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Provision of Guidance on the Radiological Impact of Rainfall on Nuclear Plant Design Basis Accidents

Study carried out for the Office for Nuclear Regulation

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Provision of Guidance on the Radiological Impact of Rainfall on Nuclear Plant Design Basis Accidents

Study carried out for the Office for Nuclear Regulation

Executive Summary

The Office for Nuclear Regulation has commissioned this report for the purpose of assisting the provision of guidance on whether the effects of precipitation should be included in Design Basis Analysis (DBA) for nuclear licensed sites.

The aim of this report is to present the likelihood and consequences of precipitation occurring during hypothetical releases, and to use the findings to assess whether precipitation should be included when licensees carry out DBA.

In the first part of the study, Numerical Weather Prediction meteorological data from the years 2018-2020 were used to estimate the likelihood of precipitation of various rates coinciding with postulated radioactive releases of various durations at six locations in the UK. The six locations were selected on the basis of being representative of the range of annual precipitation rates that occur in the UK.

In the second part of the study, a range of scenarios were modelled to highlight the effect of precipitation on dose endpoints that might be considered during DBA assessments. Three different atmospheric dispersion models were used: NAME, ADEPT and ADMS. The NAME and ADEPT models were run within UKHSA’s Probabilistic Accident Consequence Evaluation tool, PACE. ADMS was run as a standalone atmospheric dispersion model, but its outputs were subjected to post-processing to obtain the desired endpoints. The Gaussian models ADEPT and ADMS were selected to represent the models that may be used in licensees’ current DBA assessments. NAME was selected because it was considered to be a validated advanced method against which the Gaussian approaches could be compared.

Results obtained using NAME have been presented probabilistically, including the mean, 95th percentile and maximum. ADEPT and ADMS results were not probabilistic, so the ADEPT and ADMS runs were carried out for a range of precipitation rates, so that the results represented the full range of the possible effects of precipitation on dose. The range of precipitation rates used was based on the findings of the first part of the study.

Results for the first part of the study have been presented primarily as numerical tables. Results for the second part of the study have been presented primarily as line plots and bar charts.

The findings of the first part of the study indicated that there is a significant likelihood that a radiological release in the UK would encounter some precipitation. The specific probability would strongly depend on the location and duration of the release. For the scenarios considered in the present study, the probability was found to vary from between 15% and 40% for a one-hour release to effectively 100% for a thirty-day release.

The second part of the study found that the scenarios in which precipitation occurred did not necessarily give rise to the highest doses but that they can do in certain, specific, circumstances. Consequently, excluding precipitation from DBA assessments could in principle lead to an insufficiently conservative estimate of doses, but it depends on the degree of conservatism required in the analysis and how representative of reality it needs to be. If 95th percentile weather is assumed to represent an acceptable level of conservatism, then it seems likely that the modelling approaches that are currently used should be sufficiently conservative in most cases.

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

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# Introduction

As part of the safety assessment of the design of a nuclear facility, a design basis analysis (DBA) is typically undertaken. DBA is not a legal requirement set out in the license conditions, but DBA tends to play an integral role in the safety case for demonstrating the safety of operations within a nuclear licensed site. A DBA is a deterministic analysis, with the aim of providing a robust demonstration of the fault tolerance of the facility and the effectiveness of its safety measures (ONR, 2020). Notable conservatism is typically applied within the source term and meteorological assumptions to ensure that such assessments are suitably protective. To date, the meteorological conditions primarily assumed in such assessments are Pasquill Stability Category F and no precipitation. However, the impact of precipitation within such assessments is not well understood. This project aimed to address three primary questions:

* *When considering precipitation at different precipitation rates, in a DBA assessment, is there a cliff-edge effect (or a sharp increase) in the estimates of dose?*
* *Is there a lack of conservatism in the current DBA* *methodology (for off-site radiological consequences) as a result of typically assuming no precipitation?*
* *Are the current default atmospheric dispersion modelling approaches used by licensees appropriate for DBA use?*

The study also assesses the probability of various rates of precipitation occurring in the UK and the likelihood of precipitation coinciding with releases across a range of durations typical of those assumed in DBA assessments.

The aims of this project were addressed by running a number of models used to describe atmospheric dispersion processes and to estimate radiation doses. The atmospheric dispersion models considered included two Gaussian Plume Models, ADEPT and ADMS, representative of those typically used by operators of nuclear licensed sites in DBA assessments. The NAME model was also considered; this is an Lagrangian Particle atmospheric dispersion model and provided a benchmark against which all Gaussian approaches were compared. The ADEPT and NAME model runs were performed within UKHSA’s Probabilistic Accident Consequence Evaluation (PACE) software. By deriving and comparing doses on the basis of different modelling approaches applied, across different meteorological and DBA source term scenarios, answers to the three primary questions were determined.

# Probability of radioactive releases encountering precipitation

An investigation was carried out into the distribution of precipitation rates over the course of a representative year in each of six UK locations. The locations selected were Ardlui, Bradwell, Ely, Hinkley Point, Seathwaite and Trawsfynydd. These locations were chosen with the intention of covering as wide a range as possible of the precipitation rates likely to be found in the UK. To inform this choice the geographical variability of UK annual precipitation rates was assessed using the *UK actual and anomaly maps* resource available via the Met Office website[[1]](#footnote-2). Three of the selected locations corresponded to nuclear sites. Rather than selecting a single year to act as a representative year, three years were chosen, and average results were calculated.

A particular aim of the analysis was to estimate the likelihood of postulated releases of radioactive material encountering precipitation and, more specifically, precipitation of various different rates.

## Method

The three years considered were 2018, 2019 and 2020. Hourly Numerical Weather Prediction (NWP) meteorological (met) data for those three years was obtained from the UK Met Office. It was also necessary to obtain the first month of met data for 2021. That was required in order to complete modelling runs for hypothetical releases that began at the end of 2020 and which had a release duration of up to thirty days.

The met data obtained from the Met Office was analysis data taken from the Unified Model run in the UKV configuration. The UKV meteorological data has a horizontal resolution of approximately 1.5 km by 1.5 km. The NWP met data was then used with the Met Office’s NAME model to extract single-site met data for the specific locations of the six relevant sites.

## Results

### Distribution of precipitation rates

The key results are summarised in the tables below.

Table 1 shows how the individual hourly precipitation rates were distributed over the three years for each of the six sites. Specifically, an instantaneous precipitation rate was obtained at hourly intervals over the whole of the period 2018-2020 (this means that there were 26,304 results per site). Each of those results was categorised into one of the bins shown in Table 1. The total in each bin was then divided by 26,304 and multiplied by 100 in order to calculate the percentages presented in Table 1.

Table : Percentage of hourly precipitation rates in each precipitation rate bin for each site for the whole period 2018-2020

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **Precipitation rate bin (mm** **h-1)\*\*** | | | | | | | |
| 0 | 0 - 0.01 | 0.01 - 0.1 | 0.1 - 1 | 1 - 2 | 2 - 4 | 4 - 8 | > 8 |
| Ardlui | 60.5 | 2.5 | 9.1 | 16.1 | 5.7 | 4.4 | 1.6 | 0.0\* |
| Bradwell | 85.3 | 1.1 | 4.0 | 6.5 | 1.9 | 1.0 | 0.1 | 0.0\* |
| Ely | 85.0 | 1.0 | 4.0 | 6.4 | 2.3 | 1.1 | 0.1 | 0.0\* |
| Hinkley | 80.4 | 1.8 | 5.5 | 8.3 | 2.4 | 1.3 | 0.2 | 0.0\* |
| Seathwaite | 65.0 | 2.2 | 9.6 | 12.3 | 4.5 | 4.2 | 1.9 | 0.3 |
| Trawsfynydd | 73.5 | 2.2 | 6.6 | 10.2 | 3.6 | 2.9 | 1.0 | 0.1 |
| \* Values shown as *0.0\** are small but non-zero (i.e. in the range *0 < x < 0.05*). Only entries shown as *0.0* or *0* are truly zero.  \*\* In the column headers, the ranges *A - B* should be interpreted as *A < x ≤ B*. For example, *0 - 0.01* only includes values in the range *0 < x ≤ 0.01*. | | | | | | | | |

Table 1 shows that for all sites, the majority of hours have no precipitation. Nonetheless, the proportion of hours in which precipitation does occur is significant for all sites (between 15% and 40%). Among the non-zero-precipitation-rate bins considered in this study, the *0.1 ‑ 1 mm**h-1* bin was the most populated for all sites. No bin is completely unpopulated for any site.

### Probabilities of precipitation rates during a release

Table 2 to Table 4 are the result of considering what precipitation rates might occur during releases of various durations (thirty days, 48 hours and eight hours). In each case, 26,304 hypothetical releases were considered. The 26,304 hypothetical releases started at hourly intervals over the whole period of 2018-2020. For example, in the case of a thirty-day release duration, the first release was considered to start at 00:00 on 01/01/2018 and to last for thirty days; the second release was considered to start at 01:00 on 01/01/2018 and to last for thirty days; … the 26,304th release was considered to start at 23:00 on 31/12/2020 and to last for thirty days. Consequently, the releases that started near the end of 2020 continued into the first month of 2021. Nonetheless, these were considered to be 2020 releases, on account of having a start date in 2020. Note that the likelihood of different precipitation rates occurring during a release duration of one hour are reflected in the results detailed in Table 1.

The maximum precipitation rate occurring during each of the releases was determined. The resulting 26,304 “maximum” values for each site were then categorised into the same bins as were used above. The total in each bin was then divided by 26,304 and multiplied by 100 in order to calculate the percentages presented in Tables 2-4.

Table : The maximum precipitation rate bin (as a percentage) occurring during each potential release (“Potential release” means each of 26,304 hypothetical releases starting at hourly intervals over the whole period 2018-2020, where each release has a thirty-day duration)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **Maximum precipitation rate bin during 30-day releases (mm h-1)\*\*** | | | | | | | |
| 0 | 0 - 0.01 | 0.01 - 0.1 | 0.1 - 1 | 1 - 2 | 2 - 4 | 4 - 8 | > 8 |
| Ardlui | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 6.9 | 65.6 | 27.2 |
| Bradwell | 0.0 | 0.0 | 0.0 | 1.0 | 5.3 | 39.7 | 45.5 | 8.5 |
| Ely | 0.0 | 0.0 | 0.0 | 2.2 | 4.4 | 42.0 | 33.7 | 17.6 |
| Hinkley | 0.0 | 0.0 | 0.0 | 0.0 | 1.5 | 31.6 | 58.6 | 8.3 |
| Seathwaite | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 41.2 | 56.0 |
| Trawsfynydd | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 11.3 | 59.2 | 29.4 |
| NB: All values shown as *0.0* are truly zero. They are not small non-zero values rounded to zero.  \*\* In the column headers, the ranges *A - B* should be interpreted as *A < x ≤ B*. For example, *0 - 0.01* only includes values in the range *0 < x ≤ 0.01*. | | | | | | | | |

Table : The maximum precipitation rate bin (as a percentage) occurring during each potential release (“Potential release” means each of 26,304 hypothetical releases starting at hourly intervals over the whole period 2018-2020, where each release has a 48-hour duration)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **Maximum precipitation rate bin during 48-hour releases (mm h-1)\*\*** | | | | | | | |
| 0 | 0 - 0.01 | 0.01 - 0.1 | 0.1 - 1 | 1 - 2 | 2 - 4 | 4 - 8 | > 8 |
| Ardlui | 10.4 | 2.2 | 4.1 | 16.9 | 14.7 | 25.6 | 24.1 | 2.0 |
| Bradwell | 28.1 | 1.2 | 7.1 | 20.9 | 18.7 | 17.9 | 5.4 | 0.7 |
| Ely | 26.9 | 2.2 | 6.1 | 20.6 | 16.8 | 20.8 | 4.9 | 1.6 |
| Hinkley | 23.8 | 2.6 | 7.2 | 19.8 | 16.2 | 22.9 | 7.1 | 0.6 |
| Seathwaite | 13.8 | 0.8 | 6.0 | 15.6 | 11.8 | 21.4 | 23.9 | 6.6 |
| Trawsfynydd | 15.3 | 2.1 | 5.3 | 16.5 | 14.0 | 24.8 | 19.5 | 2.6 |
| \*\* In the column headers, the ranges *A - B* should be interpreted as *A < x ≤ B*. For example, *0 - 0.01* only includes values in the range *0 < x ≤ 0.01*. | | | | | | | | |

Table : The maximum precipitation rate bin (as a percentage) occurring during each potential release (“Potential release” means each of 26,304 hypothetical releases starting at hourly intervals over the whole period 2018-2020, where each release has an eight-hour duration)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **Maximum precipitation rate bin during 8-hour releases (mm h-1)\*\*** | | | | | | | |
| 0 | 0 - 0.01 | 0.01 - 0.1 | 0.1 - 1 | 1 - 2 | 2 - 4 | 4 - 8 | > 8 |
| Ardlui | 37.6 | 2.5 | 8.5 | 21.6 | 11.2 | 11.9 | 6.4 | 0.3 |
| Bradwell | 65.6 | 1.6 | 6.4 | 14.0 | 6.8 | 4.5 | 1.0 | 0.1 |
| Ely | 64.8 | 1.9 | 6.4 | 13.6 | 6.8 | 5.2 | 0.9 | 0.3 |
| Hinkley | 57.6 | 2.4 | 8.1 | 17.0 | 7.5 | 5.9 | 1.4 | 0.1 |
| Seathwaite | 40.5 | 2.2 | 11.5 | 17.9 | 9.0 | 10.6 | 6.8 | 1.4 |
| Trawsfynydd | 48.1 | 2.7 | 8.9 | 17.4 | 8.8 | 9.0 | 4.7 | 0.4 |
| \*\* In the column headers, the ranges *A - B* should be interpreted as *A < x ≤ B*. For example, *0 - 0.01* only includes values in the range *0 < x ≤ 0.01*. | | | | | | | | |

Table 2 shows that, even for the driest site, every hypothetical thirty-day-duration release would be expected to encounter some precipitation. As an example of the more specific information provided by Table 2, it can be seen that in the case of Ardlui, 0.3% of the thirty-day releases over a three-year period encountered at least some precipitation that was in the *1 - 2* *mm h-1* bin but did not encounter any precipitation that had a rate greater than 2 mm h-1 (i.e. the maximum rate encountered was in the *1 - 2 mm h-1* band). By contrast, 6.9% of the Ardlui thirty-day releases encountered at least some precipitation that was in the *2 - 4 mm h-1* bin but did not encounter any precipitation that had a rate greater than 4 mm h-1.

Table 3 shows that for hypothetical two-day releases, all sites have non-zero values in all the precipitation-rate bins. When looking at the value in the highest-rate bin *(> 8 mm h-1*), it is notable that the value for Seathwaite is significantly greater than for any other site. On the other hand, when looking at the *0 mm h-1* bin, the value for Ardlui is lower than for any other site.

Table 4 shows that for hypothetical eight-hour releases, it is still the case that all sites have non-zero values in all the precipitation-rate bins. It is also still the case that the highest value in the *> 8 mm h-1* bin occurs for Seathwaite and the lowest value in the *0 mm h-1* bin occurs for Ardlui.

### Precipitation during Pasquill Stability Category F conditions

As presented in the following sections, parts of the present study specifically considered Pasquill Stability Category D wet conditions and Pasquill Stability Category F dry conditions. Licensees typically assume Category F dry conditions when carrying out Design Basis Analysis. Those conditions are chosen because they are generally considered to represent a conservative assumption. Category D wet conditions were considered in the present study, as those also represent a potentially conservative assumption.

In principle, it would also have been possible to consider Category F wet conditions. Such conditions may be even more conservative than the ones considered; however, they were assumed to be rare enough that including them in the study would not have been warranted. An illustration of the likelihood of encountering such conditions in reality was considered in this study.

Pasquill Stability Category information was extracted from the NWP met data described above. For each of the six locations considered in the present study, the number of occurrences of Category F wet conditions during 2018-2020 was calculated. Specifically, the period 2018-2020 consisted of 26,304 hours, with each individual hour assigned a single Pasquill Stability Category. The results for each location are shown in the following table.

Table : Likelihood of Pasquill Stability Category F (PSC F) and likelihood of PSC F wet conditions

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Ardlui | Bradwell | Ely | Hinkley | Seathwaite | Trawsfynydd |
| Number of hours that are PSC F | 2392 | 765 | 2161 | 574 | 1428 | 2453 |
| Percentage of hours that are PSC F | 9.1 | 2.9 | 8.2 | 2.2 | 5.4 | 9.3 |
| Number of hours that are PSC F wet | 95 | 0 | 3 | 2 | 11 | 42 |
| Percentage of hours that are PSC F wet | 0.36 | 0.00 | 0.01 | 0.01 | 0.04 | 0.16 |
| Percentage of PSC F hours that are wet | 3.97 | 0.00 | 0.14 | 0.35 | 0.77 | 1.71 |

Whilst the above table shows how often precipitation occurred during Category F conditions, it does not show how heavy the precipitation was. The following table provides more detailed results by allocating each Category F wet hour into a precipitation rate bin.

