CRANFIELD UNIVERSITY

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ESTIMATING AND VISUALISING IMPRECISION IN RADIOLOGICAL EMERGENCY RESPONSE ASSESSMENTS

Defence College of Management & Technology

PhD THESIS

August 2010

CRANFIELD UNIVERSITY

Defence College of Management & Technology

Dept of Applied Science, Security and Resilience

PhD THESIS

Academic Year 2009 - 2010

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Supervised by Prof K D Rogers and Dr M J F Healy

August 2010

ABSTRACT

After an accidental release of radioactivity to atmosphere, modelling assessments are needed to predict what the contamination levels are likely to be and what measures need to be taken to protect human health. These predictions will be imprecise due to lack of knowledge about the nature of the release and the weather, and also due to measurement inaccuracy.

This thesis describes work to investigate this imprecision and to find better ways of including it in assessments and representing it in results. It starts by reviewing exposure pathways and the basic dose calculations in an emergency response assessment. The possible variability of key parameters in emergency dose calculations is considered, and ranges are developed for each. The imprecision typically associated with calculational endpoints is explored through a sensitivity study. This has been done using both a simple Gaussian atmospheric dispersion model and also real-time weather data in combination with a complex atmospheric dispersion model. The key parameters influencing assessment imprecision are identified. These are demonstrated to be factors relating to the release, arising from inevitable lack of knowledge in the early stages of an accident, and factors relating to meteorology and dispersion.

An alternative improved approach to emergency response assessments is then outlined, which retains a simple and transparent assessment capability but which also indicates the imprecision associated with the results through incomplete knowledge. This tool uses input from real-time atmospheric dispersion and weather prediction tools. A prototype version of the tool has been created and this has been used to produce example results. The final stage of the thesis describes the use of the new tool to develop ways in which imprecise or uncertain information can be presented to decision makers. Alternative presentational techniques are demonstrated using example results.

"*Judgement which is needed to make important decisions on imperfect knowledge in a limited time*"

Definition of the art of politics, attributed to Clement Attlee, British Prime Minister 1945-51

ACKNOWLEDGEMENTS

I would like to gratefully thank my supervisors at Cranfield University, Prof Keith Rogers and Dr Matt Healy, for letting me undertake this research project and for providing me with invaluable help, support and advice throughout. I particularly appreciate their painstaking assistance and guidance in a field that is not their normal line of work (and I hope they found it of some interest!). This thesis would not have been written without their help.

I greatly appreciate the financial support for this study provided by my employer, the Health Protection Agency (and previously the National Radiological Protection Board). I would particularly like to thank Jane Simmonds and Mary Morrey of HPA, who have provided much valuable advice throughout the study, in particular on the three journal papers which have been produced through the research. And I would also like to thank the members of my group at HPA, who have provided comments on my ideas as they have developed, particularly on the visualisation of imprecision. My especial thanks go to Pete Bedwell of HPA and Matt Hort of the UK Met Office for their generous assistance with runs of the NAME model, for their co-authorship of the second journal paper, and for their work to identify and understand the differences between the 'R91' and the NAME models.

I would like to thank my Mum and my late Dad, for encouraging and supporting me, in particular throughout school and university. Last but by no means least I would like to thank my husband Steve and my daughter Eleanor for subsisting on dinners of oven chips for longer than is really healthy, for sharing me with a laptop that received far more attention than they did, and for squeezing into a car loaded with papers and reports whenever we travelled. Now you can look forward to getting me back ('Be afraid….').

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GLOSSARY

Activity: The rate at which activity decays within an amount of a radionuclide. Unit is the Becquerel (Bq).

AMAD: Activity Median Aerodynamic Diameter, the median of the distribution of activity against the aerodynamic diameter (which is the diameter of a unit density sphere with the same settling velocity as the particle).

Averted dose: The dose avoided by the application of a countermeasure or set of countermeasures.

Becquerel (Bq): The name of the SI unit of activity, 1 Bq = 1 disintegration per second.

COBR or COBRA: Cabinet Office Briefing Room (Alpha), the crisis response committee of UK government which co-ordinates response to national crisis.

Dose equivalent: The quantity obtained when the absorbed dose is multiplied by a factor to represent the effectiveness of the absorbed dose in causing harm to tissues or organs. Unit is the sievert (Sv).

Dose Per Unit Inhaled or Ingested intake (**DPUI)**: The dose (eg effective dose) received per unit of inhaled or ingested intake (unit is typically Sv Bq^{-1}). Also referred to as dose coefficient.

Deterministic effect: Radiation induced injury characterised by a threshold dose and increase in severity of effect with increasing dose.

Effective dose: The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body. Unit is sievert (Sv). 1 Sv = 1 J kg^{-1}.

Element: A substance with atoms all of the same atomic number.

Ensemble forecasting: Enables the uncertainty in meteorological forecasts to be estimated, through the repeated running of forecast models, many times, with just slight variations in starting conditions.

ERL: Emergency Reference Level. In the UK, the term applied to the levels used in the emergency radiation protection system, comprising an upper and a lower level of dose for each emergency countermeasure.

Equivalent dose: The sum of the dose equivalents in a particular tissue or organ, taking into account all the different types of radiation affecting the specified tissue or organ of the body. Unit is sievert (Sv). 1 Sv = 1 J kg^{-1}.

NAME: Numerical Atmospheric Dispersion Modelling Environment, the Lagrangian atmospheric dispersion model of the UK Met Office.

NWP: The UK Met Office's Numerical Weather Prediction model, the 'Unified Model', which provides 3-D global weather data.

Radionuclide: An unstable isotope of an element that emits ionising radiation.

Residual dose: The dose incurred after countermeasures have been implemented.

Risk: The probability of harm. In radiological protection this is mostly in the context of the potential harm to a human being.

RIMNET: The UK's national radiation monitoring network and emergency response system.

Sievert (Sv): The SI unit of dose, used in dose equivalent, equivalent dose and effective dose. 1 mSv= 1/1000 Sv.

Source, or source term: The release of radioactive material from a nuclear installation or facility, usually in the context of an accidental release. Usually comprises a mix of radionuclides, expressed in Becquerels (Bq) of each.

σ_y: Dispersion parameter representing horizontal (cross-wind) mixing.

σ_z: Dispersion parameter representing vertical mixing.

v_g: Deposition velocity, in m s^{-1}, ratio of the deposit to the concentration in air above the surface.

1 INTRODUCTION

The use of radioactive materials in installations or facilities which are part of the nuclear fuel cycle, for radiopharmaceutical manufacture or industrial radiography, leads to the potential for an accidental release of radioactivity to the environment. Accidents may also occur during the civil transport of radioactive materials, or in connection with nuclear weapons or nuclear powered submarines. In addition to accidental releases, there is also the possibility of deliberate releases from illicitly held radioactive source material. Radiation accidents and deliberate releases, occurring both in the UK and overseas, have the potential to affect the environment and the population of the UK. National and international accidents resulting in the atmospheric release of radioactivity include the accidents at Windscale in the UK (1957), Three Mile Island in the United States (1979) and Chernobyl in the then USSR (1986).

Radioactivity released to the environment has the potential to cause injury to people. Short term ‘early’ or ‘deterministic’ health effects may be caused, if the doses are sufficiently high and above the threshold levels for the effect. These usually occur when high doses are received over short time periods, and they can include both fatal and non-fatal effects. Such effects include central nervous system death, bone marrow syndrome, pneumonitis, prodromal vomiting, skin burns and cataracts. Exposures below the threshold levels for early effects, so-called ‘late’ or ‘stochastic’ effects, may cause an increased risk of longer term health effects such as fatal and non-fatal cancer and hereditary disease. It is therefore important to have a rapid, well-practised and comprehensive emergency response capability, so that exposures may be minimised.

In the event of an accidental release of radioactivity to atmosphere from a nuclear site, decisions on the necessity for and the extent of actions to protect human health will be made rapidly in the emergency phase, either shortly after the release has occurred or, with sufficient warning time, before the release. Possible early actions include evacuation, advice to shelter, the administration of stable iodine, and restrictions on the movement, sale and consumption of foodstuffs. Longer term actions include decontamination measures and relocation of the population. Some protective actions will be triggered on the basis of a decision to activate the emergency plan for the affected site, based on the results of automated measurements or on the condition of the plant. This typically covers an area up to several kilometres away from the site boundary. However, large releases of radioactivity may require decisions on the need for actions over larger areas.

To enable such decisions to be made appropriately, decision makers need the best available information from plant operators at the site, such as prognosis for the future state of the plant and how control may be regained. They also need information on the nature and scale of the release, so that response actions are appropriate to the circumstances. The results of environmental monitoring are important in building up a picture of the radiological situation, but in the early stages there may well be insufficient monitoring data to form an adequate basis for decisions. Monitoring data will therefore be supplemented by the predictions of emergency assessment systems, to assist in making decisions on protection measures and the direction of further radiation monitoring activities. Such systems require the input of technical data, such as weather conditions and environmental measurements, and will provide as output predictions of radionuclide concentrations in environmental materials, doses to exposed people, possible health impacts and information on where countermeasures to reduce doses may be required. Key information for countermeasure decisions includes estimates of projected dose across the affected area, and these in turn require estimates of activity concentrations in air and deposited activity on the ground.

1.1 Early emergency response

The alert to an unplanned radiological release will most likely be from the site operators in the first instance, possibly before any actual release to atmosphere has occurred. Alternatively, the first warning may come from radiation detectors, when levels of radioactivity in the vicinity have exceeded the trigger levels. Measurements may be made by automatic monitoring devices, monitoring teams in the field, aerial monitoring, and information from the UK radiological information system RIMNET (see Section 2). Each measurement will be associated with a particular time and place, possibly linked to monitoring locations defined in the site's emergency plan. The first measurements, for an accident taking place at a nuclear site, are likely to be activity concentrations in air (eg Bq m^{-3}) or gamma dose rates (eg mSv s^{-1}), followed by levels of deposition on the ground (eg Bq m^{-2}).

The most significant exposure pathways in the short term are likely to be external exposure from the plume, external exposure from material deposited on the ground and inhalation of material in the plume. A major concern, while the release is continuing, is the potential scale of the inhalation doses. To protect people from these exposures it is necessary to take countermeasure decisions quickly, and to implement them quickly, preferably before the radioactive plume has arrived at the location.

As the time after the start of the release increases, more measurements of the same types as the very early measurements will be reported. These may, for example, be a range of activity concentrations in air at different places and different times. Sequential measurements from the same or very similar locations but taken at different times could indicate a change in the rate of release of radioactivity from the site, while measurements taken at similar times but at different points indicate the plume dispersal pattern. Variations in measurements also arise from fluctuations in wind and other weather conditions. Responders and decision makers need information on the current and predicted pattern of contamination (including deposition, levels of activity in air and dose rates) so that response teams can be deployed effectively.

Information on what radionuclides are present in the release is likely to be lacking in the first few hours. In the absence of a radionuclide spectrum, an estimate of the likely radionuclides released can be made based on the type of site involved in the accident. For example, an accident at a nuclear power station is likely to release radioiodine and mixed fission products such as caesium and ruthenium isotopes, and a conservative assumption in the early stages of an accident would be that the release is entirely ^{131}I, or a mix of ^{131}I and ^{137}Cs. At some point, information on the proportions of radionuclides present in the release will be obtained from gamma spectroscopy. This will relate to a total activity measurement (usually an activity concentration in air) at a particular time and place.

Eventually the release will stop and the radiological picture will become more static, apart from the effects of radioactive decay and the relatively minor effects of wind-driven or mechanical spread of contamination. From this point, a comprehensive database of radiological measurements can be built up to fully characterise the contamination.

1.2 Overview of emergency assessment systems

The focus of this section is on emergency response decision support systems. Systems are also used to support emergency planning, but the requirements for an assessment system which calculates potential dose and risk, as used in emergency planning, are somewhat different from those in a response system and are not included here.

A response system will take the information that is currently available, which may be an estimated release rate or quantity, or may be location and time specific monitoring data, and will combine this with information on the weather in the affected area to build up a picture of the radiological situation. Broadly, a response system will address several of the following:

- predicting the dispersion, deposition and environmental transfer of radioactivity released to the environment,
- estimating the radiological consequences of this dispersion, deposition and transfer, usually in terms of predicted doses and health risks to humans,

- determining what countermeasures are required, where and when,
- determining the priority locations for monitoring,
- interpreting limited measurement data collected,
- planning environmental clean-up and other longer term measures.

As the incident develops, a system will be regularly re-run to incorporate changes in the known situation. A very early assessment may be initiated only on the anticipated scale of a release, before there has been any actual release to the environment. Clearly in this case there will be no measurement data available and such an assessment could only be undertaken on the basis of a postulated source term for the release. In the first few hours after a release, whatever information is available will be used to predict the likely extent of consequences, including the area over which countermeasures may be required and the area where monitoring results are required as a priority. A range of measurements may be used, of which the most immediately helpful will be activity concentrations in air. Gamma dose rates are the least useful measurements for dose assessment purposes. They will include contributions from both material in the air at the time the measurement was made and material deposited on the ground from the start of the release to the time of the measurement (unless the monitor used was shielded to avoid cloud or ground contributions). Because of this they cannot be used to infer either ground deposition levels - unless the release is know to have stopped and the plume passed - or activity concentrations in air.

Emergency response systems and tools are continually evolving and developing, and a summary of those available at any one time can only be a ‘snap-shot’ of the current position. Many of the tools which currently exist were developed from earlier ones, with the Chernobyl accident being a particular stimulus to development. Early initiatives included, for example:

- the development of some key components of a real-time computerised support system, sponsored under a post-Chernobyl EC initiative, including models for atmospheric transport from local to long-range distances, model/measurement optimisations, and exposure pathway dose assessment (Sinnaeve (ed) 1991a).

- the RADE-AID system, designed to support the formulation of decisions on countermeasures, as an aid after an accident and also for planning and training (Sinnaeve (ed) 1991b).

More recent systems have built considerably on the basis of these earlier tools. Internationally there now exist several large and very complex systems designed for emergency response and preparedness purposes. The principal systems are ARGOS, HPAC/UDM, RODOS and NARAC, and outline details of these are given below.

Although there is a large quantity of literature published on these systems, notably on the RODOS system, it is difficult to comprehensively review the merits and drawbacks of each because of their complexity. They require extensive computing resources and training to run. Although these systems have, in most cases, been under development for a considerable number of years, the complexity of what is being attempted appears to have resulted in products which are in some ways less mature and independently tested than, for example, the probabilistic risk assessment (PRA) tools which preceded them. These latter tools were subject to major international intercomparison exercises, which enabled the user to place a considerable degree of confidence in the participating codes, but the equivalent process has not been undertaken for the large emergency response systems. The developers of the four major systems (RODOS, ARGOS, HPAC, NARAC) have been consulted and have responded that no specific project has either been undertaken or is planned to compare the system results.

ARGOS (Prolog Development Center 2006) is developed and administered by the Danish Emergency Management Agency. ARGOS is an emergency management information system used by a number of countries, including Canada, Ireland and the Nordic Countries. ARGOS performs short range atmospheric dispersion, food chain and dose modelling and is also designed to download the results of long range atmospheric dispersion models. ARGOS has a map-based interface on which results are displayed.

HPAC (DTRA 2006) is the US Defence Threat Reduction Agency system for predicting the consequences of releases from terrorist events, nuclear sites and nuclear weapons. HPAC models the release and subsequent transport of materials in the atmosphere, and the impact on civilian and military populations. It contains a weather interface, which can receive data from real-time weather forecasting systems; this supports the calculations undertaken in the system, including probabilistic assessments. HPAC has an extensive dispersion model, with some urban dispersion capability through the Urban Dispersion Model (UDM) (Hall 2001, Hall *et al* 2001) developed at the UK's Defence, Science and Technology Laboratory (DSTL).

RODOS, the Real-time On-line DecisiOn Support system for off-site emergency management in Europe, was developed by a number of European organisations with a combination of EC and national funding (Ehrhardt *et al* 1997; Ehrhardt and Weis 2000, FzK 2005). It is distributed via the Karlsruhe Institute of Technology (previously known as Forschungszentrum Karlsruhe, or FzK) in Germany on behalf of the EC. RODOS has been obtained by a number of countries, although it is not clear to what extent it would be used outside Germany in emergency response mode, rather than as a research tool. The aim of RODOS is to provide '*consistent and comprehensive information on the present and future radiological situation*' (www.rodos.fzk.de), in the event of a nuclear accident in Europe. The system is aimed at '*those responsible at local, regional, national and supra-national levels for off-site emergency management*'. However, the system also has applications in training and exercises. One of the acknowledged difficulties with RODOS has been its assumption that detailed measurement information and meteorology data will be readily available, and this requirement has limited the applicability of the tool outside Germany (where such data are more readily obtainable than in most other countries).

NARAC (National Atmospheric Release Advisory Center) is located at the University of California's Lawrence Livermore National Laboratory (LLNL), and is '*a national support and resource center for planning, real-time assessment, emergency response, and detailed studies of incidents involving a wide variety of hazards, including nuclear, radiological, chemical, biological, and natural emissions*' (Sugiyama 2004). The US Department of Energy (US DOE) maintains NARAC, at LLNL. The customer base for NARAC is primarily US government agencies (federal, state, and local). NARAC provides tools for atmospheric plume modelling and services for chemical, biological, radiological, and nuclear airborne hazards (both gases and particles), with real-time access to worldwide meteorological observations and forecasts. In some senses, NARAC is more a suite of tools than a single system, but it appears that a significant part of the tool-box can act in a co-ordinated way.

Less complex and/or purpose-specific tools have also been developed:

SEER (Spreadsheets for Early Emergency Response) was developed at HPA for internal use in the early stages of an accidental release of radionuclides to the atmosphere. SEER is a Microsoft Excel workbook containing a set of linked spreadsheets, each undertaking a particular radiological emergency assessment. SEER enables a range of calculations to be made, based on source term information or radiological monitoring data in the form of concentrations of radionuclides in the atmosphere or deposited on the ground. It assumes Gaussian-based atmospheric dispersion modelling.

HOTSPOT was developed at Lawrence Livermore National Laboratory in the US (Homann and Wilson 1995, Homann 1999) for modelling explosive releases or nuclear weapons accidents. It is included in the Lawrence Livermore National Laboratory NARAC system. HOTSPOT is a fast, fairly simple model for radiological releases, which is based on the assumption of a Gaussian plume dispersion model with the addition of a radiation dose estimate component.

DIFFAL is an atmospheric dispersion code developed by the Atomic Weapons Establishment (AWE) of UK MOD, primarily to model releases from explosions and nuclear detonations. DIFFAL is essentially a simple Gaussian model, with the inclusion of gravitational settling. AWE regard it as '*particularly applicable to large releases of particulate material such as those from fires or explosions, from which the stabilised cloud is extensive and the subsequent dispersal is significantly influenced by gravitational settling*' (Shaw 2004). DIFFAL uses wind speed and direction (in both the horizontal and vertical directions, at up to twenty different heights), and the Pasquill stability category, to determine dispersal. As input, DIFFAL needs the shape and dimensions of the cloud to be specified. Input data are also required on the mass/activity and particle size distribution in the cloud. The user-defined cloud geometry may be defined as a cylinder, or it may be calculated within the code in other shape forms.

1.3 Imprecision in emergency response predictions

Imprecision[1] is inevitably associated with the output of an emergency response system for radiological releases to atmosphere in the early stages of an accident, due to incomplete knowledge of the environmental factors (including the weather) and the nature of the release itself. Decisions on protective actions must be taken in spite of this lack of knowledge. Decision making under uncertainty, especially in the context of emergencies, has been discussed (see for example Reichert and Borsuk (2005), Bailar and Bailer (1999)). Dieckmann *et al* (2010) have said that although '*decision makers may be more likely to discount information or avoid making a decision when ambiguity is made explicit in a forecast',* their work suggests that *'decision makers were able to use the explicit probability presented as a range, and did not show a tendency to discount this information and rely on more easily evaluable information*'. Dieckmann *et al* (2010) conclude that '*the goal of presenting numerical*

[1] The term 'imprecision' is mostly used here, in preference to 'uncertainty', because strict 'uncertainty analyses' have not been undertaken (see section 3 for discussion). Imprecision has been defined (Parry 1996) as the uncertainty arising due to a lack of knowledge or information, which is the definition used here. However, the term 'uncertainty' is retained in places where this best expresses the concept referred to (for example, in quoting from published sources). To some extent the terms are interchangeable.

probabilities [to decision makers] *is to be as precise as possible when communicating uncertainty*'.

French, in particular, has addressed the issues of uncertainty in the context of emergency countermeasures following radiation accidents (French 1995, Papamichail and French 1999, French 1999, French and Niculae 2005, French *et al* 2007). Key conclusions drawn from this research by French have been that the uncertainties in using models in support of emergency management are often underestimated and under-acknowledged and that complicated models can lead decision-makers into over-confidence, in part through an incomplete representation of the uncertainty associated with model predictions. In the field of radiological emergencies, French and Niculae (2005) state that complex decision support systems developed for radiological accidents (RODOS is given as an example) contain over-detailed prediction models and often '*grossly underestimate*' the inherent uncertainty; the authors conclude that there is a genuine need for modelling, but that this should be to a level of detail commensurate with the information requirements, and not overly detailed and unnecessarily complex. Finally, French (1999) has reported that decision makers tend, if confronted with uncertainty, to assume worst case outcomes rather than to take the possible spread of outcomes into the decision.

In summary, on the basis of the above literature, it can be concluded that:

- The nature and extent of the uncertainty in model-derived predictions should be taken into account if the predictions are used in decision making, particularly in an emergency health protection context when either overestimating or underestimating the need for protective measures may have an impact on health.
- The different scales and sources of uncertainty in alternative management options should be assessed and made transparent.
- The management of risks may be made more complicated by bringing to the surface uncertainties which were previously present but hidden.

- The manner in which the uncertainty in an assessment is treated should be compatible with the requirements of the application to which the assessment results will be put.
- Large, complex decision support systems may underestimate and under-present uncertainty but their very complexity may lead to over-confidence in decision makers, because of the detailed results presented and the apparent sophistication of the tool.
- Decision makers are often not familiar with, or comfortable with, uncertainty as a scientific concept. Scientific descriptions of uncertainty provided to decision makers should therefore be clear and easily understood.

With regard to emergency response modelling for radiological accidents there are two areas where the current state of knowledge and availability of tools are lacking. First, there has been no study of the key causes of imprecision in the predictions output by emergency assessments. Second, there is no tool which currently incorporates these elements of imprecision comprehensively and which presents imprecision information to decision makers. None of the radiological emergency response systems summarised in section 1.2 include all significant sources of imprecision and most do not include any. The consequences of possible alternative weather evolutions are incorporated in the most complex systems (RODOS, ARGOS and possibly HPAC) through the use of real-time weather predictions and the optional use of 'ensemble[1]' dispersion modelling, but non-weather sources of imprecision can only be represented through a series of alternative runs, by varying input parameters. The EURANOS research programme, which concluded in 2009, incorporated a research project which was presented at the EURANOS final contractors meeting in June 2009 (Powerpoint presentation by Hiete 2009), but which does not appear to have been otherwise published. This considered the communication of uncertain results to the decision maker through two variables,

[1] Ensemble dispersion modelling is when forecast models are run many times with slight perturbations in starting conditions, to achieve a collection of plausible dispersion options. See Section 4.

the source term and the wind direction, and represented the results of example calculations on a shaded map in terms of the probability of exceeding a dose threshold, but did not include the other possible sources of imprecision. Consideration of an uncertain source term reflects the emphasis in RODOS of an estimated source term as the starting point for radiological assessments. It is not normally assumed in the UK that source term information would be available to emergency responders in the first few hours of an accident and this element of imprecision would therefore have limited application in early emergency response in the UK.

1.4 Brief overview of thesis

The purpose of this study is to fill the gap described above, to investigate comprehensively the sources of the imprecision potentially associated with the predictions of assessment support tools for assisting early phase off-site countermeasure and public health protection decisions, to consider the implications of this imprecision for decision making and to develop improved techniques for early phase assessments, including the visualisation of the results.

In particular, the study:

- investigates the variability of the key input parameters to emergency response assessments, and estimates the values they may potentially take in a particular emergency,
- explores the sensitivity of the predictions of emergency response calculations to variations in key input assumptions and parameters,
- outlines a new method for assessing radiological consequences, to be used in conjunction with real-time weather prediction and dispersion tools, to improve early phase response to future emergencies by estimating the consequences of lack of knowledge,

- develops new ways in which imprecise information, in particular that resulting from alternative weather outcomes and different radiological measurements, can be presented to decision makers and demonstrates these using example results.

The study starts by reviewing mechanisms and exposure pathways and the basics of dose calculation. Current assessment models and data and the current basis for countermeasure decisions in the UK (including the ERL system), are reviewed and the aims of an emergency response tool and the needs of the decision maker are summarised. The extent of the imprecision typically associated with emergency response calculations in the first few hours of a release is investigated through two sensitivity studies, and the key parameters influencing assessment imprecision are identified. An improved approach to emergency response assessments is then proposed which is both simple and transparent, and which uses input from real-time dispersion and weather prediction tools. Finally, techniques are developed in which imprecise or uncertain information can be presented to decision makers. This includes possible alterative weather and dispersion situations and the use of alternative measurement information, as well as other assessment input parameters.

