD file. Note that the file gives the intensity per 100 decays so the value must be divided by 100. For gamma radiation doses only Gamma-rays, X-rays and Annihilation quanta are used (ICODES 1, 2 & 3).

The SAFs are taken from Table 6 of the GSF 7/85 report (apart from Skin). SAF values are then linearly interpolated to the energies of a radionuclide. Energies below the lowest value in Table 6 are assumed to have SAF values that linearly extrapolate down to zero at 0 MeV. Energies above 4 MeV (the highest value in Table 6) are assumed to have the 4 MeV SAF value.

This calculation is repeated for all organs in the table. For the skin dose the SAFs are taken from ORNL-5000 (Snyder et al, 1974) and the result multiplied by 17000 cm^2, the surface area of the body as given in GSF Reports 14/89 and 7/85.

F1.1 Effective Dose

The calculation of effective dose involves the weighted sum of the organ doses, the weights taken from ICRP 60. As oesophagus is missing from the table, small intestine is substituted. Testes are used for gonads. Small intestine is also included as a remainder organ.

F2 Beta Radiation

The calculation for beta radiation has two parts: discrete electrons (Internal conversion and Auger electrons) and a radionuclide beta spectrum. The SAFs (in cm^2/g) for electrons are taken from Table 2 of the GSF 7/85 report; values are given at different skin depths for different contamination depths. Contamination on the surface of the skin was assumed.

For discrete electrons Equation F1 can be used with the relevant SAFs and entries for each radionuclide in ICRP38.RAD with the ICODES 6 & 7.

For the beta spectrum of a radionuclide, the frequencies (number of beta per MeV per Decay) at energy grid points were taken from the ICRP38.BET file. The energies of these grid points do not appear in the ICRP38.BET file but are generated by K.F.Eckerman's Redspec function (found in the DRATES program).

The SAF values where interpolated to these energy points using a Piecewise Cubic Hermite Interpolator. This assumed a SAF of 0 cm^2/g at 0 MeV and the interpolator is used to extrapolate to any higher energies. Equation F1 becomes:

$$\dot{D}_i(\text{Skin Layer}) = 1.6 \cdot 10^{-10} \cdot A \int f_i E_i SAF_i dE$$

Equation F2

The integral over the energy grid is calculated using Simpson rule.

The sum of the spectrum and discrete results are produced for a particular layer of skin, depending on the SAFs used. Mean values were calculated from the results from skin layers between 50 and 100 µm.

F3 Alpha Radiation

Equivalent dose rate values for α-radiation were calculated using the Jaeger and Hübner (Jaeger and Hueber, 1974) published energy dose rate values for skin depths in Figure 7-87.

These energy values for a given skin depth were linearly interpolated to the alpha emissions (ICODE=8 in ICRP38.RAD) of a radionuclide. The interpolation sets doses for energies below 4 MeV as zero and doses for energies above 7 MeV at the 7 MeV value. This means that a radionuclide with a very high energy particle would have its dose underestimated.

For the radiation weighting factor (previously known as quality factor) for α-particles, a value of 20 was used. The results were converted into SI units and the correction factor of 10^6 suggested in the GSF Report 7/85 applied.

As with the beta radiation calculation the results are averaged over 50-100 µm. There are only positive values for the 50 µm layer.

GSF-Report 7/85 suggests some values at 50 µm for some plutonium isotopes such as Pu-238, Pu-239 and Pu-238. However, these radionuclides have alpha energies predominately between 5.1 and 5.5 MeV, with no higher energies in the ICRP 38 data. As noted by Figure 7-87 and (Oatway et al, 2011) Figure 15, these energies do not penetrate to depths of 50 µm. Appendix G of (ICRP, 2010) suggest an energy of 6.5 MeV is required. Therefore, no alpha doses were produced for these radionuclides.

F4 Radioactive Progeny

The results include contributions from radioactive progeny if they are considered likely to be in secular equilibrium with their parent radionuclide. These are identified as the radionuclides having a half-life ten times shorter than the parent and the progeny half-life also being less than a year.

Only the major progeny of any branch is considered. Table F3 shows the list of nuclides that currently include progeny in their calculation and several that may have had progeny included in the original data files.

Table F3: List of radionuclides with progeny or may require progeny

Parent	Progeny	Branch Ratio	Grand-progeny	Branch Ratio	Note on comparison to original
Ag-110m	Ag-110	0.0133			
Am-241					Full chain gets to same order magnitude
Ba-140					Expects La-140
Ce-144	Pr-144	0.982			Better match if progeny not included
Cs-137	Ba-137m	0.946			
Mo-99	Tc-99m	0.876			
Ru-103	Rh-103m	0.997			
Ru-106	Rh-106	1			
Sb-125	Te-125m	0.228			
Sr-90	Y-90	1			Zero in original suggesting Y-90 not included
Sr-91	Y-91m	0.578			Matches if no progeny
Te-127m	Te-127	0.976			
Te-129					with I-129 is closer but still different
Te-129m	Te-129	0.65			
Te-132	I-132	1			
Te-133					With I-133 and Xe-133 closer but still low
U-235	Th-231	1			
U-238	Th-234	1	Pa-234m	0.998	Better match if progeny not included
Zr-95					Closer if Nb-95 included
Zr-97	Nb-97m	0.947			Better match if Nb-97m not included

F5 Noble Gases

Noble gases are considered not to settle on the skin; therefore, all results have been set to zero. If a noble gas is produced as part of a decay chain, it is considered to end that chain.

