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REPPIR 2019 consequence assessment methodology

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REPPIR 2019 consequence assessment methodology

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Summary

A full understanding of the possible consequences arising from potential radiation emergencies at sites is necessary for safe operation and appropriate emergency planning. REPPIR 2019 requires operators to undertake an assessment of the risk posed by their site to support and underlay planning for radiation emergencies if the regulations are considered to apply, for example if the site holds in excess of the levels in Schedule 1 of the REPPIR regulations.

This report describes a PHE recommended methodology for such consequence assessments. While not mandatory, the adoption of this consequence assessment methodology by operators will ensure that the requirements of schedule 3 of REPPIR are met and that the operator is able to provide the local authority with suitable information on the range of possible consequences from a release, calculated with consistency across different operators and sites. The recommended consequence assessment methodology is described in full in appendix B and the underlying assumptions are discussed in this report. This methodology is commensurate with scientific evidence and international good practice.

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Contents

1 Introduction

A full understanding of the possible consequences arising from potential radiation emergencies at sites[1] is necessary for safe operation and appropriate emergency planning. The Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR 2019) requires commensurate emergency planning for all hazards capable of resulting in a radiation emergency. The regulations require operators to undertake an assessment of the risk posed by their site to support and underlay planning for emergencies, for example if the site holds in excess of the levels in Schedule 1 of the REPPIR regulations[2].

Public Health England was asked by Department for Business, Energy and Industrial Strategy (BEIS) to propose a new recommended methodology for such consequence assessments. While not mandatory, the adoption of PHE's recommended consequence assessment methodology by operators will ensure that the requirements of schedule 3 of REPPIR are met and that the operator is able to provide the local authority with suitable information on the range of possible consequences from a release, calculated with consistency across different operators and sites: this includes a consistent approach to assessing the impact of different weather conditions at the time of release or subsequently during plume travel time.

Assessments based on this consequence assessment methodology will assist operators to make recommendations to local authorities on:

- the need for detailed emergency planning around a site
- the distance to which off-site planning is needed around a site
- possible justification for outline planning zones that are different to the default distance for outline planning, if appropriate, and possibly supporting information on the nature of outline planning

This report summarises the PHE recommended consequence assessment methodology, and discusses aspects of the underlying assumptions, including the dose criteria to be applied and default parameter values that should be used as part of the assessment. The methodology is commensurate with scientific evidence and international good practice.

2 Background

The requirements, placed by Article 97(2) of the Euratom Basic Safety Standards Directive 2013 (Council Directive 2013/59), that the "emergency management system shall be designed to be commensurate with the results of an assessment of potential emergency exposure situations and to be able to respond effectively to emergency exposure situations in connection with practices or unforeseen events" necessitates consideration of a full range of potential site events, including those of very low probability but severe impact. This requires a proportionate

[1] The term 'site' is used generically in this report to refer to the location where emergency planning may be required. The location may be a nuclear site, a hospital, an industrial location or other type of premises.

[2] Broadly, Schedule 1 values identify the sites with potential for events which could result in effective doses in the first year after a release exceeding 1mSv.

and graded approach to planning. The planning should be commensurate with the nature of the risk posed by the site and should be both proportionate and flexible to enable applicability to a full range of radiation emergencies.

Of particular relevance to this methodology is the need to consider both likelihood and severity of any exposures. The consequence assessment is based upon the operator's choice of source terms[1], selected according to published guidance (see REPPIR 2019, and Office for Nuclear Regulation and the Health and Safety Executive's Approved Code of Practice and Guidance 2019). The choice of source terms should appropriately reflect the full range of hazardous events which may occur at the site. The assessment based on these source terms provides operators with the information (the Consequence Assessment) they will present to the local authorities to aid the formulation of emergency plans, via the Consequence Report.

The information provided via this methodology will form one input into the selection of the detailed emergency planning zone, to provide an appropriate balance between the benefits of dose aversion and the potential dis-benefits which would be associated with implementing immediate protective actions in a radiation emergency across too wide an area. The methodology presented in this report is a total approach which aims to produce realistic estimates of emergency consequences through the application of realistic models in each stage. Realism is necessary in assessments supporting emergency planning, to avoid overestimation and a consequent imbalance between doses and protective actions. The consequence assessment methodology takes account of pessimistic consequences due to unfavourable weather conditions via the use of the ninety-fifth percentile of consequences based on weather variability.

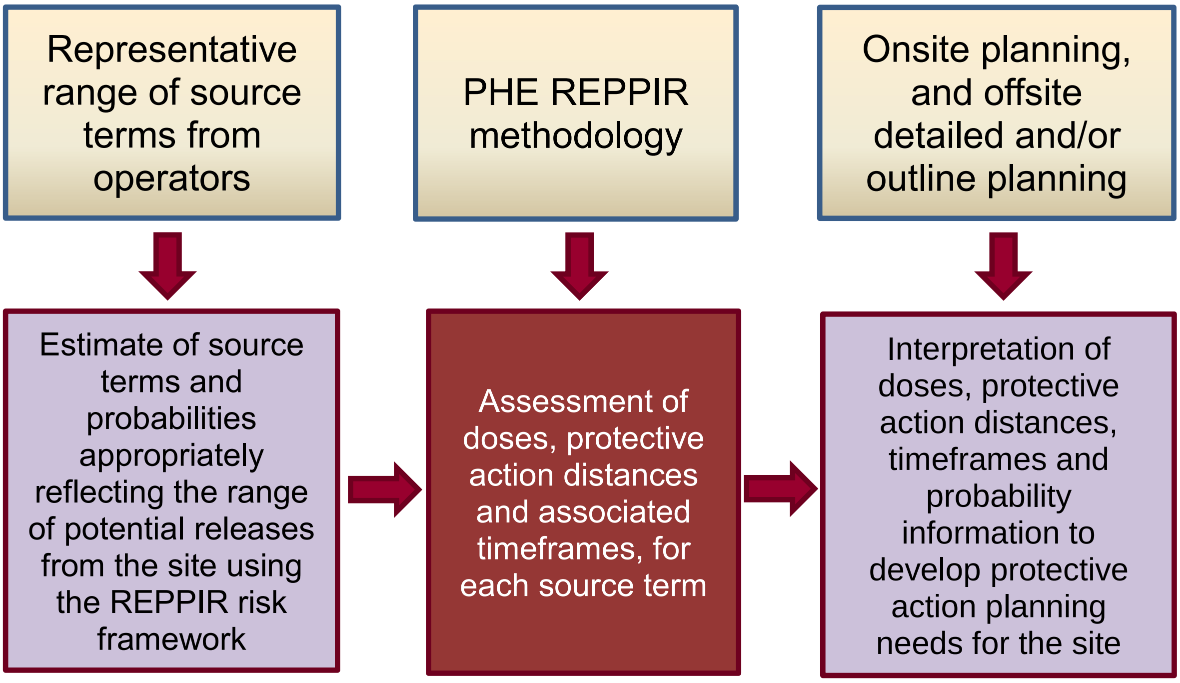
The process focussed on the use of the PHE REPPIR methodology is shown in Figure 1.

3 Key methodology assumptions

The consequence assessment methodology requires the operator's estimate of a range of source terms as an input. This range of source terms, following published guidelines, appropriately reflect the full range of hazards at the site which could give rise to a radiation emergency. The assessment of consequences based on these source terms will provide the basis for the information the operator will present to the local authorities to aid them in determining the need for, extent of and nature of off-site emergency planning for the site in question. It is intended that, through the use of a consistent methodology and the presentation of either all the results or a comprehensive selection of the results, local authorities will have better information on all the consequences of an emergency from the site to enable them to make an informed decision about off-site planning, as owners of the plan.

[1] The source term describes the release to atmosphere. It typically includes the amounts of each radionuclide released, the time distribution of the release (with variations across groups of radionuclides, where these may be expected to exhibit different time distributions) and other factors such as the energy associated with the release, the chemical and physical form of the release (also with variation by radionuclide). The warning time associated with each release is also relevant. The operator will have identified a range of source terms, each associated with a probability of occurrence. Some grouping of similar source terms may be made.

Figure 1 The consequence assessment process



Outputs from an assessment based on the consequence assessment methodology are only one input into the determination of detailed planning distances. Other factors include local considerations by the local authority, for example the existence of natural and easily understood boundaries, or avoiding the bisection of a residential road where possible.

The methodology determines doses and other endpoints to assist in determining appropriate on and off-site planning, but it does not directly determine the protective action zones for the site. The consequence assessment enables results to be calculated for *each operator-provided source term separately*. Wider UK guidance (Office for Nuclear Regulation and the Health and Safety Executive's Approved Code of Practice and Guidance 2019) advises on how these results for each source term should be used collectively to inform decisions on onsite and offsite planning arrangements.

4 Probability and consequences in assessments

Both the likelihood of event occurrence (such as the probability of each potential event or group of events) and the consequences arising from each event must be considered, including those resulting from very unlikely events.

The consequence assessment methodology therefore requires consideration of the probability of the consequences of each source term, both in considering the need for and the extent of detailed planning and also in regard to Reference Levels[1]. These results will allow local authorities to consider the estimated consequences as determined by this methodology (the impact) and the probabilities of the events that lead to the consequences (the probability of each source term), within the risk framework provided in the Approved Code of Practice and associated guidance. This is to ensure that planning considers both probability and impact appropriately. Hence events with higher probability of occurrence and generally low impact but possibly higher impact in some conditions, and also events with lower probability of occurrence but generally higher impact, will be considered.