One aspect of emergency response calculations in the UK was considered especially important. The Health Protection Agency has a responsibility in radiological emergencies to advise on what measures are necessary to protect human health from radiation. As part of this responsibility, HPA has recommended Emergency Reference Levels, which are the levels of averted dose at which the introduction of emergency countermeasures such as evacuation and sheltering should be considered (ERLs are discussed more below). During the incident in November 2006 when Alexander Litvinenko was poisoned with ^{210}Po, HPA was asked to present precise details of dose calculations to government emergency committees, while the response to the emergency was on-going. This would not be possible if a complex 'black-box' system such as RODOS or ARGOS was used. These very complex systems contain in-built calculational assumptions and models which cannot be readily explained to, or appreciated by, the decision maker. It is also easy for even a trained user to inadvertently make use of inappropriate or inadequate input data, or to not fully understand the basis of the calculations performed in the code. The need for a relatively simple and transparent calculational approach in whatever new techniques were developed was therefore considered to be of importance in the development of UK response capability.

1.5 Section summary

The section summarises why emergency response systems are needed for health protection purposes in the event of an accidental or deliberate release of radioactivity to atmosphere. The development of the accident situation over the first few hours, the impact this changing picture has on emergency assessments, and the implications of this for response systems is summarised. The section goes on to briefly review the key aims of emergency response systems and the main national and international systems currently in use. The issues for emergency decision making in a situation which is only partly understood and in which there is likely to be considerable imprecision associated with any assessment results are summarised. It is concluded that there is presently no clear understanding of what the key sources of imprecision in emergency assessments are, and also that no current system comprehensively incorporates these. There is therefore a lack in the information which can be presented to decision makers. The intention of this study to fill this gap is summarised and the key aims are outlined.

2 REVIEW OF ASSESSMENT MODELS AND DATA

This section summarises the exposure pathways and the basic dose calculations in an emergency response assessment. Currently available assessment models and data are reviewed. The possible variability of key parameters in emergency dose calculations is considered, and ranges are developed for each; this is input required for Section 3. The current basis in the UK for countermeasure decisions, including the Emergency Reference Level (ERL) system, is then summarised.

2.1 Environmental transfer and exposure pathways

The basic components of an accident consequence assessment model for early stage dose assessments are shown in Figure 2.1 below. Key elements are:

- the source term (eg. the amount and type of radioactive material released), usually estimated on the basis of early measurements,
- atmospheric dispersion, including the processes of removal of material which lead to deposition on the ground and other surfaces, and the impact of weather conditions on dispersion and deposition,
- the modelling of exposure pathways arising from atmospheric dispersion and deposition processes, including inhalation of airborne radionuclides, external irradiation from airborne radionuclides, irradiation of the skin from radionuclides deposited on to the skin, external gamma irradiation from radionuclides deposited on the ground, and inhalation of resuspended material,
- impact of exposures in terms of health effects, and the impact of measures taken to reduce exposures (countermeasures).

For longer term exposure assessments, the subsequent behaviour of the radioactive material in the terrestrial environment, and doses from contamination of the terrestrial and aquatic foodchains are potentially significant but they are not reviewed here as these pathways do not impact on the emergency actions considered in this study.

The type of information presented in this section has been included in many reports, such as McColl and Prosser 2002, NRPB and KfK 1986, IAEA 1987a. Other key references or composite sources of information for this section are NEA/OECD 1991, NEA/OECD 1989, Jones *et al* 2003.

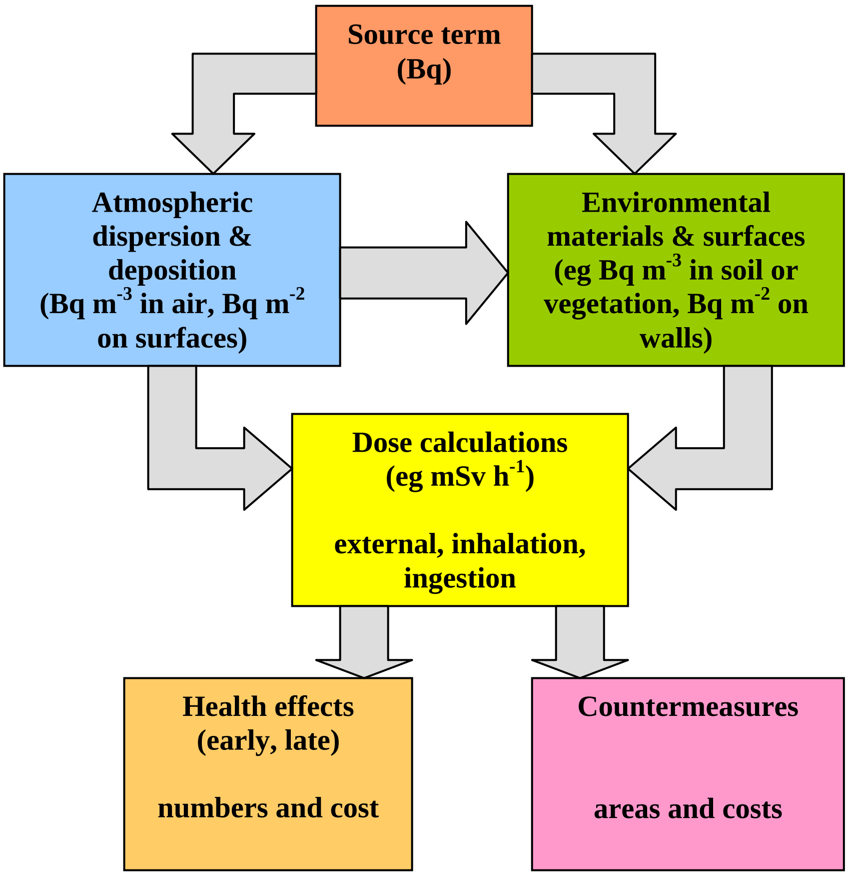

Figure 2.1 Basic components of an accident consequence assessment model

2.2 Source term

The radionuclides in the release, together with their quantity, release rate and physical/chemical characteristics comprise the release source term. The height at which the release takes place, the heat and energy content of the released plume, and the duration of the release are also classed as part of the source term. It is to be anticipated that there will be a lack of detailed source term information available in the early stages of the release. Approximate estimates of the source term may be made by engineering judgement of plant conditions, and interpretation of levels of environmental contamination in combination with atmospheric dispersion and deposition conditions. With time, iterative comparisons between measured levels of contamination and predicted levels lead to increasing refinement of the source term estimate and a more complete picture of the scale and consequences of the release. Alternatively, instead of a source term, environmental measurements may themselves be used as the basis for dose assessment; in effect, the measurements estimate the approximate source term.

2.3 Atmospheric dispersion and deposition

Radioactive material released to atmosphere will disperse under the influence of the prevailing meteorological conditions. Weather conditions influence the direction in which the material is transported, and the rate and extent of dispersion. In most circumstances, the radionuclides will eventually deposit on surfaces, which may be land (rural or urban), vegetation/crops, buildings or people, and again the weather conditions will influence the rate of deposition.

Atmospheric dispersion and deposition models are used to predict the spatial and temporal distribution of radioactivity, taking into account the particle size distribution of the released material, the chemical form of the radionuclides, the height and duration of the release and the meteorological conditions prevailing during the release and during the subsequent time of travel of the plume. Dispersion models include mechanisms for removal of activity from the plume, namely radioactive decay and dry and wet deposition processes. Depending on the characteristics of the release being considered, special features may also need to be modelled, such as the effect of release energy on the height and initial dispersion of the plume, as for example with an explosive release or a severe accident with considerable energy. The behaviour of plumes released into an area with significant buildings, for example an urban or residential area, can also be modelled with sufficient data on the structures in the area, the localised meteorology, and time.

Figure 2.2 illustrates the basic atmospheric processes following release: dispersion, transport, turbulence and dry and wet deposition. Models which simulate the dispersal of radionuclides following a release to atmosphere are an essential part of an emergency response system. The following sections summarise some of the key processes influencing dispersion and deposition.

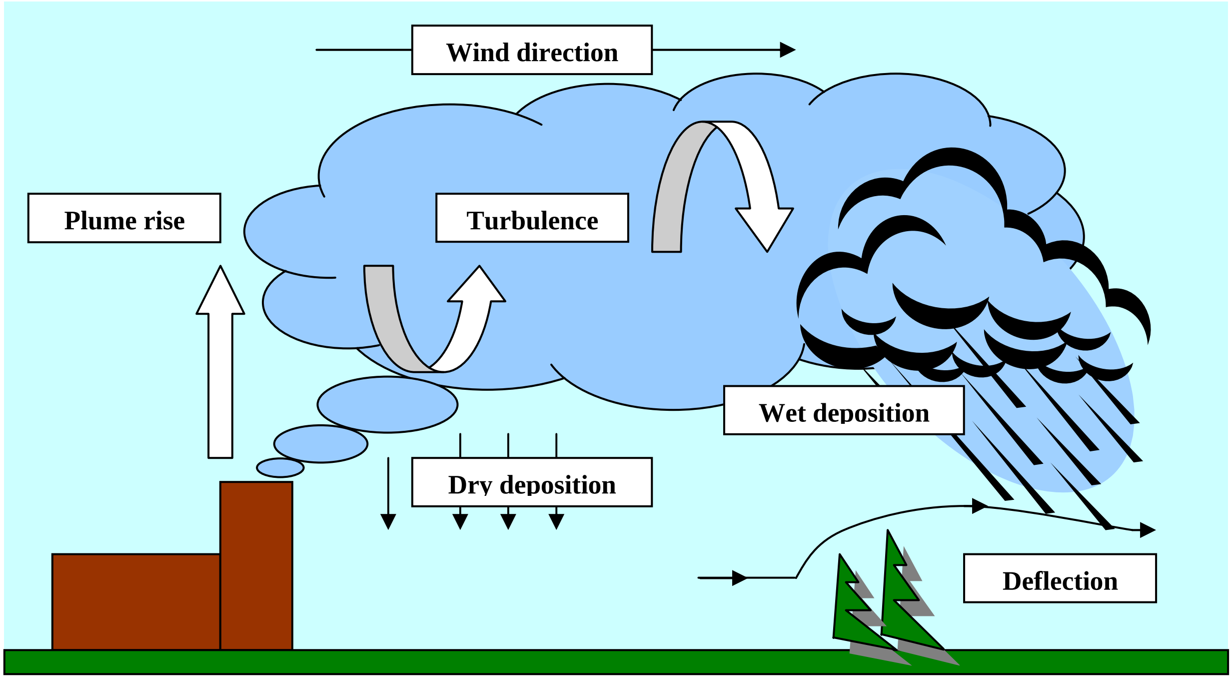

Figure 2.2 Basic atmospheric dispersion processes

Dispersion

Unless the release of radioactive material occurs with very large amounts of energy, it is likely that the material will enter into the atmospheric layer known as the boundary layer[1] which is the part of the troposphere directly influenced by the earth's surface. The height of the boundary layer is variable, typically

[1] For the purposes of this study the boundary layer has been considered to be the same as the inversion layer and the mixing layer.

being between about 200 and 2,000 metres; it is likely to be shallower at night than in the day-time. The dispersion in this area is influenced by effects from the land surface (for example, heating and cooling), and by increasing height above the ground, due to the wind speed increasing with height due to reduced friction with the earth's surface. Dispersion and diffusion depends upon the degree of turbulence, which relates to the stability of the atmosphere. There are several alternative classifications of atmospheric conditions, in terms of stability categories; terms often used include neutral, unstable and stable conditions.

Features of the accident itself may strongly influence dispersion, particularly the height of the release and the energy associated with it. In particular, the injection of material into high levels of the atmosphere, because of the initial energy associated with the release, could (as in the case of part of the Chernobyl plume) result in at least part of the released material travelling considerable distances before reaching levels low enough to be deposited on the ground. Also, material which is discharged into the atmosphere from a stack will often be at a higher temperature than the surrounding air and so will have thermal buoyancy which will effectively increase the release height. Serious accidents may well be associated with large amounts of thermal energy. The effects of these phenomena are termed plume rise, and may have a substantial influence on air and ground concentrations.

Meteorology also strongly influences dispersion and deposition processes, in particular wind speed, and fluctuations in wind direction may result in non-uniform dispersion and irregular patterns of concentrations in air. There will, in general, be less dispersion (in all directions) of the plume in stable conditions and more dispersion in unstable conditions. Air moves in different directions and at different speeds at different heights above the ground, influencing both dispersion and deposition.

Atmospheric dispersion has a fundamentally random nature and all models can only attempt to approximate the processes involved. It is, however, a field of modelling where a wide variety of approaches exist. From the late 1950's, the standard approach to modelling atmospheric dispersion was based on Gaussian plume modelling. The Gaussian plume model, and variations of this (see, for example, the 'R91' model of Clarke (1979)), assumes the plume spreads in vertical and horizontal directions by simple diffusion along the direction of the mean wind. The concentration is assumed to be normally distributed, spatially, about the plume centre-line and the plume spread is described by the dispersion parameters σ_y and σ_z, representing horizontal (cross-wind) and vertical mixing respectively. Time-integrated activity concentrations in air (Bq s m^{-3}) are related to the total amount of material released (Bq) by means of a formula using wind-speed, release height and σ_y and σ_z. Similarly, the instantaneous activity concentration in air (Bq m^{-3}) is related to the release rate (Bq s^{-1}). Reflection from the top of the atmospheric boundary layer can also be taken into account. The simple Gaussian model may be turned into a Gaussian puff model, which produces a sequence of puffs representing a release varying with time, by the addition of a further parameter σ_x to represent the spread along the wind direction. A puff model avoids some of the limitations of the basic Gaussian model (CERC 1988). The Gaussian model is a fairly simple and robust method of predicting accidental release dispersion, but there are limitations and problems associated with it. The Gaussian dispersion profile is the idealised form and significant variations on this may well arise in reality, through topography, urban areas or localised building effects. Upward and downward dispersion within a plume is not always a symmetrical process, as plumes may grow at different rates in different vertical directions, and this will lead to concentrations which are non-Gaussian in profile. It is also assumed that meteorological conditions are homogeneous over the area covered. The simple Gaussian plume model is strictly only applicable for distances of up to a few tens of kilometres in mostly flat terrain with no significant features. Also, the Gaussian plume model is not applicable in zero or very low wind speeds as the formula contains the reciprocal of the wind speed.

Two broad categories of more advanced atmospheric dispersion model are Eulerian and Lagrangian models. Eulerian models describe movement in relation to a fixed grid or reference system, dividing the air in the atmosphere into a three-dimensional grid and solving advection/diffusion equations to give the concentration at each grid point. The equations of an Eulerian model apply to a volume assumed to be fixed in space, through which the air moves. Lagrangian models consider the movement of a specific particle or puff/parcel of air, assume homogeneous mixing within the puff/parcel, and follow the particles as they are transported. Lagrangian models therefore usually require a wind-field pattern, to predict the movement of the particles/parcels/puffs, and the generation of this can be computationally intensive. For this reason, sophisticated Lagrangian models may have considerable computing requirements, and this has in the past been a significant limitation on their applicability, but with increasing computing power the run times are now sufficiently rapid to permit use in emergency response.

A widely used categorisation system to define the conditions of stability and turbulence in the atmosphere is the Pasquill system A to G, where A denotes the most unstable (most turbulent) conditions, G denotes the most stable (least turbulent) conditions and B to F are intermediate. Broadly, categories A and B are relatively low wind speed and warm conditions in which material disperses relatively quickly, categories E, F and G are associated with low wind speed and cold conditions which may be foggy, in which material disperses more slowly, and categories C and D are associated with higher wind speed. Categories A, B and C are most common during the day, and categories F and G are most common during the night. Category A is typically a hot sunny day with a gusty wind, category B a sunny warm day with some gusts of wind, category C a slightly cloudy day with a little gustiness, category D overcast conditions with a moderately strong wind but not gusty, category E a partly cloudy night, category F the inversion conditions typically found at night, category G a clear night with low wind speed. Atmospheric conditions in the UK often correspond to Pasquill category D. However, other methods are increasingly used in the newer generation dispersion models to take into account atmospheric conditions, such as the height of the boundary layer and the Monin-Obukhov length. The Monin-Obukhov length is the height in the atmosphere that separates the areas in which the mechanical or buoyant productions of turbulence dominate, and is determined by the temperature, the friction velocity and the heat flux.

The meteorological processes which affect the transport and diffusion of radioactive materials in the atmosphere vary with distance from the release point. Because of this variation different types of models are available for different distance ranges from the source. These distance ranges are often referred to as ‘close-in’, ‘short-range’ or microscale, for distances up to a few kilometres (and for time periods of minutes), ‘long-range’ or macroscale, for distances of a thousand or greater kilometres (and for time periods of days), and the intermediate mesoscale for distances and time periods in between. In the context of emergency response, the objectives of atmospheric dispersion models differ depending upon the distance from the release point at which they operate. Short-range dispersion models need to be run quickly, to enable decisions to be made at distances quite close to the release point (or to allow confirmation of the decisions that will be made based on the emergency plan), and the available input data will probably be sparse.

A particular problem in dispersion modelling is dispersion in urban environments, where building structures, the effect of the ‘urban canopy’ (where wind/turbulence varies with height), and movement of air into and out of buildings will influence dispersion. This is an area where there has been considerable work in recent years (see for example Colvile *et al* 1999, Robins and Macdonald 2001), but it still remains a problem for emergency response applications in particular. This is due not only to the difficulties in modelling the interaction between specific building structures and the plume, but also to the need for detailed 3-D weather data which are not currently available in sufficiently refined detail in an emergency situation. A report prepared for the UK Atmospheric Dispersion Modelling Liaison Committee (ADMLC) in 2003 by Cambridge Environmental Research Consultants Ltd (CERC) (CERC 2003) reviewed the current understanding of urban dispersion processes, the available modelling approaches, and urban dispersion experiments. It is clear from the review that the variability associated with urban dispersion has the potential to cause serious problems for dispersion modelling in an emergency response situation at close-in distances where complicated and variable concentration patterns are frequently seen.

Deposition

Radioactive material will be removed from the plume by both dry and wet processes. The particle size, the radionuclide, the chemical form (in terms of solubility), the nature of the surface(s), and the degree of precipitation will significantly affect deposition.

In the case of dry deposition, as the particle size of particulate material increases, the particles become more likely to be deposited by gravitational settling. Because the vertical profile of the concentration of the radioactivity in air is influenced by the wind speed, this factor also influences the deposition velocity as measured experimentally. Gravitational settling will be of importance for particles sizes above a few µm (Devell 1989). Material may also be deposited on the ground through direct contact with the surface (including on buildings and on vegetation). The nature of the underlying surface may significantly alter the extent of dry deposition. Surfaces which may be described as 'rough' such as trees and shrubs will receive more deposition (by up to a factor of 100) than relatively 'smooth' surfaces, such as paved, tarmaced or tiled areas.

The deposition of material on the ground, by dry processes, is roughly proportional to the concentration of the radionuclide in unit volume of air close to the ground; this proportionality is modelled by the use of a term called the deposition velocity (v_g). Deposition velocity has been defined (eg Chamberlain 1953) as:

$$v_g\ (\mathrm{m\ s^{-1}}) = \frac{\text{Amount deposited per m}^2\text{ of surface per second}}{\text{Concentration per m}^3\text{ above the surface}}$$

$$= \frac{\text{Amount deposited per } m^2 \text{ of surface}}{\text{Time integrated concentration per } m^3 \text{ above the surface}}$$

The dry deposition velocity may vary from 10^{-2} m s^{-1} to 10^{-5} m s^{-1} for different radionuclides in different circumstances. For most radionuclides in particulate form, a value of 10^{-3} m s^{-1} is an average value often applied, but for iodine in (inorganic) vapour form the commonly used value is 10^{-2} m s^{-1}. Values for deposition velocity are discussed in more detail in Section 3.

Precipitation removes material from the air, reducing the concentrations in air and hence leading to reduced deposit further downwind. There are two types of precipitation removal: 'rain-out' when rain droplets condense around the radioactive material, and 'washout' when the radioactive particles are below the cloud producing raindrops and are 'caught' on the drops as they fall through the air. It has been concluded (Jones 1985) that it is reasonable, for modelling purposes, to consider washout and rainout in a single coefficient; the significance of this for assessments is that it is therefore not necessary to distinguish between radioactive material below the rain cloud and material within it.

As a rule of thumb, typical levels of rainfall may be expected to increase particle deposition by about a factor of 10 compared to dry conditions, while very heavy rain can increase the deposition by around a factor of 100. A consequence of this is that if there is patchy and localised rain, the deposition levels may vary over a factor of 10 or more over a small area. The effect of deposition in snow and fog is likely to be somewhat less than that in rain, but still enhanced compared to dry deposition. In the modelling of wet deposition processes, a parameter called the washout coefficient is used. The washout coefficient, Λ (s^{-1}), represents the fraction of the plume that deposits in unit time, and can vary over several orders of magnitude depending on the type of radioactive material in the plume and the nature of the rain. Values for washout coefficients are discussed in more detail in Section 3.

2.4 Inhalation of airborne radionuclides

The direct inhalation of radionuclides in the plume is potentially one of the most significant short-term exposure pathways after an accidental release of radioactivity. The dose received from inhalation over a period reflects the time integral of the radioactivity concentration present in the atmosphere, the breathing rate of the individual and the dose conversion factor for the radionuclide:

Dose (Sv) = integrated activity concentration in air (Bq s m^{-3})

x breathing rate (m^3 s^{-1})

x dose per unit intake (Sv Bq^{-1})

This calculation can be modified if an indoor dose is required by means of a factor to represent the protection provided by buildings. For typical UK buildings with doors and windows closed, the concentration indoors in the first few hours when outdoor concentrations rise is about half of the concentration outdoors, for inhalable particles and also for iodine vapour (Brown 1988; Andersson *et al* 1995), although indoor and outdoor levels will equalise with time. After the radioactive plume has passed, further inhalation doses may be received through resuspension of the ground deposit by natural or man-made disturbance. However, this pathway is usually only significant for those radionuclides which do not give rise to a significant external radiation hazard, as there will otherwise be a greater external dose received from the material on the ground and other surfaces.

2.5 External exposure from airborne radionuclides

Beta and/or gamma emitting radionuclides which are present in the air will externally irradiate a person immersed in or situated near to the plume. In the event of a release, the importance of this pathway may be assessed directly, using measurements of gamma or beta dose rate, from, for example, installed monitoring networks, hand-held monitors, or integrating dose meters which may be placed at fixed points. Modelling can be used in addition to measurements, but requires an assumption about the location of the person in relation to the pattern of the nearby plume, which will be uncertain as well as a complex calculation. Simple modelling can be used, for example the ‘semi-infinite cloud model’. This model assumes that all the air in a hemisphere around the person is uniformly contaminated to a radius sufficient to account for the range of the radiation in air. It is further assumed that the surface of the hemisphere is flat. This is clearly a simplification of reality, and the model will not be a good representation where the assumptions are inappropriate, such as close to the release point (where the plume may be elevated, leading to low concentrations in air at ground level but still significant gamma dose rates), or at distances close to where the plume first touches the ground, as the pattern of contamination at this point is not a uniform hemisphere. More complex models are possible if the radionuclide concentrations in the plume can be estimated, for example a finite cloud model may be used for gamma emitting radionuclides. An example is MCNP (LANL 2001), a Monte Carlo code which can also be used for calculating doses from ß sources. More complex methods may utilise complex dispersion modelling, for example a Lagrangian model such as the Met Office’s NAME model now has a cloud gamma model built in on the Lagrangian equations (Bedwell *et al* 2010).

An estimated external dose may be modified for indoor occupancy (for example, to evaluate the dose saved by sheltering), by the use of a factor to represent the degree of protection afforded by buildings. A review of location factors (Brown and Jones 1993) has suggested that for typical UK houses a protection factor of 80% should be used to modify the external doses from airborne activity.

2.6 External exposure from deposited radionuclides

Gamma emitting radionuclides which are deposited on the ground and other surfaces such as buildings will give rise to external gamma exposures in the vicinity, potentially from material deposited at considerable distances from the person as they can travel hundreds of metres in air. Beta emitting radionuclides may also give rise to a dose but this would be low in most circumstances because the β dose rate from a surface decreases rapidly as the distance from the surface increases, and because clothing provides a substantial degree of shielding.

Once the plume has gone, dose rate monitoring may be used to assess the current significance of the pathway (although the normal background dose rate in the area should be deducted from the reading, if the measured dose rates do not dominate it). However, assessment of the future gamma dose rates from those currently being measured, or assessment of external doses on the basis of ground concentrations of radionuclides, requires the use of a model.