Table : Number of Pasquill Stability Category F wet hours in each precipitation rate bin

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Precipitation rate (mm h-1) | Ardlui | Bradwell | Ely | Hinkley | Seathwaite | Trawsfynydd |
| 0 - 0.01 | 30 | 0 | 1 | 1 | 1 | 15 |
| 0.01 - 0.1 | 38 | 0 | 1 | 1 | 3 | 15 |
| 0.1 - 1 | 21 | 0 | 0 | 0 | 5 | 11 |
| 1 - 2 | 5 | 0 | 1 | 0 | 2 | 0 |
| 2 - 4 | 1 | 0 | 0 | 0 | 0 | 1 |
| 4 - 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| > 8 | 0 | 0 | 0 | 0 | 0 | 0 |

The results in the two tables above confirm that Category F wet conditions are rare. Even for Ardlui, which is the location at which such conditions were least rare, less than 0.4% of the hours during 2018-2020 were both Category F and wet.

Even when Category F wet conditions did occur, such occurrences tended to be scattered throughout the year, and did not occur in a single block. So even if a release were to encounter Category F wet conditions, it is likely that most of the hours of the release would not be both Category F and wet. This can be illustrated by considering the two largest clusters of Category F wet hours, as follows.

The largest cluster occurred for Ardlui. There was a period of 219 hours during which Category F wet conditions occurred 18 times. Within that cluster, there was a period of 22 hours during which Category F wet conditions occurred ten times. All hours within that 22-hour period had a precipitation rate of less than 0.2 mm h-1.

The second largest cluster occurred for Trawsfynydd. There was a period of 247 hours during which Category F wet conditions occurred 11 times. Within that cluster, there was a period of five hours during which Category F wet conditions occurred four times. All hours within that five-hour period had a precipitation rate of less than 0.5 mm h-1.

It is acknowledged that Pasquill Stability Category E wet conditions have not been considered. It might be expected that an assumption of such conditions would be less conservative but more common than Category F wet conditions, and more conservative but less common than Category D wet conditions. Analysis of the data for the years 2018-2020 indicates that the likelihood of encountering Category E wet conditions varies greatly depending on the location of the site, but it is significantly more likely than encountering Category F wet conditions. In practice, it is not feasible to carry out modelling runs for all conceivable combinations[[2]](#footnote-3) of met conditions. This illustrates an important advantage of using a probabilistic modelling approach, which does not require arbitrary input of met parameters by the modeller.

## Ensuring representative met data

When seeking to accurately represent long-term trends, a large sample-size is required. In the context of met data, this means a large number of samples taken over a long period of time, where that period of time is as relevant as possible.

In the present study, hourly samples were taken over the course of three years. This corresponds to 26,304 samples. The three most recent complete years were used (2018-2020). NWP met data is very demanding in terms of processing duration and storage capacity, so the decision to use three years of met data was the result of balancing the desire for representative results against practical computational considerations.

A potential pitfall of using only three years of met data is that if one of those years had a particularly unusual pattern of precipitation, it could have a significant effect on the overall results. A sensitivity assessment was carried out to check whether this was the case. Specifically, the distributions of precipitation rate bins for each year were calculated and presented separately. This meant that for each site, the results could be considered for each year in isolation, to see whether there were any anomalies. The results for each of the three years were found to be broadly similar. That provided reassurance that the met data did not vary significantly as a function of year (at least, not over the period 2018-2020), and therefore there was no single year which could unduly affect the 3-year average values.

## Conclusions

The likelihood of a radioactive release encountering precipitation depends on the duration and location of the release. The investigation described above indicated that a thirty-day release in the UK is virtually certain to encounter some precipitation. Even for an eight-hour release, the probability is between 34% and 62%, depending on the location.

It can be concluded that radioactive releases in the UK have a significant chance of encountering precipitation, even for relatively short releases in relatively dry locations.

It can also be concluded that, although precipitation does sometimes occur during Pasquill Stability Category F conditions, such occurrences are not common.

# Source Terms

The source term information used in this study was provided by ONR. Note that only notional source terms are considered in this study i.e. they are not replicas of those considered by operators but are indicative of such source terms.

For the purposes of this study, it was assumed that all particles are of a size that is respirable. Specifically, a particle size of 1 µm was assumed, except for gases (notably noble gases and gaseous chemical forms of iodine). All release heights were assumed to be 10 metres. In each case, a passive release was assumed (i.e. no momentum or buoyancy).

Table 7, Table 9, Table 11 and Table 12 detail the activity (in Bq) released as a function of different phases across the release duration of the respective source terms. The durations of the phases vary significantly, as detailed in the table footers. Thus, the release rate (not presented) often varies widely between phases (over the lifetime of the release). However, for Gaussian plume modelling (considered in this study) at least, such variable release rates would have no discernible impact on the model endpoints derived, because the meteorological conditions over the period of the release were assumed to remain constant.

## Large Break Loss of Coolant Accident Source Term

A description of the Large Break LOCA (Loss of Coolant Accident) source term (which will henceforth be referred to as the LBL source term) considered in this study is detailed in the text and Table 7 and Table 8 below. The number of radionuclides in the LBL source term was too great for them all to be considered in PACE and would have significantly increased the number of model runs in ADMS (where a single run is limited to a maximum of 10 radionuclides), so the number was reduced. Further information about this is given in Section 3.1.1.

The LBL source term release duration was 30 days.

Table : LBL source term - radionuclides modelled (Bq)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Radionuclide | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Phase 6 | Phase 7 | Phase 8 |
| 134Cs | 2.15E+07 | 4.85E+07 | 6.80E+08 | 4.00E+08 | 5.00E+07 | 8.80E+09 | 1.05E+10 | 1.95E+10 |
| 137Cs | 1.35E+07 | 3.05E+07 | 4.26E+08 | 2.30E+08 | 5.00E+07 | 5.25E+09 | 6.50E+09 | 1.25E+10 |
| 131I | 3.20E+08 | 8.30E+08 | 2.24E+10 | 3.65E+10 | 5.00E+09 | 4.35E+11 | 3.00E+11 | 2.00E+11 |
| 133I | 6.50E+08 | 1.65E+09 | 3.67E+10 | 4.60E+10 | 0.00E+00 | 1.10E+11 | 5.00E+09 | 0.00E+00 |
| 88Kr | 2.70E+11 | 5.80E+11 | 5.15E+12 | 5.00E+11 | 0.00E+00 | 5.00E+11 | 0.00E+00 | 0.00E+00 |
| 133Xe | 1.00E+12 | 2.70E+12 | 8.13E+13 | 1.55E+14 | 5.00E+12 | 1.61E+15 | 9.00E+14 | 4.00E+14 |
| 135Xe | 3.15E+11 | 9.35E+11 | 3.13E+13 | 4.25E+13 | 0.00E+00 | 6.00E+13 | 0.00E+00 | 0.00E+00 |
| Phase 1 = 0-1h; Phase 2 = 1-2h; Phase 3 = 2-12h; Phase 4 = 12h-1d; Phase 5 = 1-2d; Phase 6 = 2-7d; Phase 7 = 7-15d; Phase 8 = 15-30d. | | | | | | | | |
| The LBL source term does not include all radionuclides that are listed in the original LBL source term provided by ONR. This is explained in Section 3.1.1. | | | | | | | | |

Table : LBL source term - iodine chemical form percentage breakdown

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Chemical form | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Phase 6 | Phase 7 | Phase 8 |
| Elemental | 72.60 | 72.55 | 61.65 | 48.75 | 48.30 | 18.10 | 13.70 | 11.80 |
| Particulate | 25.00 | 23.35 | 12.70 | 8.20 | 8.10 | 6.00 | 5.60 | 5.50 |
| Organic | 2.40 | 4.10 | 25.65 | 43.05 | 43.60 | 75.90 | 80.70 | 82.70 |
| Phase 1 = 0-1h; Phase 2 = 1-2h; Phase 3 = 2-12h; Phase 4 = 12h-1d; Phase 5 = 1-2d; Phase 6 = 2-7d; Phase 7 = 7-15d; Phase 8 = 15-30d. | | | | | | | | |

### Selection of radionuclides for LBL source term

The full LBL source term included 40 radionuclides. This number of radionuclides cannot be modelled in PACE, owing to data and processing limitations. Three of the 40 are not available in PACE, and so had to be excluded. Of the remaining 37, the most relevant seven were identified and included in the LBL source term.

The PACE tool’s Source Term function was used to identify the most relevant radionuclides. This gives an approximate breakdown of the proportion of the dose that is attributable to each radionuclide and is able to produce a ranked list. This was undertaken for a range of scenario conditions. A baseline scenario, plus two variations of meteorological conditions, two variations of release location to receptor distances and two variations of dose integration periods were all considered (seven scenarios in total). The seven radionuclides that were most highly ranked, in terms of dose, over the conditions considered, were included in the LBL source term. In addition to those, 137mBa was included because of its potential importance as the progeny of 137Cs.

The source term tool showed that across the range of scenarios considered, the seven selected radionuclides always contributed at least 97% of the dose[[3]](#footnote-4).

## Fuel Handling Source Term

The number of radionuclides in the Fuel Handling (FH) source term was too great for them all to be used in PACE and would also have been impractical for ADMS. The number was reduced in a manner similar to the method used for the LBL source term (see above).

The FH source term release duration was 30 days; however, the vast majority of the activity was released during the first 48 hours. Consequently, only the first 48 hours of the release was included in the FH source term that was used in the model runs.

Table : FH source term - radionuclides modelled (Bq)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Radionuclide | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 |
| 137mBa | 6.20E+08 | 3.50E+08 | 3.00E+07 | 0.00E+00 | 0.00E+00 |
| 134Cs | 3.00E+09 | 8.00E+08 | 2.00E+08 | 0.00E+00 | 0.00E+00 |
| 137Cs | 1.20E+09 | 4.00E+08 | 1.00E+08 | 0.00E+00 | 0.00E+00 |
| 131I | 7.70E+09 | 2.20E+09 | 1.00E+08 | 0.00E+00 | 1.00E+09 |
| 133I | 2.60E+09 | 7.00E+08 | 1.00E+08 | 0.00E+00 | 0.00E+00 |
| 85Kr | 2.40E+13 | 5.20E+13 | 1.00E+13 | 1.00E+12 | 0.00E+00 |
| 133Xe | 1.10E+15 | 2.30E+15 | 4.00E+14 | 1.00E+14 | 0.00E+00 |
| 133mXe | 2.50E+13 | 5.40E+13 | 1.00E+13 | 3.00E+12 | 2.00E+12 |
| 135Xe | 2.80E+13 | 5.40E+13 | 8.00E+12 | 2.00E+12 | 0.00E+00 |
| Phase 1 = 0-1h; Phase 2 = 1-6h; Phase 3 = 6-12h; Phase 4 = 12-24h; Phase 5 = 24-48h. | | | | | |
| The FH source term used in the model runs does not include all the radionuclides or release phases that were listed in the original FH source term provided by ONR. This is explained in Section 3.2 | | | | | |

Table : FH source term - iodine chemical form percentage breakdown

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Chemical form | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 |
| Elemental | 0.00 | 0.10 | 0.10 | 0.30 | 0.50 |
| Particulate | 100.00 | 99.90 | 99.90 | 99.70 | 99.50 |
| Organic | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Phase 1 = 0-1h; Phase 2 = 1-6h; Phase 3 = 6-12h; Phase 4 = 12-24h; Phase 5 = 24-48h. | | | | | |

## RCCA Ejection Source Term

The number of radionuclides in the RCCA Ejection (RCCAE) source term was small enough that they could all be used in the PACE model runs. To ensure a manageable number of ADMS model runs, a subset of six radionuclides were considered, as indicated by the asterisks in Table 11; the number of radionuclides was reduced in a manner similar to the method used for the LBL source term (see above). All iodine was assumed to be in elemental form.

The RCCAE source term release duration was 30 days.

Table : RCCAE source term - radionuclides modelled (Bq)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Radionuclide | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Phase 6 |
| 134Cs \* | 1.75E+12 | 2.51E+11 | 3.41E+10 | 1.32E+11 | 9.66E+10 | 7.16E+11 |
| 136Cs | 4.13E+11 | 5.87E+10 | 7.76E+09 | 2.79E+10 | 1.72E+10 | 7.76E+10 |
| 137Cs \* | 8.61E+11 | 1.24E+11 | 1.68E+10 | 6.48E+10 | 4.77E+10 | 3.58E+11 |
| 138Cs | 9.78E+12 | 1.08E+10 | 8.44E+05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 131I \* | 5.50E+12 | 2.92E+12 | 1.40E+11 | 4.81E+11 | 2.65E+11 | 9.97E+11 |
| 132I | 7.14E+12 | 8.58E+11 | 4.75E+09 | 3.59E+08 | 0.00E+00 | 0.00E+00 |
| 133I \* | 1.06E+13 | 4.80E+12 | 1.70E+11 | 3.32E+11 | 1.83E+10 | 1.16E+10 |
| 134I | 1.07E+13 | 1.89E+11 | 7.84E+07 | 4.60E+03 | 0.00E+00 | 0.00E+00 |
| 135I \* | 9.69E+12 | 3.02E+12 | 5.81E+10 | 5.24E+10 | 1.62E+07 | 6.46E+04 |
| 83mKr | 8.30E+12 | 6.75E+12 | 2.96E+11 | 7.68E+09 | 0.00E+00 | 0.00E+00 |
| 85Kr | 9.32E+11 | 2.86E+12 | 2.26E+12 | 8.75E+12 | 6.44E+12 | 4.82E+13 |
| 85mKr | 2.28E+13 | 3.83E+13 | 7.52E+12 | 3.80E+12 | 3.24E+07 | 3.57E+03 |
| 87Kr | 3.31E+13 | 1.73E+13 | 2.69E+11 | 6.40E+08 | 0.00E+00 | 0.00E+00 |
| 88Kr \* | 5.70E+13 | 7.02E+13 | 7.38E+12 | 1.20E+12 | 1.64E+04 | 0.00E+00 |
| 88Rb | 4.89E+12 | 4.77E+08 | 1.07E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 89Rb | 6.05E+12 | 2.55E+08 | 5.58E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 131mXe | 7.58E+11 | 2.31E+12 | 1.77E+12 | 6.34E+12 | 3.83E+12 | 1.67E+13 |
| 133Xe | 1.34E+14 | 4.03E+14 | 3.00E+14 | 9.76E+14 | 4.61E+14 | 1.48E+15 |
| 133mXe | 4.00E+12 | 1.17E+13 | 7.96E+12 | 2.15E+13 | 5.49E+12 | 1.17E+13 |
| 135Xe | 4.18E+13 | 9.43E+13 | 3.48E+13 | 4.27E+13 | 1.04E+11 | 3.24E+09 |
| 135mXe | 6.56E+12 | 5.13E+10 | 2.44E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| 138Xe | 3.18E+13 | 1.67E+11 | 2.21E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Phase 1 = 0-2h; Phase 2 = 2-8h; Phase 3 = 8-24h; Phase 4 = 1-4d; Phase 5 = 4-7d; Phase 6 = 7-30d. | | | | | | |
| All iodine was assumed to be in elemental form. | | | | |  |  |
| \* indicates radionuclides included in ADMS model runs | | | | |  |  |

## Steam Generator Tube Rupture Source Term

The number of radionuclides in the Steam Generator Tube Rupture, SGTR, source term was small enough that they could all be used in the PACE model runs. To ensure a manageable number of ADMS model runs, a subset of nine radionuclides were considered, as indicated by asterisks in Table 12; the number of radionuclides was reduced in a manner similar to the method used for the LBL source term (see above). All iodine was assumed to be in elemental form.

The SGTR source term release duration was 8 hours.

Table : SGTR source term - radionuclides modelled (Bq)

|  |  |  |
| --- | --- | --- |
| Radionuclide | Phase 1 | Phase 2 |
| 134Cs \* | 2.67E+09 | 1.23E+08 |
| 136Cs | 7.42E+08 | 3.40E+07 |
| 137Cs \* | 1.63E+09 | 7.53E+07 |
| 138Cs | 5.88E+09 | 2.32E+07 |
| 131I \* | 2.59E+11 | 9.77E+10 |
| 132I \* | 3.27E+11 | 6.35E+10 |
| 133I \* | 4.60E+11 | 1.63E+11 |
| 134I \* | 3.53E+11 | 2.54E+10 |
| 135I \* | 3.93E+11 | 1.18E+11 |
| 83mKr | 1.32E+11 | 2.78E+10 |
| 85Kr | 7.67E+11 | 1.61E+11 |
| 85mKr | 5.93E+11 | 1.25E+11 |
| 87Kr | 3.28E+11 | 6.89E+10 |
| 88Kr \* | 9.76E+11 | 2.05E+11 |
| 88Rb | 2.05E+10 | 3.91E+07 |
| 131mXe | 5.51E+11 | 1.16E+11 |
| 133Xe \* | 6.97E+13 | 1.47E+13 |
| 133mXe | 1.26E+12 | 2.64E+11 |
| 135Xe | 3.42E+12 | 7.18E+11 |
| 138Xe | 2.02E+11 | 4.25E+10 |
| Phase 1 = 0-2h; Phase 2 = 2-8h. | | |
| All iodine was assumed to be in elemental form. | | |
| \* indicates radionuclides included in ADMS model runs | | |

# Methodology

Calculations in this study were carried out using CERC’s atmospheric dispersion model called ADMS (alongside some post processing of ADMS model output), and UKHSA’s Probabilistic Accident Consequence Evaluation tool (PACE). The UK Met Office’s Lagrangian Particle NAME model, and the Gaussian plume model called ADEPT, both implemented within PACE, were both used, in addition to ADMS, for the modelling of the dispersion of material in the atmosphere. ADMS and ADEPT were applied in this study, as they are representative of the types of Gaussian plume models used historically by operators of nuclear licensed sites. NAME was considered here to be a validated advanced method and will provide a benchmark against which all Gaussian approaches can be compared.