5 Application

The consequence assessment methodology is the PHE recommended approach under regulation 5 and schedule 3 of REPPIR 2019. It determines doses and other endpoints required under those regulations. The methodology in itself does not directly determine the need for, extent of or nature of any offsite emergency planning zones for the site in question, although distances to which protective actions are required form part of the output for each specific source term. The Approved Code of Practice and associated guidance provide practical advice to duty holders on such decisions through consideration of the overall risk posed by the site in terms of both the potential events (the source terms considered) and the consequences of each event.

5.1 Proportionate consequence assessment for lower risk sites

PHE recognise that sites may have different capabilities and resources in place to undertake consequence assessments under regulation 5 and schedule 3 of REPPIR 2019. BEIS therefore commissioned PHE to develop datasets based on the PHE recommended consequence assessment methodology for use by smaller, lower hazard sites to meet regulation 5 and schedule 3 requirements.

Operators of lower hazard sites may therefore wish to utilise these pre-prepared dispersion datasets based on historic UK meteorological data and complex dispersion modelling. By use of these datasets, operators will avoid the need to obtain site-specific meteorological data and undertake dispersion modelling based on this meteorological data. Although the later stages of the consequence calculations are still required, and those aspects of the methodology discussed below remain relevant here, the use of the pre-prepared dispersion datasets will simplify the procedure considerably. These datasets, described elsewhere (PHE 2019a), represent a pessimistic but not extreme set of values, to ensure that consequences would be unlikely to be underestimated. It should be noted that not all the endpoints described in section 7.1 below can be correctly estimated using these pre-prepared datasets. The datasets do not include spatially varying information, only the maximum at specific distances, and so this data cannot correctly be combined with the data on agricultural production and population distribution

[1] A reference level (RL) relates to the total residual dose (after all protective actions) estimated to be received over the first year of the emergency from all pathways including the longer-term exposures. The aim of RLs is to achieve an optimised response over all exposure pathways and protective actions.

required in the assessment of the optional secondary endpoints (items 4 in section 7.1). This is not a significant limitation as the primary endpoints are the key ones for lower hazard sites.

For those sites presenting potentially larger risks, operators will need to undertake a probabilistic assessment of the full range of potential consequences based on historic observed weather data for their site. The methodology for this is described in this report. The pre-prepared data sets are not appropriate for use for higher risk sites.

5.2 Emergency Reference Levels (ERLs) and Reference Levels (RLs)

Response planning requires evaluation and balancing of a wide range of likely consequences of different options, including health, economic costs and social consequences. To assist in ensuring that this process of optimisation is carried out on a consistent basis across the UK, and for all types of emergency situations, PHE has specified Emergency Reference Levels (ERLs) of averted dose for use in the planning of urgent protective actions (PHE 2019b), and in particular evacuation, sheltering and stable iodine prophylaxis.

ERLs have a key role in the outputs from this methodology, in informing emergency planning arrangements. Appendix A summarises the UK approach to ERLs. REPPIR in combination with this methodology underlie the development of an understanding of possible events and consequences, enabling the development of appropriate and effective planning. Such plans will be capable of modification in the event of a specific accident, based on evaluation at the time.

In addition to the use of ERLs, the BSSD requirement for emergency response plans to include 'optimised protection strategies for members of the public who may be exposed, for different postulated events' also requires from local authorities the consideration of optimal actions over areas, populations and time, aiming to ensure the best use of available resources to protect individuals, populations and affected areas. This requirement links with the introduction of Reference Levels, which are therefore included in this methodology. Reference Levels (RLs) in emergency exposure situations relate to the total residual dose (the dose expected to be incurred by an individual after protective actions have been fully implemented) estimated to be received over the *first year* of the emergency from all exposure pathways. The doses against which the RL is compared therefore include both the short-term exposures received during the emergency and also the longer-term exposures over the remainder of the year.

A comparison of doses against Reference Levels may be used in off-site planning to ensure that plans prioritise keeping all doses below an agreed dose level, enabling consideration of options for recovery planning. Using the consequence assessment methodology, the doses over the first year from all relevant pathways may be assessed. The results of this dose assessment indicate the contribution by pathway and time, and the impact of different protective actions on these dose patterns, which is required as the quantity compared against the Reference Level is the residual dose (ie the dose after the savings from protective actions have been subtracted).

In summary, RLs:

- are expressed in terms of individual annual residual effective dose (mSv y^{-1})
- inform decisions on (i) urgent protective actions, (ii) restrictions on food and water supplies, and (iii) recovery actions, with an emphasis on their composite effect

- support the practical implementation of the optimisation principle, to ensure the best use of available resources to protect individuals, populations and affected areas
- may be used in planning to make sure that emergency plans aim to keep all doses from all exposure pathways below an upper value, which may be the selected national RL or a site specific RL, if one has been set

6 Elements of the methodology

Detailed recommendations in the consequence assessment methodology, and methods of calculation, are presented in Appendix B.

In summary, the methodology provides an approach to estimating the likelihood of predicted consequences for a given event (such as a source term). The consequence assessment methodology aims to support subsequent decisions on emergency planning which take into account the probability of the consequences of the event, as well as the probability of the event. The consequence assessment methodology is not in itself unduly conservative but rather aims for a realistic evaluation of endpoints, unlike the Schedule 1 methodology (PHE 2019c) which intentionally produces very conservative screening values. Additional conservatism would bias the results and may result in disproportionately extensive emergency plans. Consistent with this approach is (outside the consequence assessment) a realistic assessment by the operator of the probability of each event, for example through consideration of safety measures to mitigate event occurrence and consequence where appropriate.

As discussed above, the methodology determines doses and other endpoints to assist in determining the need for, extent of and nature of on and off-site planning, but it does not directly determine the emergency planning zones for the site. Wider UK guidance advises on how the results of the methodology may be combined with the estimated likelihood of each event to inform such decisions, through consideration of the overall risk posed by the site in terms of both the potential events (the source terms considered) and the consequences of each event.

The methodology relates specifically to a dispersible source with the potential for a significant release to atmosphere[1].

6.1 A probabilistic approach

The full consequence assessment methodology described in this report produces results which are probabilistic in nature. The probabilistic aspects considered are those which result from consideration of the variability in weather. Each event may occur in a range of possible conditions, because the weather is variable (for example, the location and amount of precipitation). Assessments which include variability in weather are necessary because emergency planning is now required to consider less likely outcomes, while retaining a proportionate approach to emergency preparedness commensurate with the potential magnitude of the consequences.

The methodology uses observed meteorological data together with a suitable atmospheric dispersion model. The methodology adopts the approach of considering (a) the expectation

[1] Sealed sources and/or radioactive holdings which are incapable of a significant release into the atmosphere are not assessable by this methodology.

value[1] and (b) the ninety-fifth of consequences based on weather variability, enabling endpoints to be calculated which indicate these results for each consequence for each source term. For example, results can show the distance to which the lower ERL for sheltering is exceeded 19 times out of 20 occurrences should the source term event occur (this is the ninety-fifth percentile).

There is uncertainty inherent in the choice of any dispersion model, which may lead to uncertainty in predictions greater than those associated with the parameters and assumptions used in other parts of the methodology. Straight-line Gaussian plume models have notable limitations (see Bedwell et al 2011) and their application is not recommended by PHE in the context of emergency planning.

It is important that the meteorological conditions are appropriately represented, to reflect the range of possible weather conditions. For this reason, the methodology applies a probabilistic approach to meteorology and dispersion rather than – as previously – a deterministic consideration of 1 or a few discrete atmospheric stability categories. Ideally, this approach requires the use of historical weather data for the UK, such as compiled data from previous complete years of meteorological observations. The use of historical weather data enables precipitation to be included in the assessment. The effect of considering precipitation during the release varies with exposure pathway and radionuclide; a significant effect is that exposure pathways which depend primarily upon deposition on the ground are likely to exhibit higher doses due to the increased ground deposition occurring during precipitation.

It should be noted that there is no requirement within this methodology to exclude from the calculations areas where there is no population, in particular an area of sea or another large water body in the vicinity of the site. The historic weather data for the site will to some extent be influenced by major features such as a coastline, but for the purposes of these calculations it is appropriate to consider potential doses around the entire site as if there was an individual at every location. Removing part of the surrounding area from consideration (if, for example, sea areas were to be excluded) may through an averaging effect inappropriately influence the values of the endpoints. Potentially, 2 identical installations, 1 inland and 1 on the coast, could have, for example, different distances to ERLs through this averaging effect, which would clearly be inappropriate. The effects of the local geography are subsequently considered by the local authority when establishing the off-site emergency plan such as the population at risk.

The dose assessed is the sum of all relevant direct exposure pathways, including direct external radiation and internal radiation from inhalation. Non-food exposure routes are inhalation of the plume and external exposure (to the plume or deposited material). The dose from inhalation of the plume is calculated using activity concentrations in air, habit data and inhalation dose coefficients. External exposure to the plume only occurs during the passage of the plume but external exposure to material deposited on the ground occurs after the plume has passed and may well persist throughout the first year of exposure for long-lived radionuclides. The external exposure from a unit deposit of radioactive material will vary with time due to migration through the soil and radioactive decay.

In the estimation of doses for comparison with Reference Levels, the longer-term dose routes such as ingestion, resuspension and long term external irradiation from deposited radionuclides

[1] Expectation value is a representation of the mean of the distribution. In this case, it is a weighted average of the possible values the endpoint can take, with the weighting reflecting the probability of occurrence.

are also relevant; the methodology for the assessment of these pathways is described in Appendix B.