A model for estimating external doses from deposited radionuclides, on the basis of either measured or modelled radionuclide concentrations on the ground, together with an appropriate conversion factor, will essentially be of the form:

Dose (Sv) = integrated ground deposition (Bq m^{-2})

x dose conversion factor (Sv s^{-1} / Bq m^{-2})

x time of exposure (s)

The basis for the dose conversion factors typically applied in such models is the assumption that all the ground, in a radius sufficient to account for the range of the radiation in air (of the order of several hundred metres for gamma emitters and a few metres for beta emitters) is uniformly contaminated in an infinite plane, that the doses are delivered at a height of 1m above the ground, and that the surface is flat. As in the case of the semi-infinite plume/cloud model for estimating doses from radioactivity in air, this is usually a simplification of reality, and the limitations of the modelling approach need to be borne in mind, with the use of appropriate modifications where necessary. The MCNP model referred to in the previous section on external doses from air is an example of a model used to calculate the doses from ground deposits.

Buildings provide a degree of shielding from gamma radiation, and for emergency planning and response purposes this shielding may be an important factor in determining appropriate countermeasures. Sheltering, for example, will reduce doses but the degree of protection provided will depend on how solidly built the building is. Radioactive decay and removal through weathering processes and deliberate decontamination will reduce the dose rate with time. In the longer term, downward migration through the soil will reduce the activity on the soil surface and in the upper layers of soil, and the dose will reduce accordingly because of the shielding provided by the soil, but this is not a factor in early emergency response. More complicated models, which predict the spatial and temporal movement of radioactivity in an inhabited area, and also the effects of decontamination techniques on the concentrations and exposures, have been developed (Jones and Singer 2003, Charnock *et al* 2003), but these are not of direct relevance in the early emergency phase.

Airborne radionuclides may deposit onto, and irradiate, exposed skin. On the basis of a review of experimental evidence, it has been suggested (Jones *et al* 1998) that in outdoor conditions deposition onto skin is typically about an order of magnitude greater than deposition onto ground for small particles, although the deposition velocity of large particles to skin may be similar to that to the ground (Jones 2006). In the case of gamma emitting radionuclides, it has usually been considered that, in general, the exposure from this pathway is likely to be relatively insignificant in comparison with the doses from other pathways, and in particular from the exposure to deposits on the surrounding surfaces. This is because of the relatively low surface area of the body compared with the size of the area in the vicinity of the exposed person from which gamma exposures would be received. However, more recent calculations at HPA have indicated the potential for this to be a more significant pathway than previously thought. The duration of skin contamination also influences the doses received, and hence the effect of skin and hair washing is of relevance (Bell 1998): if a person is removed from the contaminated area, but the skin and clothing deposits remain, the potential significance of the skin pathway increases. In the case of beta emitting radionuclides, the Chernobyl accident in 1986 led to the deaths of a number of emergency personnel, and it is thought that skin burns from beta emitters deposited on the skin were a contributing factor.

2.7 Key parameters in emergency assessments

In the event of an accident, certain information is likely to be quickly available. The parameters which are required as input to an emergency response system and which are likely to be approximately known in the first hours are:

- the location and approximate start time of the release,
- the end time, if the release has stopped; if the release is continuing, there may be no information on a likely end time, or the information may be very uncertain,
- a rough estimate of the current weather stability category,
- an approximate ground level wind speed and direction,
- whether it is raining or likely to rain close to the site in the near future,
- the approximate height of the release (in terms of the height of the affected stack, or an obvious escape point such as a crack, but probably not in terms of effective height due to heat content).

The possible sources of imprecision in assessments which are considered in this study are listed in Table 2.1; this list has been based on the review summarised above and includes all the parameters which have been suggested in the reviewed literature to have significant influence on assessed consequences. To undertake sensitivity studies to investigate the relative influence of imprecision in these parameters (as described in Section 3), plausible minimums and/or maximums for each parameter were derived as discussed below.

Table 2.1 Parameters considered in the study

Release duration	Release height
Plume rise	Weather stability classification
Wind speed	Wind direction
Dry deposition velocity	Precipitation and washout coefficient
Particle size	Location specific effects (terrain, buildings, coastal)

This section examines the sources and scales of imprecision in key parameters in emergency dose calculations, and develops plausible ranges. These ranges are applied in Section 3 to estimate the extent and causes of the imprecision typically associated with emergency response calculations in the first few hours of a release. The aim is to estimate the impact of the imprecision associated with predictions based on a few off-site measurements at early times, by considering the range of values each parameter may take, within the context of a specific emergency. This has been done by developing a baseline set of input parameters and then for each parameter in turn varying its value to a plausible minimum and/or maximum by considering the range of values the parameter may take within the context of a 'baseline' accident (i.e., not the full range of values the parameter may take in any accident), and hence calculating the effect on the predicted extent of countermeasures. Therefore, the plausible ranges developed in this section represent variability within a specific emergency, not the full range of values each parameter may take in any emergency, and relate to selected baseline parameter values for the reference accident considered in Section 3. The parameters of the baseline calculation are shown in Table 2.2; two radionuclides were considered, ^{137}Cs and ^{131}I, to represent two significant radionuclides in potential accidental releases, which have differences in their modelling and data requirements.

Table 2.2 Parameter values for the baseline calculation.

Release duration	1 hour
Release height (stack)	10 m
Pasquill meteorological stability category	D
Wind speed	5 m s^{-1}
Wind direction	Either initial wind direction (non-Gaussian model) or plume centre line (Gaussian model)
Particle size:	
^{137}Cs	100% 1 µm AMAD
^{131}I	Assumed elemental iodine vapour
Dry deposition velocity:	
^{137}Cs	10^{-3} m s^{-1}
^{131}I	10^{-2} m s^{-1}
Rain-out/washout coefficient	No rain
Terrain and building effects	None

2.7.1 Release duration

The release duration is a significant factor in the consequences of an accidental release as, clearly, the overall release to the environment is dependent on the release rate and the duration. Published UK PWR degraded core source terms (Kelly and Clarke 1982, Kelly *et al* 1983) were assumed to be released mostly within one hour, although the smaller degraded core accidents and the containment by-pass accidents (Jones and Williams 1988) were assumed to be released over times in excess of one day, The design basis accidents (Kelly *et al* 1983) were assumed to be released in 30 minutes. Depending on the nature of the release, it is likely that some accident scenarios could have much longer release durations than this, of the order of a number of hours or days. The Three Mile Island and Windscale accidents each released activity for around a day (although the release pattern for Three Mile Island was complicated due to activity being held up in the containment), and Chernobyl for over a week. However, in the context of assessment accuracy in the early response to an actual release, it is unlikely that the imprecision on this factor would be significantly greater than 4 hours, as a duration much longer than this would be a known factor in subsequent assessments. A 4 hour release duration has therefore been used in this study as the upper level, together with a shorter release duration of 0.5 hour as the lower level.

2.7.2 Release height and plume rise

Site information for a UK accident is likely to be sufficient to enable the release height (excluding plume rise effects) to be approximated with reasonable accuracy. Published UK source terms have attempted to associate likely release heights with scales of accident. The PWR degraded core source terms (Kelly and Clarke 1982), in which some or all of the core may become molten, were predicted to occur with a release height of 10 m (with two exceptions, for smaller degraded core accidents, which were predicted to be ground level releases). The containment bypass and degraded core source terms were all predicted to have a release height of 10 m. For the purposes of this study, it is therefore estimated that the release height (excluding modifications for plume rise) will be known to within a factor of 2 of the true value, and as a baseline release height of 10m is assumed, the influence of varying this to 5m and 20m is examined.

Serious accidents involving fires or explosions may be associated with large amounts of energy, effectively increasing the release height. The Chernobyl accident involved considerable plume rise (IAEA 1991), leading to relatively low levels of deposition (in the first stage of the release) close-in, and considerably more at distances beyond tens of kilometres from the plant. It has also been concluded (Beyea and DeCicco 1990) that a key factor in the estimate of doses received as a result of the Three Mile Island accident was the uncertainty associated with the plume rise. The Buncefield petro-chemical explosion and fire in December 2005 (in Hertfordshire, UK) was associated with very high energy, which led to much of the plume rising above the boundary layer (see Figure 2.3). Webster *et al* (2007) have discussed the difficulties which arose in emergency modelling of the Buncefield dispersion due to the uncertainty at the time over the energy released, using the Met Office's NAME model. NAME performed well once satellite imagery was used as an input, but this will not be readily available in the very early stages of emergency response and is in any case only of help with a visible plume. This is likely to be a general problem with all predictive models in the case of high energy releases.

Figure 2.3 Buncefield petro-chemical explosion and fire in December 2005

Plume rise may have a substantial influence on ground level activity concentrations in air, and may also have a significant impact on post accident decisions. For example, near-ground close-in activity concentration in air measurements may be observed to be low or zero, which could erroneously be taken to imply a low level of release, when in reality a substantial plume is present but at a higher height. The extent to which significant plume rise would be appreciated in the early stages of an accident is not clear. Some reasons for plume rise such as a major fire or explosion leading to significant building damage would be obvious, however even small accidents may be associated with some degree of thermal buoyancy, and this may be less observable. Plume rise can lead to an increase in the effective source height by a factor as great as 10 times the actual release height, reducing the maximum activity concentration in air at ground level substantially, and it may also lead to greater plume spread due to the greater vertical velocity increasing entrainment, which causes air to be pulled into the plume. For the purposes of this study the influence on the results of an effective release height of 200 m is considered.

2.7.3 Meteorological information

A key issue in emergency response assessments is the availability of meteorological information applicable to the point of release and to the areas and times covered by the dispersing plume. In UK emergency exercises, and currently in the event of a real emergency, basic meteorological information available for input to assessments includes Pasquill stability category, wind speed and direction (broadly applicable to ground level) and the presence/absence or likelihood of rain in the affected area. In the event of an emergency, UK nuclear sites provide information from on-site weather recording equipment (Nelson *et al* 2003). Such results from a single meteorological point would be of limited value as they would not be applicable to all the areas covered by the plume as it disperses. Increasingly full area meteorological information and projections are becoming available from the UK Met Office[1], but the ability to incorporate such spatial and temporal information into assessments is limited. Consideration of the imprecision in the following meteorological factors is therefore examined in this study:

- the atmospheric stability classification,
- boundary layer depth
- wind speed and wind direction

The presence or absence of precipitation is a further meteorological factor, which is considered with the washout coefficient.

[1] Such information now forms the basis, for example, for the Met Office's CHEMET and PACRAM forecasts for emergency responders (see Section 2.9).

2.7.3.1 *Atmospheric stability classification*

The Pasquill stability categories are based on wind speed and cloud cover at night, and on wind speed and the incoming solar radiation by day (Clarke 1979, McColl and Prosser 2002) and were originally developed as a rough approximation to be used in the absence of wind fluctuation data. They represent parts or sections of a continuous distribution of conditions. Table 2.3 (based on Jones 1986) shows the probability that Pasquill stability categories will persist for a given time, and also shows typical wind speeds in these categories as reported by Clarke (1979) for a height of 10 m. It can be seen that only Category D, the most likely stability category in the UK (occurring about 60% of the time), has a probability in excess of 10% of persisting for times in excess of 5 hours. The other, less likely, categories are unlikely to persist for more than 3-4 hours.

The imprecision considered here is the accuracy of the specified stability category (as measured) and its applicability to all the areas to which it is assumed to apply. It has been suggested (Jones 1986) that in selecting an appropriate category, the choice is unlikely to be in error by more than one category from the true category near to the point where the weather observations are made but that the errors involved in assigning a category increase as distance from the observation point increases. It has also been suggested (Fisher and Moore as referenced in Clarke, R H, 1979; Jones, 1986) that the concentrations in adjacent stability categories should be considered, in addition to the specified one, and this is the approach followed here, where the effect of the true category in the region of interest being one of the adjacent categories is examined. Stability category D is assumed in the baseline case, and the influence of the actual category being C or E is therefore examined. The baseline Category D considered here corresponds to overcast conditions with moderately strong wind speed, which are conditions seen in the UK for about 60% of the time. The adjacent category C is more unstable and category E is more stable. The typical nature of the other categories (for example Categories A and B being typically a warm sunny day with a low wind, and categories F and G being calm conditions usually at night time) means that there is little danger of mistaken classifications across more than neighbouring categories.

Table 2.3 Probability a stability category persists for given times, from Jones (1986)

	A Very unstable	B Unstable	C Unstable/ Neutral	D Neutral	E Stable/ neutral	F Stable	G Very stable
	Typical wind speed at 10 m (m s^{-1})						
	1	2	5	5	3	2	1
Duration (hours)	Probability that a stability category persists for given times						
1	0.5	0.6	0.6	0.9	0.4	0.6	0.6
2	0.3	0.4	0.4	0.8	0.2	0.4	0.4
3	0.1	0.3	0.3	0.7	0.1	0.3	0.3
4	0.07	0.2	0.2	0.7	0.05	0.2	0.2
5	0.03	0.09	0.1	0.6	0.03	0.1	0.1
6	0.01	0.05	0.06	0.5	0.02	0.06	0.08
9		0.003	0.009	0.5	0.003	0.01	0.02
12			0.0003	0.4	0.0001	0.003	0.0004
15				0.3		0.0003	
18				0.3			
24				0.2			

2.7.3.2 Boundary layer depth

The extent to which the boundary/mixing layer depth is linked to other factors such as stability category depends on the model. Boundary layer depth will in general only significantly affect air concentrations when the plume height reaches its vicinity. Newer models such as ADMS (a short range dispersion model developed by CERC Ltd in the UK) and NAME (the Lagrangian dispersion model of the UK Met Office) use boundary layer depth as an input into determining parameters relating to turbulence and plume growth. The older R91 model assumes a relationship between distance and plume size which is independent of both wind speed and boundary layer depth, and has an in-built boundary layer depth in the air concentration curves which is dependent on stability category (100m in categories F and G, 400 m in category E, 800 m in category D, 850 m in category C, 900 m in category B and 1300 m in category

A). In such a model, the boundary layer depth only influences activity concentrations in air at distances of typically tens of kilometres from the release point, although in conditions of low wind speed in combination with early morning and little cloud it is possible that low boundary layer heights may occur. These could theoretically result in higher air concentrations than would otherwise be predicted, however it is difficult to envisage situations in which the conditions which result in a low boundary layer would simultaneously occur with a very dispersive plume, and so this situation is unlikely to arise. The imprecision resulting from boundary layer depth is partially included through the variation in the stability category, and any residual variability is not thought to be significant over the short distances for which emergency countermeasures are likely to be applicable.

2.7.3.3 Wind speed and wind direction

Errors in estimating wind speed and direction arise from inaccuracy in instrumentation, variation within the plume (including with height above the ground), inapplicability of the measurement to the conditions experienced by the plume, and variation with time (over both release duration and plume transit).

Surface wind has been defined by the Met Office as being the wind at 10 m above the ground, over open and level terrain (Nelson *et al* 2003). Surface wind is known to be affected by factors such as buildings or a copse of trees. Wind speed is commonly measured by an anemometer, which now have start-up speeds of about 2 knots (roughly 1 m s^{-1}). Below this, if there is insufficient wind to trigger a reading, a calm will be reported. For higher levels, radiosonde stations provide data on both wind speed and wind direction at heights above the ground up to about 20 km, and this data can be input into the more sophisticated dispersion models.

Smith and Readings (1982) have estimated that the error associated with a 10 m wind speed is up to 2 m s^{-1} (for wind speeds up to about 6 m s^{-1}) as a result of a combination of instrument error and distance from the instrument location (up to a few tens of kilometres), although less error may be associated with more modern instrumentation. The measurement of low wind speed is known to be particularly inaccurate, and this affects certain stability categories more than others, particularly A and G which are associated with a mean wind speed of about 1 m s^{-1}. Wind speed will vary significantly with height above the ground, with the extent of the variation being influenced by stability category.

The approach followed here is to consider the effect of the baseline wind speed, which for stability category D is 5 m s^{-1}, being in error by ±3 m s^{-1}, hence from 2 m s^{-1} to 8 m s^{-1}. This range, although slightly in excess of the value estimated by Smith and Readings (1982), has been chosen as it covers the typical variation in wind speed at heights above 10 m; a wind speed of 5 m s^{-1} a few metres above the ground suggests a likely wind speed at 100 m above the ground of around 10 m s^{-1}, giving an average wind speed up to 100 m of about 7 m s^{-1}. In Category D, wind speeds covering this range are plausible (see Clarke 1979) although they reflect considerably different weather conditions.

Wind direction is measured by a wind vane, which usually transmits information on a dial graduated in tens of degrees from true North. If there is sufficient wind to move the vane (to record direction) but not to move the anemometer (to record speed), this is recorded as a 'variable' wind condition (if there is insufficient to record either, a calm will be reported). Smith and Readings (1982) have also estimated that the error associated with measured wind direction is up to 20º as a result of a combination of instrument error and distance from the instrument location (up to a few tens of kilometres), although again less error may be associated with modern instrumentation.

In the same way that stability categories do not persist for more than a few hours for most categories, wind directions are also likely to change over similar times. In the case of the Three Mile Island accident, it has been shown (McKenna 2000) that the direction varied greatly over a 12 hour period, around an almost complete 360º circle (and also that a considerable variation in wind speed was seen over the same period, from a few m s^{-1} to in excess of 10 m s^{-1}). A further complication may arise due to changes in wind direction with height (shear), which could cause part of the plume to travel in a direction different to that measured by instrumentation set at a different height. The Chernobyl plume is known to have split into several parts, due to different wind directions at different heights above the ground (IAEA 1991). Smith and Clark (1989) concluded, in reviewing the Chernobyl release, that '*it is almost certain that individual trajectories starting from Chernobyl at the same time differed significantly*', and that '*changes in wind speed and direction with height through the plume are a principal factor in diluting the concentration within the plume*'. Satellite imagery following the Buncefield petro-chemical explosion and fire in December 2005 also suggests that there were at times two separate smoke plumes, travelling towards the south east at lower levels of the atmosphere and south west at higher levels, and that these subsequently merged (Webster *et al* 2007). This situation may arise in many meteorological conditions, in the case of a release associated with high energy/temperature, due to the height of the initial plume above the ground and the complexities of dispersion processes involving plumes of considerable height. The initial Buncefield plume, which rose above the boundary layer due to the high energy, moved in a direction different by 60 to 70 degrees compared with that which would have occurred at ground level. The variation in wind direction with height above the ground will depend on stability, and may range from 10 degrees variation (compared to the ground level wind direction) to tens of degrees. It seems likely, however, that a very significant wind shift with height would be noticed at a fairly early stage, through the early measurements.

In this study the error associated with a measured wind direction at 10 m of 10º and 20º in either direction is investigated. Wind direction may vary more than this (for instance, with height above the ground) resulting in a greater impact on countermeasure extents than those assessed here. A very significant error in the estimate of wind direction should become apparent as more measurements become available but it is possible that factors such as plume meander and rapid variation in wind direction with time may be a confusing factor in the early stages and possibly later.

2.7.4 Particle size, dry deposition velocity, and wet deposition

Particle size may affect dispersion and deposition in several ways. Large particles are less sensitive to atmospheric turbulence than small particles, and hence the dispersal of the plume that would be due to turbulence may be less for large particles, leading to a plume which develops more slowly than one which contains smaller particles. Conversely, the gravitational settling velocity is greater for larger particles than it is for smaller ones, because the effect of turbulence is reduced, and this velocity increases with increasing particle size for particles of AMAD greater than 10 – 20 µm. As a result of these effects, the size distribution of the airborne aerosol and the deposited activity changes as distance from the source increases. As large particles are deposited more quickly than small particles, the airborne aerosol has a greater proportion of small particles as distance from the source increases, and the deposited material closer to the source has a greater proportion of large particles than that further away[1]. The overall effect is one of a reduction in mean particle size with distance from the source.

Particle size will also affect the dose received following inhalation, which depends on the particle size of the released material. This is partly because large particles are less likely to be inhaled than small particles (as they fall under gravity) and partly because large particles do not penetrate into the deep lung and are more likely to be cleared by pulmonary mechanisms than smaller particles. The respirable range is regarded as being 0.1 – 10 µm AMAD.

The dry deposition velocity v_g ($m\ s^{-1}$) depends on the wind speed, the chemical form of the released material and the nature of the underlying surface. It incorporates the effect of gravitational settling as well as the other processes which influence deposition, and is therefore also particle size dependent. An assumption frequently made for modelling purposes is that all particles in a released aerosol are of 1 µm AMAD although the aerosol released in an accident can include particles with a wide range of sizes, from sub-micron to tens or hundreds of microns. Particle sizes considered here, for dry deposition,

[1] This is with the exception of distances very close-in to the source, where there may be less large particles because of the effects of the energy associated with the initiating event, which may throw particles up into the atmosphere.

are 1 μm AMAD and 10 μm AMAD. Dry deposition velocity shows a minimum for particles of size about 1 μm AMAD and then an increasing monotonic relationship for particles in the range 1 μm to 10 μm AMAD, and also an approximately linear relationship with wind speed (see Underwood 2001). It increases rapidly with particle size, beyond AMADs of around 20 μm (see for example, Sehmel 1980).

Although radionuclides deposit to different extents on different surfaces with (for iodine and caesium) deposition to rough surfaces (trees, shrubs, grass) apparently greater than to smooth areas (paved, tarmaced or tiled), and the deposition to walls considerably less, this factor is not considered further here as the exposure received by a person does not come from just one type of surface and the use of a single value reflects an averaging process.

The dry deposition velocity for ^{137}Cs is usually taken to be 1 10^{-3} m s^{-1}, and in this study this is assumed to be within a range of an order of magnitude on either side (ie 10^{-2} m s^{-1} to 10^{-4} m s^{-1}) when combined with a particle size of 1 μm AMAD (see, for example, Jones 1986). However, to represent the 10 μm size particle, a dry deposition velocity of 10^{-1} m s^{-1} is applied, to examine the effect of large particles. For ^{131}I in elemental vapour form (as opposed to particulate), the dry deposition velocity is usually taken to be 1 10^{-2} m s^{-1}, which is the baseline value assumed here, and the range assumed in this study is 10^{-1} m s^{-1} to 10^{-3} m s^{-1} (again consistent with Jones 1986).

As wet meteorological conditions are less likely than dry conditions on a particular day in the UK (where on average it rains for approximately 10% of the time, although significantly more in the west than in the east), wet deposition has sometimes been considered to be less influential on a 'likelihood of occurrence' basis. The consequences of wet deposition are, however, considerably greater than dry deposition, for the area over which the rain extends, because wet deposition is a much more effective method of removing material from the plume to the ground. Wet deposition is often modelled through a washout coefficient, Λ (s^{-1}), which is dependent on particle size, rainfall rate and the type of rain, including raindrop size and electrostatic forces.

However, a simple multiplying factor approach is used in this study in the simple Gaussian approach (see Section 3). The multiplying factors used are supported by calculations undertaken (Bexon 2007) with the well-established PC COSYMA probabilistic risk assessment system (Jones *et al* 1995, and for international benchmarking of this system see EC and OECD NEA 1994), see Table 2.4. For heavy rain, the PC COSYMA results show the influence of plume depletion at the largest distance, as it is assumed that the heavy rain has persisted throughout the plume transit to this distance. The proportional increase in deposition in wet conditions as opposed to dry ones is dependent on many factors including the duration of rainfall, rainfall rate, particle size, release height and distance from the release point, and the values chosen are therefore only intended to be broadly indicative of the potential effect. It is assumed here that light rainfall increases deposition by a factor of 10 compared to dry conditions for ^{137}Cs particles of 1 μm AMAD and by a factor of 2 for elemental iodine. For heavy rain the factors used are 100 for ^{137}Cs and 10 for ^{131}I. For heavy rain in combination with large particles, it is possible but uncertain that a multiplying factor to convert from dry to wet deposition of the order of a few 100's may be appropriate. There is little information on washout coefficients for particles above 10 um AMAD, but the combination of large particles and wet conditions is not considered here because the effects on the extent of countermeasures would be significantly reduced by plume depletion under these circumstances.

Table 2.4 Ratio of wet deposition to dry deposition as predicted by PC COSYMA for a release height of 10m, for three downwind distances (Bexon 2007)

^{131}I	Downwind distance		
Rainfall rate (mm h^{-1})	1 km	10 km	20 km
0.5	2	3	3
10	4	8	5
^{137}Cs	Downwind distance		
Rainfall rate (mm h^{-1})	1 km	10 km	20 km
0.5	5	20	22
10	42	84	38

2.7.5 Location-specific effects

Although the area potentially affected by countermeasures has been assumed in this study to be predominantly rural, location specific effects may potentially influence the prediction of countermeasure extents. Features of the local terrain such as hills, valleys and coastline, and significant buildings, have the potential to significantly influence dispersion.

The influence of buildings on dispersion patterns will be very dependent on the specific circumstances of the release and the position and size of the buildings. In some situations, the plume may be split because of the presence of structures, leading to peak concentrations in significantly different locations to those which would have occurred otherwise. Increased turbulence may cause greater variation in air concentration measurements than would otherwise be expected. Jones (1986) has summarised investigations into the effect of buildings on model predictions, and concludes that the influence of buildings on the spread of a plume out to a distance of about 10 building heights downwind is substantial, but that the overall effect is likely to increase the horizontal spread of the plume and hence to reduce concentrations at any given point. More recently, it has been suggested (Jones 2006) that if the release height is greater than 2-3 times the height of nearby buildings, dispersion will be largely unaffected by the presence of the buildings, and that if the release point is at or below building height, the effect will be to broaden the plume and hence reduce peak concentrations.