During the course of the model runs, six hypothetical release locations in the UK were considered. These were Ardlui, Bradwell, Ely, Hinkley Point, Seathwaite and Trawsfynydd. The release location has the potential to significantly impact the model results derived when running NAME (which accounts for location specific spatially and temporally varying meteorology and location specific spatially varying agricultural production), has a much lesser impact when running ADEPT (which accounts for location specific spatially varying agricultural production only) and has no impact when running ADMS (which considers no location specific input data, as applied in this study).

## Model endpoints

Committed effective doses at a range of radial distances from the release (0.5, 1, 2 and 5 km) were calculated for a one-year-old infant and an adult.

PACE modelling is based on grid squares, so it does not, strictly speaking, output results “at” specific distances. For NAME runs in the present study, “at 0.5 km” was interpreted as including every grid square that had a centre point that was between 0.4 and 0.6 km from the release point. Similarly, “at 1 km” meant between 0.8 and 1.2 km, “at 2 km” meant between 1.6 and 2.4 km, and “at 5 km” meant between 4.0 and 6.0 km. An analogous approach was performed when applying ADEPT, for consistency with the NAME method and to acknowledge that there exists spatial variation in agricultural practices; it is recognised that as a result there is a degree of inconsistency between the ADEPT and ADMS approaches (where the latter is based on uniform integer distance receptor point values along a plume centre line). The sensitivity of this approach in ADEPT was briefly investigated. Specifically, the difference between considering (the maximum dose across) every grid square that had a centre point between 0.4 and 0.6 km from the release point as a representation of the 0.5 km receptor point, compared to considering (the maximum dose across) every grid square that had a centre point greater than 0.5 km from the release point as a representation of the 0.5 km receptor point. The sensitivity of this approach at other receptor distances was also considered in a similar way. The derived TIAC values varied by no more than a few tens of percent. Whilst NAME derives averaged air (and deposition) concentrations over each grid box, ADEPT determines a point air (and deposition) concentration value at the centre of the grid box.

In all cases, 1 year and lifetime dose integration periods were considered; and depending on the release duration, a 7 or 30 day dose integration period was also considered. For all three atmospheric dispersion modelling approaches applied in this study, ingestion dose was assessed whilst omitting the impact of food bans; for ingestion doses calculated using PACE, the impact of food restrictions on the activity concentrations exceeding the MPLs were also considered. Consideration of food restrictions was not possible in ADMS, and consideration in a post processing step would have added significant complexity to the approach applied, therefore food restrictions were not considered on the basis of any of the ADMS derived dose estimates.

The ADEPT and ADMS model runs were deterministic in the sense that each input parameter in each run was assigned a single value, and each run calculated a single value for each endpoint. This means, for example, that each run assumed a single precipitation rate and a single Pasquill Stability Category. During each run, those parameter values remained constant. However, not all runs used the same parameter values. For example, during a run it would be assumed that the Pasquill Stability Category was Category D and that would not change. However, in a different run, the Category was assumed to be F (and to remain as F for the full duration of the run). Only a small number of possible parameter values were considered. These were entered manually and were not directly extracted from any real-world dataset.

This can be contrasted with the NAME model runs, which did not use just one single set of user-defined values to describe the meteorological conditions, and did not produce just one single set of values for the modelled endpoints. Rather, each NAME run was “probabilistic” in the sense that it sampled a large range of representative meteorological conditions, calculated results for each set of conditions, and then presented the results in statistical form, including the mean, median, 95th percentile, 97.5th percentile and maximum values for the relevant endpoints.

## Definitions and modelling assumptions

For clarity, key modelling approaches and assumptions, which apply irrespective of the atmospheric dispersion modelling approach being applied, are listed below. More detail is provided in the sections that follow.

* Best estimate dry deposition velocities applied: 1 10-3 for particulates, 1 10-5 for organic iodine, 1 10-2 for elemental iodine, 0 for noble gases, all in units of m s-1
* A washout coefficient approach for modelling wet deposition
* Inclusion of the following exposure pathways: inhalation, external exposure from the plume (cloud gamma), external exposure from deposited material (deposited gamma) and ingestion
* Dose integration times: 7 or 30 days (as appropriate in respect of the release duration), 1 year, lifetime (to age 70 years)
* Inhalation and ingestion dose coefficients taken from ICRP (2012) represent the committed dose to age 70 years
* Inhalation rates of 2.57 10-4 m3 s-1 and 6.02 10‑5 m3 s-1 were assumed for adults and one-year-old infants, respectively (ICRP, 1994)
* Deposited gamma and cloud gamma calculations assumed an individual spends 10% of their time outdoors and 90% of their time indoors (for all considered dose integration periods)
* Assumed an individual spends 100% of their time in one (receptor) location
* Contaminated foods included cows’ milk & milk products and green & domestic vegetables only
* Assumed mean consumption rates (Smith and Jones, 2003)
* Assumed that 100% of the cows’ milk & milk products and green & domestic vegetables consumed were produced locally i.e. where the individual resides

The selection of contaminated foods to include cows’ milk & milk products and green & domestic vegetables only was based on:

(1) these two foodstuffs being the most likely to contribute to dose in the short term, and

(2) it being 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.

### Importance of assumptions relating to cows’ milk and milk products

The proportion of milk produced locally can be an important modelling parameter in terms of influence on the dose. The modelling in the present study assumed a value of 1.0 (which means 100% of the milk that was consumed locally had been produced locally). That is a conservative assumption. It should be noted that that assumption affects only the lifetime dose results. The 7-day and 30-day doses do not include ingestion, and so are unaffected by assumptions relating to milk consumption. The implications of this assumption are discussed in Section 5.3.4.2.

## PACE Modelling

Irrespective of whether the NAME or ADEPT atmospheric dispersion models were applied in PACE, many of the modelling assumptions, most notably the dose modelling assumptions, were identical – these assumptions are summarised in Section 4.3.1. However, there existed some distinct differences between NAME and ADEPT in PACE model runs, notably in the dispersion modelling and application of meteorological data aspects, and these are highlighted in Sections 4.3.2 and 4.3.3, respectively.

### PACE

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

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

PACE allows the model user to consider either deterministic model runs, simulating a release under a single meteorological condition, or probabilistic model runs, simulating a release under many different meteorological conditions (Charnock et al, 2013); both approaches have been considered in this study. Within the probabilistic approach, PACE builds up a picture of the possible ranges of consequences by repeatedly modelling the atmospheric dispersion and deposition of radionuclides for a given accident scenario using meteorological sequences drawn from a large historical dataset of weather conditions.

The calculation of the dispersion of radionuclides in the atmosphere is performed using either the NAME (Numerical Atmospheric-dispersion Modelling Environment) model or the ADEPT model. More details about NAME and ADEPT are given in the Sections 4.3.2 and 4.3.3, respectively. These atmospheric dispersion models estimate activity concentrations in air which are subsequently used by PACE to calculate doses from direct inhalation of the dispersing plume and external exposure to gamma radiation from the plume. NAME and ADEPT also calculate deposition of material onto the ground which is used for input to PACE’s calculation of dose from ingestion of foods and exposure to gamma emitters deposited on the ground.

In PACE a model grid must be defined. In this study, for each site, three grids were considered, each with a different resolution (i.e. two nested grids). The grids were all approximately symmetrical about the release point (even if this meant including squares that were entirely sea). The inclusion of grid squares that are entirely sea, as assumed in this study, avoids anomalous statistical effects that would be caused by assigning zero dose results to such grid squares. This is a conservative approach, because a quoted “maximum dose” result may correspond to a square that is entirely sea.

A “*brick house (env1) normal living*” environment was assumed across all PACE model runs. This assumption influences the methodologies used to calculate dose arising from the external exposure pathways (from the plume and deposited material). Such a selected environment was representative of a street of semi-detached houses (where an individual was assumed to spend 90% of their time) and a large open space characteristic of a park (where an individual was assumed to spend 10% of their time). Corresponding location factors were derived using the ERMIN model (Jones et al, 2007b).

Transfer of radionuclides through the terrestrial foodchain was modelled using FARMLAND (Brown and Simmonds, 1995) for spike releases occurring in January and June and results stored in datasets of time dependent activity concentration in foods per unit deposition. These datasets were based on an implementation of FARMLAND that takes account of detailed agricultural practices. Consequently, the time of the year when an accident occurs will influence the activity concentrations in food and, therefore, data was available for accidents occurring in both summer and winter. Datasets were also included for exposure to gamma emitters from material deposited on the ground. This data was derived using the GRANIS model (Kowe et al, 2007).

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

A modified version of PACE 3.3.4.0, with additional functionality for analysing relative amounts of wet deposition associated with probabilistic assessments of dose, was applied in this study.

#### Internal exposure from the inhalation of material from the plume

Values of inhalation dose coefficients were taken from ICRP Publication 119 (ICRP, 2012). Assumed lung absorption types were in accordance with advice provided in NRPB (1999). Inhalation rates were taken from ICRP Publication 66 (ICRP, 1994). No dose reduction was assumed as a result of time spent indoors.

#### External exposure from material in the radioactive plume

NAME has the capability to calculate the effective dose arising from external exposure from material in the radioactive plume (cloud gamma dose) using a finite or semi-infinite cloud model. The finite cloud model involves simulating the plume by a series of model particles (point sources) and then integrating over these sources to estimate the dose at a point. The semi-infinite cloud model is much simpler and uses the activity concentration in air at the point of exposure to calculate dose. Implicit in this approach is the assumption that the activity concentration in air is uniform over the volume of the plume from which photons can reach the point at which the dose is delivered and that the cloud is in radiative equilibrium. Because the finite cloud model is more computationally expensive it was not practicable to use that approach in this study; furthermore, the semi-infinite cloud model was identified as being fit for purpose.

ADEPT does not calculate cloud gamma dose. Therefore, PACE calculates cloud gamma dose using ADEPT’s derived time integrated activity concentration in air (TIACs) at the point of exposure and factors based on a semi-infinite cloud model (akin to the approach applied in NAME). To reduce the potential for error under circumstances of an inhomogeneous plume, the user can choose to apply cloud gamma correction factors to ADEPT. PACE cloud gamma correction factors were calculated using a Monte Carlo approach for 2 roughness categories, 4 stability classes, 4 release heights, ten angles from the plume centre line and 8 distances from the point of release. These factors used at a given point for a given release, roughness category and stability class need to be interpolated horizontally and vertically. The cloud gamma correction factors were developed for PC Cosyma (Jones et al, 1995) and cause a noticeable narrowing of the plume cloud shine out to 20 km when viewed on a map. Such correction factors were applied in this study.

#### External exposure from material deposited on the ground

External gamma dose from deposited material (or deposited gamma dose) was calculated by multiplying the amount of material deposited by the dose per unit deposition, where the latter was obtained from a data library. The library contained dose per unit deposit values for a series of times and a large number of radionuclides. The contribution from progeny products formed after deposition was also included. This library was generated by combining information from different sources, and so included doses calculated using three different models. The values for the radionuclides which typically make the most significant contributions to deposited gamma dose from typical accidental releases from nuclear fission reactors (103Ru, 106Ru, 131I, 132Te, 134Cs, 137Cs, and 140Ba) were calculated using the NRPB model EXPURT (Crick and Brown, 1990). This considers the amounts of material deposited on different surfaces in residential areas, the movement of material between these surfaces and into the soil column, and the dose from material deposited on the different surfaces. The doses for other radionuclides were calculated using a simpler model which assumes that the dose in the area where people live can be represented by the dose received over an open field (Charles et al, 1982) (Hill et al, 1988). The doses were calculated allowing for material to move into the soil column. The anterior-posterior (AP) irradiation geometry was used for calculating the effective dose from the air dose.

#### Internal exposure from ingested material

Underpinning the ingestion dose calculations in PACE are libraries of food contamination factors created using the terrestrial food chain model FARMLAND (Brown and Simmonds, 1995). Activity concentrations and integrated activities per unit mass of food for a unit deposition onto the ground (Bq kg-1 per Bq m-2 and Bq y kg-1 per Bq m-2) were calculated for a broad range of terrestrial food groups that are important in the UK diet. However only cow milk & milk products and green & domestic vegetables were considered in this study.

The individual dose calculation is the sum of two components; the first representing local production, i.e. the consumption of food grown in the vicinity of the individual, and the second representing the consumption of food drawn from national production. However, in the present study, it was assumed that all (contaminated) milk and green vegetables were produced locally.

The calculation assumed that all deposition occurred at time zero.

Corrections for delay times from harvest to consumption (for fresh and processed products) were included and doses were truncated to 100 years. The fraction of food consumed fresh (0.5 for milk and 1 for green vegetables) and the fraction processed (0.5 for milk and 0 for green vegetables) were specified in the PACE interface.

PACE considers two times of year in respect to the modelling of the transfer of deposited radioactive material to food: summer (June) and winter (January). Summer is the most conservative for all food types. The “June” FARMLAND results are applied for releases from mid-April to the start of November; the “January” FARMLAND results are applied for releases from the start of November to mid-April. NAME in PACE runs, sampling over annual variations in meteorology, will account for the two times of year accordingly. The deterministic ADEPT model runs conservatively assumed a release start date of 1st June.

Note that in the terrestrial food chain model FARMLAND there is no option to truncate individual ingestion dose to 69 years. Thus, whilst for the deposited gamma exposure pathway one year old infant doses can be integrated to 69 years, for the ingestion exposure pathway one year old infant doses can only be truncated to 50 years. However, this will have only a minimal impact on the doses estimated in this study.

Furthermore, there is no option in PACE to consider individual ingestion dose truncated to less than 1 year. Therefore only 1 year and lifetime integrated doses will include doses from the ingestion exposure pathway. Doses from the ingestion exposure pathway will be omitted from the assessment for 7 and 30 day dose integration periods.

The values used for individual consumption rates were based on NRPB-W41 (Smith and Jones, 2003) and on Brown and Sherwood (2012). Individual consumption rates of cow milk and cow milk products for adults and one year old infants were assumed to be 115 kg y-1 and 145 kg y‑1, respectively. Individual consumption rates of green and other domestic vegetables for adults and one year old infants were assumed to be 35 kg y-1 and 5 kg y-1, respectively. These values assumed a mean consumer of these foodstuffs.

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

#### Food restrictions

The method used to determine the amount of activity estimated in foodstuffs is described in Section 4.3.1.4, noting that such activity concentrations do not include any preparation losses, and the total deposition value was always assumed.

The duration and extent of food restrictions were calculated by comparing the estimated activity concentrations in foods against the EURATOM Maximum Permitted Levels (MPLs) (CEC, 2016) at a series of times. The MPLs are defined for specific radionuclide and food groups and are given in Table 13. PACE considers restrictions on most of the foodstuffs relevant for UK production but two key foods, cows’ milk and green vegetables, were presented in this study.

Table : EURATOM Maximum Permitted Levels (MPLs)

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

### NAME in PACE Modelling

The UK Met Office’s Numerical Atmospheric-dispersion Modelling Environment, NAME, is a Lagrangian particle-trajectory model designed to predict the atmospheric dispersion and deposition of gases and particulates (Jones et al, 2007a). The mean flow or advection of a particle is determined by the flow information, primarily the wind velocity, detailed in the required meteorological data. Diffusion is described by random walk (Monte Carlo) processes, determined by the turbulent velocity. Each particle carries a mass or activity of one or more pollutant species and evolves by various physical and chemical processes during its lifespan. A box-averaging scheme is used to derive activity concentrations in air from particle activities. The dry deposition scheme in NAME uses a deposition velocity, whereby the flux of a pollutant to the ground is proportional to the concentration in air and deposition velocity. The wet deposition scheme in NAME uses scavenging coefficients (a function of the precipitation rate, type of precipitation and type of deposition process). For radiological releases, NAME incorporates both radioactive decay processes and estimates of external dose from the radioactive plume (Bedwell et al, 2010). NAME version 6.5 was applied in this study.

#### Meteorological data

The Met Office’s Unified Model (UM) is a Numerical Weather Prediction (NWP) meteorological model which is used for both weather prediction and long term climate modelling (Cullen, 1993; Staniforth and Wood, 2008). The meteorological data obtained from Met Office was analysis data taken from the Unified Model run in the UKV configuration. The UKV meteorological data has a horizontal resolution of approximately 1.5 km by 1.5 km. The total spatial extent of the UKV meteorological data covers the UK, Ireland and small portions of neighbouring countries; however, the present study used geographical cut-outs of more limited extent, as appropriate for each of the six sites. Accounting for the effects of terrain and surface roughness is implicit in the NWP data.