Dose criteria for the introduction of urgent protective actions (sheltering, evacuation and stable iodine) are related to the lower and the upper ERLs. Dose criteria for comparison with the Reference Levels are 20mSv and 100mSv effective dose over the first year[1], which are the current lower and upper values for the range of Reference Levels for emergency exposure situations as defined by ICRP (ICRP, 2007).

Consideration is not given within the methodology to dose to the lens of the eye or skin as the lower and upper ERLs which relate to effective and thyroid dose will under most circumstances provide adequate protection. If the operator believes the protection of the ERLs to be inadequate for site-specific reasons, it will be necessary for the operator to additionally consider such exposures.

Three age groups are considered in the methodology, to represent the differing habits and dosimetric data for the range of ages (infants aged 1 year, children aged 10 years, young adults aged 20 years). Additionally, doses to the foetus and breast fed-infant should also be considered for those radionuclides where these could be potentially limiting (see Appendix B). However, in the application of ERLs it is assumed that 10-year-old children are considered in assessing the doses potentially averted (the doses which are then compared to the values of the ERLs), in recognition of their higher cancer risk.

7 Outputs from the methodology

7.1 Endpoints

A number of endpoints are assessed from application of the consequence assessment methodology and these are described below.

As there are consequences of radiation emergencies other than direct health impact, which will require planning considerations, the endpoints include not only doses and distances to which protective actions are required for each source term, but also other adverse consequences such as the extent of the impact on food, which will enable consideration of, for example, alternative food supplies. The local authorities will also wish to bear in mind that the impact on public health is not limited to the exposure of a member of the public to a particular level of radiation dose, but may be wider including, for example, psychological damage. Effective emergency preparedness, planning and response will mitigate such effects, including consideration of the endpoints derived from this methodology for each source term.

It should be noted that the methodology requires doses to be calculated over 2 time periods, which are 0 to 2 days, and 0 to 365 days, where the time 0 represents the start of the release. The value of 2 days has been selected because it is assumed to be the period for which the urgent protective actions of sheltering and evacuation will be in force. The period of time for which a protective action will actually be applied will depend on many factors, such as the magnitude of the doses, the duration of the release, time of day, availability of transport to

[1] A Reference Level may also be applicable under some circumstances to acute time periods (PHE, 2019c).

implement evacuation. However, for simplification and for planning purposes the duration of 2 days has been chosen here. This in particular applies to the period over which it is assumed doses will be averted by the protective actions, for comparison with the ERLs. The time period of 0 to 365 days relates primarily to dose calculations related to the Reference Level, which requires consideration of the residual dose (after protective actions) over the first year.

The number of endpoints below potentially amounts to a significant number. However, it is important to note that many of these endpoints will not be required for many sites; endpoints should only be presented in the Consequence Report if they are pertinent to decisions. For example, the smaller sites may well be able to undertake assessments for only a few close-in distances; if the doses are shown to be low and protective actions demonstrated to not be required at a small distance, there is no need to progress to greater distances. Also, systems and tools are available which can readily and semi-automatically (once an input dataset has been developed) generate such endpoints.

1) The evaluation of doses by distance and pathway, assuming no protective actions, to 2 days and to 1 year:

For each source term:

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

2) The determination of distances for urgent protective actions:

For each source term:

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

The above endpoints provide information relating to urgent protective actions. The underlying calculations estimate the dose received, assuming no other protective actions, in the first 2 days of exposure (including the dose committed during this time): the calculations of total dose to 2

[1] Note that the largest distance for which calculations are required will be limited by the default outline planning distance for the site – calculations are not required beyond this. Furthermore, the distances considered may be terminated once low doses have been demonstrated – the consideration of distances beyond this is not necessary.

days are those described above under (1). The doses then calculated for comparison against the ERLs are those that will be averted by application of each urgent protective action separately (see Appendix A and Appendix B). On the basis of these results, the distances to which lower and upper ERLs are exceeded for each source term in a range of weather conditions are identified. For example, the ninety-fifth percentile results will show the distance to which the lower ERL for sheltering is exceeded 19 times out of 20 occurrences should the source term event occur. It should be noted that smaller sites may gain no benefit from consideration of the upper ERL, if the distances at which the lower ERL are exceeded are small or zero; in such a case, calculations for the upper ERL may be disregarded.

3) Doses for comparison against the appropriate Reference Level:

For each source term:

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

The use of doses for comparison with RLs is still to be developed nationally, to ensure that the most appropriate endpoints are derived for the development of optimised plans. Some analysis by distance for the above endpoints is likely to be required, but even results for a single distance, such as at 1km, will give some information for RL planning.

Residual doses are calculated by removing the doses averted by the protective actions from the total doses integrated to 1 year that would have been received if no protective actions had been put in place. The doses averted come from urgent protective actions, food restrictions and recovery actions. It is not considered either feasible or appropriate to attempt to pre-estimate all these dose savings. Instead the residual dose after the urgent protective actions and food restrictions have been applied is estimated. By considering the total doses, and the dose savings by urgent protective actions and food, broken down by exposure pathway, the local authorities will have information on which to base consideration of other recovery measures.

The endpoints given above will provide a range of information on the significant pathways after implementation of protective actions, and can be compared with the doses estimated under (1) which do not assume protective actions. The intention is that the entire dose in the first year (including the dose in the first day) is calculated. In applying the results in the planning of an optimised strategy, it is appropriate to assume that protective actions within the detailed emergency planning zone are implemented as in the emergency plan, as planned, but consideration should be given on a site-specific and event-specific basis as to whether it is reasonable to assume protective actions are implemented in areas beyond the detailed emergency planning zone within the first 24 hours.

Only calculations of effective dose are required for comparison with the RL. There is no RL specified for thyroid dose, or for doses to other organs. Effective dose is the most appropriate quantity for considering the effect of exposures from multiple pathways and radionuclides.

4) Optional secondary results which the local authority might find helpful in planning, but which require location-specific grids for population and agricultural production:

For each source term:

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

It should be noted that these optional secondary endpoints cannot be correctly estimated using the pre-prepared dispersion datasets discussed in section 5.1. The pre-prepared datasets do not include spatially varying information, only the maximum at specific distances, and so this data cannot correctly be combined with the data on agricultural production and population distribution required in the assessment of these optional secondary endpoints.

7.2 Application of the results of the methodology

A consequence assessment based on the PHE recommended methodology informs, rather than prescribes, emergency planning decisions and distances. This is, in part, because of the uncertainties associated with the completeness, likelihood, consequences and measures both inherent within accident analysis and applicable to specific accident circumstances.

Also, the endpoints are derived separately for each source term, each of which has an associated estimate of likelihood of occurrence. The likelihood of each source term will influence the significance attached to the results for that source term, in terms of the degree and nature of planning required. It would also be expected that results for the same source term are treated differently when assessed for the expectation (average) value compared to the ninety-fifth percentile. Guidance on the approach to take to such likelihoods and consequence probabilities is given in Office for Nuclear Regulation and the Health and Safety Executive’s Approved Code of Practice and Guidance 2019.

In general, the detailed planning zones primarily (but not exclusively) relate to ‘plausible’ events, and less likely and unforeseen events relate more to outline planning distances. The decision on which source terms to select, to represent all events ranging from plausible through to those which are unforeseen, rests with the operator. Guidance on this is also given in Office for Nuclear Regulation and the Health and Safety Executive’s Approved Code of Practice and Guidance 2019.

In application of the estimates of the distances to which urgent protective actions are indicated (for example, the distance to which the lower ERL for sheltering is exceeded 19 times out of 20 occurrences should the source term event occur), the local authority may choose to interpret this as a circular zone within this radius around the site. While a site may have a prevailing wind direction, the use of this in determining emergency planning zone shapes may be regarded as too uncertain for reliance or emphasis to be placed on it; an event may occur at any site in any wind direction or weather condition, and in addition releases which continue over periods in excess of an hour or so will experience fluctuations in wind direction. Undue reliance on plume direction in planning is therefore not recommended.

7.3 Summary of key features

The key features of the PHE recommended consequence assessment methodology are:

- fundamental requirements in the assessment of the consequences of a release to atmosphere are estimates of time integrated activity concentrations in air (Bq s m^{-3} per Bq release) and ground depositions (Bq m^{-2} per Bq release). Such estimates require the application of an atmospheric dispersion model.
- straight-line Gaussian plume models are not recommended. Instead, the preferred approach is the use of historical weather data for the UK in combination with an atmospheric dispersion model capable of applying such weather data. This enables consideration of a full range of weather conditions including those which are less likely and also the conditions which include precipitation. In REPPIR 2001 (HSE, 2002) the use of Pasquill Category D weather was recommended in guidance, but this is no longer recommended here.
- probabilistic output from application of the methodology will provide the expectation value and also the ninety-fifth percentile, to enable the local authority to appreciate the dependence of the results on variability with weather conditions.
- the methodology provides a total approach, with the aim of producing realistic estimates of emergency consequences through the application of realistic models in each stage, avoiding overestimation and a consequent possible imbalance between doses and protective actions. Within the supporting risk framework, estimates of pessimistic consequences due to unfavourable weather conditions may be considered via the use of the ninety-fifth percentile.

The data and methods recommended in the consequence assessment methodology are summarised in Appendix B, including those for meteorological data, atmospheric dispersion, food chain modelling, the modelling appropriate for other exposure pathways (external dose, inhalation) and individual location and habits.