There would therefore seem to be only a limited number of circumstances in which the presence of buildings will significantly *increase* the peak activity concentration in air. These circumstances are a split or channelled plume, and these are likely to be accompanied by a shift in plume location which should be at least partially detected by early measurements.

Terrain effects can be regarded simplistically as the effects of valleys and hills. Hill and Lurman (2006) refer to '*the highest relative increases in concentrations due to the effects of complex terrain'*, and for UK conditions it is suggested that these highest increases are approximately a factor of 3. This study supports the conclusion that the effects of valleys on dispersion are complicated and both site and release specific.

The effect of hills depends on the position and height of the hill relative to the release point and the height of the release. If a plume encounters a significantly sized hill during its early dispersion in stable weather conditions, the peak concentration is likely to occur at the point where the plume encounters the hill. In this case, the peak concentration will be increased (as it will occur at a point earlier in the plume's travel than would have happened otherwise). However, the scale of the impact will be very dependent on release height and travel distance. In unstable conditions, the plume is more likely to go over the top of the hill, and the overall effect is unpredictable. The peak may occur around the top of the hill, due to the plume being carried over the hill and depositing earlier than it would otherwise have done, but there is a compensating effect of increased wind speed over hill tops which will reduce concentrations. Hunt *et al* (2002) have suggested that hilly terrain may change activity concentrations in air at ground level by a factor of up to 2 or 3 compared to the dispersion over level ground. Lawson *et al* (1989) have presented results showing the influence of terrain which indicate an increase in the peak air concentration (compared to that seen in flat terrain) of a factor of up to 4.

Coastal effects were reviewed in Jones (1986), where it is suggested that sea breezes penetrate 50 km inland approximately 5 times per year, and 100 km inland less than once per year. Sea breezes would give rise to less vertical mixing, hence increasing concentrations, but would also typically be associated with higher wind speeds, which would reduce concentrations. The effects may therefore be expected to often compensate for each other, unless the release is very short (a few minutes) when concentrations may be increased by a factor of about 2 (Jones, 1986). Jones (1985) has reviewed the influence of coastal effects other than sea breezes on inland concentrations. He shows that coastal effects, in certain weather conditions, may affect concentrations inland by up to a factor of 2 for distances up to a few tens of kilometres from the coastal site. It is possible that peak concentrations at distances of a few kilometres from the site could be up to a factor of 5 times higher, depending upon the assumptions made concerning, for example, the depth of the boundary layer.

On the basis of the above, the influence of terrain effects, coastal effects and buildings on the peak concentration may increase the magnitude of the peak concentration by up to a factor of 5, and this is the value used in this study. It appears to be more likely that the peak concentration will be reduced by hills or buildings. It is possible that the direction of dispersion will be altered, but the extent of this (and the duration of the effect) is totally dependent on the specific circumstances, and, as it is also likely to be identified in the early measurements, it is not considered further here.

2.8 Emergency Reference Levels and countermeasures

This section reviews the current basis in the UK for countermeasure decisions, including the Emergency Reference Level (ERL) system, what emergency countermeasures are available for use in protecting the public from the effects of an accident and what is the typical effectiveness of these in reducing doses.

2.8.1 Emergency countermeasures and their effectiveness

The key objective of emergency countermeasures, in the short term crisis phase, is to minimise health effects, in particular to prevent the occurrence of early (deterministic) health effects, and to limit the occurrence of late (stochastic) health effects.

A range of emergency protective measures may be implemented to avoid the public being exposed to radiation, or to reduce exposures. These measures may be introduced during a release, after a release or - if there is thought to be a strong likelihood of a release occurring - before it. Very early countermeasure decisions are more likely to be based on information on plant damage and status than on measurements (IAEA 1987a). In the UK this will occur through the activation of a site emergency plan, where, for a release for which there is adequate warning time of imminent system failure, implementation of the emergency plan would take place in the planning zone prior to measurement data being available. However, in the area beyond the planning zone, it may be likely for certain types of reactor (particularly older generation plant) that there would not be a meaningful warning time, and in such cases decisions are more likely to be measurement based.

The measures justified in a particular situation will depend on many factors, which include the severity and type of the release (or of the anticipated release), whether there is a release still in progress, the proximity to the release site, the principal exposure pathways, the meteorological conditions, and the nature of the land affected (for example, whether it is predominantly urban or agricultural, and the density of the population). Consideration in this study is limited to the emergency countermeasures, which may be defined as those which must be implemented rapidly if they are to be effective. They are usually only considered in areas fairly close to the point of release, to protect against the inhalation and external dose pathways. The emergency countermeasures are sheltering, evacuation and the administration of stable iodine.

Sheltering simply means people staying inside a robust building with doors and windows closed. It is a countermeasure which may be used to provide a good degree of protection to the public, especially in circumstances where the release is underway and where evacuation, while the plume is present, would lead to unnecessarily high exposures. Sheltering provides some protection from both the inhalation pathway and from external irradiation, although the effectiveness of the countermeasure will depend on the type of building used. Sheltering is a low-risk countermeasure, and is therefore undertaken at fairly low levels of projected dose.

Evacuation is removing people from the affected area for a short time, into an area where there is considerably less contamination, and preferably none. It is a very effective countermeasure in terms of dose reduction, providing considerable and possibly total protection from inhalation and external irradiation pathways. The evacuation process does, however, have risks associated with it which are not insignificant (see for example, Aumonier and Morrey (1990)) and for this reason it is undertaken at higher levels of projected dose than is sheltering. The practicability of evacuation depends on the particular circumstances, for example the accessibility of the area in terms of transport links. The weather conditions may also have an impact, for example the road conditions may be poor, making the evacuation process hazardous. In such circumstances, sheltering may be regarded as the optimal measure, in terms of overall risk reduction. Practical implementation of evacuation may differ from theoretical implementation. For example, it has been observed that in chemical emergencies 50% of the people recommended to shelter evacuate themselves, and 10% refuse to evacuate if told to (Crick *et al* 2003).

The ingestion of stable iodine as a countermeasure reduces or prevents the uptake of radioactive iodine to the thyroid gland, by the dilution of radioiodine with stable iodine. It is effective in reducing the risk from both ingestion and inhalation of radioactive iodine, but only if taken fairly quickly after the intake (or, preferably, before), and for this reason pre-distribution of iodine tablets in the vicinity of nuclear sites has been recommended for the UK (NRPB 1990). The tablets are usually in the form of potassium iodate. The issue of stable iodine is not regarded as a stand-alone countermeasure, because external exposure from the radioactive iodine is not reduced by stable iodine, and also the contribution to dose from the other radionuclides present in the release is unaffected by stable iodine intake.

In addition to these three main emergency countermeasures, other actions may be recommended. These include potentially contaminated people bathing/showering and changing into clean clothes. These actions may lead to some dose savings, although they are unlikely to be as significant as those achieved by the principal countermeasures. They will also limit the transfer and spread of contamination.

Both nationally and internationally, it is generally agreed that countermeasures should only be introduced if they are expected to achieve more good than harm, that they should be introduced and withdrawn in such a way that the protection of the public is optimised, and that they should be introduced at levels of dose which would avoid the occurrence of serious deterministic health effects. As the aim of introducing countermeasures is to ensure the most good for the most people, implemented countermeasures should aim to maximise the overall benefit, taking into account the advantages and disadvantages of each measure. The advantages include risk/dose saving and reassurance. The disadvantages include disruption, expense, practical problems (eg the provision of alternative accommodation) and stress. The optimum level will depend on factors such as the nature of the accident, the weather conditions, the resources available, the nature of the affected area (size of population, type of buildings, land use), seasonal demographic factors, and likely shielding provided by buildings.

2.8.2 The UK Emergency Reference Level (ERL) system

In the HPA Emergency Reference Level recommendations (NRPB 1990, NRPB 1997b) and also in other international advice (for example, ICRP 1992), the recommended levels of dose at which countermeasures are introduced is on the basis of the dose it is estimated will be averted by the measure (see Figure 2.4). Most recently, ICRP (2007) has proposed a new system in which the overall benefit and detriment of the countermeasures are considered collectively under a reference level of dose, but these recommendations have yet to be interpreted and implemented into a UK approach to emergency protection.

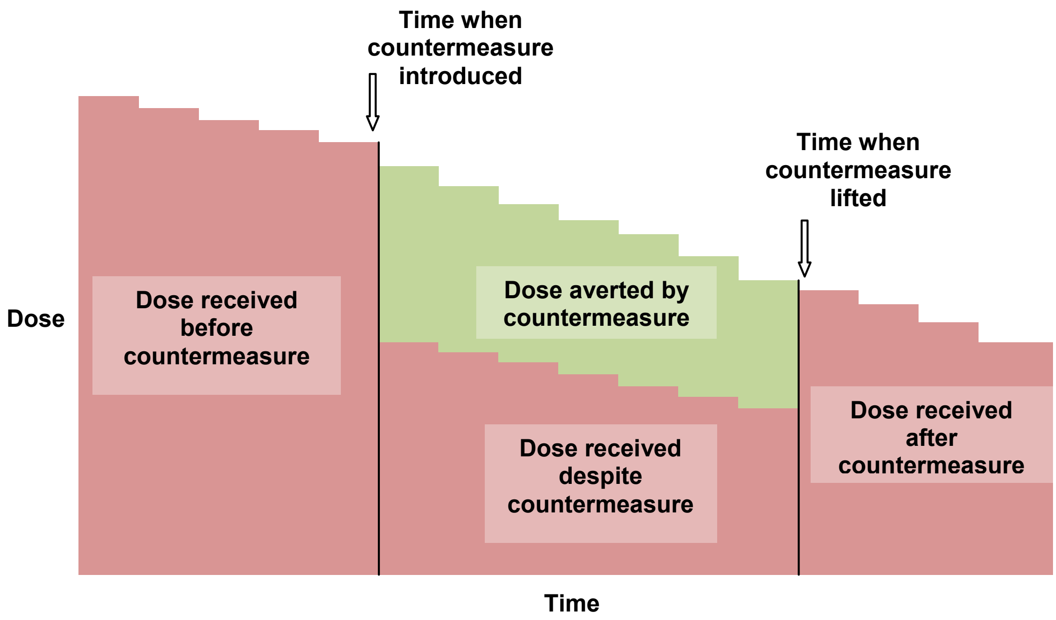

Figure 2.4 Averted and residual doses before, during and after a countermeasure

Two levels of dose are given for each emergency countermeasure (see Table 2.5). If it is estimated that the dose averted by the countermeasure will be greater than the upper level, implementation of the countermeasure is regarded as being almost always justified, whereas if it is estimated that averted doses will be less than the lower level, the countermeasure is unlikely to be justified in almost all circumstances. The reasoning behind this dual level system is that the appropriateness of a countermeasure will depend very much on the circumstances (location, severity etc) of a particular accident, and these factors cannot be known in advance. In the UK, the lower ERLs are intended for situations which are 'favourable for the introduction of a countermeasure' (NRPB 1990), in particular where relatively few people are affected and where the implementation of the countermeasure has been planned in some detail. The upper ERLs are intended for those situations where it is more difficult to undertake the countermeasure, for example in more heavily populated areas or in areas where the implementation of the countermeasure has not been planned. However, it was not intended that ERLs would completely bound the total possible range of intervention levels, because extreme situations may indicate optimum ERLs outside the range.

Table 2.5 HPA recommended ERLs for emergency countermeasures (NRPB 1990)

Countermeasure	Averted dose (mSv)		Effective dose/organ
	Lower ERL	Upper ERL	
Sheltering	3	30	Effective dose
Evacuation	30	300	Effective dose
Stable iodine	30	300	Thyroid dose

ERLs are intended to apply to the averted dose to young children, as it is recognised that society gives priority to the protection of children in an emergency (NRPB 1997b). It was envisaged (NRPB 1997b) that the primary use of ERLs is in emergency planning, as an input to the development of optimum site-specific action levels as part of the emergency plan for each site. If an accident occurs, there is not enough time available to undertake a detailed optimisation analysis of all the issues, because emergency countermeasures need to be implemented quickly to be effective, and also because they are applied in areas close to the site of the accident where the plume will arrive very quickly once the release has started. Hence, a key part of licensed nuclear site emergency plans in the UK is the semi-automated introduction of emergency countermeasures close to the site on the basis of the appropriate intervention levels and the features of the specific site. NRPB (1997b) gives guidance for the UK on how the concept of averted dose should be incorporated into a plan designed for urgent response, and on how ERLs may be applied in the development of an emergency plan. ERLs may also be used in emergency response as a broad check on the adequacy of the measures being implemented, but they should not be used directly and inflexibly, as firm numerical levels, to determine appropriate response because they are generic and do not take into account the features of a particular accident or site. In emergency situations which require consideration of the implementation of countermeasures outside the pre-planning zone, the requirement to consider in any detail – once the emergency is underway - the benefits and disadvantages of a measure are reduced, because there will not be time available, or adequate data, on which to base a comparison. However, issues of practicability are still important. In areas beyond those covered by the emergency plan (extendibility), the optimum intervention levels are thought likely to be higher than the lower ERL (as these relate to favourable conditions and small numbers of people).

Emergency reference levels, or intervention levels, are not the same as action levels, which are either levels of received or projected dose or quantities which are directly measurable (for example, a dose rate or a concentration in air) above which a particular action or actions should be taken. A commonly used action level in the UK is a total activity concentration in air of 10^5 Bq m^{-3}; this level may be used to trigger evacuation (see, for example, British Energy Generation Ltd 2004).

The concept of optimised and averted dose leads to several issues for decision making after an accident:

- As countermeasures can only influence the dose that will be received in the future, only future doses are relevant to decisions[1].
- Future doses cannot be measured and therefore there must be a modelling component in their assessment.
- Dose estimates should not be overly cautious when being estimated for comparison with ERLs; because countermeasures have potential risks they should be introduced on the basis of realistic dose estimates.

2.9 Supporting services for emergencies

2.9.1 The UK Met Office

The UK Met Office, as a Regional Specialist Meteorological Centre (one of eight worldwide), has international responsibilities for environmental emergency response modelling in the event of a serious atmospheric pollution incident in the European and African regions. A range of operational and support services

[1] The exception to this is if there is a possibility that cumulative doses may exceed the thresholds for serious deterministic health effects, in which case both past and future doses, over an appropriate time period, need to be considered. However, the ERL system is not intended for use in protection against serious deterministic effects, as it is a general principle that every effort must be made to avoid these.

are provided in the event of atmospheric releases, including chemical and biological incidents as well as radiological, from the Environmental Monitoring and Response Centre (EMARC), and these are available around the clock and throughout the year. Met Office predictions are automatically forwarded to over 50 met services worldwide.

A key component of the Met Office's emergency capability is the Numerical Atmospheric Dispersion Modelling Environment (NAME) dispersion model, a sophisticated Lagrangian dispersion model, with air parcel trajectories used to compute concentrations in air and ground deposits. NAME was originally developed in the late 1980's, following the Chernobyl accident, to give long range (>100km) emergency response dispersion predictions for nuclear incidents (Maryon and Ryall 1996, Maryon *et al* 1999). Although originally designed as an emergency response nuclear accident model NAME is now used for both accident analysis and general pollution forecasting; it was, for example, used in the Icelandic volcanic ash release in Spring 2010. The current version is NAME III (Jones *et al* 2007). NAME is capable of backtracking to identify the cause of pollution incidents[1]. It includes plume rise, boundary layer simulation and transport at multiple atmospheric levels, and can now do this on all spatial scales from short range up to global. Both short-term and long-term releases can be considered. For UK emergency use, a key strength of NAME is its ability to incorporate 3-D global weather data from the Met Office's Numerical Weather Prediction (NWP) model, the 'Unified Model' (Cullen 1993, Jones 2007).

Validation studies with NAME against experimental data have indicated that its predictions compare satisfactorily with observations (see for example Webster and Thomson 2002 which presents NAME predictions against the Kincaid experimental data set, and Webster *et al* 2006).

Two specific services provided by the Met Office are of relevance to radiological emergency response:

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[1] Termed 'source attribution': calculating a source term (source strength) and source location based on monitoring information.

- The CHEMET service is available to all emergency authorities, with the main users being the emergency services. The service provides detailed forecast weather information, and also basic plume modelling for any atmospheric release (for example, for fires or tanker accidents). The information is initially provided by phone, and is followed up by a weather commentary and a map of the area at risk, by FAX or email, within 10-20 minutes. Predictions are then updated on demand, using the predictions of the Met Office's NAME atmospheric dispersion model.
- The PACRAM (Procedures And Communications in the event of a release of Radioactive Material) service, provides government and the nuclear industry with access to predictions of the trajectory of a contamination plume, also originating from predictions from the NAME model. PACRAM can either use default release source terms, or can base its results on a provided source term, if this is available.

The UK Met Office is continually developing improved techniques for assessing the uncertainty associated with weather prediction, and the assessment of risks arising from such predictions (for example, Mylne 2004). The projection of weather conditions into the future, for times beyond about a day to a few days, are influenced by the chaotic nature of the atmosphere and by the considerable uncertainty associated with weather details, such as rainfall rate and location. The Met Office, and other major international meteorological organisations, therefore use 'ensemble forecasting' to enable the uncertainty in meteorological forecasts to be estimated. This entails the repeated running of forecast models, many times, with just slight variations on starting conditions. Currently 51 international member organisations contribute to ensemble forecasting via the European Centre for Medium Range Weather Forecasts. The resulting spread of forecasts may be very diverse. If there is a wide spread, the resulting weather forecast can be presented cautiously, while similarity in the results will give greater confidence. The associated uncertainty, and the risk of the various different outcomes, may be quantified, and probabilities associated. This is particularly helpful with high impact weather conditions, as the decision maker can then take appropriate decisions on the basis of the likelihood of the event and the costs associated with preparations to mitigate for the possible consequences. This ensemble meteorological forecasting can theoretically be taken forward into dispersion predictions, through the generation of an ensemble of dispersion scenarios associated with multiple forecasts of the meteorology, where results are obtained from running a number of dispersion models with the same input data for the same release scenarios.

The EC ENSEMBLE project has used an internet-based platform to collect (in real-time) the dispersion forecasts produced by 22 different models operational in the EC and around the world to produce a 'pan-European' ensemble dispersion forecast. However, the project found significant differences between the participating models due to different national meteorological predictions, and differences in the dispersion modelling. There has been disagreement during this project on the usefulness of the ENSEMBLE system for decision making. The collation of modelling results is only representative of the predictions of the set of participating models. It is not necessarily representative of the results of all possible models, and it is also not necessarily representative of reality. Some participating codes were essentially the same model, with national modifications and refinements added, giving a false impression of agreement. Many of the participating models also shared weather forecast projections. Political difficulties arose in weighting the models by judgement of their respective merits.

2.9.2 Environmental radiation monitoring networks

The Chernobyl accident led to organisations and authorities in the UK and elsewhere around the world establishing their own local automatic environmental monitoring networks, with the primary aim of detecting and measuring any abnormal increases in the background levels of gamma dose rate. Some of these networks are very simple, while others are sophisticated national monitoring networks established with government funding. Monitoring results are transferred automatically, on a frequent and regular basis (eg hourly), to some form of centralised computing system, often with the capacity to increase the frequency of measurements if a predetermined alarm level is reached. In the UK, the average background level of gamma dose rates range from about 50 to 120 nanoGray per hour (NRPB 1997a); the levels may be naturally elevated for a short duration due to the washout of radon gas in heavy rain. The reliable detection of a genuine elevation in levels requires dose rates to be a significant fraction of the normal background levels, with the likelihood of the elevation being due to washout of radon gas having been considered and (if appropriate) rejected on the basis of a pre-agreed protocol.

The UK's national radiation monitoring network and emergency response system, RIMNET (Defra 1993), is now managed by the UK Met Office in partnership with DECC (Department for Energy and Climate Change, the nominated lead Government Department) and Defra (Department for Environment, Food and Rural Affairs). RIMNET is part of the UK's National Response Plan to nuclear emergencies and is available to all UK government departments and agencies with responsibilities for reacting to major nuclear incidents. Originally developed following the Chernobyl accident in 1986, RIMNET is applicable both to overseas releases and also to releases originating in the UK. RIMNET is primarily a platform for data co-ordination. It contains a fixed and fully automated network of 94 gamma dose rate monitoring stations across the UK, which automatically and constantly measure, analyse and report on gamma radiation dose rates. These would enable increases in gamma radiation levels to be speedily detected.

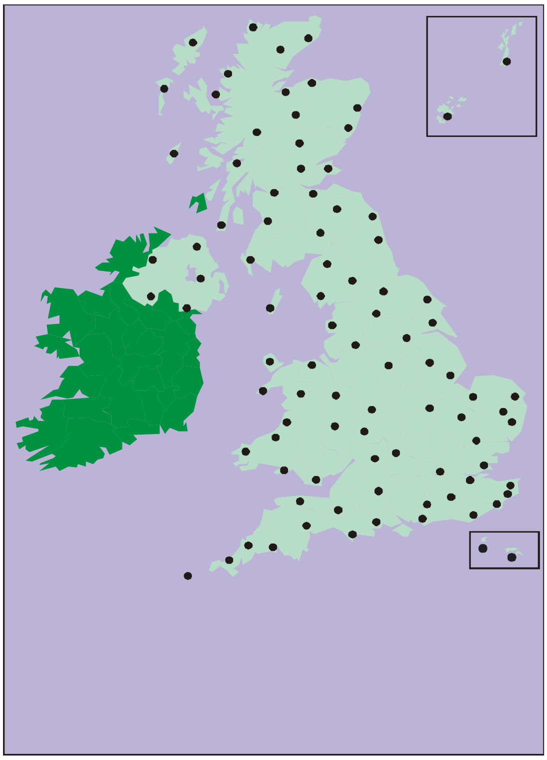


Figure 2.5 Location of RIMNET monitors (McColl and Prosser 2002)

At a European level, EURDEP is the EUropean Radiological Data Exchange Platform. It is a network for the exchange of automatic monitoring data, and is currently at version 2.0. Currently (2010) EURDEP provides a data exchange for 31 European countries. In an emergency, participating organisations would make data available at least every 2 hours.

2.10 Section summary

This section has summarised the processes underlying environmental transfer of radioactive material and the subsequent doses to man, and has reviewed the principles of modelling these, and the assessment models and data currently available. The section goes on to look at the possible variability of key parameters in emergency dose calculations, developing minimum/maximum ranges for these in the context of the baseline calculation applied in Section 3. The current basis in the UK for countermeasure decisions, including the ERL system, is summarised. Finally there is a summary of the emergency data input which may be available in an emergency from the national and international environmental radiation monitoring networks and from the UK Met Office.

3 ANALYSIS OF SOURCES OF IMPRECISION

3.1 Introduction

In the first few hours after an accidental release of radioactivity to atmosphere, model predictions will supplement monitoring data to increase understanding of the radiological situation and to form a basis for emergency health protection decisions. The model predictions will be based on either measurements or on an estimate of the release source term. There will be imprecision associated with these predictions, partly resulting from lack of knowledge (for example, about the nature of the release and the actual state of the weather), partly due to imprecision in the models themselves and partly due to intrinsic imprecision associated with the accuracy of the measurements. Although there is a common view that weather parameters are among the most significant in estimating the radiological consequences of releases in emergency response, with a correspondingly significant impact on the decisions regarding early countermeasures in the local affected region, this conclusion has not yet been clearly demonstrated by a modelling study considering the imprecision associated with a wide range of input parameters.

This section therefore investigates the key sources and extents of imprecision in radiological emergency response assessments, in the very early phase – the first few hours of a release - when there are limited off-site measurements. This has been done in two separate analyses, one applying a simple approach to atmospheric dispersion modelling in the R91 model, the other using the more complex Langrangian model NAME. The focus was on the imprecision associated with assessing the extent of countermeasures in the area beyond that covered by the emergency planning zone, typically in excess of a few kilometres from the site. This reflects the areas in which the doses are predicted to exceed given criteria. These endpoints were chosen as they are key to the information typically required by decision makers; they also incorporate other endpoints, such as estimates of effective dose.

The aim was to identify the key parameters influencing assessment imprecision in the predictions of countermeasure extents, and in particular to determine whether the key influences are parameters relating to the accident itself (some of which may only become known a while after the release has started) or parameters affecting the dispersion, for which real-time weather data are potentially available which could improve predictions and which a new tool could then incorporate.

A full uncertainty assessment has not been attempted, as:

- There is insufficient information available on the likelihood (the shape of the probability distributions) of the range of values many of the input parameters may take, and there is even less information on the ranges which they may take in the event of other parameters being constrained.

- Many of these parameters are inter-related and there is insufficient information on the nature of these correlations.

- As such a detailed uncertainty analysis could not be made generic, but would be strongly influenced by the features of the particular accident considered, there is a danger that accident specific results would be extrapolated to other situations for which they were not valid.