#### Run set-up

The dispersion scenarios considered in this study were derived using three full years of meteorological data covering the period 2018 to 2020. A large number of meteorological sequences were sampled over that period. In general, sampling a larger number of met sequences gives greater statistical accuracy; however, it was necessary to balance that with the need for manageable run-times. The balance was different for the different source terms, in particular because of the differences in release durations. That meant that different sampling parameters had to be used in runs that used different source terms. In the case of runs using the LBL source term, 152 different meteorological sequences were sampled, with each meteorological sequence having a duration of 732 hours and a start-time that was 168 hours later than the start-time of the previous sequence. This resulted in 152 overlapping met sequences equally distributed over the full three-year period. The Fuel Handling source term runs sampled 162 met sequences of 54 hours duration with a gap between start-times of 163 hours. The Steam Generator Tube Rupture source term runs sampled 571 met sequences of 54 hours duration with a gap between start-times of 46 hours. The RCCA Ejection source term runs sampled 152 met sequences of 732 hours duration with a gap between start-times of 168 hours. In all cases, one thousand model particles were released per hour modelled.

When modelling wet deposition, the NAME model default input parameters were assumed, specifically Washout Coefficient A rain – BC = 8.4 10-5, Washout Coefficient B rain – BC = 7.9 10-1, Washout Coefficient A snow – BC = 8.0 10-5, Washout Coefficient B snow – BC = 3.05 10-1, Washout Coefficient A rain – IC = 3.36 10-4, Washout Coefficient B rain – IC = 7.9 10-1, Washout Coefficient A snow – IC = 5.2 10-5, and Washout Coefficient B snow – IC = 7.9 10-1. “BC” represents “below cloud” and “IC” represents “in cloud”. These assumptions applied to all radionuclides barring noble gases. Noble gases do not wet deposit, and therefore all washout coefficients were assumed to be 0.

#### PACE Analysis

After completing the PACE modelling stage, the *PACE Analyse Results* tool was used to produce a statistical analysis. The tool aggregates data extracted from each meteorological sequence to calculate the endpoint in each grid square. It then summarises the endpoint across the whole grid to generate a single value for each meteorological sequence. Finally, from this set of values, the tool is able to calculate mean, maximum and minimum values as well as percentiles that indicate the likelihood of particular (overall) outcomes.

In the present study, statistical outputs were obtained by running over 152 meteorological sequences for the LBL source term (using three years of met data). For each meteorological sequence, a set of endpoints were calculated. A statistical analysis of those results was carried out to determine mean, median, 95th percentile, 97.5th percentile and maximum values for each model run. Note that where the relevant endpoint was maximum dose, this means that a single maximum dose value was identified for each meteorological sequence. That means 152 “maximum” values, one for each met sequence. Statistical analysis was then carried out on those 152 “maximum” values. When terms such as “mean”, “median”, etc, are applied to such endpoints, it must be remembered, that they are referring to the mean, median, etc, *of the 152 “maximum” values*. They are not referring to the mean, median, etc, of *all* values. To make the meaning clearer, terminology such as “mean maximum dose” may be used.

The same explanation applies to the runs carried out for the other source terms, except that the number of met sequences iterated over was different, depending on the requirements of the run. In the case of the Fuel Handling source term, 162 met sequences were iterated over, for the Steam Generator Tube Rupture source term, 571 met sequences were iterated over, and for the RCCA Ejection source term, 152 met sequences were iterated over.

### ADEPT in PACE Modelling

ADEPT implements a Gaussian plume approach (Clarke, 1979). The approach assumes that the dispersion of material is described by a Gaussian distribution characterised by standard deviations in the horizontal (y axis) and vertical (z axis) directions (also known as the horizontal and vertical dispersion coefficients, respectively). The former accounts for both turbulent diffusion and a component due to fluctuations in wind direction. When the value of the latter is less than the depth of the boundary layer, a term accounting for the reflections from the ground and inversion layer is considered. Conversely, when the value of the vertical dispersion coefficient becomes greater than the depth of the boundary layer, the vertical concentration distribution effectively becomes uniformly distributed through the mixing layer, and the formula is modified accordingly. Dry deposition is described by means of a source depletion model (Jones, 1981a) (Jones, 1981b) and deposition velocities (ADMLC, 2000) (Jones, 1983). Wet deposition is modelled using washout coefficients, applied to a plume depletion model accounting for wet deposition processes (Jones, 1981a) (Jones, 1981b). The washout coefficients were derived by way of an approach detailed in Jones et al (1995) and are dependent on the precipitation rate and coefficients *a* and *b.* The coefficients *a* and *b* are dependent on the type of pollutant (notably they differentiate between particulates and elemental iodine vapour). ADEPT assumes no radioactive decay during the plume’s passage.

A surface roughness (or roughness length) value of 0.3 m is a hard-wired assumption (representative of agricultural areas).

ADEPT does not account for meteorology changing as a function of space and accounts for the meteorology changing as a function of time in a simplistic manner. For example, consider a two hour release. Radioactivity released in the first hour will be dispersed in accordance with the respective meteorology in that same hour, and will continue to be dispersed in accordance with the meteorology that occurred during the first hour of the release for all subsequent hours modelled (thus no account of the second hour of meteorology and any subsequent changes in meteorology thereafter is considered). The radioactivity released in the second hour will be dispersed in accordance with the respective meteorology in that same hour, and will continue to be dispersed in accordance with the meteorology that occurred during the second hour of the release for all subsequent hours modelled.

#### Meteorological data

Constant meteorological conditions were assumed, primarily comprising of Pasquill Stability Category D conditions, a mixing layer depth of 800 m, a single wind direction of 225 degrees from North (i.e. a south-westerly wind and the prevailing wind direction in the UK), a wind speed of 5 m s‑1, and precipitation rates of 0, 0.01, 0.1, 1, 2, 4 and 8 mm h-1. Further model runs assumed Pasquill Stability Category F conditions, a mixing layer depth of 100 m, a single wind direction of 225 degrees from North, a wind speed of 2 m s‑1, and dry conditions (only).

#### Run set-up

The same meteorological conditions, as described in Section 4.3.3.1 were assumed throughout a model run, for the entire release duration.

Fluctuations in the wind direction are recognised to increase, with increasing release duration. These fluctuations result in meander in the plume and therefore a broader plume. When running ADEPT in PACE the user has the option to account for the cumulative fluctuations in the wind direction beyond a default period of one hour. The method employed is that detailed in equation 12 in the NRPB-R91 report (Clarke, 1979). This option was included in all ADEPT model runs in this study. This resulted in a more representative description of the modelled plume, especially for the LBL and RCCAE source terms, which had exceptionally long (30 day) release durations.

When modelling wet deposition, the ADEPT model default input parameters were assumed, specifically Washout Coefficient A = 8 10-5, Washout Coefficient B (for all radionuclides barring elemental iodine) = 8 10-1 and Washout Coefficient B (for elemental iodine only) = 6 10-1. These assumptions applied to all radionuclides barring noble gases. Noble gases do not wet deposit, and therefore all washout coefficients were assumed to be 0.

## ADMS Modelling

The ADMS model (Carruthers et al, 1994) is based on improvements in the understanding of both the structure of the atmospheric boundary layer and dispersion within the boundary layer, from that detailed in the R91 model (Clarke, 1979). The improvements in the understanding of the structure of the boundary layer, stem from the recognition that the state of the boundary layer can be represented in terms of a small number of dimensionless groups of parameters, the most important of which is the ratio h/LMO, where h is the boundary layer height and LMO is the Monin-Obukhov length. The boundary layer depth can be measured directly or calculated from other measured quantities. The Monin-Obukhov length can be calculated from other quantities that can be measured at or near the ground. The ratio h/LMO can be regarded as a measure of the stability of the atmosphere, and therefore a replacement and improvement for the original Pasquill stability categories.

ADMS is based on a simplification of the research grade models, which has been achieved by separating the calculation into two steps, namely the determination of the mean plume height and the spread around that height. The approach uses ordinary differential equations for the variation of the mean plume height with distance downwind (for passive plumes) and formulae for the spread of the plume which are based on the understandings developed in research grade dispersion models.

Diffusion of gases and particulates and gravitational settling of particulates to ground (dry deposition) is calculated by using a dry deposition velocity that may be user defined or calculated by the model. The former approach was applied in this study.

In ADMS, the washout coefficient may be specified as a constant value by the user, in which case the wet deposition calculated would be independent of the precipitation rate and, indeed, wet deposition will be predicted in the absence of precipitation. Alternatively, the user may specify the washout coefficient parameters. The latter approach was applied in this study.

As well as estimating activity concentrations in air and activity concentrations on the ground, ADMS also estimates cloud gamma dose rates and the rate of change of deposited gamma dose rates.

The method used to estimate cloud gamma dose is based on two calculation stages; the first stage estimates the effective flux of gamma rays at a point distance “r” from a monoenergetic source dispersed in air for a particular energy level, and is a function of the branching ratio, the average air concentration, the Berger build-up factor, and the linear attenuation coefficient; the second stage estimates the effective dose by multiplying the flux, by an absorption coefficient, a conversion coefficient, the gamma energy and then summing over all energy levels.

The method used to estimate deposited gamma dose is very similar to the cloud gamma approach and is based on two calculation stages; the first stage estimates the effective flux of gamma rays at a point distance “r” from a monoenergetic source deposited on the ground for a particular energy level, and is a function of the branching ratio (which in turn is a function of the gamma energy), the deposition rate, the Berger build-up factor, and the linear attenuation coefficient; the second stage estimates the effective dose by multiplying the flux, by an absorption coefficient, a conversion coefficient, the gamma energy and then summing over all energy levels. The deposited gamma dose is based on the contribution from dry deposition only; there is no accounting of the contribution from wet deposition. Furthermore, the ADMS method does not account for the radioactive decay of material after it has been deposited.

There is no indication in any of the ADMS documentation which age group the cloud gamma and deposited gamma dose estimates apply to.

ADMS version 4.2 was applied in this study.

### ADMS Method and Input Parameters

#### Source Term

ADMS requires a number of additional source term input parameters to be defined. The specific heat capacity of the source material and the molecular mass of the release material were both set to the ADMS model default values (typical values for air). The release temperature and pressure were set to ambient values (defined as “NTP” or normal temp and pressure in the model). A point source (P) was also assumed.

#### Meteorological Data

Constant meteorological conditions were assumed. Pasquill Stability Category D conditions comprised of a mixing layer depth (or boundary layer height) of 800 m, a surface heat flux of 0 W m-2, a cloud amount of 8 oktas, a single wind direction (angle) of 270 degrees from North (noting that this selection has no bearing on the model results produced), a wind speed of 5 m s-1, and precipitation rates of 0, 0.01, 0.1, 1, 2, 4 and 8 mm h-1. Pasquill Stability Category F conditions comprised of a mixing layer depth of 100 m, a surface heat flux of -16 W m-2, a single wind direction of 270 degrees from North, a wind speed of 2 m s-1, and dry conditions (only).

A release location latitude and a time and date when the meteorological data begins must both be defined. The latitude and timing of the release can be used by the model to help determine the prevailing conditions (notably solar radiation and subsequently the stability of the atmosphere) depending on the availability of the data. However, in this instance, the relatively comprehensive nature of the meteorological data provided was sufficient to not warrant the consideration of the latitude, time and date.

An ADMS model default surface roughness value at the dispersion site of 0.1 m was assumed (corresponding to a region of root crops). It was further assumed that the surface roughness at a possible meteorological measurement site was the same as at the dispersion site.

The ADMS model default height (10 m) of the “recorded” wind was assumed.

#### Run set-up

The same meteorological conditions, as described in Section 4.4.1.2 were assumed throughout a model run, for the entire release duration.

When specifying time varying emissions for a source term with multiple radionuclides, as was the case in this study, the source term length in hours and the number of hours of meteorology considered must be the same. For example, in the case of the LBL source term model runs, the source term length and the length of the meteorological dataset was programmed to be 30 days. This is typical of Gaussian Plume modelling approaches, and the same assumption was applied when running ADEPT. However, when running the NAME model, to capture the “tail” of the plume, a suitable lag in the meteorological data was required (after the release was assumed to have ended).

For all considered source terms (where applicable) it was assumed that all isotopes of Caesium and the particulate form of isotopes of iodine were modelled as particles, and all noble gases and elemental and organic forms of iodine were modelled as gases.

When modelling wet deposition, model default input parameters were assumed, specifically Washout Coefficient A = 1 10-4 and Washout Coefficient B = 6.4 10-1. These assumptions were applied to all radionuclides barring noble gases. Nobles gases do not wet deposit, and therefore all washout coefficients were assumed to be 0.

The terminal velocity of modelled particles was assumed to be 0 m s-1 i.e. no gravitational settling; an appropriate assumption for particles of ~1 μm in size. A model default mass fraction (used to consider particles of different sizes) of 1 was assumed.

Short term average (i.e. hourly) output was assumed because it was necessary to determine a set of model endpoints for every line (or hour) of meteorological data (as opposed to long term average output, which would include only a single set of model endpoints, averaged over all lines of meteorological data). Because of the very small number of receptor locations considered, an ad hoc specification of receptor points (rather than a formal grid) was assumed. A one hour model output averaging time was assumed. Output was produced via a \*.pst text file. Model output included hourly values for all radionuclides specified across considered source terms, plus progeny (including 137mBa). Model endpoints comprised of:

* time averaged activity concentrations in air, in units of Bq m-3
* deposition activity concentration rates, in units of Bq s-1 m-2
* cloud gamma dose rates (represented by the term “Gam”), in units of Sv s-1
* the rate of change of deposited gamma dose rates (represented by the term “GamD”), in units of Sv s-1 s-1

### Determining TIACs, integrated deposition concentrations, cloud gamma dose and deposited gamma dose

The time integrated activity concentration in air (TIAC) was estimated by scaling each hourly value of the time averaged activity concentrations in air by 3600 s h-1. The hourly TIAC values were then summed over all hours (of the release), to determine the total TIAC, in units of Bq s m-3.

The time integrated activity deposition concentration rates were estimated by multiplying each hourly value of the deposition activity concentration rate by 3600 s h-1. The hourly time integrated activity deposition concentration rate values were then summed over all hours (of the release), to determine the total deposition concentration, in units of Bq m-2.

The cloud gamma dose was estimated by scaling each hourly value of the cloud gamma dose rates by 3600 s h-1. The hourly cloud gamma dose values were then summed over all hours (of the release), to determine the total cloud gamma dose, in units of Sv.

The deposited gamma dose for a single hour over the release period was estimated using the following approach:

Deposited Gamma Dose (Sv) = GamD x t2 + D’1 x t + D’2 x (1 - e-λT) / λ (1)

Where t = time and is the number of seconds in one hour, 3600 s

D’1 is the dose rate at the beginning of each hour over the release period (Sv s-1)

D’2 is the dose rate at the end of each hour over the release period (Sv s-1)

λ is the radionuclide decay constant (s-1)

T is the dose integration period (s), assuming that all of the deposition occurred at T = 0 (i.e. at the beginning of the release).

Subsequently the contribution to the deposited gamma dose from each hour over the release period was summed in order to determine the total deposited gamma dose.

### Dose assessment based on ADMS derived environmental concentrations

The method for assessing the committed effective dose from four exposure pathways (inhalation, cloud gamma, deposited gamma and ingestion) based on environmental concentrations derived using ADMS is described below.

#### Internal exposure from the inhalation of material from the plume

The approach and data applied (barring the source of derived TIACs) was identical to that implemented in PACE. Inhalation dose coefficients were taken from ICRP Publication 119 (ICRP, 2012) and inhalation rates from ICRP Publication 66 (ICRP, 1994).

#### External exposure from material in the radioactive plume

For all radionuclides considered barring 137mBa, the approach applied was to multiply the external cloud gamma dose coefficients, with the TIAC values derived by manipulating ADMS model output as described in Section 4.4.2. The external cloud gamma dose coefficients represent the effective dose rate per unit activity concentration in air (as a function of age) and were derived from Bellamy et al (2017).

For 137mBa, the semi-infinite cloud approximation was applied (as in PACE). The semi-infinite cloud approximation is a two-staged approach. The first stage of the approach is to estimate the absorbed dose rate in air (Gy y-1) (Simmonds et al, 1995). It was assumed that the conversion factor, k1, was 2.0 10-6 Gy y-1 per MeV m-3 s-1, the number of photons of particular energies emitted per disintegration, n, was equal to 1, the photon intensity, Ij, was 8.98 10-1 (Eckerman and Ryman, 1993) and the photon energy, Ej, was 6.62 10-1 MeV (Eckerman and Ryman, 1993). The second stage of the approach is to multiply the absorbed dose rate in air by the adult dose per unit air kerma to estimate the adult effective cloud gamma dose. An adult dose per unit air kerma of 6.90 10-1 Sv Gy-1 was assumed (ICRP, 1996). The cloud gamma dose rate (for each hour of the release) was then converted to cloud gamma dose. The contributions to dose from each hour over the entire release period were then summed.