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Appendix A Emergency Reference Levels (ERLs)

Response planning requires evaluation and balancing of a wide range of likely consequences of different options, including health, economic costs and social consequences. To assist in ensuring that this process of optimisation is carried out on a consistent basis across the UK, and for all types of emergency situations, PHE have specified Emergency Reference Levels (ERLs) of averted dose for use in the planning of urgent protective actions (PHE 2019), and in particular evacuation, sheltering and stable iodine prophylaxis.

It is the dose averted or avoided by these protective actions that determines their benefit. The aim of ERLs is the reduction of early exposures so that the benefits and drawbacks of each protective action are separately balanced. ERLs relate to the dose averted in the first few days by a specific protective action (sheltering, evacuation and stable iodine prophylaxis), from the short-term exposure pathways only. ERLs are not intended to be limits on dose or indicators of doses which may be 'safely' received by an individual, but indicate the range of levels of dose (expected to be averted by the protective action) within which the greatest overall benefit of taking that protective action would be maximised, taking into account the potential for harm and disruption which arise from it. It is recognised that factors other than ERLs influence both planning and response, for example precautionary protective actions may be introduced if estimated projected doses are lower than ERLs and if there is sufficient advanced warning of an imminent event.

Since the exact consequences of a protective action depend very much upon the circumstances prevailing at the time and location of an emergency, and because many of the consequences cannot be directly quantified, PHE specifies a range of doses, bounded by an upper and a lower ERL for each protective action. The lower ERL indicates the likely balance of averted dose against all the other consequences of implementing the measure in situations that are favourable for its implementation. In other words, this is likely to be the smallest quantity of expected averted dose for which it would be justified to implement the measure. 'Favourable' circumstances usually include the availability of detailed plans and the involvement of small numbers of people. The upper ERL indicates the likely balance in unfavourable circumstances, for example, where there is only outline planning in place, weather conditions are extreme or larger numbers of people are involved. The ERLs are only indicative levels: plans may involve implementation of a protective measure for lower or higher levels of averted dose, owing to local factors. There could be circumstances where it would be inappropriate to implement the protective action, particularly evacuation, at the upper ERL due to the potential for harm (in terms of actual health consequences, societal disruption, economic cost etc) to outweigh the benefits of dose reduction. This is particularly the case for very large, extremely unlikely or unpredictable releases with the potential to expose major population centres. In such situations, the best protection may be afforded by initially advising sheltering and then identifying particularly vulnerable groups and initiating the selective, planned evacuation of these groups together with their families/carers. Table A.1 lists PHE recommended ERLs for urgent protective actions.

In developing a plan for urgent protective actions, the potential dose savings from the implementation of each urgent protective action should be compared with the appropriate ERLs for each scenario. In general, if the potential dose saving at a particular location is expected to be less than the lower ERL for a protective action, the emergency plan should not include that protective action for that location. Similarly, if the expected dose saving is greater than the relevant upper ERL, then in general PHE would recommend that provision should be made either for that protective action or, if appropriate for site and event-specific circumstances, for a more protective one.

TABLE A.1 Recommended ERLs for planning urgent protective actions (PHE 2019)

Protective action	Effective dose or organ dose	Averted dose (mSv)[a]	
		Lower	Upper
Sheltering	Effective	3	30
Evacuation	Effective	30	300
Stable iodine	Thyroid[b]	30	100

[a] In recognition of their higher cancer risk, the doses are those potentially averted by young children.

[b] mSv equivalent dose to the thyroid.

A1 References

PHE (2019). Public Health Protection in Radiation Emergencies, Public Health England. PHE-CRCE-049.

Appendix B Detailed recommendations and methods of calculation

The following sections describe in more detail how the endpoints should be calculated.

B1 Source term

A source term describes the nature and composition of a release (or potential release) to atmosphere.

For simple source terms, the activity (Bq) of each radionuclide released is required, along with information about the location of the release, its height and duration. With more complex source terms and release scenarios, and depending on the dispersion model used, additional information may be required. This may include time-varying release rates for each radionuclide or groups of radionuclides where these may be expected to exhibit different time distributions, the energy, buoyancy or momentum associated with the release, the chemical form of each radionuclide, and if in particulate form, the particle size. The warning time associated with each release is also relevant. With all source term data, the most appropriate parameter values for each potential release event should be selected based on expert judgement.

The operator will develop 1 or more source terms, each associated with a probability of occurrence. In general, the endpoints from this methodology will be calculated for each source term; however, some grouping of similar source terms may be used.

B2 Dispersion and deposition

Activity concentrations in the environment resulting from the release of each source term need to be modelled to enable dose and other endpoints to be estimated. Primarily, for each radionuclide, the concentrations required are time integrated activity concentrations in air for various time periods (the 'TIAC', in Bq s m^{-3}), and activity concentrations in material deposited on the ground (Bq m^{-2}).

An atmospheric dispersion model will either be required or, in the case of pre-prepared datasets, will already have been applied, to calculate these concentrations. The model must adequately enable the complexity of the source term and release characteristics to be taken into account. It should ideally be capable of modelling dispersion using historical meteorological data (see below), in order to estimate percentile concentrations in the calculated endpoints to represent the variability of weather. The model must where appropriate consider the different rates at which different radionuclides and chemical forms dry deposit (for example, differentiating between dry deposition velocities of different chemical forms of isotopes of iodine). The model must also suitably model wet deposition. Accounting for the terrain or urban environment can in most cases be considered simply (for example by way of a surface roughness).

Simple tools which use straight-line Gaussian plume models, such as NRPB-R91 (Clarke, 1979), are not recommended in this methodology. There is no longer the concept of a straight plume centre line, as concentrations will vary due to the temporally and spatially varying meteorological data. Gaussian plume models also have recognised limitations in their applicability.

The application of an atmospheric dispersion model which bases its predictions on real weather data will result in estimated concentrations at a range of locations around the release site. Typically, if a probabilistic dose assessment system is used, concentrations will be calculated on a grid of points around the release location. The spacing between the locations, or the resolution of the grid selected, will determine the accuracy with which the protective action distances derived in this methodology can be given. A spacing of 0.5 km close to the release location may be appropriate, and the spacing may increase further away.

The furthermost extent of predictions should be appropriate for the release consequences to be covered; in particular, food restrictions can potentially extend to significant distances from the release location.

B3 Meteorological data

It is the intention of the consequence assessment methodology that the ninety-fifth percentile value should be estimated, together with the expectation value, for each source term and each endpoint. This percentile information shows the impact on predicted consequences of varying weather, as an input into emergency planning considerations. To obtain such results, data on the variation of weather conditions in the affected area is needed.

Ideally, spatially and temporally varying historical meteorological data for the release site and its vicinity may be applied. By sampling historical meteorological data, time integrated activity concentrations (TIACs) in the air and deposits on the ground for a large number of meteorological sequences, at various locations, and for each source term can be calculated, and this will enable probabilistic endpoints to be calculated.

Care must be taken to sample historical meteorological data such that calculations are made that are representative of the full range of weather experienced at the site. For instance, data should be sampled at an appropriate frequency to ensure that different times of day, season, precipitation, wind direction and other meteorological conditions are adequately represented. Typically, this will require data to be sampled from multiple years, at least 3, if such data is available. A single year is in general insufficient, due to weather variations from year to year.

For the smallest releases, with consequences which extend only short distances from the release location, it may be acceptable for single-site meteorological data to be used. This means that it will be assumed that the weather data at a single location will be used to model the entire plume over the distance it travels. However, it is still important to have sufficient temporally varying historical data to obtain a representative sample of the weather experienced by the site.

For some operators of low hazard sites, the cost of obtaining suitable meteorological datasets may be disproportionately large. Pre-prepared datasets of time integrated activity concentrations (TIACs) in the air and deposits on the ground, per unit release have been developed and may be applied. The datasets are based on historical UK meteorological data, with regional variation. Although based on pessimistic weather data and therefore conservative in the results derived from them, the use of such data sets will enable operators to base potential exposure calculations on probabilistic dispersion and deposition results without the need for site-specific meteorological records or a complex dispersion model.

B4 Exposure pathways

The endpoints required from this methodology should be calculated by considering all relevant exposure pathways. The radionuclides and their activities (in Bq) in the source terms will determine which pathways contribute notably to human exposures. The area surrounding the release location will also have an impact on the significant pathways, for example the prevalence of local agricultural practices. Generally, the estimates of dose by location do not require consideration of the distribution of the population but simply the assumption that there is an individual at each location. However, the actual population distribution is an important factor in the interpretation of the endpoints in the development of the emergency plan.

Different exposure pathways will be important as time progresses. During the release, the inhalation of radioactive material from the plume, and external exposure to radioactive material in the plume and from material deposited on the ground are likely to be the primary pathways contributing to exposure. In the longer term, external exposure from material deposited on the ground is likely to remain important and activity in foodstuffs (or, more accurately, the management of food production in the area where levels may exceed the maximum permitted levels) is significant. For more unusual releases, the inhalation of material resuspended from the ground into the air may also need to be taken into account, although the contribution from this exposure pathway is generally small.

It is anticipated that a model will be used to calculate the doses from the various pathways and the concentrations in food that are required for the methodology endpoints. The model must be sophisticated enough to model the pathways adequately. Default parameter values and assumptions must be critically examined to ensure that they adequately reflect the exposure situation. Overly cautious assumptions should be avoided, as the calculations should aim for realism; best estimates should be applied where possible.

The following sections describe the approaches recommended when estimating activity concentrations in food and dose from the various exposure pathways.