For these reasons, the extent of the imprecision on emergency assessments has been explored by means of sensitivity analyses. While work has been undertaken to assess the uncertainties associated with meteorology and dispersion, much of this has related to the prediction of dispersion from a known or estimated release, which is not the same as estimating the imprecision associated with predictions based on a few off-site measurements at early times, although the issues are clearly related. Also, although extensive work has been undertaken to analyse the uncertainty associated with probabilistic risk assessment systems (see for example Päsler-Sauer and Jones 2000, Goossens and Kelly 2000), this is also not of direct relevance here, as such studies focused on the uncertainty associated with the best estimate of each parameter, rather than with the range of values each parameter may take in an specific emergency situation which is incompletely understood, which is the issue of interest in emergency response calculations.

3.2 Methodology

3.2.1 Simple Gaussian model

The Gaussian plume model is a simple and robust method of predicting dispersion, although with recognised limitations, which are summarised in Section 2. The 'R91' straight line Gaussian plume dispersion model (Clarke 1979) requires limited information. It needs an assumed effective release height and release duration, the atmospheric stability category (eg Pasquill) (which in turn assumes a default wind speed for each category), and either a release rate or a total release or the value and location of a measurement(s), in terms of downwind and off-axis distances. As applied here, it assumes no radioactive decay during the plume passage and does not include plume depletion due to deposition processes. Dry deposition is modelled through deposition velocities (see Jones, 1983). Also as applied here, wet deposition is represented empirically as enhancement factors to dry deposition, representing light and heavy rainfall.

The basic Gaussian plume model equation for time integrated activity concentration in air on the plume centre line at ground level[1] (including contributions from the first plume reflection from the ground but ignoring later reflection terms) is as follows (from Higgins and Jones 2003):

$$C\,(x) = Q\,(2\pi\,\sigma_y\,\sigma_z\,u_{10})^{-1}\,\exp(-h^2/2\sigma_z^2) \qquad (1)$$

where:

C (x) is the time integrated activity concentration in air over the release period (Bq s m^{-3}) at downwind distance x (m)

Q is the total amount of activity released (Bq)

[1] Activity concentrations in air at 'ground level' are assumed here to be 1 m above the ground.

σ_y and σ_z are the standard deviations of the horizontal and vertical plume size at distance x (m)

u_{10} is the wind speed at 10 m above the ground (m s^{-1})

h is the effective release height (m).

The σ_y term can be represented as follows (from Clarke 1979):

$$\sigma_y^2 = \sigma_{yt}^2 + \sigma_{yw}^2 \tag{2}$$

where:

σ_{yt} is the component of σ_y due to turbulent diffusion, and

σ_{yw} is the component of σ_y due to fluctuation in wind direction.

One approximation for the σ_{yw} term (also from Clarke 1979) is:

$$\sigma_{yw} = 0.065 \sqrt{(7T/u_{10})}\ x \tag{3}$$

where:

T is the release duration (hours)

x is the downwind distance on the plume centre-line (m).

The exponential term in equation 1 tends to 1 in circumstances other than at distances close to the release point in combination with very high release heights. For the conditions considered in this study, C varies monotonically with release height, release duration and weather category (with an exception, again, in the case of very high effective release heights). Although, using the above formulation, C does not strictly vary monotonically with wind speed, the σ_{yw} term only becomes significant in terms of its impact on σ_y for long duration releases, otherwise C is inversely proportional to wind speed. Both σ_y and σ_z are predominantly a function of downwind distance rather than wind speed. Therefore, for the application considered here, the calculations can be considered to be approximately multiplicative (if the complexities introduced by very elevated release heights are ignored) and the peak concentration or deposit will correspond to the maximum or minimum value of the parameter considered. The results will therefore indicate to a first approximation the significance of the input parameters considered in a sensitivity study of the type presented in this section.

This simple approach enables changes in key input parameters to be made simply and the link between changes in input parameters and changes in the results to be transparent because of the relative simplicity of the calculations involved. The method reflects that used at HPA at present for the early stages of an accidental release of radionuclides to the atmosphere or in a national or international exercise, which produces robust dose assessments through transparent calculations, and requires very few input data to produce predictions on which an early understanding of the scale of the accident can be based.

3.2.2 NAME model

The UK Met Office's Numerical Atmospheric-dispersion Modelling Environment (called NAME III, but referred to as NAME for simplicity here) is a Lagrangian particle-puff model for predicting dispersion and deposition of gases and particulates. In emergency response applications, NAME can use as input observed local meteorological data, 3-D meteorology from a Numerical Weather Prediction (NWP) model such as the Unified Model (UM) and radar measured rainfall data. For radiological releases, NAME incorporates both radioactive decay processes and estimates of the external dose from the radioactive plume, in addition to non-radiological features such as plume rise and the effects of buildings. NAME provides as output the time-averaged and time integrated activity concentrations in air, and wet, dry and total ground depositions of radionuclides.

NWP meteorological models are run at global or large region scale, primarily for the purpose of operational weather forecasting. However, the UK Met Office's

Unified Model is an NWP model used for both weather prediction and long term climate modelling (Cullen 1993; Staniforth and Wood 2008). The UM comprises a set of sub-models and processing systems that can be configured in alternative ways to suit the particular application. The latest version of UM has a grid resolution of 1.5 km^2, sufficient to enable plume dispersal resulting from an accidental release to be adequately indicated at the distances over which the early countermeasures of sheltering and evacuation may potentially be required (up to a few 10s of kilometres from the release point), although still finer resolution may be available in the next few years.

3.2.3 General method

The method that has been used is to combine the predictions of a dispersion model with simple dose assessment and countermeasure prediction calculations. Theoretical measurement locations are used, together with assumptions on basic meteorological data (wind direction, rainfall presence/intensity and stability category) to estimate the locations where evacuation and sheltering are required. In terms of the dispersion modelling applied, both in the simple R91 model and NAME, the affected area is assumed here to be predominantly rural.

Inhalation doses are estimated on the basis of predicted activity concentrations in air. The doses are calculated for 10 year old children, and for effective dose, for comparison against the ERLs for sheltering and evacuation. The calculation assumes standard breathing rates and dose per unit intake factors (see Table 3.1).

The calculation of external doses from deposited radionuclides requires predicted levels of ground deposition. These are based on activity concentrations in air and require assumptions concerning dry and wet deposition velocities. Wet deposition requires assumptions on the type of rainfall (eg light or heavy). From ground deposition, external doses can then be calculated using a model which allows for radioactive decay, including ingrowth of daughter products, and simple redistribution through the underlying soil following a single instantaneous deposition; the model used here is that specified in Kowe *et al* (2007). The values of dose per unit deposited activity used are shown in Table 3.1. Estimation of external dose requires an assumption about the length of time a person is present at the location for, which for the purposes of estimating the need for countermeasures is here taken as 2 days.

Table 3.1 Basic data assumptions in the assessments

Breathing rate, 10 year old child (m^3 s^{-1})	$1.8\ 10^{-4}$
Inhalation dose per unit intake (Sv Bq^{-1}): ^{137}Cs ^{131}I	 $3.7\ 10^{-9}$ $3.4\ 10^{-8}$
External dose per unit deposit for 2 days exposure (Sv per Bq m^{-2}): ^{137}Cs ^{131}I	 $6.44\ 10^{-11}$ $4.37\ 10^{-11}$

The measure of dose used in emergency planning to determine the need for a countermeasure is the dose averted by the countermeasure, which is then compared with the ERL. Here, the countermeasure extents are based on the addition of the committed effective inhalation dose to a 10 year old child from the cloud and the effective external dose to a 10 year old child from deposited activity, from the start of the release up to 2 days afterwards, compared against the criteria of the lower ERLs for sheltering and evacuation[1]. The period of 2 days has been selected as an approximation to the duration of the sheltering and evacuation countermeasures. The indicator of the need for countermeasures is expressed in terms of the distance on the plume centre line out to which the appropriate ERL is exceeded.

The doses are the sum of doses from the plume arrival time to the disappearance of the cloud from the location (for inhalation dose) or to 2 days (for external dose). The doses used here are therefore the total dose to 2 days at each location rather than the dose averted, which is the measure of dose

[1] These ERLS are averted doses of 3 mSv and 30 mSv effective dose, respectively.

which is used for comparison against ERLs in emergency planning. However, since the purpose of this study is to identify the key parameters likely to introduce imprecision into the decision making process, this distinction is not important here.

Single values of effective dose per unit intake (DPUI) for inhalation were used in the study as shown in Table 3.1 and no variation on these was considered as it is common practice to base early countermeasure predictions on a single assumed value for the DPUI of each radionuclide in a form considered likely to be released in an accident. More refined DPUIs, for specific chemical forms, may be used in later assessments on the basis of measurement information. The values used here are applicable to a 10 year old child, and are standard assumptions for ^{137}Cs and ^{131}I in early emergency calculations at a time prior to identification of chemical form[1].

Using this method, the impact of the imprecision associated with predictions based on a single postulated off-site measurement at an early time has been estimated. This has been done by developing a baseline set of input parameters (see Table 3.2) and then for each parameter in turn varying its value to a plausible minimum and/or maximum by considering the range of values the parameter may take within the context of the baseline accident (i.e., not the full range of values the parameter may take in any accident), and hence calculating the effect on the predicted extent of countermeasures. In effect, this has investigated the consequences, in terms of the furthermost extent of required countermeasures, of a set of related accidents. By varying a single parameter at a time, the difference caused by making a plausible error in that one parameter can be seen. The calculations using the R91 model and also the NAME model are based on an assumed single 'measured' activity concentration in air at 2 km which is then extrapolated to other downwind distances using the dispersion model. For the NAME analysis, the calculations were then repeated for an assumed single 'measured' activity concentration in

[1] For ^{137}Cs the DPUI is for absorption Type F and a particle AMAD of 1 μm, and for ^{131}I is for an average of the dose coefficients for the inhalation of elemental iodine vapour and inhalation of particulate aerosols with AMAD of 1 μm, with an absorption type F.

air at 5 km. By holding unchanged the 'measured' activity concentration while changing a single parameter in the calculation, in effect a new source strength is estimated and the dispersion model is rerun with this source strength to estimate concentrations elsewhere. In the derivation of the parameter ranges below, it is important to note that the calculations are not based on an assumed release or source term but on this single assumed downwind activity concentration in air.

Table 3.2 Parameter values for the baseline calculation (R91 and NAME)

Release duration	1 hour
Release height (stack)	10 m
Plume rise (effective release height)	None (i.e., the release height is the baseline 10 m)
Pasquill meteorological stability category	D
Wind speed (in NAME, wind speed at 10m above ground)	5 m s^{-1}
Wind direction	'Measured' activity concentrations in air at 2 km and 5 km are assumed to be on plume centre line
Particle size: ^{137}Cs ^{131}I	 100% 1 µm AMAD Assumed elemental iodine vapour
Dry deposition velocity: ^{137}Cs ^{131}I	 10^{-3} m s^{-1} 10^{-2} m s^{-1}
Rain-out/washout coefficient	No rain
Terrain and building effects	None

3.3 Assessment of imprecision using a simple dispersion model

Baseline calculations were set up, for hypothetical releases of ^{137}Cs and ^{131}I; the parameters of the baseline calculation are shown in Table 3.2. The calculations assume a single measurement of activity concentration in air at 2 km downwind, based on the relationship implied by the Gaussian plume model between the source term and the activity concentration in air at 2 km, using the baseline parameter values. The baseline source term for ^{137}Cs was 1 10^{16} Bq, and the baseline for ^{131}I was 10 times smaller to ensure a similar predicted extent of countermeasures for the two radionuclides, see Table 3.3.

Table 3.3 Source terms and measurements assumed

	R91	NAME
Assumed source term:		
^{137}Cs	$1\ 10^{16}$ Bq (released uniformly over 1 hour)	-
^{131}I	$1\ 10^{15}$ Bq (released uniformly over 1 hour)	-
'Measured' instantaneous activity concentration in air at 2 km downwind and 1 m above ground level on plume centre line[a]:		
^{137}Cs	$1.1\ 10^{7}$ Bq m^{-3}	$1.1\ 10^{7}$ Bq m^{-3}
^{131}I	$1.1\ 10^{6}$ Bq m^{-3}	$1.1\ 10^{6}$ Bq m^{-3}
'Measured' instantaneous activity concentration in air 5 km downwind and 1 m above ground on plume centre line[a]:		
^{137}Cs	-	$2.6\ 10^{6}$ Bq m^{-3}
^{131}I	-	$2.6\ 10^{5}$ Bq m^{-3}

[a] Dividing an air sample measurement, in units of Bq s m^{-3}, by the number of seconds in the measurement period gives an instantaneous air concentration in Bq m^{-3} which is analogous to the value given here. In the case of the R91 runs the measurement was assumed to be constant over the release duration, while in the case of the NAME runs the measurement was assumed to be taken 50-60 minutes after the start of the release.

Plausible minimums and/or maximums for each parameter considered were derived as discussed above in Section 2 and as summarised in Table 3.4, and the impact on the predicted countermeasure extents (as indicated by the distance to which these are required on the plume centre line) and on the source term, of the variation of each parameter in turn was then calculated, with all parameters other than the one being varied held at the value in the baseline case.

In addition, certain combinations of parameter changes were also considered. The impact of variations in two or more parameters on the time integrated activity concentration in air may be different in combination compared to their separate effects; in some instances the parameters themselves may have correlated likelihood (eg, if one is high or low, the other is more likely to also be high or low). To explore this impact, several joint parameter variations have been considered:

- The persistence of stability category, and hence wind speed and wind direction, is linked to the duration of the release. The effect of this combination has been investigated by considering a 4 hour release duration in conjunction with adjacent stability categories to the baseline category, wind speeds at the minimums and maximums for the categories and a 10º off centre-line wind direction.

- Wind speed increases with height above the ground, hence there is a correlation between higher release heights and higher average wind speeds. The effect of this combination has been explored by considering a 200 m effective release height with an 8 m s^{-1} wind speed; an 8 m s^{-1} wind speed has been chosen to remain within the limitations of the R91 approximations. Wind speed is also linked to stability category, but typical wind speeds for the stability categories considered here (C, D, E) are similar (in the range 3 to 5 m s^{-1}).

A number of possible parameter combinations have not been analysed jointly. Although there is an approximately linear relationship between dry deposition velocity and wind speed, combining a high deposition velocity with a high wind speed will not influence the results obtained if Gaussian dispersion is assumed, because the relationship between activity concentrations in air at different points downwind is constant regardless of wind speed. Some correlation between high plume rise and the degree of variation in wind direction seems likely, but this effect is likely to be observed through early deposition measurements in combination with visual observations and so has not been considered separately here. The combination of large particles and rain has not been considered because of the interaction between this effect and plume depletion, which would have an impact on countermeasure extents which would be both accident and location specific, and is therefore beyond the scope of the simple Gaussian approach used here to model. Similarly, the combination of rain with a high effective release height would have an effect on time integrated activity concentrations in air but this has not been assessed as the impact on the extent of countermeasures of such a combination would again be complex and dependant on both the accident and the location. Finally, correlation between very low wind speeds and variable wind direction is to be expected but simple models are currently inadequate for very low wind speed (ADMLC 2004) and it is also likely that decision makers would be aware of very low wind speed situations and would take them into account in emergency decision making.

Table 3.4 Summary of the assumed meteorological and dispersion imprecision ranges

Parameter	Range	Notes
Release duration	0.5 hours 4 hours	Baseline duration is 1 hour.
Release height	5 m 20 m	A factor of 2 from the baseline release height (10 m), excluding plume rise effects.
Plume rise	200m	Effective release height.
Pasquill stability category	C E	The effect of the true category being either side of the baseline category (D) is considered.
Wind speed	2 m s^{-1} 8 m s^{-1}	It is assumed that the possible error in estimating wind speed is +/- 3 m s^{-1} of the baseline value of 5 m s^{-1}
Wind direction	+/- 10 degrees and +/- 20 degrees	The error associated with a measured wind direction of 10 and 20 degrees in either direction is investigated.
Particle size	Dry: 10 µm AMAD and 10^{-1} m s^{-1} deposition velocity Wet: 10 µm AMAD with a rain multiplying factor of 100	Particles of 10 µm AMAD are considered, and for these a dry deposition velocity of 10^{-1} m s^{-1} is assumed, in combination with a multiplying factor of 100 for wash-out.
Dry deposition velocity	^{137}Cs: 10^{-2} m s^{-1} to 10^{-4} m s^{-1} ^{131}I: 10^{-1} m s^{-1} to 10^{-3} m s^{-1}	An order of magnitude either side of the baseline deposition velocity is assumed.
Precipitation and washout coefficient	(a) Moderate rain (multiplying factor x10) (b) Heavy rain (multiplying factor x100)	It is assumed that (a) there is moderate rainfall (about 1 mm h^{-1}), increasing deposition by a factor of 10 compared to dry conditions, and (b) there is very heavy rainfall, increasing deposition by a factor of 100 compared to dry conditions.
Terrain & building effects	Peak concentration x 5	It is assumed that concentrations over the first 10km from a release point will be 5 times greater than predicted by a model which does not take terrain or building effects into account.

No correlation between location specific effects and the other parameters considered in the study are thought to exist which would significantly increase the effect on the time integrated activity concentrations in air at ground level.

Table 3.5 summarises the influence of varying each of the parameters singly on the source term (defined here as the estimated release which gives rise to the same baseline activity concentration in air at 2 km), and also on the predicted downwind extent of countermeasures on the plume centre line, assuming an unchanging ‘measured’ activity concentration in air at 2 km, as described above, and using the simple R91 Gaussian dispersion model.

It can be seen from Table 3.5 that some of the parameters influence the predicted effective release but not the downwind countermeasure extents, while others influence the countermeasure extents but not the corresponding effective release. Most of the parameter variations which are of significance influence both endpoints. At high deposition velocities and rainfall rates, the influence of plume depletion would be significant and the countermeasures estimated would not in reality extend as far as the simple model used here (which does not allow for plume depletion) suggests; this is discussed further below when the more complex NAME model is used. The results obtained by considering several factors in combination show that combined effects do not significantly alter the results for the effects considered singly, which tend to be largely dominated by a single factor, notably plume rise or release duration.

It can be seen that the results are in close agreement for both radionuclides, with the partial exception of the influence of rain; in this situation, the external doses for ^{137}Cs are enhanced because of the greater levels of deposition but the same degree of enhancement is not seen for ^{131}I because of the domination of the inhalation pathway for this radionuclide.

Certain parameter alterations (for example, deposition velocity and wash-out coefficient) have no effect on the estimated release but do have an effect on the predicted extent of countermeasures. This is because the alteration affects the amount of activity deposited on the ground, which alters the external dose from deposited activity and hence influences the countermeasures required. However the alteration does not affect the air concentration at 2km, and hence has no influence on the amount of activity assumed to be released.

Table 3.5 Effective release and extent of evacuation/sheltering at lower ERL predicted by R91 from anchor air concentration at 2 km[a]

	Effective release of ^{137}Cs (Bq)	Extent of evacuation, sheltering on plume centre line at lower ERL[b] for release of ^{137}Cs	Effective release of ^{131}I (Bq)	Extent of evacuation, sheltering on plume centre line at lower ERL[b] for release of ^{131}I
Baseline source term	$1\ 10^{16}$	2 km, 10 km	$1\ 10^{15}$	2 km, 10 km
Release duration:				
0.5 hours	$8\ 10^{14}$	<1 km, 2 km	$8\ 10^{13}$	<1 km, 2 km
4 hours	$6\ 10^{16}$	5 km, 30 km	$6\ 10^{15}$	5 km, 20 km
Release height (stack):				
5 m	$1\ 10^{16}$	2 km, 10 km	$1\ 10^{15}$	2 km, 10 km
20 m	$1\ 10^{16}$	2 km, 10 km	$1\ 10^{15}$	2 km, 10 km
Plume rise (effective release height):				
200 m	$3\ 10^{17}$	20 km, >30 km	$3\ 10^{16}$	20 km, >30 km
Pasquill stability category:				
C	$2\ 10^{16}$	2 km, 10 km	$2\ 10^{15}$	2 km, 10 km
E	$4\ 10^{15}$	2 km, 10 km	$4\ 10^{14}$	2 km, 10 km
Wind speed:				
$2\ m\ s^{-1}$	$5\ 10^{15}$	2 km, 10 km	$5\ 10^{14}$	2 km, 10 km
$8\ m\ s^{-1}$	$1\ 10^{16}$	2 km, 10 km	$1\ 10^{15}$	2 km, 10 km

Wind direction:				
+/- 10º from assumed plume centre line	$4\ 10^{16}$	5 km, 30 km	$4\ 10^{15}$	5 km, 20 km
+/- 20º from assumed plume centre line	$3\ 10^{18}$	>30 km, >30 km	$3\ 10^{17}$	>30 km, >30 km
Particle size:				
10 µm AMAD (10^{-1} m s^{-1} deposition velocity)	$1\ 10^{16}$	10 km, >30 km	Not applicable for elemental iodine	
Dry deposition velocity:				
10^{-2} m s^{-1} for ^{137}Cs, 10^{-1} m s^{-1} for ^{131}I	$1\ 10^{16}$	3 km, 20 km	$1\ 10^{15}$	3 km, 20 km
10^{-4} m s^{-1} for ^{137}Cs, 10^{-3} m s^{-1} for ^{131}I	$1\ 10^{16}$	2 km, 10 km	$1\ 10^{15}$	2 km, 10 km
Precipitation and washout coefficient:				
Light rain	$1\ 10^{16}$	3 km, 20 km	$1\ 10^{15}$	2 km, 10 km
Heavy rain	$1\ 10^{16}$	10 km, >30 km	$1\ 10^{15}$	3 km, 20 km
Terrain and building effects:	$2\ 10^{15}$	<1 km, 4 km	$2\ 10^{14}$	<1 km, 3 km
Combination effects:				
4 hour release, Cat C, 2 m s^{-1} wind speed	$6\ 10^{16}$	5 km, 20 km	$6\ 10^{15}$	5 km, 20 km
4 hour release, Cat C, 8 m s^{-1} wind speed	$1\ 10^{17}$	5 km, 20 km	$1\ 10^{16}$	5 km, 20 km
4 hour release, Cat E, 2 m s^{-1} wind speed	$2\ 10^{16}$	5 km, 30 km	$2\ 10^{15}$	5 km, 20 km
4 hour release, Cat E, 8 m s^{-1} wind speed	$5\ 10^{16}$	5 km, 30 km	$5\ 10^{15}$	5 km, 20 km
4 hour release, Cat D, 5 m s^{-1} wind speed, 10º off plume centre line	$1\ 10^{17}$	10 km, >30 km	$1\ 10^{16}$	10 km, 30 km
200m effective release height, Cat D, 8 m s^{-1} wind speed	$4\ 10^{17}$	20 km, >30 km	$3\ 10^{16}$	30 km, >30 km

Notes:

a. The baseline activity concentration in air at 2 km on the plume centre line is $1.1\ 10^{7}$ Bq m^{-3} for ^{137}Cs, and $1.1\ 10^{6}$ Bq m^{-3} for ^{131}I.

b. The lower ERLs for sheltering and evacuation are averted doses of 3 mSv and 30 mSv effective dose, respectively.

While the approach used here is a simple Gaussian-based method, the results do give a clear indication of the parameters which separately have the most influence on the predicted downwind extent of countermeasures and hence which are most significant if inadequately known in a particular accident situation. These are:

- the duration of the release,
- the extent of plume rise,
- an inaccurate wind direction (including changes with height),
- a high deposition velocity (possibly as a result of large particle sizes),
- the effect of heavy rain (in the case of ^{137}Cs; the effect is less marked for ^{131}I).

The significant parameters can be subdivided into two categories, those which result from the nature of the accident itself (duration, plume rise, particle size) and those which result from or are influenced by the weather conditions in the area at the time (wind direction, rain, deposition velocity). Imprecision in the parameters which relate to the accident itself is to some extent unavoidable in the early stages of an emergency; this lack of knowledge will only be significantly reduced when more information is available about the state of the plant and the nature of its discharges. However, the imprecision which is related to the weather has the potential to be reduced through linkage between a radiological emergency assessment tool and high quality real-time weather/dispersion prediction tools, if results from the latter are available with sufficiently detailed resolution and on an adequate timescale. In conclusion, the assessment with simple Gaussian dispersion has demonstrated that weather parameters are among the most significant in estimating the radiological consequences of releases in emergency response and that they have implications for decisions on emergency countermeasures in the local affected region.

3.4 Assessment of imprecision using a complex dispersion model

This section re-evaluates the key imprecision parameters as derived above using the simple Gaussian plume model, using a more complex dispersion model, the UK Met Office's NAME III (Numerical Atmospheric dispersion Modelling Environment version 5.2) dispersion model (Jones *et al* 2007; Thomson and Jones 2007), which is part of the Met Office's real-time weather and dispersion prediction capability. The reassessment is important, to demonstrate that the findings above were not a consequence of the simple dispersion model used, and to show that the results obtained are robust despite the choice of dispersion model. The imprecision is estimated on the basis of the same baseline input parameters as shown above in Table 3.2, and varying these parameters to their plausible minimum and/or maximum as shown above in Table 3.4. Again, the result indicators used are the extent of the estimated sheltering and evacuation countermeasures, and the predicted source term. The reassessment with the NAME model also explores the impact on the results of considering a different location point for the assumed measurement.