For both approaches described above, a reduction in the dose accounting for the effect of shielding was taken into account. It was assumed that an individual spends 10% of their time outdoors and 90% of their time indoors (during the passage of the plume), as agreed with ONR and applied in DBA assessments. Combined with an indoor location factor of 0.15 (Bexon et al, 2019), and an outdoor location factor of 1 (Bexon et al, 2019), an overall location factor of 0.235 was derived and applied in this study. This approach is deemed appropriate for the large (30 day) release duration of the LBL and RCCA Ejection source terms (noting that there is no accounting for protective actions in this assessment). This approach is less appropriate for the source terms considered which assume a shorter release duration, notably the 8 hour SGTR source term. However, a consistent approach was applied throughout, and it is thought that this assumption does not significantly impact the total doses derived.

It was assumed that the cloud gamma dose to a 1 year old infant and an adult are the same.

#### External exposure from material deposited on the ground

For all radionuclides barring 137mBa, the approach applied was based on effective dose rate per unit deposit coefficients derived by Veinot et al (2017). These values are a function of age (adult and 1 year old infant) and are in units of Sv s-1 per Bq m-2. The effective dose rate per unit deposit coefficients were scaled by deposition concentration values taken from the manipulated ADMS output as described in Section 4.4.2, the dose integration periods (7 or 30 days depending on the source term, 1 year and to age 70 years) in units of seconds, an overall location factor of 0.235 (see Section 4.4.3.2 for details) and an integrated decay term, accounting for the radioactive decay that will occur after the process of deposition has occurred.

For 137mBa the approach applied was based on the integrated effective dose rate at 1 m above the ground after an instantaneous deposit of 1 Bq m-2 on undisturbed soil values, derived by the GRANIS model (Kowe et al, 2007). Values of 2.34 10-10 Sv per Bq m-2 at 7 days, 9.96 10‑10 Sv per Bq m-2 at 30 days, 1.14 10-08 Sv per Bq m-2 at 1 year and 1.30 10-07 Sv per Bq m-2 at 50 years were assumed. The tabulated value “to infinity” was very similar to the value at 50 years, therefore a value of 1.30 10-07 Sv per Bq m-2 was also assumed for a time period of 69 years (for one year old infant lifetime dose assessments). The external dose coefficients described were scaled by the deposition concentration values taken from the manipulated ADMS output as described in Section 4.4.2. It was assumed, that all deposition occurred at time, t = 0 (therefore making the external dose coefficients relatively straightforward to apply). As for all other radionuclides considered, an overall location factor of 0.235 was assumed.

#### Internal exposure from ingested material

The methodology applied for estimating ingestion dose from the consumption of contaminated milk (and milk products) was based on time integrated activity concentration in food per unit deposit values derived using FARMLAND for accidents (Brown and Simmonds, 1995). The activity concentration in food per unit deposit values are a function of the integration period and are in units of Bq y kg-1 per Bq m-2. As for PACE, there was no estimated value for a 69 year integration period (which would be preferentially applied when estimating the dose to a one year old infant and integrated to age 70 years); therefore the 50 year value was assumed (akin to PACE). In the calculation of effective ingestion dose, the time integrated activity concentration in food per unit deposit values were scaled by the integrated deposition concentration values taken from the manipulated ADMS output as described in Section 4.4.2, the ingestion effective dose coefficient in units of Sv Bq-1 (ICRP, 2012), and the consumption rate of milk and milk products (which is a function of age) and in units of litres (or kg) per year (Byrom et al, 1995).

The same approach, based on time integrated activity concentration in food per unit deposit values derived using FARMLAND for accidents, was applied for estimating the ingestion dose from the consumption of green (and domestic) vegetables. And, as for milk, the consumption rate of green and domestic vegetables was derived from (Byrom et al, 1995). The produce was assumed to be fresh from the “farm gate” and the release period was assumed to be June.

## Other modelling considered

### ADEPT, ADMS and NAME model validation

The fundamental approach of deriving a washout coefficient applied within wet deposition modelling across the three models (ADEPT, ADMS and NAME) considered in this study is essentially the same. However, the application of the washout coefficient in the derivation of wet deposition differs across the different models, as does the assumed default washout coefficient constant input parameters. Appendix A describes the wet deposition modelling approaches considered in this study and the validation performed in support of such modelling approaches. It was evident that there is a significant lack of such validation studies. That said, there does exist significant scientific justification for the implementation of the wet deposition methods applied. In addition, there has been comprehensive validation of the atmospheric dispersion calculations (in the models considered), upon which the wet deposition calculations are dependent.

### The Symbiose Model

The *Symbiose* model was developed by IRSN and jointly funded by EDF Energy. It is relevant to the present study because the model might plausibly be used as part of future DBA assessments. UKHSA does not have access to the Symbiose model itself, so no Symbiose runs were carried out during the present study. However, Symbiose model documentation was obtained, which gave an indication of the form of the model and the parameterisations and assumptions made within the model. This information was used to explain how the model might behave relative to the other models considered and is detailed in Appendix B.

It was evident that the model is most similar to ADEPT. However, if the Symbiose model was run for the same scenarios as considered in this study, the model results may be more akin to ADMS (given that the majority of the ADEPT model results presented here include the option of “Full Duration Sigma” – see Section 5.3.2 for details).

# Results and Analysis

The present study addressed three questions:

* *When considering precipitation at different precipitation rates, in a DBA assessment, is there a cliff-edge effect in the estimates of dose?*
* *Is there a lack of conservatism in the current DBA methodology (for off-site radiological consequences) as a result of typically assuming no precipitation?*
* *Are the current default atmospheric dispersion modelling approaches used by licensees appropriate for DBA use?*

Each of those questions is dealt with in turn below, and the relevant results are presented.

## Is there a cliff-edge effect when considering precipitation?

This question sought to investigate whether an increase in precipitation might lead to a sudden significant increase in the estimated dose.

In this study, the phrase “cliff-edge effect” has been interpreted in the conventional sense of a sudden large change in output caused by a small change in input. If the phrase is interpreted more broadly to include a large difference in predicted dose between scenarios of moderate precipitation and zero precipitation, then it would be outside the scope of the investigation described. Whether a “cliff-edge effect” exists in that broader sense can be judged by reference to the subsequent sections. An example would be Figure 11. This shows the modelled dose being significantly greater for scenarios with light precipitation than those with zero precipitation. Although Figure 11 may appear to show a cliff-edge effect in the broader sense, it is also important to remember that the doses shown in the figure were calculated on the assumption that each given precipitation rate persisted for the full 30-day duration of the release. A change in precipitation rate from zero to 1 mm h-1 may at first sight seem relatively small, but that is not what the figure is showing. Figure 11 is showing the effect of changing from a scenario of zero precipitation to a scenario in which there is constant 1 mm h-1 precipitation for 30 consecutive days. Such sustained precipitation is unrealistic (in the UK), so in reality the change in input between the two scenarios is very large. That could be interpreted as not indicative of a cliff-edge effect. In practice, the term “cliff-edge effect” might need to be carefully defined if it were to be used as part of a decision-making process.

Model runs were initially carried out assuming zero precipitation. The runs were then repeated with all parameters kept the same except that precipitation rate was increased in each successive run. The results were then plotted and the plots were examined to determine whether any sharp increases in dose were apparent.

ADEPT and ADMS were used in the model runs, as those models are representative of the types of models historically applied by operators of nuclear licensed sites.

All model runs discussed in this section relate to the Large Break LOCA source term, and Pasquill Stability Category D conditions. The ADEPT model runs relate to the Seathwaite location; however, release location has relatively little impact on doses derived in the ADEPT runs performed in this study. The ADMS model runs are not dependent on location. The *30-day* doses are maximum 30‑day effective dose assuming no ingestion, whereas the *lifetime* doses are maximum lifetime effective dose including ingestion and assuming no food restrictions.

### Results derived using ADEPT

Figure : Maximum 30-day effective dose at 0.5 km assuming no ingestion (ADEPT)

Figure : Maximum 30-day effective dose at 5 km assuming no ingestion (ADEPT)

Figure : Maximum lifetime effective dose at 0.5 km assuming no food restrictions (ADEPT)

Figure : Maximum lifetime effective dose at 5 km assuming no food restrictions (ADEPT)

### Results derived using ADMS

Figure : Maximum 30-day effective dose at 0.5 km assuming no ingestion (ADMS)

Figure : Maximum 30-day effective dose at 5 km assuming no ingestion (ADMS)

Figure : Maximum lifetime effective dose at 0.5 km assuming no food restrictions (ADMS)

Figure : Maximum lifetime effective dose at 5 km assuming no food restrictions (ADMS)

### Discussion

The figures above present results for 30-day and lifetime doses at 0.5 km and 5 km from the release. Results were also generated for one-year doses and for distances of 1 km and 2 km, but those have not been plotted, as they are not thought to give any additional useful information. Plots of results for one-year (not shown) looked very similar to the plots for lifetime doses.

None of the eight figures above shows anything that could be described as a “cliff-edge”. All show a relatively smooth and gradual increase in dose as precipitation rate increases. This is consistent with what might be expected from an inspection of the washout coefficient approaches implemented in the two models. In the derivation of the washout coefficient, the precipitation rate is raised to the power of the constant B, which varies between 0.6 and 0.8 depending on the model being applied. Thus, for relatively large precipitation rates, the washout coefficient varies relatively little. For relatively small precipitation rates, the washout coefficient varies much more markedly but the dose from wet deposition exposure pathways is moderated to a degree by the contribution from dry deposition and non-deposition exposure pathways.

Since the purpose of the present section is solely to investigate the possible presence of “cliff-edge” effects, no comment is made here about other notable features of the plots. However, further discussion can be found in the sections that follow.

## Is there a lack of conservatism in the current DBA methodology?

This question sought to investigate whether there is a lack of conservatism in the current DBA methodology (for off-site radiological consequences) as a result of the operators of nuclear licensed sites typically assuming no precipitation. Operators commonly assume Pasquill Stability Category F conditions, alongside a 2 m s-1 wind speed and no precipitation (precipitation tends not to be considered alongside such a stability category because it is typically recognised as not being a physical representation of the state of the atmosphere – see Section 2.2.3 for details); such meteorological conditions have been considered to be sufficiently conservative by ONR. To answer the posed question, two sets of model intercomparisons were performed, detailed in Sections 5.2.1 and 5.2.2.

### Pasquill Stability Category F versus Pasquill Stability Category D conditions

The Gaussian models ADMS and ADEPT were both used to estimate doses for a range of precipitation rates in Pasquill Stability Category D conditions. Similar model runs were carried out for Pasquill Stability Category F conditions with no precipitation. The results were then compared.

The model runs were carried out for all four source terms considered in the present study (LBL, FH, SGTR and RCCAE). In the case of the LBL source term, seven precipitation rates were considered: 0. 0.01, 0.1, 1, 2, 4 and 8 mm h-1. For the other three source terms, only three precipitation rates were considered: 0, 1 and 8 mm h-1. This was so as to keep to a manageable number of model runs.

The ADEPT model runs were carried out for the Seathwaite location, though location actually makes little difference to the doses calculated in such ADEPT runs. The ADMS model runs were independent of location.

The 7-day and 30-day doses were maximum 7-day and 30-day effective dose assuming no ingestion, respectively, whereas the lifetime doses were maximum lifetime effective dose including ingestion and assuming no food restrictions.

#### Short dose integration period results and discussion

For the shorter integration periods (which in this context means 7- or 30-day doses), the doses estimated for Pasquill Stability Category F dry conditions were nearly always greater than the doses estimated for any of the analogous runs carried out for Pasquill Stability Category D conditions (including those in which there was non-zero precipitation). This was true for ADMS and ADEPT and for all four source terms considered. In some cases, the difference was large; an example is given in Figure 9.

For these shorter integration periods, only one instance was found of Pasquill Stability Category F conditions not resulting in the highest dose. That unique instance was the ADEPT model run for the RCCAE source term, and specifically the 30-day integrated effective dose to an adult at 0.5 km from the release. The results are shown in Figure 10. Even in that unique case, it was only for the 8 mm h-1 precipitation rate that the Pasquill Stability Category D derived dose was higher than the Category F derived dose. In reality, a sustained precipitation rate of 8 mm h-1 over a 30-day period would be unheard of. That said, any “single description of the meteorological conditions”, such as PSC F and dry conditions, persisting throughout a 30-day period, has never before been observed (in the UK).

This indicates that when estimating doses for relatively short dose integration periods and on the basis of a Gaussian Plume Model, Pasquill Stability Category F is not necessarily the most conservative assumption, but will be in most cases.

Figure : Maximum infant 30-day effective dose at 5 km on the basis of the LBL ST (ADMS)

Figure : Maximum adult 30-day effective dose at 0.5 km on the basis of the RCCAE ST (ADEPT)

#### Lifetime dose integration period results and discussion

For a large proportion of the scenarios considered in this study, on the basis of lifetime integration periods, dose estimates derived assuming Pasquill Stability Category D and an 8 mm h-1 precipitation rate were greater than the respective dose estimates derived assuming Pasquill Stability Category F and dry conditions (Figure 11 being an example). The exception being for some RCCAE and SGTR ST scenarios.

In a handful of cases, as demonstrated in Figure 11, dose estimates derived assuming Pasquill Stability Category D and a 1 mm h-1 precipitation rate were greater than the respective dose estimates derived assuming Pasquill Stability Category F and dry conditions. There were no instances, for the scenarios considered in this study, in which dose estimates derived assuming Pasquill Stability Category D and a 0 mm h-1 precipitation rate were greater than the respective dose estimates derived assuming Pasquill Stability Category F and dry conditions.

In a few cases, Pasquill Stability Category F remained the dominant meteorological condition, as presented in Figure 12.

Figure 11 and Figure 12 were included to demonstrate the relative differences in estimated dose when assuming PSC F (and dry) conditions compared to PSC D conditions with varying rates of precipitation. Irrespective of the source terms or the meteorological conditions, the dominant contribution to dose in Figure 11 and Figure 12 was from the ingestion of radioiodine in milk. The differences in the patterns of estimated doses as a function of meteorological condition between the two figures arose because of differences in the makeup of the source terms and differences in dry deposition velocities; specifically, the LBL source term included iodine in all three common chemical forms (released in differing amounts), whilst the SGTR source term included iodine in only elemental vapour form, and elemental iodine vapour was assumed to dry deposit one thousand times more readily than iodine in organic form. A further key factor was the uniformity of the wet deposition as a function of the chemical form of iodine. Thus in Figure 11, for the LBL source term, the estimated dose derived assuming PSC F conditions was relatively small because relatively large quantities of iodine in organic form were released, leading to dominant organic iodine air concentrations (relative to elemental iodine vapour), which wet deposits in significantly greater amounts than it dry deposits. In Figure 12, for the SGTR source term, the estimated dose derived assuming PSC F conditions was relatively large because of the significantly greater air concentrations arising in stable (compared to neutral) conditions, resulting in significantly greater quantities of dry deposition of elemental iodine vapour (which wet deposits only moderately more than it dry deposits).

Figure : Maximum infant lifetime effective dose at 5 km on the basis of the LBL ST (ADMS)

Figure : Maximum infant lifetime effective dose at 0.5 km on the basis of the SGTR ST (ADMS)

### Pasquill Stability Category F and a Gaussian Plume Approach versus more representative meteorological conditions and a Lagrangian Particle Approach

A comparison of estimates of dose on the basis of Pasquill Stability Category F and dry conditions, and on the basis of a broad spectrum of representative meteorological conditions, including precipitation, for a range of UK locations, was performed, where the former utilised Gaussian Plume dispersion modelling (ADMS and ADEPT) and the latter utilised Lagrangian Particle modelling (NAME). The same range of source terms (LBL, FH, RCCAE and SGTR) was considered here.

The ADEPT model runs were carried out for the Seathwaite location, though location actually makes little difference to the doses calculated in such runs. The ADMS model runs were independent of location.

The *7-day* and *30-day* doses were maximum 7-day and 30‑day effective dose assuming no ingestion, respectively, whereas the *lifetime* doses were maximum lifetime effective dose including ingestion and assuming no food restrictions.

Note that for all source terms except the LBL ST, the number of UK locations considered when running NAME was reduced (from six) to three (Ardlui, Ely and Seathwaite), to ensure a more manageable number of model runs.

Figure : Maximum Gaussian Plume and Mean of the Maximums NAME infant lifetime effective dose at 0.5 km on the basis of the LBL ST

In a large proportion of the cases, assuming Pasquill Stability Category F conditions applied to a Gaussian Plume approach (such as ADMS), resulted in larger estimates of effective dose, compared to probabilistically sampling over a representative (NWP) meteorological dataset and applying the resulting meteorological data to the NAME model, as demonstrated in Figure 13. Pasquill Stability Category F conditions resulted in larger estimates of dose across all LBL ST scenarios considered in this study. Furthermore, Pasquill Stability Category F conditions resulted in larger estimates of dose at a distance of 0.5 km from the release, irrespective of the source term assumed or the dose model endpoint derived. Some of the largest disparities in ADMS and NAME derived results occurred for lifetime dose model endpoints, as demonstrated in Figure 13.

However, for a handful of scenarios, spanning the FH, RCCAE and most notably the SGTR source terms, larger estimates of effective dose were determined when applying NAME compared to ADMS. Examples of this can be seen in Figure 14 to Figure 16.

In Figure 14 it is apparent that for all three of the UK locations considered in NAME, the estimated dose was greater than that derived assuming Pasquill Stability Category F conditions within a Gaussian Plume Model; the caveat being that doses detailed in Figure 14 are the Maximum Maximum[[4]](#footnote-5) doses, which represent the most conservative approach when applying the NAME model.