F6 References

Eckerman KF, Westfall RJ, Ryman JC and Cristy M (1993). *Nuclear decay data files of the dosimetry research group.*

Henrichs K, Eiberweiser C and Paretzke HG (1985). *Dose factors for the contamination of the skin and the clothes.* München, GSF-Bericht 7/85.

ICRP (1983). Radionuclide transformations: energy and intensity of emissions. ICRP Publication 38. *Annals of the ICRP* **11-13**.

ICRP (2010). Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116. *Annals of the ICRP* **40**(2–5).

Jacobi W, Paretzke HG and Henrichs K (1989). *Dose Conversion Factors for Internal Emitters and Contamination of the Skin.* GSF - Bericht 14 / 89.

Jaeger RG and Hueber W (1974). *Dosimetrie und Strahlenschutz*, Georg Thieme Verlag.

Oatway WB, Brown J, Etherington G, Anderson T, Fell TP, Eslava-Gomez A, Hodgson A, Pellow P and Youngman MJ (2011). *Supporting Information for the Assessment of the Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site.* HPA, CRCE, HPA-CRCE-018 (supplement).

Snyder WS, Ford MR, Warner GG and Watson SB (1974). *A Tabulation of Dose Equivalent per Microcurie-Day for Source and Target Organs of an Adult for Various Radionuclides.* ORNL-5000.

APPENDIX G Run set files

File	Contents	Required
Blackpool.xml Heathrow.xml Honmtr01-2.xml Plymouth.xml Rhomtr91.xml	Files of meteorological data for use with ADEPT model	No
Example_sourceterm.xml	An example source term. This file is provided as an example of a source term structure with no guarantee as to the accuracy or suitability of its contents for a particular purpose.	No
CloudGammaFactors.xml	Cloud gamma correction factors	Yes, if ADEPT used and cloud gamma correction selected
Defaults_preProcess2.xml Defaults_NAMEIIIRun.xml Defaults.xml Defaults_AnalyseResults3.xml	Default form contents for Preprocessor, NAME3 Run tool, PACE tool and Analysis tool.	Yes
ExtCloud.xml	Dose factors for cloudshine	Yes
ExtDep.xml	Dose factors for groundshine	Yes
FoodConcData.xml	Food concentration factors for calculating ingestion dose	Yes
Ing.xml	Dose coefficients for ingestion	Yes
Inh.xml	Dose coefficients for inhalation	Yes
SkinDCF.xml	Dose factors for skin deposition	Yes
Nuclide Physical Data.xml	Basic radionuclide data	Yes
Results_Endpoints2.xml	Example calculations for Analysis tool	No
NAMEIII	Folder containing files for using NAME model	Yes, for using NAME run tool

APPENDIX H Analysis Tool Default Calculations

An XML file of default calculation specifications for the analysis tool is provided in the PACE run set. These specifications each refer to one of the calculation types identified in Table H1, and this appendix describes the context in which each one is used in the default file.

Table H1 lists the default calculations in the XML file “Results_Endpoints2”. Many of the calculations are repeated to give the results “without countermeasures” and “with countermeasures” respectively. The suffix “_CM” is added to those calculations for which countermeasures are included. To avoid unnecessary repetition, a description of the “_CM” versions has not been given where it is otherwise the same as the calculation without countermeasures.

TABLE H1 Default calculation specifications

Name	Description
Deterministic	The total population exposed to potentially deterministic doses ie reports total population in areas where there are any deterministic health effects. Skin burns mortality not included.
Fatalities	The number of fatalities from deterministic health effects, truncated by the population ie since people cannot be killed by more than one effect, the number of fatalities cannot exceed the population. Skin burns mortality not included.
NonFatalReactions	The number of non-fatal deterministic health effects (not truncated).
HereditaryEffects	The number of first-generation hereditary effects (not truncated).
CostFatalities	The cost (in GBP) of fatalities from deterministic health effects.
CostNonFatalReactions	The cost (in GBP) of non-fatal deterministic health effects.
TotalCostDeterministic	The total cost (in GBP) of fatal and non-fatal deterministic health effects.
CostHereditaryEffects	The cost (in GBP) of first-generation hereditary effects.
LeukaemiaFatalities	The number of fatalities from leukaemia (not truncated).
SolidCancerFatalities	The number of fatalities from solid cancers (not truncated).
TotalCancerFatalities	The number of fatalities from all cancers (not truncated).
LeukaemiaIncidence	The total number of leukaemias (not truncated).
SoildCancerIncidence	The total number of solid cancers (not truncated).
TotalCancerIncidence	The total number of all cancers (not truncated).
CostSolidCancerFatalities	The cost (in GBP) of solid cancer fatalities.
CostSolidCancerIncidence	The cost (in GBP) of solid cancers (not including the cost associated with mortality).
CostLeukaemiaFatalities	The cost (in GBP) of leukaemia fatalities.
CostLeukaemiaIncidence	The cost (in GBP) of leukaemias (not including the cost associated with mortality).
TotalCostCancer	The total cost (in GBP) of all cancers.
NumberEvacuated	The number of people evacuated ie the population where evacuation criteria met.
AreaEvacuated	The area evacuated in m^2 ie the area where evacuation criteria met.
NumberSheltered	The number of people sheltered ie the population where sheltering criteria met.
AreaSheltered	The area sheltered in m^2 ie the area where sheltering criteria met.
LostDirBusinessGVA	The loss (in GBP) of direct business production due to countermeasures.