3.4.1 Differences between R91 and NAME dispersion predictions for a short-duration release

Before discussing the results and considering how they compare to the results of the previous section, it is useful to first compare the underlying dispersion predictions as indicated by the R91 and NAME models, assuming the same source term and the same baseline input parameters. Table 3.6 shows the plume centre-line activity concentrations in air obtained from R91 and NAME, for a release of 1 10^{16} Bq of ^{137}Cs, and for a release of 1 10^{15} Bq of ^{131}I. A release duration of 1 hour and a release height of 10 m were assumed, together with Pasquill meteorological stability category D, a wind speed of 5 m s^{-1} and no rain. The terrain assumed is typical rural land with no significant features to influence the dispersion. NAME models explicitly the time taken for the plume to reach each grid point, and the average activity concentrations in air from NAME given here are those predicted to occur 50-60 minutes after the start of the release; the values are the time-averaged concentrations over this 10 minute period. In contrast, R91 calculates the total eventual time integrated air concentration (TIAC) at each point, and the average activity concentrations in air from R91 given in Table 3.6 are obtained by dividing the TIAC by the numbers of seconds in one hour; these therefore represent an average over the total time of plume passage.

It can be seen from Table 3.6 that for the same source term NAME predicts time-averaged activity concentrations in air which are somewhat smaller than those predicted by R91 but the difference decreases with distance (a factor of about 4 at 1 km, 3 at 2 - 5 km, and less than 2 at 10 - 20 km). There is less difference if the time integrated concentrations are considered.

Table 3.6 Activity concentrations in air predicted by R91 and NAME for a release of 1 10^{16} Bq of ^{137}Cs and 1 10^{15} Bq of ^{131}I over 1 hour

^{137}Cs	Time-averaged activity concentration in air at given down-wind distance on plume centre line, (Bq m^{-3})[a]				
	1km	2km	5km	10km	20km
R91	4 10^7	1 10^7	3 10^6	9 10^5	3 10^5
NAME	1 10^7	4 10^6	1 10^6	5 10^5	2 10^5
	Time integrated activity concentrations (TIAC) in air at given down-wind distance on plume centre line (Bq s m^{-3}) over total time of plume passage				
	1km	2km	5km	10km	20km
R91	1 10^{11}	4 10^{10}	9 10^9	3 10^9	1 10^9
NAME	4 10^{10}	2 10^{10}	5 10^9	2 10^9	8 10^8
^{131}I	Time-averaged activity concentration in air at given down-wind distance on plume centre line, (Bq m^{-3})[a]				
	1km	2km	5km	10km	20km
R91	4 10^6	1 10^6	3 10^5	9 10^4	3 10^4
NAME	1 10^6	4 10^5	1 10^5	5 10^4	2 10^4
	Time integrated activity concentrations (TIAC) in air at given down-wind distance on plume centre line (Bq s m^{-3}) over total time of plume passage				
	1km	2km	5km	10km	20km
R91	1 10^{10}	4 10^9	9 10^8	3 10^8	1 10^8
NAME	4 10^9	2 10^9	4 10^8	2 10^8	7 10^7

a. The activity concentration in air in NAME given here is the average 50-60 minutes after the start of the release whereas the R91 value is the average over the time of plume passage.

The results are not sensitive to assuming that the average activity concentrations in air occur 50-60 minutes after the start of the release, as there is little variation with time in the NAME air concentrations at 2km on the plume centre line for all the times except those near the start and finish of the release. Figure 3.1 shows the time variation in activity concentrations in air at 2km downwind for the baseline release of 1 10^{16} Bq of ^{137}Cs over 1 hour (Bedwell *et al* to be published).

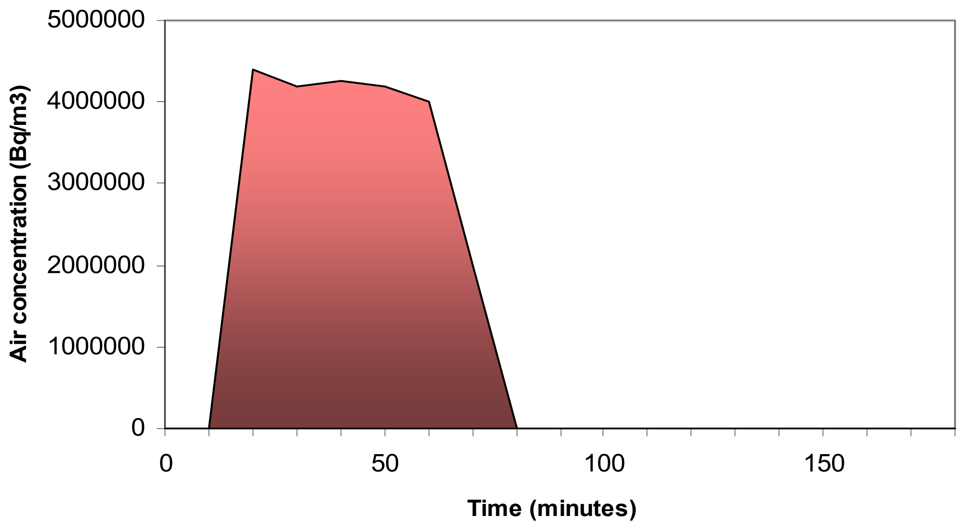


Figure 3.1 Activity concentrations in air at 2km predicted by NAME for a release of 1 10^{16} Bq of ^{137}Cs over 1 hour

The reasons for differences between the predictions of NAME and R91 are complex, being due to the way in which the two models apply meteorological data and the different approaches to modelling plume dispersion. The issues have been explored and resolved, and are discussed in detail by Bedwell *et al* (to be published). While R91 considers each input parameter independently (for example, atmospheric stability and wind speed are incorporated in separate parameters with no dependency or inter-relationship), in NAME the impact of one parameter on another is taken into account (for example, atmospheric wind speed impacts on stability). Also, the treatment of wind speed with height above the ground is different in the two models as R91 assumes a single wind speed whereas NAME considers a continuous profile of wind speeds, wind directions and other meteorological parameters over the depth of the atmosphere, enabling more realistic modelling of turbulence and mixing. Some reduction in the ground level activity concentrations in air predicted by NAME compared to those predicted by R91 would be expected to result from this in typical situations. Furthermore, in the particular examples considered in this study, differences between the two models in the standard deviation of the cross wind plume profile (σ_y) and vertical plume profile (σ_z) result in the NAME plume being somewhat wider and deeper than the R91 plume at 2km, and somewhat narrower but of similar depth at distances approaching 20km. Again, the effect is that the activity concentrations in air close to the ground are predicted to be less by NAME than by R91 at short distances.

Because NAME explicitly models the time taken for the plume to reach each grid point, unlike the calculation in R91 which assumes instantaneous travel, the NAME predictions for different distances reach a steady-state level at different times. For example, the average activity concentration in air at 20km in the period 50-60 minutes after the start of the release is not yet a steady-state value; the activity concentration in air predicted by NAME is about a factor of 50% lower than the levels reached about 20 minutes later.

By scaling the results presented in Table 3.6 it can be seen that a release of 3 10^{16} Bq of ^{137}Cs would result in NAME predicting an instantaneous activity concentration in air of approximately 1 10^{7} Bq m^{-3} at 2km on the plume centre line, for the 50-60 minute 'measurement' period, which approximates to the value used in the R91 assessment above as the baseline 'measurement'. Similarly, for ^{131}I, an instantaneous activity concentration in air of 1 10^{6} Bq m^{-3} at 2km on the plume centre line (approximately the value used in the R91 assessment above as the baseline 'measurement' for ^{131}I) for the 50-60 minute 'measurement' would be predicted by NAME from a release of 3 10^{15} Bq of this radionuclide. These values are relevant in explaining the results of the two models, as discussed below.

Table 3.7 shows the countermeasure extents implied by NAME's dispersion prediction for the 1 10^{16} Bq release (the source term for ^{137}Cs used in the R91 assessment above) and by the scaled 3 10^{16} Bq release (for which NAME predicts the baseline 2km activity concentration in air ‘measurement’ for ^{137}Cs used in the R91 assessment). It can be seen that the predicted extent of countermeasures for the 3 10^{16} Bq release is similar to that obtained using R91 but that the extent of sheltering is somewhat greater (15km compared to 10km). The equivalent results for ^{131}I show that for this radionuclide, for the scaled 3 10^{15} Bq release, the predicted extent of countermeasures is the same as that obtained using R91. The difference in the predictions of the extent of countermeasures for the source terms used in the R91 assessment (1 10^{16} Bq for ^{137}Cs and the 1 10^{15} Bq for ^{131}I) is due to the fundamental difference in the model predictions as described above, namely the lower predictions by NAME in comparison to R91 of a factor of up to 3 for distances from 2 km outwards.

For both radionuclides, R91 predicts larger activity concentrations in air at distances up to 20 km than those predicted by NAME for the same source term, and in this sense R91 is ‘conservative’. However, for the same simulated measurement at 2km the opposite effect is seen on the predicted extent of countermeasures, because the same ‘measurement’ at 2 km implies a greater source term if NAME is used than if R91 is used. The use of R91 to predict the extent of countermeasures based on a measured value therefore may well not be the conservative approach commonly assumed, being dependent on the location of the measurement.

The differences between R91 and the NAME model are explained further in Appendix 1.

Table 3.7 Extent of evacuation and sheltering based on R91 and NAME dispersion predictions for the baseline calculation

^{137}Cs	Extent of evacuation / sheltering for ^{137}Cs
R91 (1 10^{16} Bq total release and 1.1 10^{7} Bq m^{-3} average instantaneous activity concentration in air at 2km on plume centre line)	2 km / 10 km
NAME 1 10^{16} Bq total release 3 10^{16} Bq total release (giving 1 10^{7} Bq m^{-3} instantaneous activity concentration in air at 2km on plume centre line at 50-60 minutes)	 1 km / 5 km 2 km / 15 km
^{131}I	Extent of evacuation / sheltering for ^{131}I
R91 (1 10^{15} Bq total release and 1.1 10^{6} Bq m^{-3} average instantaneous activity concentration in air at 2km on plume centre line)	2 km / 10 km
NAME 1 10^{15} Bq total release 3 10^{15} Bq total release (giving 1 10^{6} Bq m^{-3} instantaneous activity concentration in air at 2km on plume centre line at 50-60 minutes)	 1 km / 5 km 2 km / 10 km

3.4.2 Key imprecision parameters based on NAME dispersion predictions

As in the R91 analysis above, the NAME-based results assume a 'measured' activity concentration in air at a specific location in relation to the release point in the downwind direction; by holding unchanged the 'measured' activity concentration while changing a single parameter in the calculation, in effect an altered source strength is estimated and the NAME model is rerun with this new source strength to estimate concentrations elsewhere, which are then used to determine the extent of countermeasures. The assumed 'measured' activity concentrations in air are the same values as used in the R91 assessment above, being derived from the R91 model's prediction of the activity concentration on the plume centre line from a release of the baseline source term. The baseline R91 source term for ^{137}Cs was 1 10^{16} Bq, and the baseline R91 source term for ^{131}I was 10 times smaller to ensure a similar predicted extent of countermeasures for the two radionuclides. The 'measurement' period is assumed to occur between 50 – 60 minutes after the start of the release, at which point the activity concentration levels in air in the area of interest (2km on the plume centre line) are steady. As discussed above, the assumed source terms implied by these 'measurements' when the NAME model is used differ from those indicated by the R91 model, suggesting releases of 3 10^{16} Bq of ^{137}Cs and 3 10^{15} Bq of ^{131}I. This reflects the differences in the predictions of the two dispersion models at 2km downwind. However, it can be seen from Table 3.7 that the predicted extents of countermeasures based on the NAME results are similar to those predicted using R91.

Table 3.8 shows the results of the imprecision analysis based on the NAME dispersion predictions, in terms of the extent of evacuation and sheltering predicted from the single assumed activity concentration in air measurement at 2km downwind on the plume centre line, this being the assumed measurement location used in the previous study. However, Table 3.8 also shows the influence on the results of repeating the calculations for a baseline measurement at a different location, to investigate whether there are significant differences in the results obtained.

Table 3.8 Effective release and extent of evacuation/sheltering at lower ERL predicted by NAME from anchor air concentrations at 2 km and 5 km[a]

	Effective release of ^{137}Cs (Bq)		Extent of evacuation, sheltering on plume centre line at lower ERL[b] for release of ^{137}Cs		Effective release of ^{131}I (Bq)		Extent of evacuation, sheltering on plume centre line at lower ERL[b] for release of ^{131}I	
Location of 'anchor air concentration 'measurement'	2km	5km	2km	5km	2km	5km	2km	5km
Baseline source term	$3\ 10^{16}$	$2\ 10^{16}$	2 km, 15 km	2 km, 10 km	$3\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
Release duration:								
0.5 hours[c]	-[c]	-[c]	-[c]	-[c]	-[c]	-[c]	-[c]	-[c]
4 hours	$1\ 10^{17}$	$8\ 10^{16}$	5 km, > 30 km	5 km, 30 km	$1\ 10^{16}$	$8\ 10^{15}$	5 km, 30 km	4 km, 25 km
Release height (stack):								
5 m	$3\ 10^{16}$	$2\ 10^{16}$	2 km, 10 km	2 km, 10 km	$3\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
20 m	$3\ 10^{16}$	$2\ 10^{16}$	2 km, 10 km	2 km, 10 km	$3\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
Plume rise (effective release height):								
200 m	$1\ 10^{17}$	$4\ 10^{16}$	3 km, > 30 km	0 km, 15 km	$1\ 10^{16}$	$4\ 10^{15}$	0 km, > 30 km	0 km, 10 km
Pasquill meteorological stability category:								
C	$8\ 10^{16}$	$5\ 10^{16}$	2 km, 15 km	2 km, 10 km	$9\ 10^{15}$	$5\ 10^{15}$	2 km, 15 km	2 km, 10 km
E	$7\ 10^{15}$	$6\ 10^{15}$	2 km, 10 km	2 km, 10 km	$8\ 10^{14}$	$7\ 10^{14}$	2 km, 10 km	2 km, 10 km
Wind speed (assuming stability category D):								
2 m s^{-1}	$2\ 10^{16}$	$2\ 10^{16}$	2 km, 10 km	2 km, 10 km	$2\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
8 m s^{-1}	$4\ 10^{16}$	$3\ 10^{16}$	2 km, 15 km	2 km, 10 km	$4\ 10^{15}$	$3\ 10^{15}$	2 km, 10 km	2 km, 10 km

Wind direction:								
Plume centre line +/- 10º from direction assumed	$7\ 10^{16}$	$9\ 10^{16}$	4 km, 25 km	5 km, 30 km	$7\ 10^{15}$	$9\ 10^{15}$	4 km, 20 km	4 km, 25 km
Plume centre line +/- 20º from direction assumed	$1\ 10^{18}$	$7\ 10^{18}$	>30 km, >30 km	>30 km, >30 km	$1\ 10^{17}$	$7\ 10^{17}$	30 km, >30 km	>30 km, >30 km
Particle size:								
10^{-1} m s^{-1} deposition velocity	$4\ 10^{16}$	$4\ 10^{16}$	10 km, 30 km	10 km, 30 km	Not applicable for elemental iodine			
Dry deposition velocity:								
10^{-2} m s^{-1} for ^{137}Cs, 10^{-1} m s^{-1} for ^{131}I	$3\ 10^{16}$	$2\ 10^{16}$	3 km, 20 km	2 km, 15 km	$4\ 10^{15}$	$4\ 10^{15}$	3 km, 10 km	2 km, 10 km
10^{-4} m s^{-1} for ^{137}Cs, 10^{-3} m s^{-1} for ^{131}I	$3\ 10^{16}$	$2\ 10^{16}$	2 km, 10 km	2 km, 10 km	$3\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
Precipitation and washout coefficient:								
Light rain	$3\ 10^{16}$	$2\ 10^{16}$	3 km, 25 km	2 km, 20 km	$3\ 10^{15}$	$2\ 10^{15}$	2 km, 10 km	2 km, 10 km
Heavy rain	$3\ 10^{16}$	$3\ 10^{16}$	10 km, >30 km	5 km, >30 km	$3\ 10^{15}$	$3\ 10^{15}$	2 km, 10 km	2 km, 10 km

Notes:

a. The baseline activity concentration in air at 2 km on the plume centre line is 1.1 10^{7} Bq m^{-3} for ^{137}Cs, and 1.1 10^{6} Bq m^{-3} for ^{131}I. The baseline activity concentration in air at 5 km on the plume centre line is 2.6 10^{6} Bq m^{-3} for ^{137}Cs, and 2.6 10^{5} Bq m^{-3} for ^{131}I.

b. The lower ERLs for sheltering and evacuation are averted doses of 3 mSv and 30 mSv effective dose, respectively.

c. NAME predicts zero activity in air concentrations at 2km and 5km in the 50-60 minute period, and therefore no corresponding source term or countermeasure extents can be predicted for this parameter value on the basis of an assumed measurement of activity concentration in air at 50-60 minutes after the start of the release.

The assumed 'measured' activity concentrations in air at 5km downwind on the plume centre line are for consistency also derived from the R91 model's prediction of the activity concentration on the plume centre line in baseline conditions. This location was selected as being one of the further locations from which very early monitoring results are simulated in UK emergency exercises. The R91 predictions of the activity concentration in air at 5 km from a 1 10^{16} Bq release of ^{137}Cs and a 1 10^{15} Bq release of ^{131}I in the baseline calculations are 2.6 10^{6} Bq m^{-3} and 2.6 10^{5} Bq m^{-3} respectively, and Table 3.8 shows the results for the scaling to these concentrations at 5km. It can be seen from Table 3.8 that changing the measurement location to 5km makes little difference to the extent of countermeasures based on the NAME dispersion results, for the baseline case.

The results in Table 3.8 show that release height, Pasquill meteorological stability category and wind speed are not significant contributors to imprecision, as the parameter variations result in similar countermeasure extents to the baseline results for both measurement location anchor points (ie both 2km and 5km). The key parameters are discussed in turn below.

For a *release duration* of 0.5 hours, NAME predicts zero activity concentrations in air at 2km and 5km in the period 50-60 minutes after the start of the release, as the plume has already passed these points. Therefore no corresponding source term or countermeasure extents can be predicted for this parameter value on the basis of an assumed measurement of activity concentration in air at 50-60 minutes after the start of the release. For a release duration of 4 hours, a considerable increase in the extent of countermeasures compared to the baseline results is predicted. Thus, release duration is concluded to be a significant contributor to imprecision if a duration considerably different to the actual duration is assumed in assessments based on an environmental monitoring result.

For the elevated *release height* considered (200m), for the 2km measurement, there is little predicted requirement for evacuation, but sheltering is predicted to be required beyond 30km. The difference from the baseline case is less if the assumed measurement point is 5km, for which there is no predicted requirement for evacuation and a 10-15 km requirement for sheltering. Table 3.9 shows the time integrated activity concentrations in air for ^{137}Cs and ^{131}I for the results normalised to 1.1 10^7 Bq m^{-3} at 2km on the plume centre line for ^{137}Cs, and 1.1 10^6 Bq m^{-3} at 2km on the plume centre line for ^{131}I. Table 3.9 also shows the time integrated activity concentrations in air for ^{137}Cs and ^{131}I for the results normalised to 2.6 10^6 at 5km on the plume centre line for ^{137}Cs, and 2.6 10^5 at 5km on the plume centre line for ^{131}I. These more detailed results show the doses as a function of distance and demonstrate why the extent of countermeasures shown in Table 3.8 for plume rise are predicted to occur, by showing where the predicted doses fall below the 30 mSv (evacuation) and 3 mSv (sheltering) countermeasure criteria assumed in this study. NAME predicts the peak activity concentration in air to occur at around 2-3 km. In summary, the sensitivity of the results to errors in the estimation of an elevated effective release height of the order of 200m depends on the location, within the 1km to 5km region, at which the scaling measurement is assumed to be taken. It is a potentially significant parameter, in particular in terms of its impact on the predicted extent of sheltering, for measurements in the vicinity of 2km, but appears to be less significant for measurements further away for the elevated release height considered here. The differences between R91 and the NAME model in terms of plume rise are discussed further in Appendix 1.

For *wind direction*, if the plume centre line is +/- 10º from the baseline direction, predictions of the required extent of countermeasures based on the NAME dispersion results show, for both the 2km and 5km measurement locations, a considerable increase in the extent of countermeasures compared to the baseline results. In the case of the +/- 20º deviation in wind direction from the baseline direction, extensive requirements for countermeasures (> 30km) are predicted for both measurement locations. In these results, the horizontal spread of the NAME plume is significant. At 2km, NAME predicts a ratio between the 20º activity concentration in air and the plume centre line concentration of 40, and at 5km, the ratio is 250; these points are relatively close to the ‘edge’ of the plume. The very considerable increase in the predicted extent of countermeasures indicates that this factor is a significant contributor to imprecision in assessments which are Gaussian based and require an assumed plume centre line wind direction. In a non-Gaussian assessment, the significant feature is plume direction fluctuations and spread rather than inaccuracies in the estimation of a plume centre line; the significance of this aspect is considered further below, and is also discussed further in Appendix 1.

Table 3.9 Time-integrated activity concentrations in air (TIACs) for ^{137}Cs and ^{131}I from NAME for a 200m release height

Release scaled such that instantaneous air concentration at 2km is 1.1 10^{7} Bq m^{-3} ^{137}Cs						
	1km	2km	5km	10km	20km	30km
NAME TIAC on plume centre line (Bq s m^{-3})	2 10^{10}	4 10^{10}	3 10^{10}	2 10^{10}	9 10^{9}	6 10^{9}
Total effective dose (mSv)	14	30	23	14	6	4
Release scaled such that instantaneous air concentration at 2km is 1.1 10^{6} Bq m^{-3} ^{131}I						
NAME TIAC on plume centre line (Bq s m^{-3})	2 10^{9}	4 10^{9}	3 10^{9}	2 10^{9}	8 10^{8}	5 10^{8}
Total effective dose (mSv)	12	27	21	12	5	3
Release scaled such that instantaneous air concentration at 5km is 2.6 10^{6} Bq m^{-3} ^{137}Cs						
	1km	2km	5km	10km	20km	30km
NAME TIAC on plume centre line (Bq s m^{-3})	5 10^{9}	1 10^{10}	9 10^{9}	6 10^{9}	3 10^{9}	2 10^{9}
Total effective dose (mSv)	4	9	7	4	2	1
Release scaled such that instantaneous air concentration at 5km is 2.6 10^{5} Bq m^{-3} ^{131}I						
NAME TIAC on plume centre line (Bq s m^{-3})	5 10^{8}	1 10^{9}	9 10^{8}	5 10^{8}	2 10^{8}	2 10^{8}
Total effective dose (mSv)	4	8	6	4	2	1

For large *particle size*, modelled here for ^{137}Cs by an enhanced deposition velocity of 1 10^{-1} m s^{-1}, predictions based on NAME show a considerable increase in the extent of required countermeasures for both the 2km and 5km measurement anchor points, indicating that enhanced deposition velocity is a significant contributor to imprecision for radionuclides where deposition pathways contribute substantially to dose. A similar although less marked effect is seen for the deposition velocity of 1 10^{-2} m s^{-1} for ^{137}Cs. For the enhanced deposition velocity of 1 10^{-1} m s^{-1} for ^{131}I, no significant effect is observed, as deposition does not significantly impact on the dose delivered by this radionuclide, for which the dominant exposure pathway is inhalation. The results for the reduced deposition velocities of 1 10^{-4} m s^{-1} for ^{137}Cs and 1 10^{-3} m s^{-1} for ^{131}I indicate that this is not a significant parameter at levels below the baseline values.

For both light and heavy *rainfall rates*, for ^{137}Cs, a considerable increase in the extent of countermeasures compared to the NAME baseline results is shown for both the 2km and 5km measurement anchor points, indicating that the presence and degree of rainfall are significant contributors to imprecision for radionuclides where deposition pathways contribute substantially to dose. For ^{131}I, no significant effect on countermeasure extents is observed as deposition does not significantly impact on the dose delivered by this radionuclide, for which the dominant exposure pathway is inhalation.

Unlike in the R-91 based analysis, the effects of combinations of parameter changes in the NAME model were not explicitly considered. The simplicity of R-91 enabled this to be done by simply setting combinations of input parameters to the given values. In the case of NAME, this simple approach was not feasible because of the complexity of the model structure and its in-built inter-relationship between input parameters. Through this fundamentally different approach, the impact of one parameter on another is already taken into account (as, for example, in the relationship between wind speed and stability, and in the continuous profile of wind speeds, wind directions and other meteorological parameters over the depth of the atmosphere). Although in discussion with the developers of NAME it was possible to set up the model to do the baseline analysis in a manner consistent with that in R-91, the forcing of combinations of linked parameters into a system which already assumed a relationship between them would have been artificial and would not have given meaningful results. However, the analysis with real meteorological data records, as discussed below in this section and in more detail in Section 5, does demonstrate predictions based on true interlinked meteorological and release-based parameter values.