In Figure 15 it is apparent that for one of the UK locations (Ely) considered when running NAME, the estimated 97.5th percentile maximum dose was greater than the maximum dose derived assuming Pasquill Stability Category F conditions by way of either Gaussian Plume Model. For two of the UK locations (Ely and Seathwaite) considered in NAME, the estimated dose was greater than that derived assuming Pasquill Stability Category F conditions for at least one of the Gaussian Plume Models.

Likewise, in Figure 16 it is apparent that for one of the UK locations (again Ely) considered in NAME, the estimated 95th percentile maximum dose was greater than the maximum dose derived assuming Pasquill Stability Category F conditions by way of either Gaussian Plume Model.

Once the mean of the maximum doses derived using NAME in PACE are considered (Figure 17), Pasquill Stability Category F conditions always result in larger estimates of effective dose than the respective NAME-derived dose estimates (for the scenarios considered in this study).

Figure 14 to Figure 17 were included to demonstrate the existence of cases whereby assuming Pasquill Stability Category F conditions applied to a Gaussian Plume approach (such as ADMS), resulted in smaller estimates of effective dose, compared to probabilistically sampling over an (NWP) meteorological dataset and applying the resulting meteorological data to the NAME model. However, it is recognised that such cases are in the minority. In addition it is further recognised that this case does not align with the conditions set for dose assessments in SAPs Target 4, notably that lifetime doses are considered at a distance from the release location more akin to 0.5 km. Infant (and adult) lifetime effective doses at 0.5 km on the basis of the SGTR ST were larger when assuming PSC F conditions in a Gaussian Plume Model compared to more representative meteorological conditions in a Lagrangian Particle Model, but the respective figures were not presented here for reasons of brevity.

Figure : Maximum Gaussian Plume and Maximum of the Maximums NAME infant 7-day effective dose at 5 km on the basis of the SGTR ST

Figure : Maximum Gaussian Plume and 97.5th percentile of the Maximums NAME infant 7‑day effective dose at 5 km on the basis of the SGTR ST

Figure : Maximum Gaussian Plume and 95th percentile of the Maximums NAME infant 7‑day effective dose at 5 km on the basis of the SGTR ST

Figure : Maximum Gaussian Plume and Mean of the Maximums NAME infant 7-day effective dose at 5 km on the basis of the SGTR ST

### Discussion

The results presented above demonstrate that there are scenarios in which assuming Pasquill Stability Category D conditions and non-zero precipitation can result in higher doses than assuming Category F and dry conditions.

Specific examples are given in Figure 10 and Figure 11. Those results were for a scenario in which there was a 30-day release duration. In practice it is not realistic that any given rate of precipitation would persist over such a long period. More generally, it is not realistic that any “single description of the meteorological conditions”, such as PSC F and dry conditions, would persist over a long period such as 30 days (in the UK). However, 1 mm h-1 precipitation persisting for 48 hours or 2 mm h-1 persisting for eight hours is more plausible. The results of the model runs indicate that each of those precipitation scenarios would result in doses (assuming Category D conditions) being higher than the analogous doses estimated for Category F dry conditions. Care must be taken not to over-generalise those results, as the present study’s 48-hour release duration related specifically to the FH source term and the eight-hour release duration related specifically to the SGTR source term.

It must also be borne in mind that defining meteorological conditions in terms of Pasquill Stability Category and precipitation rate, results in a significant degree of simplification. The NAME model provided more representative modelling of actual UK meteorological conditions due to its use of NWP meteorological data. Scenarios were identified whereby doses derived on the basis of NAME model runs were greater than the analogous doses that had been derived by simply assuming Pasquill Stability Category F and dry conditions. The extent to which this was the case depended on which statistical endpoint was considered. It was commonly observed to be the case when considering the maximum maximum statistical values, with the likelihood decreasing for the 97.5th percentile maximum and 95th percentile maximum values. No instances were observed of the mean maximum dose results exceeding the analogous Category F dry dose results. Nonetheless, it is plausible that there could be scenarios in which the mean of the maximum estimated doses exceeds the analogous dose estimated by assuming Pasquill Stability Category F and dry conditions.

The 95th percentile is a frequently used threshold value in radiation assessments; in this study only one instance (Figure 16) was identified, across all of the scenarios considered, in which the NAME derived 95th percentile maximum dose exceeded the respective dose assuming Pasquill Stability Category F and dry conditions in the ADMS model (notably more instances were identified as a result of the application of the ADEPT model). This occurred for only one of the three considered sites, and in this case the magnitudes of the doses estimated were relatively similar. Thus, the application of Pasquill Stability Category F and dry conditions in a Gaussian Plume Model such as ADMS appears to be a reasonable proxy for dose assessments assuming the 95th percentile and greater conservatism of meteorological conditions in a Lagrangian Particle Model such as NAME. However, there are a number of caveats, some of which have been highlighted previously. A further caveat being that in a large proportion of scenarios the dose estimates are likely to be beyond that of the 100th percentile (or maximum maximum) i.e. not representative of reality (and a likely cause being the assumption of meteorological conditions which are rarely or never observed in the UK).

To provide a specific answer to the original question, it seems reasonable to conclude that there is a suitable level of conservatism in the current DBA methodology (for off-site radiological consequences) as a result of the operators of nuclear licensed sites typically assuming no precipitation (and PSC F conditions) if the threshold conservatism of the meteorological conditions is the 95th percentile (or less). There is the potential for a lack of conservatism in the current DBA methodology if it is necessary to assume greater than 95th percentile meteorological conditions. However, these conclusions are dependent on the atmospheric dispersion model being applied. Further caveats include a frequent lack of realism when assuming PSC F (and dry) conditions, particularly in the act of assuming such conditions persist for extended periods of time; and that the degree of conservatism varies (depending on the scenario concerned) when assuming a single meteorological condition (PSC F) within a Gaussian Plume Model.

## Are the current modelling approaches appropriate?

The preceding sections have to some extent already considered how appropriate the modelling approaches currently used in DBA assessments are. However, those sections have focused on a few specific aspects. The present section aims to broaden the investigation to consider other ways in which the current modelling approaches may or may not be appropriate for DBA use.

Model runs cannot on their own comprehensively answer the question as to whether a particular modelling approach is appropriate; however, the results can highlight the potential consequences of different approaches. That should assist in making a judgement as to whether the approaches are capable of meeting the requirements of the DBA process.

### Intercomparison of models and their application

The modelling approaches used in the present study can be broadly categorised as *NAME-in-PACE* (referred to as NAME or NiP for the remainder of the section), *ADEPT-in-PACE* (referred to as ADEPT or AiP for the remainder of the section) and *ADMS*. As part of the “appropriateness” investigation, it is useful to consider the differences in the results generated by these three modelling approaches.

#### Strategy for comparing models of different types

This study applied the models in the manner that they are likely to be employed when performing dose assessments. And the NAME model was included in this study to provide a benchmark against which all Gaussian approaches could be compared. Thus, NAME model runs were performed probabilistically (and not deterministically) alongside the application of NWP met data (as opposed to single site met data). As a result, a simple model comparison (in which exactly the same modelling parameter values would be entered into each of the models) was not possible. For example, the NWP met data used in the NAME runs meant that the precipitation rate could not be arbitrarily defined (as it could be in the ADEPT and ADMS runs). Also, dose results were output from NAME runs in statistical form, which was not the case for ADEPT or ADMS.

In order to enable a meaningful comparison, the following steps were carried out.

* The *Mean Maximum*, *95th percentile Maximum and Maximum Maximum[[5]](#footnote-6)* results were extracted from the NAME runs.
* The results for precipitation rates of 0 mm h-1 and 8 mm h-1 in Pasquill Stability Category D conditions and 0 mm h-1 in Pasquill Stability Category F conditions were extracted from the ADEPT and ADMS runs. This was to give an indication of the range of results that could arise from those runs. It does not mean that those results were analogous to the NAME runs’ *Mean Maximum,* *95th percentile Maximum and Maximum Maximum* results.
* Runs were carried out for all four source terms.

#### Results

A selection of results from the runs described above are presented below. Only infant doses are presented, but the adult doses did not reveal any significantly different patterns. The results are notionally for the Seathwaite location, except that ADMS results are not associated with any particular location.

In the graphs in this section “NiP” represents NAME-in-PACE, “AiP” represents ADEPT-in-PACE, “Mean Max” represents the Mean Maximum value, “95pc Max” represents the 95th percentile Maximum value, “Max Max” represents the Maximum Maximum value, “F 0” represents Pasquill Stability Category F conditions and a 0 mm h-1 precipitation rate, “D 0” represents Pasquill Stability Category D conditions and a 0 mm h-1 precipitation rate, “D 8” represents Pasquill Stability Category D conditions and an 8 mm h-1 precipitation rate.

In general, the doses estimated by the ADMS runs tended to be much higher than the doses estimated by the NAME or ADEPT runs. That was particularly true for longer integration periods and for longer-duration source terms.

More detailed discussion of the results accompanies each set of figures below. An investigation as to why the ADEPT and ADMS results are so different from each other is presented in Section 5.3.2.

##### Results for the Large Break LOCA source term

This source term had a 30-day release duration.

The figures below show that the doses estimated by ADMS were significantly higher than the doses estimated by NAME or ADEPT. The disparities were particularly apparent for lifetime doses and were large enough that the other models’ doses could barely be seen when viewed on the same axis. Consequently, two extra plots have been provided with the ADMS results excluded.

NAME and ADEPT doses were broadly similar, albeit with some variation. The ADEPT lifetime dose estimates on the basis of an 8 mm h-1 precipitation rate appeared high when compared to the NAME lifetime doses. This was unsurprising given that a sustained precipitation rate of 8 mm h-1 throughout a 30-day release period is unheard of, and so was a significantly more conservative assumption than was represented by the NAME results. As mentioned previously, although the model inputs have been made as analogous as possible, it must be borne in mind that the deterministic outputs of the ADEPT (and ADMS) runs are not directly comparable with the statistical outputs of the NAME runs.

Figure : Maximum infant 30-day effective dose at 0.5 km assuming no ingestion – LBL ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – LBL ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – LBL ST (excluding ADMS)

Figure : Maximum infant 30-day effective dose at 5 km assuming no ingestion – LBL ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – LBL ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – LBL ST (excluding ADMS)

##### Results for the Fuel Handling source term

This source term originally had a 30-day release duration, but most of the activity was released during the first 48 hours, so the release duration of the source term used in the modelling runs was reduced to 48 hours.

ADMS again tended to estimate significantly higher values than the other two models. It is noteworthy that the NAME model dose estimates were typically greater than those derived using ADEPT.

Figure : Maximum infant 7-day effective dose at 0.5 km assuming no ingestion – FH ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – FH ST

Figure : Maximum infant 7-day effective dose at 5 km assuming no ingestion – FH ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – FH ST

##### Results for the Steam Generator Tube Rupture source term

This source term had an eight-hour release duration, which was the shortest release duration of any source term considered in the present study. The seven-day doses were broadly comparable across the three models; the lifetime doses a little less so. The disparities tended to be smaller than was the case for the Large Break LOCA or Fuel Handling source term runs.

Figure : Maximum infant 7-day effective dose at 0.5 km assuming no ingestion – SGTR ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – SGTR ST

Figure : Maximum infant 7-day effective dose at 5 km assuming no ingestion – SGTR ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – SGTR ST

##### Results for the RCCAE source term

This source term had a 30-day release duration. As might be expected, the results showed some similarities with the Large Break LOCA results, which had the same release duration and integration periods. However, the differences between the ADMS 30-day doses and the other models’ 30-day doses were smaller in the RCCAE results than they were in the Large Break LOCA results.

Figure : Maximum infant 30-day effective dose at 0.5 km assuming no ingestion – RCCAE ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – RCCAE ST

Figure : Maximum infant 30-day effective dose at 5 km assuming no ingestion – RCCAE ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – RCCAE ST

#### Discussion

Operators commonly assume Pasquill Stability Category F conditions, applied alongside a Gaussian Plume model, to represent a suitable level of conservatism in the meteorological conditions applied within a DBA assessment. The results above show that the application of a single set of meteorological conditions combined with a Gaussian Plume approach, notably ADMS, almost always results in the largest estimates of dose. However, there was one occasion where the application of a Lagrangian Particle approach, notably NAME, resulted in the largest estimates of dose. For the scenarios presented in Section 5.3.1.2, Pasquill Stability Category F and dry conditions most often resulted in the greatest estimates of dose, but in a significant number of cases, Pasquill Stability Category D conditions and a precipitation rate of 8 mm h-1 resulted in the greatest estimates of dose. Thus, depending on the level of conservatism required across a range of DBA assessment scenarios, multiple meteorological conditions may need to be considered. Upon analysis of Figure 18 - Figure 35 it was evident that although the highest estimated dose nearly always resulted from Pasquill Stability Category F and dry conditions or Pasquill Stability Category D and a precipitation rate of 8 mm h-1, this was often not true for the second highest dose. In fact, in a number of cases, the second highest dose was the NAME derived Maximum Maximum value. This implies that there are likely to be other meteorological conditions, beyond the two mentioned, which can be significant and result in relatively large estimates of dose. As a result of the comparisons, most notably between the ADMS results, which tend to be the most conservative, and the NAME model results, which are intended to provide a benchmark, it is evident that the degree of conservatism as a result of the application of ADMS varies significantly, depending on the scenario concerned; therefore, when applying a Gaussian Plume model in this way, there is the potential for a lack of consistency in the level of conservatism applied.

A feature clear from the analysis in this section is that despite ADEPT and ADMS both being Gaussian Plume dispersion models, they produce significantly different results. It is necessary to investigate why there are such large differences in the results produced by these two models. That is the subject of Section 5.3.2.

### Differences between ADEPT-in-PACE and ADMS results

The previous section shows that there were large differences between doses estimated by ADEPT-in-PACE (referred to as ADEPT for the remainder of the section) runs and doses estimated in equivalent ADMS runs. In most cases the ADMS doses were significantly higher. At first sight, this may appear surprising, as both models use a Gaussian Plume dispersion approach. Indeed, there was actually more similarity between the ADEPT and NAME results than between the ADEPT and ADMS results, despite the fact that the NAME model uses a completely different modelling approach (Lagrangian Particle rather than Gaussian Plume).

Gaussian Plume models are less well suited to modelling long-duration releases than Lagrangian Particle models are, especially if they are set up to assume constant meteorological conditions as a function of time, as was the case in this study. This tends to be a very conservative assumption, and tends to become less and less representative of reality as the duration of the release increases. In this regard, it is relevant that the previous section indicates that the differences between the ADMS results and the other models’ results was greater for source terms with longer release durations.

ADEPT gives users the option to use “Full Duration Sigma” (FDS). This is an enhancement to the simple Gaussian Plume approach that is designed to better account for the dispersion of plumes over longer timescales, as the tendency for fluctuations in the wind direction increases (with potential added value over timescales greater than a few hours; and almost certain added value over timescales greater than a few tens of hours). ADEPT (and ADMS) considers the horizontal component of dispersion in the plume to be determined by two terms: a turbulent diffusion term and a term recognising the contribution from fluctuations in the wind direction. It is this latter term (which is a function of wind speed, distance between the release and receptor and the release duration), allied with an assumed cumulative release duration greater than a default of one hour, which is the basis of the FDS option in ADEPT. The FDS option was used in all ADEPT runs in the present study unless otherwise stated. ADMS does not have an equivalent of the FDS option. ADMS applies the same equation as ADEPT to describe the contribution to the dispersion from fluctuations in the wind direction, but ADMS applies this approach individually to each one hour segment of a release (and does not include an option to apply the approach cumulatively to an entire release). It is plausible that that could account for much of the difference in results between the two models. In order to investigate this, some of the ADEPT runs were repeated, but with the FDS option switched off. The results are presented below. Note that all model runs in this section assumed Pasquill Stability Category D conditions and a 0 mm h-1 precipitation rate.

#### Results

##### Results for the Large Break LOCA source term

The figures below show the results of: ADEPT runs in which FDS was used; ADEPT runs in which FDS was not used; and equivalent ADMS runs. Runs were carried out for 30-day doses and lifetime doses at 0.5 km and 5 km from the release. The Large Break LOCA source term was used, which has a release duration of 30 days.

In each case, switching off FDS in an ADEPT run significantly increased the estimated dose to a value which was more like the dose estimated in the equivalent ADMS run.

Figure : Maximum infant 30-day effective dose at 0.5 km assuming no ingestion – LBL ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – LBL ST

Figure : Maximum infant 30-day effective dose at 5 km assuming no ingestion – LBL ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – LBL ST

##### Results for the Steam Generator Tube Rupture source term

The figures below show the results of: ADEPT runs in which FDS was used; ADEPT runs in which FDS was not used; and equivalent ADMS runs. Runs were carried out for 7-day and lifetime doses at 0.5 km and 5 km from the release. The SGTR source term was used, which has a release duration of eight hours and which was the shortest-duration source term used in the present study.