B4.1 Inhalation of material in the plume

For most releases of radioactivity into the atmosphere, the inhalation pathway is likely to be a significant route of exposure and therefore it is anticipated that such an exposure pathway would be considered in almost all assessments.

Equation 1 represents the committed (effective or thyroid) dose arising from the inhalation of airborne radionuclides, assuming inhalation occurs for the full duration of the passage of the plume. Note that estimates of thyroid dose to be used in considering the need for stable iodine prophylaxis only need to consider isotopes of iodine.

$$IHD_{o,a} = BR_a \times LF \times \sum_{n,p} (TIAC_{n,p} \times IHDF_{o,a,n,p}) \qquad (1)$$

where:

$IHD_{o,a}$	= thyroid or effective inhalation dose (for organ o, and age group a)	(Sv)
BR_a	= breathing rate (for age group a)	($m^3\ s^{-1}$)
LF	= location factor	

$TIAC_{n,p}$ = time-integrated activity concentration in air (for radionuclide n, and particle size or chemical form p) (Bq s m^{-3})

$IHDF_{o,a,n,p}$ = thyroid or effective inhalation dose coefficient (for organ o, age group a, radionuclide n, and particle size or chemical form p) (Sv Bq^{-1})

Quantities:

TIAC: the time integrated activity concentration in air, for a particular radionuclide, at a particular location, usually calculated using an atmospheric dispersion model in conjunction with meteorological data. Results for a range of distance bands from the release point are likely to be required.

When a full probabilistic analysis is undertaken with historical meteorological data, it is usual to take, for each sampled sequence of weather and for each distance, the maximum value of the TIAC calculated around the full radial band (note that use of the full band is recommended, even if this includes areas which are not inhabited, for example sea, as discussed in the main text). These maximum values (the maximum will be different for each weather sequence) should then be used in the calculation of both the expectation value of the consequences and the ninety-fifth percentile[1]; for the expectation value, the mean of all these maximum TIACs is used[2], and for the ninety-fifth percentile it is the ninety-fifth percentile of all the maximum TIACs. This selection of the maximum value, the probabilistic statistical analysis, and the use of these in subsequent dose calculations, would be undertaken automatically within some available tools.

Alternatively, TIACs may be estimated on a more ad hoc basis at a number of locations of interest.

IHDF: age-dependent committed dose coefficient for a member of the public to age 70 years. Inhalation dose coefficients must be derived from the most recently published ICRP datasets. At the time of publication of this methodology effective inhalation dose coefficients are available from ICRP Publication 119 (ICRP, 2012), equivalent dose coefficients for organs, including the thyroid, are available from ICRP Publication 72 (ICRP, 1995), dose coefficients to the foetus are available from ICRP Publication 88 (ICRP, 2001), and dose coefficients to the breast fed infant are available from ICRP Publication 95 (ICRP, 2004).

BR: age-dependent breathing rate. The activity(s) of a particular exposed individual will be variable and it is appropriate to assume values which are representative of the general population. Breathing rate is dependent on the activity(s) the individual is undertaking (whilst the plume is passing), which in turn is dependent on the duration of exposure. The duration of

[1] This complex point arises because, unlike in a simple Gaussian approach there is no longer a plume centre line and environmental concentrations are much less uniform, both in terms of distance downwind and "cross axis". Because meteorological conditions are not uniform (or homogeneous), the plume and deposition footprint are also not uniform (or homogeneous). It is not feasible for an atmospheric dispersion model to consider a very large number of receptor points covering the entire modelled space, which would be necessary to identify the true modelled maximum, and the calculations are therefore based on a grid of an appropriate resolution to cover each radial distance band. For each radial distance band, the maximum value of the TIAC should be estimated i.e. the maximum value across the grid points which "sit" in each radial distance band; this maximum value at each distance band will then contribute to the calculation of the expectation value and the ninety-fifth percentile, where the results for the full set of weather sequences are used; for the expectation value, the mean of all these maximum TIACs is used, and for the ninety-fifth percentile it is the ninety-fifth percentile of all the maximum TIACs.

[2] In calculating the expectation value of the consequences, it is still appropriate to estimate the maximum TIAC and the maximum deposited concentration, although this may seem counter-intuitive. This is because the maximum value is akin to the value on the 'plume centre line' for a single met sequence.

exposure is not necessarily equivalent to the release duration for a variety of reasons, including variation in wind speed and wind direction. However, for the purposes of informing the range of activity(s) the individual is likely to undertake, it is reasonable to assume that the duration of exposure is approximated by the release duration.

For a release duration of less than 7 hours, for all age groups, it is recommended that a breathing rate which reflects one third of the time spent sitting and two thirds of the time spent undertaking light exercise should be assumed. For a release duration greater than 15 hours, for all age groups, it is recommended that an average breathing rate which comprises a proportion of sleeping, resting, and being active, should be assumed. For a release duration between 7 and 15 hours the level of activity will vary as a function of age and a suitably representative breathing rate should be determined, reflecting the level of activity likely to be undertaken. At the time of publication of this methodology ICRP Publication 66 (ICRP, 1994), Smith and Jones (2003) and Robinson (1996) are recommended references. However, the most up to date reputable source of data should be applied if these references have been superseded.

LF: location factor. For all averted and residual dose calculations, the impact of protective actions must be taken into account. For evacuation, a location factor of 0 is recommended, such as individuals are moved away from the release location in time to avoid all exposures, and their subsequent dose is negligible. For sheltering, a dose reduction factor typical of housing stock in the area affected must be applied. For general UK housing stock, as a default value, a location factor of 0.6[1] should be assumed for inhalation doses to an individual sheltering during the entire passage of the plume, until both the indoor and outdoor air concentrations fall back down to (or close to) zero, with no opening of windows and doors to the external environment. However, location-specific factors which may be considered include: the air permeability of a dwelling; the meteorological conditions; the particle size; the effectiveness/timing of opening windows and doors; and the release duration, all of which could vary significantly from 1 scenario to another (or even within a single scenario). In general, the most up to date reputable source of data for the UK should be applied if this reference has been superseded. A location factor of 1 is recommended if an individual is assumed to be outdoors during the passage of the plume.

B4.2 External exposure from deposited material

For gamma-emitting radionuclides which deposit onto the ground, the external exposure from deposited material is likely to be a significant exposure pathway and it is anticipated that such an exposure pathway would be considered for all potential releases that include such radionuclides. External exposure to material deposited on the ground begins as soon as the release starts. It continues after the plume has passed, and potentially persists throughout the first year of exposure (and beyond) for long-lived radionuclides.

Equation 2 represents the effective dose arising from external exposure to material deposited on the ground, for a person at location I,

$$EGD_{t,i} = LF_i \times OCC_i \times \left[\sum_n (GD_{n,i} \times EDF_{n,t}) \right] \quad (2)$$

where:

[1] A location factor of 0.6 means that the inhalation dose will be reduced to 60% of that outdoors.

$EGD_{t,i}$ = effective dose integrated to time t, from radionuclides deposited at location i (Sv)
$GD_{n,i}$ = initial deposit of a radionuclide n, at a particular location i ($Bq\ m^{-2}$)
$EDF_{n,t}$ = integrated external dose conversion factor to time t after unit deposition of radionuclide n (Sv per $Bq\ m^{-2}$)
OCC_i = fraction of time at a particular location i

and where:

$$LF_i = SF_{indoors,i} \times FT_{indoors,i} + SF_{outdoors,i} \times FT_{outdoors,i} \quad (3)$$

where:

LF_i = location factor at a particular location i
$SF_{indoors,i}$ = indoor shielding factor at a particular location i
$FT_{indoors,i}$ = fraction of time indoors at a particular location i
$SF_{outdoors,i}$ = outdoor shielding factor at a particular location i
$FT_{outdoors,i}$ = fraction of time outdoors at a particular location i

Quantities:

GD: the concentration of activity deposited on the ground for a particular radionuclide, at a particular location, up to a particular time, usually calculated using an atmospheric dispersion model. Results for a range of distance bands from the release point are likely to be required. For each of these distances, the maximum value calculated around the full radial band should be estimated, as discussed above for inhalation of material in the plume. Alternatively, deposition concentrations may be estimated on a more ad hoc basis at a number of locations of interest.

For a dose integrated to 1 year after the release it is acceptable to assume all the deposition occurs at the time of the release and therefore a single effective dose factor integrated over 365 days can be assumed.

For a dose integrated to 2 days after the release it may be necessary to consider the duration of the release (and therefore whether or not the activity is likely to be deposited over a short period or an extended period), the half-life of the radionuclide (and therefore whether the integrated dose rate varies over periods of a few hours to 2 days) and the relative significance of the contribution to dose via this exposure pathway (as, if the radionuclide in question is known to make very small contributions to dose via this exposure pathway, it can be omitted from the assessment). By assessing these factors, it can be determined whether a single effective dose factor integrated over 2 days can be assumed or whether the consideration of multiple effective dose rates integrated over a number of time periods between 0 and 2 days is required.

EDF: integrated dose rate per unit deposit. The external exposure from a deposit of radioactive material will vary with time due to migration through the soil, radioactive decay and ingrowth of decay products. These processes should be considered when estimating the external effective doses per unit deposit over time. The dose 1 metre above the ground surface is typically assumed. At the time of publication of this methodology the GRANIS model (Kowe et al, 2007) is the recommended approach. Kowe et al (2007) details effective dose integrated over numerous time periods, including 2 days and 1 year, however only for a limited number of radionuclides. For radionuclides not considered in Kowe et al (2007) but thought to be significant, integrated dose rate per unit deposit values must be determined, for example as described in Veinot et al (2017). The most up to date reputable source of data should be applied if these references have been superseded.