The overall conclusion from the above analysis is that while there are some recognised differences in the predictions of the R91 and NAME models in the context of short duration releases, this does not significantly change the results of the previous analysis using the simple model, in that the relatively important contributors to imprecision in emergency response assessments remain the same. The key parameters remain: a prolonged release duration, wind direction (if the assessment requires an assumed plume centre line wind direction), enhanced deposition velocity and rainfall (for those radionuclides for which deposition contributes significantly to dose), and a significantly elevated release height such as might arise if there were substantial energy associated with the release. The significance of the latter factor is shown here to depend on the distance from the release point of the measurement used as the basis for the assessment, being limited - at least for the effective release height considered here (200m) - to those distances, mostly in the 1km to 5km region, where plume rise significantly affects the dispersion pattern. Assessments based on measurements from within this region may give rise to misleading results, particularly in terms of the predicted extent of sheltering, if plume rise is not taken into account.

3.5 Impact of using real weather sequences from stored NWP files

The previous section has used the NAME model to repeat the R91 assessment of the parameters important to imprecision by estimating the extent of countermeasures resulting from straight line, theoretical dispersion conditions. This section examines what countermeasures would be predicted for past ‘real weather’ meteorological conditions, in which those weather-related features which have been shown to significantly affect the predicted extent of countermeasures (namely wind direction[1] and rainfall rate) are variable but the other parameters are fixed (within narrow bands) to those specified in the baseline case as defined above. Here, NAME has been used to assess the variations in sheltering areas resulting for alternative weather evolutions, resulting from a hypothetical release in real weather conditions occurring in 2007 and 2008.

The UK Met Office holds NWP data for past weather conditions. Sequences have been extracted from 2 years of data (2007 and 2008), in which the weather features approximate to the hypothesised baseline weather, ie Category D and approximately 5 m s^{-1} wind speed. From these two years of data, there were 51 data records lasting for 4 hours or more which are categorised in terms of the NAME model definitions as Category D and 4.5 - 5.5 m s^{-1} wind speed. Of these, 28 were dry conditions throughout the four hours considered and 23 showed at least one period of rain over the period. For each of these weather sets NAME was run to predict the dispersion of a plume of 3 10^{16} Bq of ^{137}Cs with a release duration of 1 hour from a 10m release height. A deposition velocity of 1 10^{-3} m s^{-1} was assumed. For presentational clarity, to enable the extent of the plume spread to be clearly seen and also the effect of subsequent shifts in wind direction over the period to be shown, the results exclude the effects of the initial wind direction, and all the initial wind directions have been set as 'from 270 degrees', ie towards due East.

The results presented here are for the sheltering countermeasure only, as this extends further than the evacuation countermeasure and therefore shows the impact of the weather conditions more clearly. Table 3.10 summarises the results from the real weather NAME runs and for comparison shows the NAME predictions for theoretical Gaussian dry weather conditions. The average extent of the sheltering countermeasure in real weather conditions is around 15 to 20 km, within a range of about 5km to 40km. This encompasses the predicted extent of the straight-line Gaussian predictions for dry weather conditions of

[1] In a non-Gaussian assessment, the significant feature here becomes plume direction fluctuations and spread rather than inaccuracies in the estimation of a plume centre line.

15 km. The pattern and extent of the sheltering areas are influenced by the spatial distribution of doses in the region of 3 mSv, which is the criterion assumed here for the introduction of sheltering. The dose distributions in the area vary widely even under the similar weather conditions considered here. The influence of rain is, as indicated by the sensitivity study above, one of the key reasons for this. Two examples of the varying distribution of dose in different weather conditions can be seen in Figures 3.2a and 3.2b below. The non-zero dose areas extend considerably beyond the area shown in the figures, but are truncated here to show the detail in the closer-in regions.

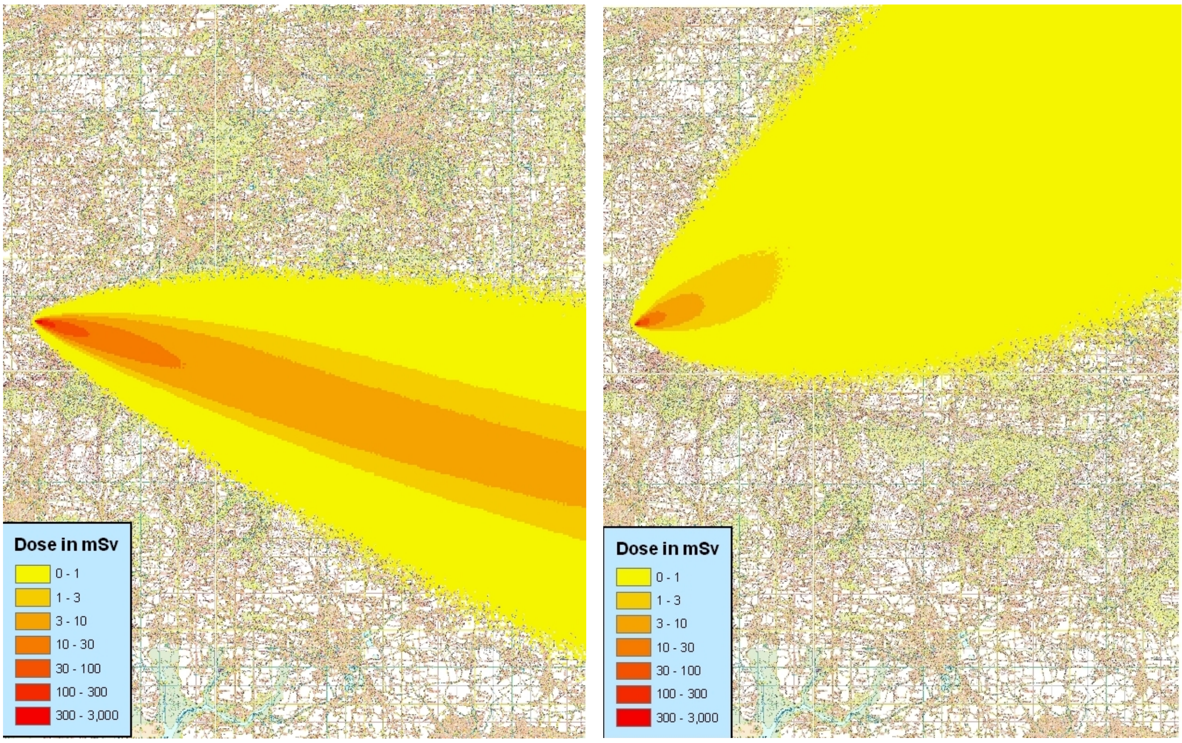


Figure 3.2a and 3.2b Effective dose to 2 days based on NAME dispersion predictions for a release of 3 10^{16} Bq of ^{137}Cs in alternative real weather conditions

Figure 3.3 shows the overlaid sheltering countermeasure areas from all the 51 weather sequences from 2007 and 2008 considered here, so that the density indicates the probability of a countermeasure being required (in terms of a total dose, as defined above, of 3mSv being exceeded). It can be seen that the majority of sheltering areas overlay, assuming (as here) the same initial wind direction. However, there are a minority of weather conditions which lead to elongated or angled sheltering areas. Several of the weather sequences lead to sheltering extending considerably beyond the area shown here, which again is truncated to show greater resolution in the area closer in. These results demonstrate again the importance of linking emergency response assessment systems with real-time weather predictions.

Table 3.10 Extent of sheltering for release of 3 10^{16} Bq of ^{137}Cs, real weather conditions

Weather condition[a]	Minimum extent of sheltering (km)	Maximum extent of sheltering (km)	Average extent of sheltering (km)	Average peak TIAC[b] at 2km (Bq s m^{-3})
Dry	4	31	14	6 10^{10}
Wet	9	> 40	19	5 10^{10}
Total	4	> 40	16	6 10^{10}
NAME Gaussian Dry			15	5 10^{10}

Notes:
a. The weather conditions were all Category D, 4.5 – 5.5 m s^{-1} wind speed, and the release duration was 1hour from a 10m release height.
b. Time integrated activity concentration in air.

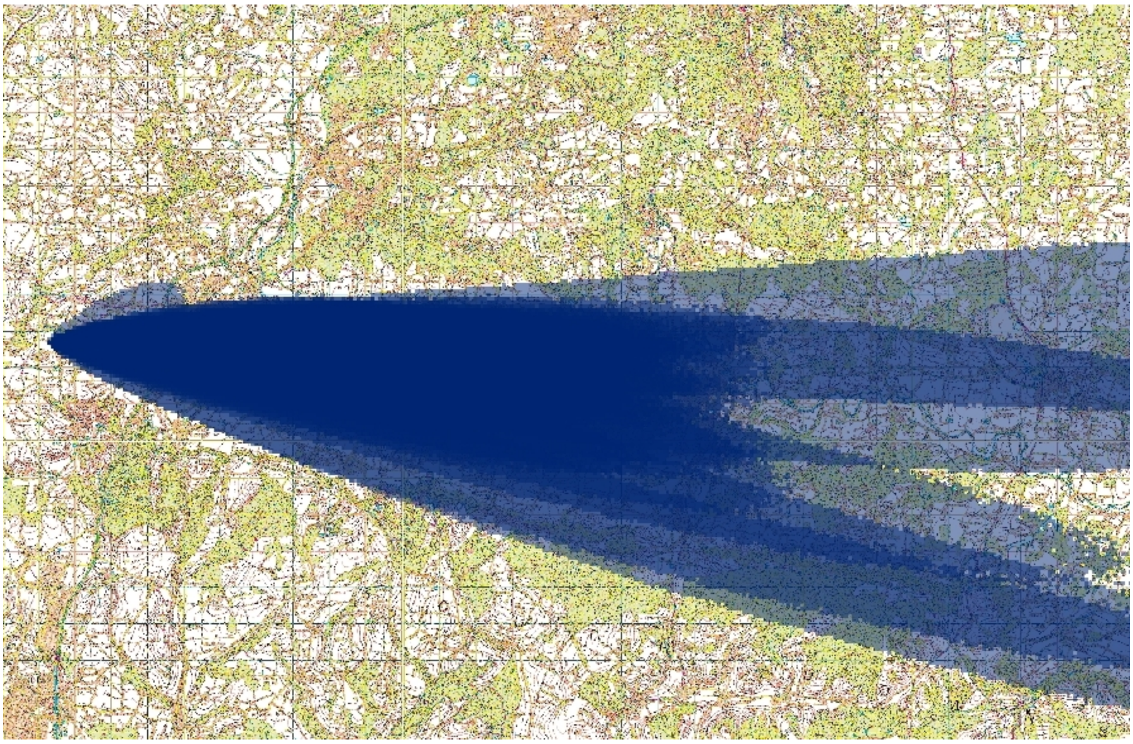


Figure 3.3 Predicted extent of sheltering for release of 3 10^{16} Bq of ^{137}Cs in 51 real weather conditions from 2007 and 2008, with colour density built up to reflect the likelihood of the area being affected

3.6 Section summary

On the basis of the variability ranges estimated in Section 2, this section estimates the extent of the imprecision typically associated with emergency response calculations. The focus is on the imprecision associated with assessment support for decisions on countermeasures in the area beyond that covered by the emergency planning zone (ie extendibility). The imprecision evaluated is that which is associated with predictions of air concentrations, ground deposition levels, and the resulting predicted extent of evacuation and sheltering areas, based on a few off-site measurements at early times.

The results summarised in this section have demonstrated the key parameters contributing to imprecision in emergency response assessments. The two analyses, using the R91 and NAME dispersion models, have indicated consistent results; the key parameters for both are the release duration, wind direction (where an assumed plume centre line wind direction is required), enhanced deposition velocity and rainfall, and a significantly elevated release height. The results demonstrate the importance of a radiological emergency assessment tool being linked to an appropriate real-time weather/dispersion prediction tool, and in particular for UK application with the NAME/NWP models of the UK Met Office. The section also shows the influence of real weather conditions, linked to NAME plume predictions, on the predicted extent of countermeasures, using real meteorological sequences from 2007/2008, and demonstrates the potential impact of variation in weather on the estimated location and extent of sheltering areas, even for weather conditions which are similar.

The section shows that the imprecision due to lack of knowledge in the early stages of an emergency has potentially significant implications. It is therefore concluded that it is important to have techniques which display the consequences of imprecision in a way that is easily understandable in the context of emergency decision making. This includes combining the effect of weather uncertainty with lack of knowledge on other key parameters. The specification of a tool which will use NAME dispersion input to predict and display areas where countermeasures may be required is therefore developed in the next section.

4 SPECIFICATION OF NEW GIS-BASED EMERGENCY ASSESSMENT TOOL

4.1 Introduction

It has been concluded in Section 1 that it is vital, when decisions are being based on assessment results in emergencies, for the decision maker to be fully aware of any significant imprecision or uncertainty associated with the results. In Section 3 the importance of weather parameters in assessing the consequences of a release has been demonstrated. This, in conjunction with the availability of increasingly detailed weather data on a three dimensional grid for the UK, means that it is now appropriate to develop radiological emergency response tools for application in the UK which include both real-time weather predictions and imprecision analysis.

This section describes a proposed new tool which would link radiological emergency assessment models to the predictions of the UK Met Office's NAME dispersion model. The aim of the new tool is to minimise lack of knowledge of the significant weather-related parameters through using the best and most up to date dispersion predictions available, while also taking into account any lack of knowledge in the key non-weather parameters, by reflecting the significance of possible variation in these on the endpoints produced.

It was concluded in Section 1 that for decision making in the UK in the very early stages of an emergency (within, say, 12 hours of a release starting) it is important that the tools used are transparent, with the technical basis easily explainable to decision makers. Ideally, they should be based on simple calculational assumptions which would permit approximate checking to be feasible through hand calculations. Complex models used at early times may generate overconfidence through their apparent sophistication and possibly hidden uncertainties (as discussed, for example, by French and Niculae 2005). For this reason, undue complexity in the new tool's design has been avoided. It is also important to retain calculational simplicity to reduce the chance of inadvertent user errors through incomplete understanding of what the tool is doing. The inclusion of imprecision due to lack of knowledge and the display of results which demonstrate this is a fundamental part of the new tool's design. The approach taken to these issues is summarised in this section.

The new tool predicts areas where countermeasures may be required and other radiological endpoints through the display of spatial data in a Geographic Information System (GIS). The UK Met Office generated NAME predictions of atmospheric dispersion and deposition levels are also based on spatial data. The analysis and presentation of information in a spatial format is important in emergency response systems unlike, for example, probabilistic risk assessment systems where results can meaningfully be presented by using percentile distributions and expectation values. The prediction and display of areas where emergency countermeasures may be required, together with other endpoints relevant to emergency response such as the distribution of predicted doses, may be shown using, for example, the ArcMap system as developed by ESRI(UK); this is a comprehensive mapping application for ArcGIS Desktop, with the ability to combine calculations with map-based displays. A GIS framework has the advantage of being able to display a wide range of features in the affected area, such as population, schools, hospitals and roads, in addition to the assessments endpoints.

The tool described in this section has been partially implemented as a spreadsheet which is then linked manually with ArcMap. This is a limited prototype version for research purposes, rather than a fully functioning system which would link in real time with Met Office predictions. This combination of a spreadsheet linked to the ArcMap system was the tool used in the previous section to show the impact of the NAME model predictions on the sources of imprecision.

4.2 Atmospheric dispersion modelling in UK emergency response

In emergencies (which would include radiological emergencies, but also other emergencies such as chemical releases such as that from Buncefield in 2005 and emissions of volcanic ash such as the Eyjafjallajökull release in Iceland in

2010) the Met Office's NAME dispersion model is run by the Met Office with input from their Numerical Weather Prediction (NWP) model. NAME is linked to the Met Office's Unified Model (UM), a unified Numerical Weather Prediction (NWP) meteorological model which is used for both weather prediction and long term climate modelling (Cullen 1993, Staniforth and Wood 2008). NAME can also utilise radar data on current and past rainfall. The resolution of the underlying NWP data is now on a grid size of 1.5 km^2, which is adequate for the estimation of early countermeasure areas (which may potentially extend up to a few 10's of kilometres in distance from the release point, but more likely only to a few kilometres). The use of the Unified Model in conjunction with radar data enables regularly updated NAME dispersion predictions to be made of the instantaneous and time integrated activity concentrations in air, and wet, dry and total ground depositions of radionuclides, at all grid location points and on a suitably defined temporal grid. These predictions may be used as input into radiological dose assessments. NAME incorporates both radioactive decay processes and estimates of external dose ('cloud gamma') from the radioactive plume, and is therefore a model with appropriate capability for radiological assessments.

The projection of weather conditions into the future is influenced by the chaotic nature of the atmosphere. There is also considerable uncertainty associated with predictions of future weather details, such as rainfall rate and location. Major international meteorological organisations, including the Met Office, therefore use ensemble forecasting to enable the uncertainty in meteorological forecasts to be estimated. This entails the repeated running of forecast models many times, with slight perturbations in starting conditions. Ensemble meteorological forecasting can be continued into dispersion predictions, through the generation of an ensemble of dispersion scenarios associated with multiple forecasts of the meteorology. The uncertainty associated with ensemble predictions can therefore arise both from the uncertainty in the meteorology and the uncertainty in the dispersion aspects. Ensemble forecasting and its use in emergency response applications is a current research area both in the Met Office and elsewhere.

Ensemble predictions and their associated probabilities may be used as input into radiological consequence assessments. Ensemble modelling is being introduced in the UK Met Office's use of the NAME model. Runs of the dispersion model NAME can therefore generate not only single 'best estimate' predictions of plume dispersal and deposition but also alternative plausible dispersion patterns, taking into account possible variations in the development of future weather conditions. This developing capability fits in well with the proposal in this work of developing a tool which takes into account lack of knowledge and alternative possibilities in multiple input parameters and data.

4.3 Outline of assessment tool

The main stages of the new ArcMap tool are shown in Figure 4.1.

The starting point for the calculations is NAME predictions of activity concentrations in air and ground depositions, in combination with either an estimated source term or environmental measurements. The measurement most likely to be useful is an activity concentration in air. These are measured by air sampling, with a measured air sample being reported typically in units of Bq s m^{-3}. This quantity divided by the number of seconds in the measurement period gives an instantaneous activity concentration in air in Bq m^{-3}. In the absence of radionuclide breakdown information, this measurement can be assumed to be the measurement for either a particular radionuclide, or a group of radionuclides.

In the early stage of a release, the Met Office's NAME predictions of activity concentrations in air and ground depositions will be for unit release of key radionuclides, due to lack of knowledge at this stage about the source term[1]. The NAME prediction of the activity concentration in air for unit release of the appropriate radionuclide (or combination of radionuclides), at the time and location of the measurement, may be compared to a measured value of the actual quantity.

[1] The Met Office would aim to rapidly generate NAME runs, for the release site and the estimated start time, after being notified of an accident; at such short times, the source term is very unlikely to be known.

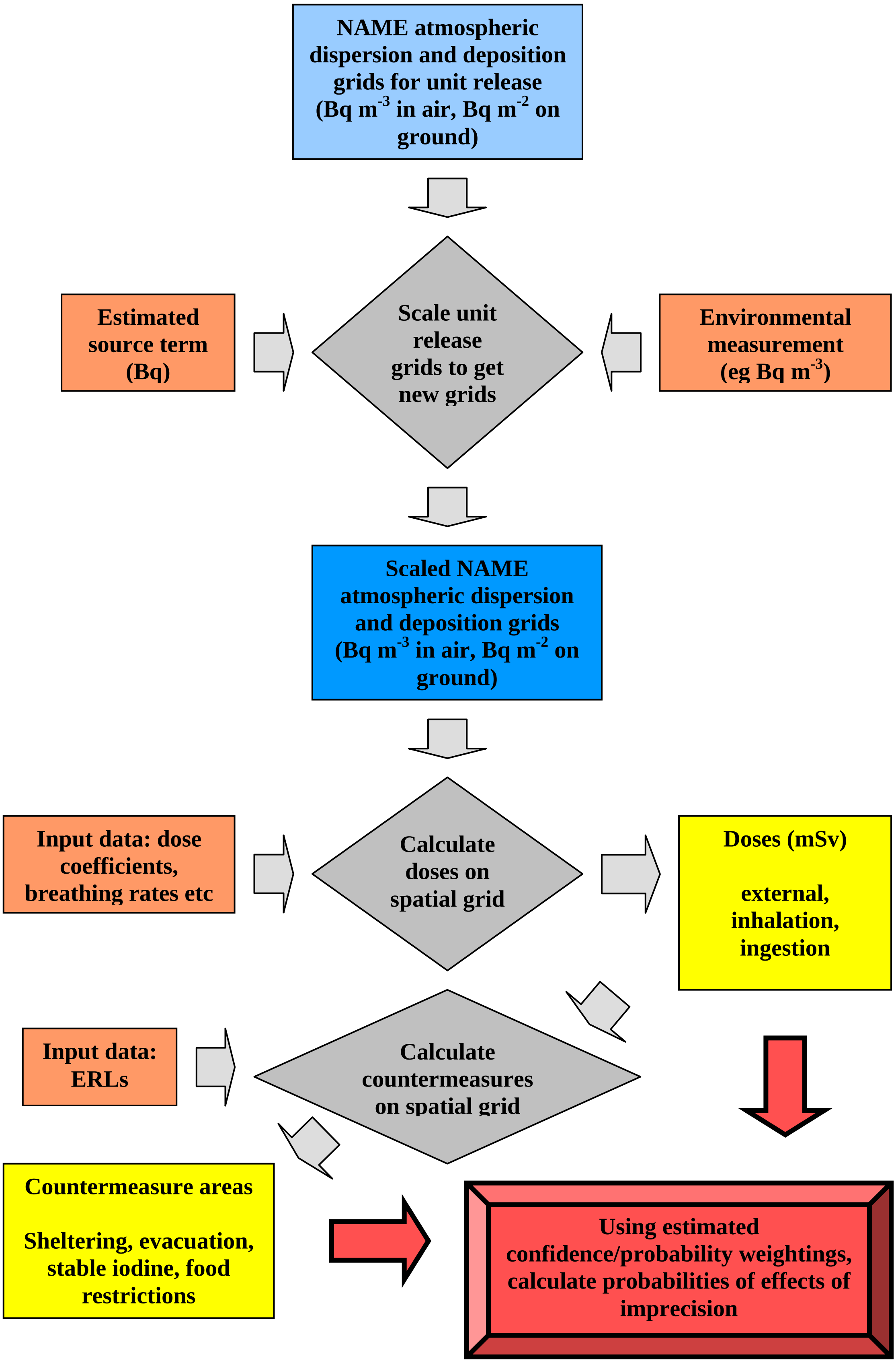


Figure 4.1 Stages of the ArcMap tool

This comparison enables a ratio to be calculated between the measured value and the predicted value for the ‘unit release’ run of NAME, and with this ratio all the NAME predictions of activity concentrations in air and depositions, both spatially and temporally, may be scaled to the size of the release indicated by the ratio. Through this scaling, new NAME-based spatial and temporal predictions of activity concentrations in air and deposition may be produced; these scaled results will include a predicted activity concentration in air which is in agreement with the measurement at the appropriate time and spatial location. In effect, this scaling process estimates a source strength on the basis of the single measurement and this estimated source strength is then used to estimate concentrations elsewhere. This scaling process may also be done on the basis of a comparison between NAME predictions of total deposition at a point and measurements of total deposition at the same location, but because these deposition quantities are integrals over the period of time from the start of deposition to the time of measurement, this is likely to be of more limited value.

As the new tool is ArcMap-based, the modified NAME predictions derived by scaling to each measurement may be stored as new layers of data, in addition to the base ‘unit release’ layer of the NAME predictions of activity concentrations in air and deposition. Each layer, both original and modified, may be subdivided into further sublayers to reflect radionuclide composition, which may be either measurement-based or user-assumed. On the basis of this multiple layer information, dose and countermeasure calculations are undertaken, as described below.

A key feature of the tool is the input of a range of values for key parameters which affect the calculated consequences, and the treatment of the predicted results in a probabilistic framework. The endpoints of dose and countermeasure consequences are therefore presented in a way which demonstrates the influence of imprecision.

4.4 Method

The NAME 'unit release' datasets which are input into the tool are in the form of spatial grids containing air concentrations and ground depositions. The air concentrations will be in the form of Bq m^{-3} as a function of time. These will be for pre-specified time intervals, most likely of around 15 minutes duration as a compromise which gives sufficient representation of fluctuations in activity concentrations with time while not requiring data sets which are too large to store and manipulate. The ground depositions will be the total deposition at each location up to each time (again probably every 15 minutes) in Bq m^{-2}.

As described above, by comparison between measured activity concentrations in air and the NAME predictions for the appropriate time and location, modified grids can be calculated. In ArcMap this will produce for measurement M a new layer of predicted activity concentrations in air (in Bq m^{-3}) called **AM(t_x)** where t_x is the time in 15 minute intervals, and a new layer of predicted total depositions to each time period (in Bq m^{-2}) called **DM(t_x)**, again where t_x is the time in 15 minute intervals.