The results for the SGTR source term were not as straightforward as the results for the Large Break LOCA source term. For the SGTR results, it was still true that in each case, switching off “Full Duration Sigma” in an ADEPT run significantly increased the estimated dose. For the lifetime doses, it was also still true that the “Not Full Duration Sigma” dose was more similar to the ADMS dose than the “Full Duration Sigma” dose was. However, in the case of the seven-day doses, the “Full Duration Sigma” and ADMS doses were already quite similar, so switching off “Full Duration Sigma” resulted in higher doses than had been found in the analogous ADMS runs.

Figure : Maximum infant 7-day effective dose at 0.5 km assuming no ingestion – SGTR ST

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – SGTR ST

Figure : Maximum infant 7-day effective dose at 5 km assuming no ingestion – SGTR ST

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – SGTR ST

#### Discussion

In general, switching off FDS makes the ADEPT results more similar to the ADMS results. It is important to emphasise that making the ADEPT results more similar to the ADMS results does not mean that the ADEPT results are being “corrected”. On the contrary, switching off “Full Duration Sigma” introduces further inaccuracy into the ADEPT results. Or, to phrase it differently, the ADEPT results are being made deliberately less accurate in order to demonstrate the inaccuracy of the ADMS results.

The discrepancies are associated with the use of a single set of meteorological conditions over a sustained period of time, i.e. it is the way the model is applied, rather than the model itself that is most relevant in this case. It is not representative of reality to assume that the wind direction is constant for days on end, and this adds significant conservatism to the assessment. In ADEPT, amending the cross wind atmospheric dispersion by modifying the approach used to determine the “sigma y” term (when switching on FDS) better represents the fluctuation in the wind direction, resulting in a more representative dose assessment, for relatively long release durations. ADMS does not include this option. However, both ADMS and ADEPT do include the option to consider time varying (hourly) single site meteorological data, which would significantly improve the representativeness (and significantly reduce the level of conservatism) of the dose assessments being performed, for relatively long release durations.

In Figure 40 and Figure 42, switching off FDS actually made the ADEPT results less similar to the ADMS results. This is because the Gaussian Plume atmospheric dispersion modelling approaches employed in the two models differ (see Sections 4.3.3 and 4.4 for details), with the approach implemented within ADMS generally viewed as superior. Bedwell et al (2011) highlighted that the “R91 model” (upon which ADEPT is based) estimates greater activity concentrations in air than both ADMS and NAME (by a factor of 2-3 in the case of the latter), for model scenarios similar to those considered here. Carruthers et al (1996) specifically compared R91 and ADMS with LIDAR data and substantiated findings by other studies that R91 under-predicts σy and σz and thereby overpredicts activity concentrations in air (in the relatively near field). The consequence is an overprediction in inhalation doses derived on the basis of ADEPT, which contributed a significant proportion of the ADEPT 7-day doses detailed in Figure 40 and Figure 42. This observation is not a feature of Figure 41 and Figure 43, because in those cases the ingestion exposure pathway (rather than the inhalation exposure pathway) was dominant. The assumed fraction of milk consumed fresh and processed in the assessment of ingestion dose differed when modelling on the basis of ADMS and ADEPT. Therefore in Figure 41 and Figure 43 the over prediction in deposition concentrations in ADEPT (as a result of the under-prediction of σy and σz) was somewhat negated by the reduction in the estimate of ingestion dose by the assumption of 50% of milk being processed.

It is clear that a determination of whether a particular model is appropriate for DBA use or not, is dependent not only on the model itself, but also on the way in which that model is applied. Nonetheless, if Gaussian Plume models are to be used to estimate doses arising from long-duration releases, alongside the assumption of constant meteorological conditions, this must be done with an appreciation of the potential for significant inaccuracies and conservatism.

### Calculation of external dose in ADMS

The ADMS model includes the ability to estimate cloud gamma and deposited gamma dose (as described in Section 4.4.2). However due to the limited description of the dose estimation approaches in the ADMS model User Guide and the desire to better understand any potential differences observed between ADMS and alternative model derived dose estimates, dose estimates based on ADMS derived environmental concentrations were also determined (as part of a post processing step outside of the ADMS model). For methodology details see Section 4.4.3. Note that the approach applied when modelling doses from inhalation of the plume and ingestion of contaminated foodstuffs did not differ, as neither of these exposure pathways are explicitly considered in ADMS.

Both methods of estimating external dose by way of ADMS assumed a range of precipitation rates in Pasquill Stability Category D conditions. Similar model runs were carried out for Pasquill Stability Category F conditions with no precipitation. The results were then compared.

The model runs were carried out for all four source terms considered in the present study (LBL, FH, SGTR and RCCAE). In the case of the LBL source term, seven precipitation rates were considered: 0. 0.01, 0.1, 1, 2, 4 and 8 mm h-1. For the other three source terms, only three precipitation rates were considered: 0, 1 and 8 mm h-1. This was so as to keep to a manageable number of model runs.

The doses presented and discussed in this section are the total doses summed over all (four) exposure pathways (considered in this study). In Figure 44 and Figure 45 the doses labelled "Ext1" are the external doses derived by way of a significant post processing step outside of the ADMS model, on the basis of environmental concentrations estimated by ADMS; the doses labelled "Ext2" are the external doses derived explicitly within the ADMS model (alongside a relatively small amount of formatting as part of a minor post processing step). The *7-day* and *30-day* doses were maximum 7-day and 30‑day effective dose assuming no ingestion, respectively, whereas the *lifetime* doses were maximum lifetime effective dose including ingestion and assuming no food restrictions.

In almost all cases, “Ext 2” dose estimates were greater than the respective “Ext 1” dose estimates (see Figure 44 and Figure 45). In some cases the “Ext 2” dose estimates were significantly greater than the respective “Ext 1” dose estimates (see Figure 44); this was most evident where the release duration was 30 days (LBL and RCCAE source terms). Although not shown in any of the figures detailed in this report, the 7-day dose integration period and a Fuel Handling source term scenario was an exception, whereby the “Ext 1” dose estimates were greater than the respective “Ext 2” dose estimates.

Some potential sources of inaccuracy have been identified in the way ADMS estimates deposited gamma dose:

* It is based on the contribution from dry deposition only; there is no accounting of the contribution from wet deposition.
* It does not account for the radioactive decay of material after it has been deposited. CERC advise in the ADMS User Guide that the approach is satisfactory if the isotopes of interest have half-lives much longer than the period of interest. Thus, for example, estimates of dose based on 131I in the environment would be significantly uncertain for all dose integration periods considered in this study (given the approximate 8-day half-life). And as a further example, estimates of dose based on 137Cs in the environment would be significantly uncertain for the lifetime dose integration period considered in this study (given the approximate 30-year half-life).
* There is no assumed transfer of radioactive material to soil, and migration down the soil column.
* There is no accounting for the shielding provided by materials in the environment (e.g. vegetation) i.e. a smooth infinite plane is assumed.
* There is no indication in any of the ADMS documentation which age group the dose estimates apply to (an issue also affecting the cloud gamma pathway).

It is unclear if any of these issues have been addressed in more recent versions of the model than the version used in this study (v4.2).

Figure : Maximum infant 30-day total effective dose at 0.5 km – LBL ST – ADMS

Figure : Maximum infant lifetime total effective dose at 5 km – LBL ST – ADMS

### Iodine chemical form

A further important consideration was the chemical form that should be assumed for iodine. The proportions of the different chemical forms of iodine in the Large Break LOCA source term are listed in Table 8. In order to investigate the effect of changing the iodine chemical forms, some of the LBL source term runs were repeated with all parameters unchanged except that all iodine was assumed to be in elemental form.

#### Results

In the figures below, *LBL* indicates the original Large Break LOCA source term, whereas *LBL\** indicates the Large Break LOCA source term with all iodine assumed to be in elemental form.

Because the doses estimated in the ADMS runs were so different from the doses estimated in the NAME-in-PACE (referred to as NAME or NiP for the remainder of the section) and ADEPT-in-PACE (referred to as ADEPT or AiP for the remainder of the section) runs, they have been plotted separately.

The values 0, 1 and 8 on the x-axis indicate the precipitation rate (mm h-1) assumed in the corresponding runs. Pasquill Stability Category D conditions were assumed in the ADEPT and ADMS runs.

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – NAME and ADEPT

Figure : Maximum infant lifetime effective dose at 0.5 km assuming no food restrictions – ADMS

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – NAME and ADEPT

Figure : Maximum infant lifetime effective dose at 5 km assuming no food restrictions – ADMS

#### Discussion

The figures above present the results for the specific case of the infant lifetime effective dose arising from the LBL source term at the Seathwaite location. They show that assuming all of the iodine is in elemental form led to an increase in estimated dose. In general, the figures indicate that the effect on dose decreased with increasing distance from the release (i.e. the two sets of doses became more similar at greater distances).

In the case of the NAME runs, the mean maximum infant effective lifetime dose at 0.5 km was higher by a factor of approximately 2.3 if all iodine was assumed to be in elemental form. At 5 km, the difference had decreased to a factor of approximately 1.8.

NAME runs include a range of precipitation rates, and so cannot be used to infer a direct relationship between precipitation rate and dose. However, the ADEPT and ADMS runs indicated that the effect on dose appeared to decrease as rainfall increased (i.e. the “iodine all elemental” dose and “iodine not all elemental” dose became more similar at higher precipitation rates). This is logical when applying ADMS as it is only the dry deposition velocity which is assumed to be a function of the iodine chemical form; the wet deposition washout coefficients are not assumed to be a function of chemical form (in this study at least). Therefore, as the precipitation rate increases, wet deposition becomes the more dominant deposition process, and the distinction between the “iodine all elemental” dose and “iodine not all elemental” dose estimates becomes increasingly small.

When applying ADEPT, both the dry and wet deposition are a function of the iodine chemical form, such that for dry deposition and at rainfall rates less than 1 mm h-1, the total deposition concentration for iodine in elemental vapour form would be expected to be greater, and for rainfall rates greater than 1 mm h-1, the wet deposition concentration for iodine in particulate (and organic) form would be expected to be greater (and the total deposition concentration may be greater).

In general, it seems clear that assuming iodine is all in elemental form would increase the conservatism of the modelling for DBA assessments, at least in the case of infant lifetime effective dose for a long-duration source term. However, assuming iodine remains in elemental form for such a long period seems unrealistic. In practice, the judgement might need to be made on a case-by-case basis, and would depend on the specific details of the source term, including the release duration.

It should be noted that when modelling the dose from iodine, assumptions about milk consumption are important and, in particular, the proportion of milk produced locally. The modelling in the present study assumed a value of 1.0 (which means 100% of the milk that was consumed locally had been produced locally). It was found that the dose received as a result of ingestion of milk and milk products tended to dominate the overall lifetime dose. In the most extreme cases, it was found to contribute more than 90% of the total lifetime dose, though the proportion varied significantly according to the source term and the percentile of total dose considered. The 7-day and 30-day doses did not include ingestion, so they were unaffected by any assumptions about milk consumption.

### Summary

The question originally posed was whether the current default modelling approaches used by licensees are appropriate for DBA use. The results presented above demonstrate that there is not one simple answer to that question. Certainly, the approaches currently used are not always the most conservative ones possible, but that does not necessarily mean they are not appropriate.

Section 5.2 demonstrated that in the case of Gaussian Plume models, assuming Pasquill Stability Category F and dry conditions is a conservative approach; however, it may not always be the most conservative. In some circumstances, Pasquill Stability Category D with precipitation was found to be a more conservative assumption than Category F dry conditions. Thus it may be appropriate to consider both of those sets of assumptions collectively to obtain a sufficient degree of conservatism. The degree of conservatism increases as the modelled precipitation rate increases; however, that needs to be balanced against the fact that arbitrarily increasing the precipitation rate means that the assumptions become less representative of reality. Section 5.3.1 shows that even the two sets of meteorological conditions just discussed may not always represent the most conservative assumptions. Attempting to predict an appropriate simplified set of conditions will always carry some risk of overlooking conditions that happen to be more conservative in the specific scenario being considered. Thus, whether or not the current default modelling approaches used by licensees are appropriate for DBA use depends on the required degree of conservatism of the meteorological conditions assumed. Application of a probabilistic rather than a deterministic approach may help to address this issue, by considering a much larger spread of meteorological conditions.

Furthermore, Section 5.3.1 indicates, as a result of comparisons between ADMS and NAME, that the degree of conservatism as a result of the application of ADMS varies significantly, depending on the scenario concerned. Again, whether or not the current default Gaussian Plume modelling approaches used by licensees are appropriate for DBA use, depends on a number of factors, including whether it is necessary for consistency in the level of conservatism applied.

Section 5.3.2 highlights that the current application of Gaussian Plume models in DBA assessments, most notably alongside the assumption of constant meteorological conditions for scenarios of relatively long duration releases, may (or may not) be fit for purpose, depending on the need for assessments to be representative of realistic (meteorological) conditions and depending on the level of conservatism required. Likewise, Section 5.3.4 highlights that assuming all iodine in a source term is released in elemental vapour form may also not be fit for purpose, depending on the need for assessments to be representative of realistic (source term) conditions and depending on the level of conservatism required. The model itself, as well as the way the model is applied, may also not be appropriate for use in assessments; specifically, the deposited gamma dose approach implemented within the ADMS model has some limitations that should be considered before use (Section 5.3.3).

# Conclusions

The findings of the first part of the study indicated that there is a significant likelihood that a radiological release in the UK would encounter some precipitation. The specific probability would strongly depend on the location and duration of the release. For the scenarios considered in the present study, the probability was found to vary from between 15% and 40% for a one-hour release to effectively 100% for a thirty-day release.

In the second part of the study it was found that when considering precipitation at different rates, in a DBA assessment, there is no cliff-edge effect in the estimates of dose (although it is appreciated that the term “cliff-edge effect” is somewhat subjective). It was also found that excluding precipitation from DBA assessments means that some of the more conservative modelling scenarios are not taken into account. Whether that is acceptable depends on the degree of conservatism required for DBA. If “95th percentile weather” is considered to provide sufficient conservatism, then the present investigation indicates that Pasquill Stability Category F with no precipitation will typically be a sufficiently conservative assumption. However, the percentile associated with that assumption will vary according to the scenarios and source term, and may also differ for different models and modelling implementations. This means it is not possible to conclusively say that Category F dry conditions will represent 95th percentile weather in every case. It is also important to note that assuming constant meteorological conditions for the whole duration of an extended release is very unrealistic. The current default atmospheric dispersion modelling approaches used by licensees could in principle lead to an insufficiently conservative estimate of doses, but it depends on the degree of conservatism required in the analysis and how representative of reality it needs to be.

Appendix A describes the validation performed in support of the wet deposition modelling approaches considered in this study. It was evident that there is a significant lack of such validation studies. From the literature identified, it was evident that NAME is the standout model (of those considered in this study) in respect of best representing the atmospheric and deposition processes. The meteorological data available alongside the NAME model further strengthens its capability, especially bearing in mind the tendency for precipitation to be highly spatially and temporally variable. Future work on this topic should seek to perform wet deposition model validation studies.

When producing guidance for operators performing DBA assessments, the following two aspects must be carefully considered: (1) the degree to which the modelling should be representative of reality; and (2) how much conservatism is required within the modelling.

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###### Validation of wet deposition approaches

Wet deposition modelling approaches

The fundamental approach of deriving a washout coefficient applied within wet deposition modelling across the three models (ADEPT, ADMS and NAME) considered in this study is essentially the same:

|  |  |  |
| --- | --- | --- |
|  | Λ = A PB | (Equation A1) |

where Λ is the washout coefficient (s-1), P is the precipitation rate (mm h-1), and A and B are constants.

All three models account for plume depletion as a result of wet deposition processes, however the details of such approaches do differ. The application of the washout coefficient in the estimation of the amount of activity removed from the plume varies from model to model, as do the values of the constants A and B (used to determine the washout coefficient).

ADEPT employs the simplest approach based upon equation 17 in Jones (1981). This approach considers the activity concentration in air at ground level, rather than considering the vertical column of the atmosphere through which the precipitation will fall. This assumption is likely to be most uncertain relatively close to the release location where the activity concentrations in air over the vertical column are most variable. For elevated releases, estimates are expected to be even more uncertain. Within this study, where a 10-metre release height was assumed, wet deposition estimates derived on the basis of ADEPT are likely to be conservative and an overestimate.

ADMS (v4.2) estimates wet deposition (per unit horizontal area per unit time) by integrating the product of the washout coefficient (not a function of vertical height (z)) and the “local” airborne activity concentration in air (a function of z) through the (entire) vertical column of air. ADMS considers precipitation in the form of rain only. The rainfall rate is assumed to be constant and uniform. All plume material is assumed to lie in or below the (rain) cloud. No distinction is made between in-cloud scavenging (rainout) and below-cloud scavenging (washout). Irreversible uptake is assumed i.e. uptake in rain does not lead to a redistribution of material in the plume.