LF: location factor. For all averted and residual dose calculations, the impact of urgent protective actions must be taken into account. The location factor accounts for the reduction in the dose as a result of undertaking representative activities and/or urgent protective actions for the entire period that an individual is considered to be at a specific location. It is assumed that the location factor is not dependent on the age of an individual. For evacuation, a location factor of 0 is recommended, such as individuals are moved away from the release location in time to avoid all exposures, and their subsequent dose is negligible. A location factor of 1 is recommended if an individual is outdoors during the passage of the plume.

SF: shielding factor. Sheltering provides protection against external radiation from airborne gases and particles which have been deposited on the ground in inhabited areas. For people indoors, either as part of the act of sheltering or as part of everyday life, a dose reduction factor typical of housing stock in the area affected must be applied. For general UK housing stock, as a default value, the location factors[1] for external gamma dose are 0.15 for typical residential brick-built homes and 0.05 for multi-storey buildings (Bedwell et al., in preparation). In general, the most up to date reputable source of data for the UK should be applied if this reference has been superseded.

FT: fraction of time spent indoors or outdoors at a particular location. When evaluating dose assuming no protective actions, typical activities should be assumed; therefore, for both the dose integrated to 2 days and to 1 year a suitably representative fraction of time spent indoors and outdoors should be assumed. Clearly, for an individual sheltering it should be assumed that such an individual will spend 100% of their time indoors. It is known that individuals in the UK spend the majority of their time at home (Lader et al, 2006). Data describing the fractions of time an individual spends indoors are detailed in Lader et al (2006). However, the most up to date reputable source of data should be applied if this reference has been superseded.

OCC: fraction of time spent at a particular location (occupancy). Consideration of occupancy is necessary because individuals do not spend all of their time at a single location. It is recommended that individuals are considered to reside at up to 2 locations following an accident, depending on the model endpoint being derived. When evaluating dose (to 0 to 2 days and from 0 to 365 days) assuming no protective actions, it should be assumed that an individual spends the majority of their time at home (indoors and outdoors) and a proportion of their time at a location assumed to be far enough away from the release for the dose to be negligible (for example, representative of activities such as work or education). The 2005 Time Use Survey (Lader et al, 2006) details the time individuals in the UK spend at home and is recommended here. However, the most up to date reputable source of data should be applied if this reference has been superseded. During the act of sheltering it should be assumed that an individual spends 100% of their time, over a 2-day period, at home. For individuals who are not sheltering, as a default it may be assumed that 0.133 of the dose (such as, 13.3 %) at the location is received, based on current references. It is assumed that the location factor is not dependent on the age of an individual.

[1] A LF of 0.15 means that the external dose will be reduced to 15% of that outdoors

B4.3 External exposure from material in the plume

For gamma-emitting radionuclides which do not deposit onto the ground (noble gases are the prime example), the external exposure from material in the plume may be a significant exposure pathway. To be comprehensive, it is anticipated that such an exposure pathway would be considered in the majority of assessments, however, significant contributions to dose are likely to be limited to a relatively small number of radionuclides.

Modelling the external exposure from the plume is usually undertaken within a dispersion model, unlike other exposure pathways which may be considered subsequent to the dispersion modelling; this is particularly important where the contribution to dose is likely to be significant. Recommended approaches include that described by Raza and Avila (2001) for calculating direct plume gamma dose rates assuming a point isotropic source formula or that described by Simmonds *et al* (1995) for calculating direct plume gamma dose rates assuming a volume source formula. Such approaches should be applied where the plume is not well mixed in the boundary layer (up to about 7 kilometres from the release).

At distances greater than about 7 kilometres from the release, application of the semi-infinite cloud approach (Simmonds *et al*, 1995) is recommended. The semi-infinite cloud approach assumes 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. It also assumes that the cloud is in radiative equilibrium i.e. that the amount of energy absorbed by a given element of cloud is equal to that released by the same element). For photons with energies less than 20 keV the semi-infinite cloud model will always be adequate.

For all averted and residual dose calculations, the impact of urgent protective actions must be taken into account. For evacuation, a location factor of 0 is recommended, such as individuals are moved away from the release location such that their subsequent dose is negligible. For sheltering, a dose reduction factor must be applied. For general UK housing stock, as a default value, the location factor for external gamma dose is 0.15 for typical residential brick-built homes (Bedwell et al., in preparation). In general, the most up to date reputable source of data for the UK should be applied if this reference has been superseded. A location factor of 1 is recommended if an individual is outdoors during the passage of the plume.

B4.4 Inhalation of material resuspended from the ground into the air

Radionuclides deposited on the ground may be resuspended into the atmosphere by natural or man-made disturbance. Radiation exposure may result from inhalation of the resuspended radionuclides. For radionuclides which have a relatively long half-life and contribute significantly to inhalation dose per unit activity, the inhalation of material resuspended from the ground into the air may be a significant exposure pathway (primarily for actinides). It should be noted that this exposure pathway need only be considered for assessments of total effective residual dose in the first year; it will not be significant in the estimation of the dose to 2 days. To be comprehensive it is anticipated that such an exposure pathway would be considered in the majority of assessments of residual dose in the first year, however, significant contributions to dose are likely to be limited to a relatively small number of radionuclides.

Equation 4 represents the committed effective dose arising from the inhalation of resuspended radionuclides, assuming inhalation occurs over the first year following an accident,

$$RID_a = BR_a \times LF \times \sum_{n,p} (GD_{n,p} \times RIF_n \times IHDF_{a,n,p}) \tag{4}$$

where:

RID_a = effective inhalation dose from resuspension as a function of age group a (Sv)

BR_a = breathing rate as a function of age group a (m^3 s^{-1})

LF = location factor

$GD_{n,p}$ = initial level of ground deposition of radionuclide, n, and particle size or chemical form p (Bq m^{-2})

RIF_n = time-dependent resuspended (integral) air concentration factor for radionuclide n (Bq s m^{-3} per Bq m^{-2})

$IHDF_{a,n,p}$ = effective inhalation dose coefficient as a function of age group a, radionuclide n, and particle size or chemical form p (Sv Bq^{-1})

Quantities:

GD: the concentration of activity deposited on the ground for a particular radionuclide, at a particular location, up to a particular time, usually calculated using an atmospheric dispersion model. If deposition concentrations are estimated on a grid, the maximum value should be inferred for each of a range of radial bands from the release, for each weather sequence, and then applied in the estimation of the expectation value and the ninety-fifth percentile as discussed above for inhalation of material in the plume. Alternatively, deposition concentrations may be estimated on a more ad hoc basis at a number of locations of interest.

For a dose integrated to 1 year after the release it is acceptable to assume all the deposition occurs at the time of the release and therefore a single effective dose rate integrated over the year can be assumed.

RIF: time integrated activity concentration in air following resuspension per unit deposit. This value estimates the total activity resuspended from the ground into the air, in this case over the period of 1 year. Such values can be obtained from Wellings et al (2019), which recommends an approach for representing and modelling wind driven resuspension and is suitable for long term averages. Wellings et al (2019) provides tabulated values for a limited number of radionuclides, but the approach used to derive such values is described and can be applied alongside knowledge of the decay constant to determine values for additional radionuclides. Note that the most up to date reputable source of data should be applied if this reference has been superseded.

IHDF: committed dose coefficient for a member of the public to age 70 years. Inhalation dose coefficients must be derived from the most recently published ICRP datasets. At the time of publication of this methodology effective inhalation dose coefficients are available from ICRP Publication 119 (ICRP, 2012).

BR: breathing rate. The activity(s) of an exposed individual will be uncertain and values typical of the general population should be assumed. Breathing rate is dependent upon the activity(s) the individual is undertaking over the duration of exposure – such as 1 year. For all age groups, it is recommended that an average breathing rate which comprises a proportion of sleeping, resting, and being active, should be assumed. At the time of publication of this methodology ICRP Publication 66 (ICRP, 1994), Smith and Jones (2003) and Robinson (1996) are recommended references. However, the most up to date reputable source of data should be applied if these references have been superseded.

LF: location factor. For all residual dose calculations, the impact of protective actions would typically be taken into account. However, because the inhalation dose from resuspended material will vary little if integrated from 0 to 365 days compared to 2 to 365 days, the former may be assumed if this simplifies the assessment. If the dose from 0 to 2 days accounting for the impact of protective actions is sought, for evacuation a location factor of 0 is recommended, such as individuals are moved away from the release location such that their subsequent dose is negligible. For sheltering, a dose reduction factor typical of the UK housing stock must be applied, as discussed above for the inhalation pathway.

B4.5 Consumption of contaminated foodstuffs

Airborne radionuclides may be deposited directly on to vegetation or transferred through the environment into foodstuffs. The dynamics of this environmental transfer depend on the physical, chemical and environmental behaviour of the radionuclides, the foodstuffs concerned, seasonal growth and agricultural practices. It is anticipated that such an exposure pathway would be considered in the majority of assessments for rural sites but potentially less so for densely populated urban sites if the affected area is small.

Consideration of the consumption of contaminated milk and leafy green vegetables is recommended. This selection is based on (1) these 2 foodstuffs are most likely to contribute dose in the short term, and (2) it is unlikely that individuals will source all their grain, beef and sheep meat from specific and localised areas, in particular, there is no evidence to indicate that grain in the UK is grown, milled and consumed on a very local scale. However, the foodstuffs considered could be modified according to the agricultural practices in the vicinity likely to be affected.

B4.5.1 Comparison of activity concentrations in foods with the Euratom Maximum Permitted Levels (MPLs)

The concentration of activity deposited on the ground (Bq m^{-2}) for a particular radionuclide, at a particular location, up to a particular time, is required and is usually calculated using an atmospheric dispersion model. If deposition concentrations are estimated on a grid, the maximum value should be inferred for each of a range of radial bands from the release, for each weather sequence, and then applied in the estimation of the expectation value and the ninety-fifth percentile as discussed above for inhalation of material in the plume.

Alternatively, deposition concentrations may be estimated on a more ad hoc basis at a number of locations of interest.

To determine the extent over which contamination levels are expected to exceed the relevant food intervention level, the concentration of activity deposited on the ground (Bq m^{-2}) for a particular radionuclide, at a particular location, up to a particular time, can be compared with the threshold level of initial ground deposition which would be expected to lead to peak concentrations in the foodstuffs exceeding the relevant Euratom maximum permitted level (MPL). Values for a selection of radionuclides of key importance for ingestion doses are given in McColl and Prosser (2002), for the respective radionuclide, location and time period, and are repeated below.

Table 1 Radionuclide transfer to foodstuffs – Milk

Radionuclide	Peak concentration (Bq kg^{-1} per Bq m^{-2})	Time to reach peak (d)	Relevant MPL (Bq kg^{-1})	Threshold deposit for exceeding MPL (Bq m^{-2})
^{60}Co	2.5 10^{-3}	2	1000	4.0 10^{5}
^{89}Sr	1.1 10^{-2}	5	125	1.1 10^{4}
^{90}Sr	1.2 10^{-2}	5	125	1.0 10^{4}
^{95}Zr	2.5 10^{-4}	2	1000	4.0 10^{6}
^{95}Nb	9.7 10^{-6}	2	1000	1.0 10^{8}
^{103}Ru	2.5 10^{-5}	2	1000	4.1 10^{7}
^{106}Ru	2.5 10^{-5}	2	1000	4.0 10^{7}
^{131}I	7.2 10^{-2}	4	500	7.0 10^{3}
^{133}I	1.4 10^{-2}	2	500	3.6 10^{4}
^{135}I	2.5 10^{-3}	1	500	2.0 10^{5}
^{134}Cs	7.2 10^{-2}	5	1000	1.4 10^{4}
^{137}Cs	7.3 10^{-2}	5	1000	1.4 10^{4}
^{140}Ba	1.1 10^{-2}	2	1000	8.8 10^{4}
^{144}Ce	2.5 10^{-3}	2	1000	4.0 10^{5}
^{234}U	1.5 10^{-2}	2	1000	6.6 10^{4}
^{235}U	1.5 10^{-2}	2	1000	6.6 10^{4}
^{238}U	1.5 10^{-2}	2	1000	6.6 10^{4}
^{238}Pu	1.2 10^{-6}	7	20	1.7 10^{7}
^{239}Pu	1.2 10^{-6}	7	20	1.7 10^{7}
^{241}Pu	1.0 10^{-6}	7	1000	1.0 10^{9}
^{241}Am	1.2 10^{-6}	7	20	1.7 10^{7}
^{242}Cm	1.0 10^{-6}	6	20	2.0 10^{7}
^{244}Cm	1.0 10^{-6}	7	20	1.9 10^{7}

Table 2 Radionuclide transfer to foodstuffs – Leafy green vegetables

Radionuclide	Peak concentration (Bq kg^{-1} per Bq m^{-2})		Relevant MPL (Bq kg^{-1})	Threshold deposit for exceeding MPL (Bq m^{-2})	
	Without processing losses*	Including processing losses*		Without processing losses*	Including processing losses*
^{60}Co	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{89}Sr	0.3	0.06	750	2.5 10^{3}	1.3 10^{4}
^{90}Sr	0.3	0.06	750	2.5 10^{3}	1.3 10^{4}
^{95}Zr	0.3	N/A†	1250	4.2 10^{3}	N/A†
^{95}Nb	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{103}Ru	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{106}Ru	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{131}I	0.3	0.06	2000	6.7 10^{3}	3.3 10^{4}
^{133}I	0.3	0.06	2000	6.7 10^{3}	3.3 10^{4}
^{135}I	0.3	0.06	2000	6.7 10^{3}	3.3 10^{4}
^{134}Cs	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{137}Cs	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{140}Ba	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{144}Ce	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{234}U	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{235}U	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}
^{238}U	0.3	0.06	1250	4.2 10^{3}	2.1 10^{4}

^{238}Pu	0.3	0.06	80	2.7 10^2	1.3 10^3
^{239}Pu	0.3	0.06	80	2.7 10^2	1.3 10^3
^{241}Pu	0.3	N/A†	1250	4.2 10^3	N/A†
^{241}Am	0.3	0.06	80	2.7 10^2	1.3 10^3
^{242}Cm	0.3	N/A†	80	2.7 10^2	N/A†
^{244}Cm	0.3	N/A†	80	2.7 10^2	N/A†

* Processing losses take account of reduction in radionuclide content of crops due to basic preparation i.e. removal of unpalatable parts and washing prior to consumption. This loss (typically 80% (Wilkins, Bradley et al. 1987)) only applies to the activity from direct deposition, i.e. the plant surface, and not to activity that is in the crop from translocation and root uptake.

† Data including processing losses was not available.

Table 3 Euratom Maximum Permitted Levels in food

Radionuclide	Intervention levels (Bq kg^{-1})				
	Baby foods	Diary produce	Minor foods	Other foods	Liquid foods
Isotopes of strontium, notably ^{90}Sr	75	125	7,500	750	125
Isotopes of iodine, notably ^{131}I	150	500	20,000	2,000	500
Alpha-emitting isotopes of plutonium and transplutonium elements	1	20	800	80	20
All other radionuclides of half-life greater than 10 days, notably ^{134}Cs and ^{137}Cs†	400	1,000	12,500	1,250	1,000

† This category excludes ^{3}H, ^{14}C and ^{40}K.

Note that because the mobility of radionuclides in the environment varies, the time it takes for the activity concentration for specific radionuclides in a foodstuff to peak varies. For example, the peak activity concentration in milk for ^{135}I occurs after 1 day; in contrast the peak activity concentration in milk for ^{241}Am occurs after 7 days. Clearly the latter does not conform to considering the potential exposure over the first 2 days; and the former may not conform to considering the potential exposure over the first 2 days for a protracted release duration. However, because food restrictions are not considered over the same timeframes as other protective actions such as sheltering and evacuation, it is acceptable to determine distances to which milk and leafy green vegetable restrictions are placed, based on the MPLs, beyond the first 2 days after the release. Furthermore, it is acceptable to assume all the deposition occurs at the time of the release. In light of these assumptions, it would be of value to determine the timings of the deposition peak(s) relative to the time of the release, which can be determined by the atmospheric dispersion model, and the time to reach the peak concentration in food relative to the time of the release, which can be determined from McColl and Prosser (2002).

Note that the values detailed in Council of the European Union (2016) assume that a single radionuclide is deposited. The regulations associated with the Euratom intervention levels require that the summed concentrations of radionuclides in the same group are compared with the relevant intervention level. Four groups are considered: isotopes of strontium, isotopes of iodine, alpha emitting isotopes of plutonium and trans-plutonium elements and a group of “other radionuclides” all with half-lives greater than 10 days, and detailed in Council of the European Union (2016). The threshold deposition concentrations presented by McColl and Prosser (2002) should therefore be used with caution since more than 1 radionuclide within the same group may contribute significantly to the summed concentration.

The peak radionuclide concentrations in food and their associated threshold deposition concentrations are based on a fixed pessimistic set of assumptions regarding the time of year at which the deposition occurs. This may not align with the seasonality of the weather considered to determine the ninety-fifth percentile and expectation values of the environmental activity concentrations, but further complexity in this regard is considered to be inappropriate.

It is recognised that McColl and Prosser (2002) consider only a limited number of radionuclides. Further threshold deposits for exceeding the MPLs can be determined for additional radionuclides by way of food chain modelling, for example via application of the FARMLAND model (Brown and Simmonds, 1995). Note that no data are presented for tritium since this is specifically excluded from the MPL categories. Very short-lived radionuclides, ^{132}Te and ^{140}La, are excluded since these fall outside the scope of the MPL radionuclide groups. Owing to its short half-life, ^{132}I is also omitted. In practice, very-short-lived radionuclides would not be expected to influence decisions on food restrictions.

Note that although McColl and Prosser (2002) is the recommended reference at the time of publication of this methodology, the most up to date reputable source of data should be applied if this reference has been superseded.

B4.5.2 Doses from the consumption of contaminated foodstuffs

Note that this exposure pathway need only be considered for assessments of total effective residual dose in the first year.