NAME includes two approaches to modelling wet deposition; a bulk wet scavenging parameterization, which was applied in this study, and also a particle dependent wet deposition scheme, which accounts for the particle size and solubility, and was applied with notable success when modelling the large scale wet deposition of radioactivity following the accidental release at the Fukushima Nuclear Power Plant (Dacre et al, 2020). The bulk wet scavenging approach accounts for the removal of material by wet deposition processes as a function of time as well as space (based on the depletion equation) and specifically considers the depletion of radioactivity on a model particle by way of:

|  |  |  |
| --- | --- | --- |
|  | Δm = m[1 – exp(-ΛΔt)] | (Equation A2) |

where m is the mass of the particle at the start of the timestep, and Δm is the change in mass over the timestep Δt. Whilst equation A1 is applied in NAME, because NAME has the capability to consider different forms of precipitation (e.g. dynamic (or large scale, typically frontal) precipitation and convective (typically smaller scale and showery) precipitation), this equation may take a more complex form depending on the availability of the meteorological data applied within the model. NAME also has the ability to differentiate between rain and snow, and in-cloud and below-cloud scavenging. The rainfall rate applied is variable as a function of time and space, but the extent to which this is the case depends on the NWP met data being applied. Irreversible uptake is assumed.

The washout coefficient constant parameters detailed in Table A1 are the default values recommended by each of the models. On the basis that the default values are the most likely values to be used by operators in a DBA assessment, these values were applied in this study. ADEPT allows the user to modify the constant A and B values but not for each individual radionuclide. Likewise, ADMS and NAME allow the user to modify the constant A and B values, but these models also give the model user the option to select different constant A and B values for each individual radionuclide. A larger Constant A value will increase the respective washout coefficient and thus increase the amount of wet deposition occurring. For a rainfall rate of less than 1 mm h-1, a larger Constant B value will decrease the respective washout coefficient and thus decrease the amount of wet deposition occurring. For a rainfall rate greater than 1 mm h‑1, a larger Constant B value will increase the respective washout coefficient and thus increase the amount of wet deposition occurring.

Table A1: Default Model Washout Coefficient Constant Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Description | Constant A | Constant B |
| ADEPT | All radionuclides except elemental iodine | 8 10-5 | 8 10-1 |
| ADEPT | Elemental iodine only | 8 10-5 | 6 10-1 |
| ADMS | - | 1 10-4 | 6.4 10-1 |
| NAME | Rain - BC | 8.4 10-5 | 7.9 10-1 |
| NAME | Snow - BC | 8.0 10-5 | 3.05 10-1 |
| NAME | Rain - IC | 3.36 10-4 | 7.9 10-1 |
| NAME | Snow - IC | 5.2 10-5 | 7.9 10-1 |
| These assumptions were applied to all radionuclides except noble gases. Noble gases do not wet deposit, and therefore all washout coefficients were assumed to be 0. | | | |

Validation

No validation studies were identified for the specific implementation of modelling wet deposition in ADEPT. Nor were any appropriate studies identified validating the wet deposition approach implemented in ADMS. Only for the NAME model was any validation of the wet deposition method applied in evidence, and this was still relatively limited.

NAME was one of five atmospheric dispersion models taking part in a study that used data published by the World Meteorological Organization. Atmospheric dispersion model estimates of activity concentration in air and on the ground were compared to field measurements taken following the accident at the Fukushima Daiichi nuclear power plant (Draxler et al, 2015). Measurements of deposited activity concentrations of 137Cs (comprehensive in number and geographical coverage) were considered. NAME ranked midway but outperformed all models in terms of the statistical metric, fractional bias. It was also found that the meteorological analyses (i.e. the way meteorological fields are processed and the way atmospheric processes are parameterized within the atmospheric dispersion models) were generally better resolved in NAME, thus resulting in smaller over- and under-predictions compared to other models. Leadbetter et al (2015) expanded upon this work, noting that NAME model predictions of 137Cs deposits showed mixed agreement with observations across eastern Japan, with correlation coefficients ranging from 0.44 to 0.80 (with a perfect linear relationship represented by the value 1).

Hort (2004) conducted NAME runs to investigate the behaviour of the deposition routines. Mesoscale meteorological data were used with a single six-hour point release of sulphur dioxide over the South East of England, and a tracer release, in the same location. It was concluded from these limited runs that the NAME deposition schemes are working at least as well as previous versions of the model.

Whilst there is little or no validation of the methods implemented, there does exist significant scientific justification for the implementation of the methods applied. None more so than for the wet deposition approach applied in NAME. Webster and Thomson (2014) document the wet deposition scheme in great detail, highlighting the origins of the scheme, elements that have evolved over time, and the justification for the evolution. Webster and Thomson (2014) also acknowledge elements of the scheme which are less scientifically robust and compare some of the parameterizations with other modelling approaches. There is very little information on the ‘in-cloud scavenging by rain’ parametrization originally used in NAME and consequently the origin of this scheme is not fully understood. However, all other aspects of the approach are supported by scientifically rigorous studies. Elevated deposition resulting from orographic enhancement cannot currently be accounted for in the model. Increases in NWP model resolution is changing the division between model resolved and model parametrized precipitation, with the recent UKV configuration of the Met Office’s Unified Model in the extreme situation of having all resolved, and no parametrized, precipitation; whilst this is proving challenging from a wet deposition modelling perspective, ultimately this will help to improve the modelling of wet deposition.

The bulk wet scavenging parameterization (applied in NAME in this study), assumes that the scavenging is equally efficient for aerosols of different sizes. Such schemes have been shown, however, to overestimate the scavenging of aerosols during heavy rain or long-duration medium rain conditions (Feng, 2007). The particle dependent wet deposition scheme implemented in NAME makes significant strides to address this problem.

Validation of the wet deposition approach implemented in each model is only one of a number of factors which determine whether or not the model can suitably represent the wet deposition process. The ability of the model to consider suitably representative meteorological data is also paramount. The NAME model is able to utilise NWP met data derived from the Met Office’s Unified Model, which is recognised as a world leading weather (and climate) model. Jones (1986) recognises the significant modelling difficulties caused by the spatial and temporal variability of rainfall rate; ADEPT and ADMS will tend to be notably more limited in terms of the (hourly single site) meteorological data which the models can consider. Furthermore, the ability of the models to suitably describe the atmospheric dispersion process is also fundamental to determining the level of confidence which can be achieved in the wet deposition estimates derived further down the modelling chain. There exists significant validation across all three models (ADEPT, ADMS and NAME) in respect of the atmospheric dispersion process. Many of the key validation studies which include ADEPT (or applications of the R91 model) and NAME are summarised by Bedwell et al (2011) and Smith et al (to be published). Bedwell et al (2011) also indicates that ADEPT is likely to overpredict activity concentrations in air relative to NAME by a factor of 2-3 under Pasquill Stability Category D conditions and by a factor of 6 or more under Pasquill Stability Category F conditions (where the NAME model was run in a simplified mode to enable a fair comparison).

The ADMS dispersion models are continually validated against available measured pollutant concentration data obtained from real world situations, field campaigns and wind tunnel experiments. Validation has been performed using many experimental datasets that test different aspects of the model (ground/high level sources, passive and buoyant releases, buildings, complex terrain and plume visibility). These studies are both short-term as well as annual and involve tracer gases or specific pollutants of interest. A large amount of documentation detailing the validation of the primary ADMS model can be found on the CERC web site (currently: <http://www.cerc.co.uk/environmental-software/model-validation.html>). However, this only applies to developments relating to the latest version of the model (ADMS 5.0) and therefore is predominantly applicable to complex terrain and building modules. Model validation documentation pertaining to aspects of the model which have not been developed recently, such as deposition, are not detailed on the website, however CERC hope to set up an archive page in the future for such purposes. All of the validation of ADMS detailed below relates to derivations of air concentrations.

One of the earliest major ADMS validation studies was performed for continuous releases over flat terrain (Carruthers et al, 1993). For the majority of the comparisons there existed good agreement between estimates derived by ADMS and measurements, and ADMS outperformed R91. However, ADMS struggled to describe a low-level source in stable conditions.

CERC (2013) present a summary of ADMS model results compared against three well known field datasets: Kincaid, Indianapolis and Prairie Grass (Carruthers et al, 1998; Carruthers et al, 1995; Carruthers et al, 1994). ADMS performed well when comparing estimated mean values with observations for the Kincaid and Indianapolis datasets but significantly underestimated the mean concentration, predicting approximately 70% of the observed mean, for the Prairie Grass dataset. The proportion of values within a factor of 2 of the mean (FA2) was considerable across all three datasets (ranging from 0.5 – 0.7). However, the correlation (represented by R2) was weaker for the Indianapolis dataset (~0.3), although this is somewhat expected given the more challenging nature of modelling in an industrial environment.

Carruthers et al (1996) noted that there were significant differences in rates of dispersion between ADMS and R91 in the neutral to unstable flows represented by most of the field data considered. The ADMS model generally gave significantly higher plume spread rates than the R91 model. Also, the ADMS model tended to overestimate plume spread rates from the datasets and the R91 model tended to underestimate them. Overall the ADMS model was the better fit to the datasets.

UKHSA compared wet deposition concentrations derived by ADEPT and NAME (where the NAME model was run in a simplified mode to enable a fair comparison) for a range of precipitation rates (0.5, 1, 2, 4 and 10 mm h-1). The estimates of wet deposition derived using ADEPT were as much as a factor of two greater than the analogous estimates using NAME. However, the findings were different when the results were normalised by the respective time integrated activity concentration in air. In that case, it was the NAME estimates that were higher, albeit by less than a factor of two.

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###### Symbiose

The *Symbiose* model was developed by IRSN and jointly funded by EDF Energy. It is relevant to the present study because the model might plausibly be used as part of future DBA assessments. UKHSA does not have access to the Symbiose model itself, so no Symbiose runs were carried out during the present study. However, Symbiose model documentation was obtained, which gave an indication of the form of the model and the parameterisations and assumptions made within the model. This information was used to explain how the model might behave relative to the other models considered.

Symbiose models the transfer of radioactive contamination emitted by one or more emission sources, as well as deposition onto continental or marine surfaces. The model is split into various modules, which enables the user to choose between different modelling approaches. Many of the input parameters can be defined directly by the user if necessary.

Plume modelling

The most relevant atmospheric dispersion module for the present study uses a Gaussian approach in which the user can specify the type of parameterisation to be adopted for the calculation of the standard deviations of diffusion. More specifically, the user can choose to use standard deviations of diffusion tabulated according to Briggs, Doury or Pasquill stability classes.

The modelled processes are: thermokinetic elevation of the plume, advection, turbulent dispersion, radioactive decay chains and depletion of the plume by atmospheric deposition.

The Gaussian plume is modelled by breaking it down into a succession of "slices" advected at the relevant speed, up to a maximum distance beyond which it is no longer modelled. Concentration is integrated along a section perpendicular to the axis of the plume. Horizontal and vertical turbulent diffusion are also taken into account.

Wind speed is assumed to be homogeneous and over flat terrain. The increased horizontal dispersion caused by oscillations (“meandering”) in low-wind situations is also modelled. This is done via an empirical approach which consists in increasing the standard deviation of horizontal dispersion by multiplying it by a corrective factor greater than 1. The value of this factor depends on the characteristics of the temporal variability of the oscillations as well as on the duration of the release. In practice, its value is imposed by the user.

Plume elevation caused by the vertical ejection speed is calculated using the Briggs formulas. This can take into account high-temperature releases (e.g. in the event of fire). The user can specify whether the plume confinement is maintained below the boundary layer or not.

Aerosols are assumed to follow the same laws of atmospheric dispersion as gases.

Dry deposition is modelled using a dry deposition flux (which can be simply obtained from the dry deposition velocity if it is assumed that dry deposition velocity does not vary with geographical position). For noble gases and the various physicochemical (non-particulate) forms of carbon, tritium and iodine, the values for the dry deposition velocity are the same as the ones that were assigned in the *pX* and *ldX* models in 2010 (*cf*. Tombette, 2010). For all aerosol isotopes, the value used is the one that was adopted by default in Tombette (2010), specifically: 5 x 10-3 m s-1. Tombette (2010) also explains that, in general, the dry deposition rates used in the IRSN atmospheric dispersion codes are in the upper range of the rates used by other models such as RODOS, RIMPUFF and NAME or rates that have been measured. That statement is made in the context of *pX* and *ldX*, but would presumably also apply to Symbiose if the default values are used.

Wet deposition is assumed to be proportional to a washout coefficient rate, which is the washout rate of atmospheric pollutants and depends on the pollutant. The user can specify the type of parameterisation to be adopted. A constant value can be chosen for the washout coefficient rate or a value proportional to the intensity of the rain can be applied. In the second case, the washout coefficient rate is the product of the intensity of rainfall and the rainfall capture coefficient, *Λ0* (which is assumed to be independent of space and time and depends on the pollutant). The values attributed to the rainfall capture coefficient are those attributed in the models *pX* and *ldX* in 2010 (*cf*. Tombette, 2010). The values assigned to the washout coefficient are derived by assuming a rainfall intensity of 5 mm h-1.

It is unclear whether Symbiose uses exactly the same formula for wet deposition as the one quoted in the context of *pX* and *ldX* in Tombette (2010), but it is suspected that this formula is applied. The formula quoted in Tombete (2010) is *Λ = Λ0* *PB*, where *Λ* is the washout coefficient, *P* is the rainfall intensity in mm h-1, and *Λ0* and *B* are both constants. Tombette (2010) states that the value used for *B* in *pX* and *ldX* is 1, and notes that that is larger than the values that tend to be used in other references, and that the value of 0.8 occurs in many references. On the other hand, Tombette (2010) notes that the value of 1 x 10-4 seems to be the consensus for *Λ0*.

In the case of the Pasquill and Briggs formulations, a roughness factor, which corrects the vertical standard deviations of the plume, is used to represent the effect of the roughness of the terrain. The default value of the roughness parameter is 0.03 m, but other values can be chosen, as appropriate for the relevant terrain.

Sites with complex orography

As an alternative to the primary atmospheric dispersion module, the user may in certain circumstances be able to use a module designed to carry out modelling on sites with complex orography such as Flamanville, Penly, Paluel and Chooz. It relies on the results of wind-tunnel tests carried out on models of those sites. The user must enter the wind-tunnel data for each of the relevant sites and for each source considered. The four sites mentioned above seem to be the only ones listed in the Symbiose documentation in relation to the wind-tunnel data. It is likely that no such wind-tunnel data is available for UK sites, and therefore the module is effectively not available for use in the UK.

The module has certain limitations. The wind-tunnel measurements were not carried out below a hundred metres, nor beyond 2-3 km. The model is not applicable for a source term varying at timescales less than an hour. Decay chains were not taken into account in the dispersion calculations.

Alternative dispersion approaches

Symbiose gives users the option of not using Symbiose’s own dispersion modelling. The model has the facility to specify, read, process, and transmit to the other simulator modules, the spatio-temporal results produced by an external atmospheric dispersion code or specified by the user. Atmospheric deposition, air activities and plume dose rates can be specified directly, bypassing atmospheric dispersion or deposition calculations.

Calculation of stability classes

In the absence of met data, a meteorological pre-processing module can be used to calculate the Pasquill stability classes, the wind speed at 10 m and the vertical temperature gradient, if applicable. The Pasquill classes are calculated from measurements carried out on site. This module is upstream of the primary atmospheric dispersion and complex orography dispersion modules.

Behaviour of the model relative to other models considered

It was evident that the model is most similar to ADEPT. However, if the Symbiose model was run for the same scenarios as considered in this study, the model results may be more akin to ADMS (given that the majority of the ADEPT model results presented here include the option of “Full Duration Sigma” – see Section 5.3.2 for details).

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About the UK Health Security Agency

The [UK Health Security Agency](https://www.gov.uk/government/organisations/uk-health-security-agency) is an executive agency, sponsored by the [Department of Health and Social Care](https://www.gov.uk/government/organisations/department-of-health-and-social-care).

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1. https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps [↑](#footnote-ref-2)
2. Pasquill Stability Category C was outside the scope of the present investigation. However, it is notable that PSC C was found to be much less common than PSC E. Particularly notable was that all six sites had more non-zero-precipitation PSC E hours than non-zero-precipitation PSC C hours. Indeed, for four of the six sites, the *proportion* of PSC E hours that were wet was higher than the proportion of PSC C hours that were wet. That is significant because it is sometimes assumed that precipitation occurs only in PSC C and PSC D conditions. [↑](#footnote-ref-3)
3. These results do not take into account the possible contribution of the three radionuclides that are not available in PACE; however, it is not expected that those radionuclides would significantly affect the results. [↑](#footnote-ref-4)
4. *Maximum* in this context refers to the highest value for the relevant endpoint in each individual met sequence, regardless of grid square. Hence, if the NAME-in-PACE runs were iterated over 152 met sequences, then the endpoint would have 152 “maximum” values. The *Mean Maximum* value would then be the mean of those 152 “maximum” values. Similarly, the *95th percentile Maximum* value would be the 95th percentile of those 152 “maximum” values, and the *Maximum Maximum value would be the largest of those 152 “maximum” values*. For further explanation, please refer to Section 4.3.2.3. [↑](#footnote-ref-5)
5. *Maximum* in this context refers to the highest value for the relevant endpoint in each individual met sequence, regardless of grid square. Hence, if the NAME-in-PACE runs were iterated over 152 met sequences, then the endpoint would have 152 “maximum” values. The *Mean Maximum* value would then be the mean of those 152 “maximum” values. Similarly, the *95th percentile Maximum* value would be the 95th percentile of those 152 “maximum” values, and the *Maximum Maximum value would be the largest of those 152 “maximum” values*. For further explanation, please refer to Section 4.3.2.3. [↑](#footnote-ref-6)