Equation 5 represents the committed effective dose arising from the ingestion of radionuclides within contaminated foodstuffs,

$$IGD_a = \sum_f \left[IR_{a,f} \times \sum_{n,p} (GD_{n,p} \times ACF_{f,n} \times IGDF_{a,n,p}) \right] \tag{5}$$

where:

IGD_a = effective ingestion dose as a function of age group a (Sv)

$IR_{a,f}$ = ingestion rate as a function of age group a and foodstuff f (kg y^{-1})

$GD_{n,p}$ = initial level of ground deposition of radionuclide n, and particle size or chemical form p (Bq m^{-2})

$ACF_{f,n}$ = time integrated activity concentration (over the first 365 days after the accident) in food per unit deposit (Bq y kg^{-1} per Bq m^{-2})

$IGDF_{a,n,p}$ = effective ingestion dose coefficient as a function of age group a, radionuclide n and particle size or chemical form p (Sv Bq^{-1})

GD: the concentration of activity deposited on the ground for a particular radionuclide, at a particular location, up to a particular time, usually calculated using an atmospheric dispersion model. If deposition concentrations are estimated on a grid, the maximum value should be inferred for each of a range of radial bands from the release, for each weather sequence, and then applied in the estimation of the expectation value and the ninety-fifth percentile as discussed above for inhalation of material in the plume. Alternatively, deposition concentrations may be estimated on a more ad hoc basis at a number of locations of interest.

For a dose integrated to 1 year after the release it is acceptable to assume all the deposition occurs at the time of the release and therefore a single activity concentration in food per unit deposit value integrated over 365 days can be assumed.

ACF: time integrated (over the first 365 days after the accident) activity concentration in food per unit deposit (Bq y kg^{-1} per Bq m^{-2}). It is recommended that the FARMLAND model (Brown and Simmonds, 1995) is used to determine the activity concentrations in food for the majority of radionuclides. However, in some cases, radionuclide-specific models may be more appropriate. For example:

- for tritium (^{3}H), the TRIF model (Higgins et al, 1996) is recommended.
- for gaseous and vapour forms of carbon isotopes (notably, ^{11}C and ^{14}C), an approach detailed in Smith et al (1998) is recommended for determining the activity concentrations in leafy green vegetables. The resulting values can then be used to determine the activity concentrations milk, by applying a suitable scaling factor, as detailed in Smith and Simmonds (2015).
- for gaseous forms of sulphur (notably ^{35}S), an approach using the SGAS model is recommended (Smith et al, 2004)

Whichever model is used, it should conservatively be assumed that leafy green vegetables are produced locally (in this context, ‘local’ means produced in the middle of the grid point in question if a grid is used, or at the location considered). Losses of activity due to food preparation and cooking (for example, the outer leaves of a cabbage are removed and the remaining cabbage is washed and cooked) should be accounted for. It is acceptable to assume that the release occurs during the summer months when cows are outdoors grazing pasture.

IGDF: committed dose coefficient for a member of the public to age 70 years. Ingestion dose coefficients must be derived from the most recently published ICRP datasets. At the time of publication of this methodology effective ingestion dose coefficients are available from ICRP Publication 119 (ICRP, 2012).

IR: ingestion rates. It is recommended that ingestion rates for food are representative of people who consume at the 50th percentile rate of intake of the individual annual ingestion rates for green vegetables and milk. Such values can be found in Smith and Jones (2003).

B4.6 Age groups

The standard age groups to be considered are 20-year-old adults, 10-year-old children and 1-year-old infants for all endpoints stipulated in this assessment (noting that the comparison of activity concentrations in foods with the EC Maximum permitted levels is independent of age).

Additionally, doses to the foetus and breast fed-infant should also be considered, for those radionuclides where these could be potentially limiting. Regarding the consideration of doses to the breast-fed infant and foetus, the following approach is recommended:

- only for the evaluation of dose by distance and pathway, assuming no protective actions, to 2 days and to 1 year, should a breast-fed infant (3 months old) and foetus be considered.

- only for the following radionuclides is the dose to the foetus considered to be potentially significant: ^{3}H, ^{14}C, ^{32}P, ^{33}P, ^{35}S, ^{45}Ca, ^{47}Ca, ^{89}Sr, ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I and ^{132}Te. If the assessment does not consider any of these radionuclides, the dose to the foetus can be ignored.
- only for the following radionuclides are the dose to the breast-fed infant considered to be potentially significant: ^{32}P, ^{33}P, ^{45}Ca, ^{89}Sr and ^{131}I. If the assessment does not consider any of these radionuclides, the dose to the breast-fed infant can be ignored.
- only the inhalation exposure pathway need be considered when assessing doses to the foetus and breast-fed infant (but noting that for the latter the contribution to dose direct from inhalation and indirect from the consumption of breast milk contaminated following inhalation by the mother should be taken into account).

B4.7 Radioactive decay

It is important that in the dose integrated to 1 year radioactive decay is accounted for in the assessment. Therefore, consideration of radioactive decay is particularly important for assessments of external dose from deposited material, the dose from inhalation of material resuspended from the ground into the air and the dose from the consumption of contaminated foodstuffs. Tabulated modelling results often include radioactive decay but such inclusion should be checked before use.

B5 Averted dose

To estimate the extent of the urgent protective actions, the averted dose should be calculated at a range of locations (for example on a spatial grid, if this is being used). These averted dose estimates will then be compared with the upper and lower ERLs. Then, by reviewing the estimates for the locations/grid, the furthest extent of each protective action for each source term at the expectation value and also the ninety-fifth percentile can be determined.

The averted dose is the dose that would be saved as a result of implementing an urgent protective action, for example sheltering, evacuation or administration of stable iodine tablets. Thus, the averted effective dose is the difference between “the effective dose (summed over inhalation, external ground, external cloud pathways) evaluated over the first 2 days following the accident assuming no protective actions” and “the effective dose (summed over inhalation, external ground, external cloud pathways) evaluated over the first 2 days following the accident assuming protective actions”. This dose difference is calculated separately for sheltering and evacuation. The averted thyroid dose, which is only applied in consideration of the extent of stable iodine prophylaxis, is the difference between “the thyroid dose evaluated over the first 2 days following the accident assuming no protective actions (for the inhalation pathway only and isotopes of iodine only)” and “the thyroid dose evaluated over the first 2 days following the accident assuming protective actions (for the inhalation pathway only and isotopes of iodine only)”.

The period of time for which a protective action will actually be applied will depend on many factors, such as the doses, the duration of the release, time of day, availability of transport to aid evacuation, etc. However, for planning purposes averted doses should be calculated as follows:

B5.1 Sheltering

Sheltering is assumed to be in place for 2 days, and the averted dose is assessed on this basis.

As a default assumption, it may be assumed[1] that sheltering is put in place so as to maximise the dose saving, so that there is no delay in its implementation, for instance. In particular, it may be assumed that sheltering is in place for the entire duration of the plume passage at each location. This assumption means that the dose averted by the countermeasure is maximised, and hence that the distance to the ERL is also maximised.

However, for practical purposes, the operator may wish to consider the timings appropriate for sheltering at this particular location. For example, an initial delay of 1 or 2 hours may be assumed, depending on the warning associated with the source term. Such assumptions may, counterintuitively, have the effect of reducing the distance to the ERL because the estimated averted dose will be lower and hence the distance to the point at which the ERL is exceeded will be closer to the release point, and the impact of this result should be considered.

B5.2 Evacuation

Evacuation is assumed to be in place for 2 days, and the averted dose is assessed on this basis.

As a default assumption, it may be assumed[2] that there is no delay in implementation of evacuation and that evacuation will avert the entire 2-day effective dose. It may further be assumed that people are evacuated to a location where they are unaffected by release, and therefore do not receive any subsequent dose. This assumption means that the dose averted by the countermeasure is maximised, and hence that the distance to the ERL is also maximised.

However, for practical purposes, the operator may wish to consider the timings appropriate for evacuation at this particular location. For example, an initial delay of 1 or 2 hours may be assumed, depending on the warning associated with the source term. If the source term considerations are insufficient to enable an accurate assessment, a pessimistic assumption is appropriate. This may extend to the assumption regarding exposures during driving/transfer time to a place of zero dose. Such assumptions may, counterintuitively, have the effect of reducing the distance to the ERL, and the impact of this result should be considered.

B5.3 Stable iodine prophylaxis

Stable iodine prophylaxis works by blocking the uptake of radioactive iodine by the thyroid, and therefore it will only avert doses from iodine isotopes. The key endpoint is the estimation of thyroid equivalent doses to the most restrictive age group (in simple calculations this is typically assumed to be a 10-year-old child but a more sophisticated calculation is capable of determining the most restrictive age group within the calculations) from the inhalation of iodine isotopes in the plume.

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[1] In simple calculations this is typically assumed to be a 10-year-old child but a more sophisticated calculation is capable of determining the most restrictive age group within the calculations.

[2] In simple calculations this is typically assumed to be a 10-year-old child but a more sophisticated calculation is capable of determining the most restrictive age group within the calculations.

It is assumed that stable iodine prophylaxis is administered without delay, and that it is taken at a time to maximise the dose saving. Therefore, it is assumed that stable iodine prophylaxis will avert the entire 2 day thyroid equivalent dose from the inhalation of iodine isotopes.

It should be noted that stable iodine is not typically used to avoid doses from <u>ingestion</u> of radioisotopes of iodine, as this would be achieved more appropriately by imposing food restrictions based on the MPL. Ingestion doses should therefore not be included in these calculations.

B6 Residual dose

Residual doses should also be calculated at a range of locations (for example, on a spatial grid, if this is being used), and then compared with the national (and/or site) Reference Level. Then, by reviewing the results of this comparison for the locations/grid, the furthest extent of the exceedance of the Reference Level for each source term at the expectation value and also the ninety-fifth percentile can be determined.

The residual dose is the dose remaining as a result of implementing an urgent protective action, for example sheltering and evacuation. Thus, the residual effective dose is the dose (summed over inhalation, external ground, external cloud, resuspension, food pathways) evaluated over the first 365 days following the accident *assuming* default protective actions including food bans. The calculation of residual thyroid dose is not required.

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