Each **AM(t_x)** and **DM(t_x)** layer may be subdivided into further sublayers to reflect radionuclide composition (either actual or user-assumed). These layers are essential before dose and countermeasure calculations can be undertaken, as dose is dependent upon the radionuclide. Although in the early stages of a release the measured activity will probably be assumed to be a particular radionuclide or group of radionuclides, as time progresses a fuller radionuclide breakdown can be expected. Radionuclide spectrum data will not normally apply equally to both the activity in air concentration data and the deposition data, due to different deposition velocities for some radionuclides (notably iodine). Scaling factors between activity concentrations in air and ground depositions will enable approximate values to be calculated, and this approach will be essential to enable calculations to be performed before revised NAME runs based on new source term information become available from Met Office, although these factors would not be equally applicable at all distances from the release point due to phenomena such as plume depletion. Accurate use of radiospectrum data for both deposition and air concentration grids would require revised, radionuclide-specific results to be obtained directly from the NAME model.

The tool may alternatively operate on the basis of an input source term (eg 10^{16} Bq of ^{137}Cs and 5 10^{15} Bq of ^{90}Sr), rather than on ratioing to a measurement. This is just another way of obtaining the multiplying factors to produce the $\mathbf{AM(t_x)}$ and $\mathbf{DM(t_x)}$ layers.

Table 4.1 shows the radionuclides most likely to have a significant effect on doses in the event of a reactor accident or an accident involving a major nuclear transport facility (see for example Charles *et al* 1983). Additional radionuclides to cover the noble gases should be added when these have the potential to be released, to enable the external doses from cloud to be calculated. However, the prototype version created for the analyses in this study includes only ^{137}Cs and ^{131}I.

Table 4.1 Significant radionuclides for ArcMap tool

Cobalt-60 (^{60}Co)	Iodine-132 (^{132}I)	Cerium-144 (^{144}Ce)
Strontium-89 (^{89}Sr)	Iodine-133 (^{133}I)	Uranium-234 (^{234}U)
Strontium-90 (^{90}Sr)	Iodine-135 (^{135}I)	Uranium-235 (^{235}U)
Ruthenium-103 (^{103}Ru)	Caesium-134 (^{134}Cs)	Uranium-238 (^{238}U)
Ruthenium-106 (^{106}Ru)	Caesium-137 (^{137}Cs)	Plutonium-238 (^{238}Pu)
Tellurium-132 (^{132}Te)	Barium-140 (^{140}Ba)	Plutonium-239 (^{239}Pu)
Iodine-131 (^{131}I)	Lanthanum-140 (^{140}La)	Americium-241 (^{241}Am)

4.5 Inclusion of imprecision

As discussed in previous sections, the inputs into an emergency assessment tool will often not be well-defined in the early stages of an emergency. Section 3 has concluded that the key categories where early information will not be readily available and where there will be a number of plausible alternatives are:

- Multiple predictions from the weather/dispersion model, of alternative weather and dispersion evolutions, including uncertainty in the wind direction and the rainfall rate. Each of these would lead to different projected patterns of activity concentrations in air and ground depositions for input to the emergency assessment.

- Multiple environmental measurements, varying in location point and sampling time, each potentially suggesting a different estimated release quantity, together with a lack of information on the radionuclide composition of each radiological measurement (measurements may, for example, be reported as total beta or total gamma). Even in the early stages of an accident it is likely there will be a number of off-site measurements, and eventually there will be many.

- Uncertainty regarding aspects of the release, including the degree of associated energy (heat content and plume rise), the particle size distribution and associated dry deposition velocity, and the assumed release duration. The emission rate of radionuclides is likely to vary with time, and also with radionuclide.

Specifically, the results presented in Section 3 show that key contributors to the imprecision are:

- release duration,
- deposition velocity
- weather factors, particularly wind direction and rainfall rate,
- a significantly elevated release height.

All of these factors, considered separately and in combination, will lead to different spatial and temporal predictions of dose distribution and hence different locations and extents of areas in which countermeasures may be required. While some of these will more accurately represent reality than others, early stage assessments cannot ignore the full spectrum of possible outcomes, in so far as these can realistically be estimated. The approach suggested in the new tool is therefore to consider a wide spread of possible combinations and to present estimates of the confidence associated with each combination.

As an example, consider first only the weather and measurement aspects of imprecision. Assume there are four different measurements of activity concentration in air ($\mathbf{m_1}$, $\mathbf{m_2}$, $\mathbf{m_3}$, $\mathbf{m_4}$) of radionuclide **r**. Also assume there are three alternative weather predictions ($\mathbf{w_1}$, $\mathbf{w_2}$, $\mathbf{w_3}$), and for each of these there is a separate NAME dispersion prediction. For weather $\mathbf{w_1}$, NAME will predict for a unit release of radionuclide **r** spatial and temporal grids of activity concentrations in air and total ground deposition.

Measurement $\mathbf{m_1}$, which was taken at a particular location and time, can be compared to the NAME unit release prediction of activity concentration in air for the same location and time, for weather $\mathbf{w_1}$. Ratioing these values provides a scaling factor which can then be applied to the entire NAME activity concentration in air grid for $\mathbf{w_1}$, such that the scaled grid shows measurement $\mathbf{m_1}$ at the correct spatial and temporal location and similarly scaled activity in air concentrations at all other points and times. However, for the locations and times of measurements $\mathbf{m_2}$, $\mathbf{m_3}$ and $\mathbf{m_4}$, this new grid may well not predict the values measured at these locations and times.

For measurements $\mathbf{m_2}$, $\mathbf{m_3}$ and $\mathbf{m_4}$ new scaled NAME grids can also be generated for each, respectively showing measurements $\mathbf{m_2}$, $\mathbf{m_3}$ and $\mathbf{m_4}$ at the correct points and times, but values which do not necessarily agree with the measured values at the other locations. Using these four sets of new grids, assessment results can then be generated separately for each.

As an example, four alternative areas predicted to require sheltering may be produced, one for each measurement, and all applying to the plume prediction for weather $\mathbf{w_1}$. Examination of each of these alternative outputs is of interest to the decision maker. For example, similarity between the predicted sheltering areas would suggest that for weather evolution $\mathbf{w_1}$ the measurements are broadly consistent with each other, whereas similarity between three zones but not the fourth would suggest that one measurement is inconsistent with the others, at least for this weather evolution and the sheltering area endpoint. It is also of interest to combine these four predicted sheltering areas (or other endpoints) for weather evolution $\mathbf{w_1}$, which may be done by a simple arithmetic mean or by weighting the four measurements according to the confidence considered to apply to each in such a way that the weighting sums to one. Repeating this process for the weather sequences $\mathbf{w_2}$ and $\mathbf{w_3}$ will result in five sheltering areas for each weather evolution, four of which correspond to a single measurement with the fifth being representative of the average, or the weighted average, across all four measurements.

Alternatively, each weather evolution can be considered in turn, in the context of a single measurement. For measurement $\mathbf{m_1}$, NAME's 'unit release' grids of activity concentration in air and ground deposition corresponding to each of the weathers $\mathbf{w_1}$ to $\mathbf{w_3}$ can be scaled to give three alternative grids for each, all with measurement $\mathbf{m_1}$ at the correct location and time. As above, a sheltering zone, for example, based on measurement $\mathbf{m_1}$ can be predicted for each weather, demonstrating the impact of the different weathers on the endpoint and a simple arithmetic average or a weighted average across weather evolutions can also be shown. Again, the information is of significance in terms of decision making, in that it clearly highlights the possible impact of each weather evolution, possibly giving early warning of particular weather developments to be alert to.

The approach described above for alternative weathers and measurement data may be extended to the other contributors to imprecision, such as alternative dry deposition velocities (eg $\mathbf{v_1}$, $\mathbf{v_2}$) and durations of release (eg $\mathbf{d_1}$, $\mathbf{d_2}$, $\mathbf{d_3}$). Each of the different variable values is given an estimated likelihood or confidence weighting by the operator of the assessment system. In the case of the weather/dispersion combinations the estimated likelihood would be provided by the Met Office, on the basis of their expertise. The likelihoods are attached during the analysis, based on the situation at that time and for the particular emergency. It is likely that both values and likelihoods will change as the accident progresses. For example, initial estimates of release duration may be set at 1 hour, 3 hours and 5 hours but if the release is not stopped then later runs may take this ongoing release into account by using 6 hours, 8 hours, 10 hours as the possible durations. The sum of the likelihood weightings applied to each uncertain parameter should sum to unity.

A scheme has therefore been developed to estimate the likelihood associated with imprecision alternatives, as additional information for the decision maker. Figure 4.2 shows an example structure of the scheme used to generate alternative outcomes of results; different input parameters for all four variables shown here are used in all possible combinations (in the example shown in Figure 4.2, there are 4 x 3 x 2 x 3 = 72 combinations). It should be noted that the alternative weather/dispersion alternatives include a number of the elements identified previously as having a significant bearing on the outcomes of the accident, for example wind fluctuation, wind speed and rain presence/intensity. The dry deposition velocity options may be regarded alternatively as options on particle size.

Table 4.2 shows a possible application of the scheme. The entries in the table are examples only; in a particular emergency, specific values appropriate to the emergency would be selected at the start and would be altered and updated according to improved understanding as the emergency develops. Each of the columns in Table 4.2 represents a different variable, and an estimated probability. The first column contains the key measurements (or sets of similar measurements) taken after the release has started, each of which can be used to scale the NAME 'unit release' predictions. The second column contains the key alternative weather and dispersion evolutions for a unit release of each radionuclide, each of which will give rise to a different pattern of activity in air concentrations and deposition predictions over space and time. The third column is the likely release duration in hours, and the fourth column contains the particle size and deposition velocity options. The probabilities are attached during the analysis, as the most likely probabilities based on the situation at that time and for the particular emergency. It is likely that they will change as the accident progresses. The probability weightings applied to each uncertain parameter must be selected such that the total probability in each column sums to unity. User input through manual dragging of a probability curve may be a feasible way of inputting the probabilities.

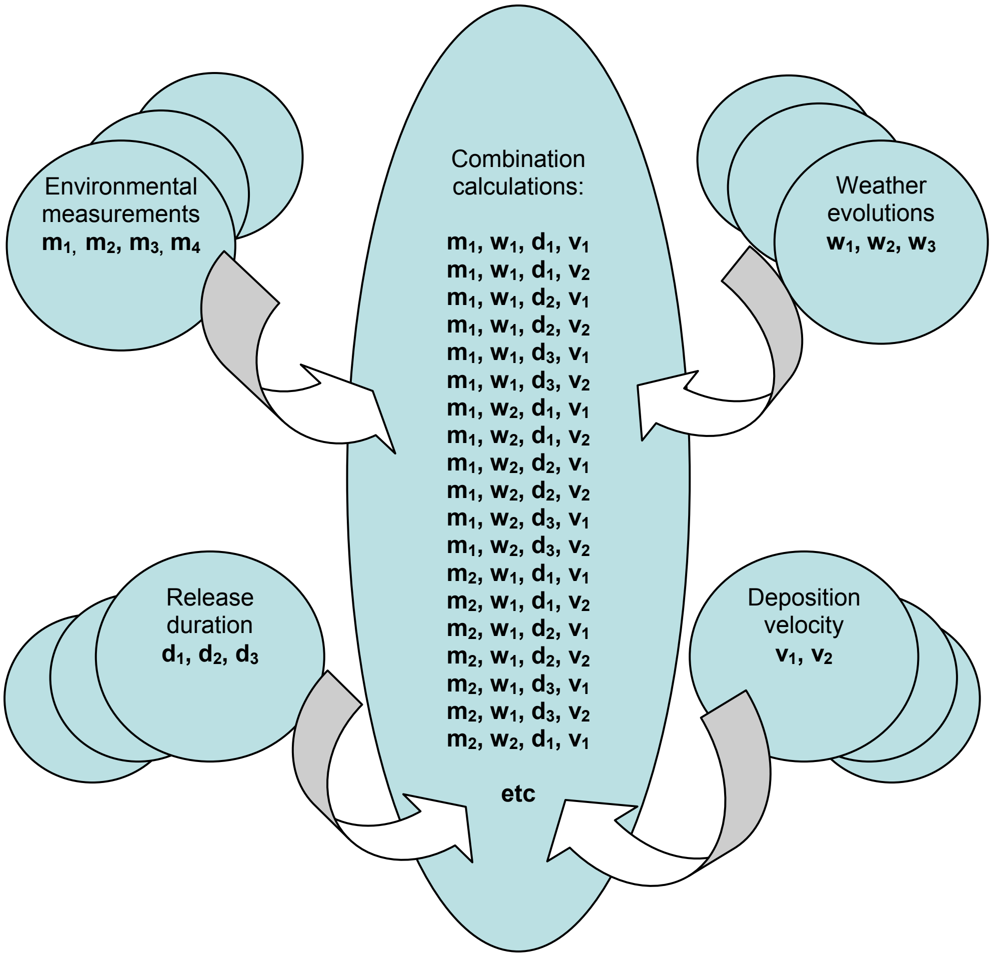


Figure 4.2 Structure of imprecision calculations

The fifth column is different in nature. A significant difference in countermeasure zones may be seen if the effective release height is low to medium (around 10m to 30m in height) as compared to high (100m to 200m) but there is relatively little difference around these two assumptions. For this parameter two entirely separate analyses are required, each giving rise to separate sets of assessment results. Both of these analyses are only required while both scales of release height remain a possibility, for a particular accident.

Table 4.2 Example of possible variables and probabilities in a particular emergency

Environmental measurements set	Weather evolutions	Likely release duration	Particle size and deposition velocity (µm and m s^{-1})	Release height[1] (m)
m_1 Confidence weighting 0.2	**w_1** Probability 20%	**d_1 3 hours** Probability 25%	**v_1** Nuclides except iodine: 1µm & 10^{-4} m s^{-1} Iodine nuclides: 1µm & 10^{-3} m s^{-1} Probability 40%	10m
m_2 Confidence weighting 0.3	**w_2** Probability 50%	**d_2 6 hours** Probability 50%	**v_2** Nuclides except iodine: 1µm & 10^{-3} m s^{-1} Iodine nuclides: 1µm & 10^{-2} m s^{-1} Probability 60%	150m
m_3 Confidence weighting 0.3	**w_3** Probability 30%	**d_3 10 hours** Probability 25%		
m_4 Confidence weighting 0.2				

[1] Release height is not to be treated as a weighting, the alternatives are 'either/or' and will each produce two different countermeasure zone sets which are alternatives and cannot be combined.

To use this structure as a basis for assessments in the new tool requires the generation of a series of real-weather dispersion predictions, with associated estimates of likelihood. In the UK such predictions would be produced by the Met Office, for the release location and the estimated release start time as appropriate for the particular incident, and so the requirement is for a series of NAME weather evolutions to be provided by Met Office. In the examples in Figure 4.2 and Table 4.2, three weather evolutions are assumed. However, because release duration, particle size (or deposition velocity) and release height are also required inputs to NAME, the requirement for the NAME runs to be supplied from the Met Office includes the alternative values for these parameters as well. NAME 'unit release' runs for a series of weather evolutions, a pre-specified set of release durations, a set of particle sizes (or deposition velocities) and maybe two alternative release heights are required, hence in an emergency the Met Office may automatically generate around 50 alternative NAME runs for HPA. For each of these runs, the release location and the release start time will be as required for the particular incident, and each will include a default set of radionuclides, all of which are assumed to be released in unit quantities. An experienced assessment analyst will then pick a set of key measurements and will select appropriate probabilities for the release durations and particle size/deposition pairings. The analyst will also judge the confidence weightings to be applied to each of the key measurements. This may be done on the basis of information received from monitoring teams, which are co-ordinated in the event of a nuclear site incident by HPA. It is likely that equal weighting may be given to the different measurements, but the possibility of attaching a reduced confidence to one or more is available for use if considered appropriate to the circumstances.

On receipt of these NAME runs from Met Office, every combination of the above with the associated probabilities is automatically passed through the new system and at every point, for every combination, doses (inhalation, external and total) in the absence of countermeasures are calculated. Possible countermeasure zones can then be estimated by comparing the predicted dose at each point against the chosen dose criterion for each countermeasure. As there are multiple combinations of input parameters, there will be, for each location, multiple countermeasure on/off indicators, each corresponding to a different combination of assumptions. As the likelihood of each combination is also passed through the system, each result will have an associated estimate of probability of occurrence. These probabilities may then be used to generate probability maps of predicted countermeasure zones and also probabilistic dose maps. As more information is gained, as the emergency progresses, individual measurements may be replaced by assumed source terms.

As a particular example, consider two points, A1 and A2, to determine whether there should be evacuation at those points. Assume there are two weather evolutions (both equally plausible), two environmental measurements of activity concentrations in air in the affected area, which can be from points elsewhere than points A1 and A2 (there is equal confidence in each), two release durations (both thought equally plausible) and 2 particle size and deposition velocity combinations (both thought equally plausible). In this example, there are therefore 2 x 2 x 2 x 2 = 16 dose calculations at point A1 and the same number at point A2. If at point A1 there are 4 of the calculated doses which are in excess of the chosen ERL, then there is a probability of 25% of there being a need for evacuation at that point. If at point A2 there are 8 of the calculated doses which are in excess of the chosen ERL then there is a probability of 50% of there being a need for evacuation at that point.

The system will treat each component of the uncertainty separately by 'holding' one or more constant to demonstrate how these elements affect the results. For example, probability maps of endpoints may be generated for each measurement separately, or for each weather evolution separately, or for each release duration separately, with the other components varying. The user may wish to view several alternative presentations of the available results information, for example those for:

- weather $\mathbf{w_1}$ + measurement $\mathbf{m_2}$ + duration $\mathbf{d_3}$ + deposition velocity $\mathbf{v_2}$

or

- average over all weathers $\mathbf{w_a}$ + measurement $\mathbf{m_2}$ + duration $\mathbf{d_1}$ + deposition velocity $\mathbf{v_1}$

or

- weather $\mathbf{w_2}$ + average over measurements $\mathbf{m_a}$ + duration $\mathbf{d_2}$ + deposition velocity $\mathbf{v_1}$

or

- average over all weathers $\mathbf{w_a}$ + average over all measurements $\mathbf{m_a}$ + duration $\mathbf{d_2}$ + deposition velocity $\mathbf{v_2}$

or

- average over all weathers $\mathbf{w_a}$ + average over all measurements $\mathbf{m_a}$ + average over all durations $\mathbf{d_a}$ + average over all deposition velocities $\mathbf{v_a}$

4.6 Input

a) NAME predictions from Met Office.

These will either be for unit release of a set of pre-defined radionuclides, or will be for a specific source term.

For a unit release of each of the pre-defined radionuclides, assuming a release in a particular location (the known location of the accident), for an assumed release start time and for a series of default assumptions (eg release duration) described further below, the NAME output is in the form of spatial and temporal grids containing activity concentrations in air and ground deposition data. The underlying spatial grid is based on UK National Grid co-ordinates, at an approximate resolution of 100m x 100m. The default temporal grid time periods are 15 minute intervals from time 0 (the start of the release) up to the time at which the plume leaves the area being considered, up to a maximum of 2 days. However, to reduce run times the use is proposed of a set of nested grids of increasing coarseness both spatially and temporally from the location and start time of the accident.

Specifically, the NAME output used as the basic input data is of the following form, for each radionuclide:

- the average instantaneous activity concentration in air for a sequence of 15 minute periods, in Bq m^{-3},
- the time integrated activity concentration in air from time 0 to the end of each 15 minute period, in Bq s m^{-3},
- the wet deposition from time 0 to the end of each 15 minute period, in Bq m^{-2},
- the dry deposition from time 0 to the end of each 15 minute period, in Bq m^{-2},
- the total (wet plus dry) deposition from time 0 to the end of each 15 minute period, in Bq m^{-2}.

For a specific source term, the NAME files will be in the same form as above but the scaling to measurements as described in the next step is not required.

Table 4.3 shows an example of NAME output. The release assumed here was 1 10^{16} Bq of ^{137}Cs released uniformly over 1 hour, and for simplicity the results shown are only the integrated activity concentrations in air and the dry, wet and total depositions to the end of 12 hours after the start of the release.

The new tool requires a series of Met Office files to be provided as input. The precise details of these will be determined by a pre-established agreement. Each will correspond to a different set of assumptions regarding weather development (ie alternative plumes), release duration, particle size (or deposition velocity), and also high/low release heights. All of these except weather will be pre-agreed. It would also be necessary for the Met Office to provide indicators of the confidence/likelihood associated with the weather.

b) Measurements

For each measurement to be used, the measurement itself (eg the instantaneous activity concentration in air in Bq m^{-3}), the time the measurement was taken, its location in terms of UK national grid co-ordinates, and an indication of user confidence is required. Each measurement is (or is assumed to be) either for a specific radionuclide, or the sum for more than one radionuclide (possibly the total). The user will specify the assumption made, including the ratioing of the activity across radionuclide, so the subsequent calculation knows how to combine over radionuclide. Defaults can be supplied for this (eg 50% ^{137}Cs and 50% ^{131}I).

c) Dose coefficients

There are two types of dose coefficient required as input to the system:

- Inhalation dose coefficients (Sv Bq^{-1}) for each default radionuclide, for four age groups (adult, 10 year old child, 1 year old child, fetus) and for effective dose and three organs (lungs, thyroid and bone surface). The information should also include the associated chemical form and absorption type.

- External dose coefficients for each deposited radionuclide (for example, using GRANIS results as obtained by Kowe *et al* 2007, which include decay, ingrowth of daughter products, and redistribution through the underlying soil following a single instantaneous deposition). These are doses per unit deposit to a series of times after deposition in Sv per Bq m^{-2}.

d) Breathing rates

These are required for the three age groups of adult, 10 year old child and 1 year old child.

e) Emergency Reference Levels (ERLs)

Current ERL values are required as input, these are both the upper and lower levels, for evacuation, sheltering, stable iodine, and also the user's choice of which criterion they wish to use for each, in the current run.

f) EC maximum permitted levels in foodstuffs.

The current CFILs (Community Food Intervention Levels) are required as input.

g) Concentrations in milk and green vegetables per unit deposit

Data on the peak radionuclide concentrations in milk and green vegetables for unit deposit of each radionuclide may be pre-calculated using the FARMLAND (Brown and Simmonds 1995) model. These peak concentrations from a unit deposit, in units of Bq kg^{-1} per Bq m^{-2} or Bq l^{-1} per Bq m^{-2}, are scaled within the tool to the predicted ground deposition and the result compared with the EC intervention levels to determine the required food intervention area for each foodstuff. For green vegetables the peak concentration occurs immediately after deposition, whereas for milk the peak occurs at different times depending on the isotope, because of the time taken for the activity to be metabolised through the cow and transferred to milk.

h) Confidence/probability estimates for imprecision parameters

These are user input values for the probability/confidence estimates for the release durations and particle size and deposition velocity pairings, and the confidence weighting to be applied to each of the key measurements.

Table 4.3 Example of start of NAME output file

NAME III (version 5.3)

Run name:	HPA_RPD_dry_dd1_1hr
Run time:	28/10/2009 09:36:14.693 UTC
Met data:	Single Site Flow.Met Station
Start of release:	21/02/2008 15:00 UTC
End of release:	21/02/2008 16:00 UTC
Source strength:	2.7777780E+12 Bq / s
Release height:	10.000m agl +/- 0.000m
Run duration:	12hr 0min
X grid origin:	430267.0
Y grid origin:	82766.00
X grid size:	801
Y grid size:	801
X grid resolution:	100.0000
Y grid resolution:	100.0000
Number of preliminary cols:	4
Number of field cols:	4

Fields:

RADIONUCLIDE	RADIONUCLIDE	RADIONUCLIDE	RADIONUCLIDE
Air Concentration	Dry deposition	Wet deposition	Deposition
CAESIUM-137	CAESIUM-137	CAESIUM-137	CAESIUM-137
Bq s / m^3	Bq / m^2	Bq / m^2	Bq / m^2
All sources	All sources	All sources	All sources
No ensemble averaging	No ensemble averaging	No ensemble averaging	No ensemble averaging
12hr 0min integral	12hr 0min integral	12hr 0min integral	12hr 0min integral
No horizontal averaging	No horizontal averaging	No horizontal averaging	No horizontal averaging

X (UK National Grid (m))	Y (UK National Grid (m))				
470167	122666	2.98E+07	149478.2	0.00E+00	149478.2
470167	122766	1.19E+08	238898.8	0.00E+00	238898.8
470167	122866	0.00E+00	29721.74	0.00E+00	29721.74
470267	122566	2.97E+07	29775.06	0.00E+00	29775.06
470267	122666	5.66E+08	2777190	0.00E+00	2777190
470267	122766	5.02E+11	1.09E+09	0.00E+00	1.09E+09
470267	122866	9.53E+08	3555199	0.00E+00	3555199
470267	122966	5.95E+07	89421.51	0.00E+00	89421.51
470367	122466	0.00E+00	29695.47	0.00E+00	29695.47
470367	122566	1.19E+08	443779.6	0.00E+00	443779.6
470367	122666	9.01E+09	3.54E+07	0.00E+00	3.54E+07
470367	122766	7.20E+11	2.11E+09	0.00E+00	2.11E+09
470367	122866	1.45E+10	5.28E+07	0.00E+00	5.28E+07
470367	122966	2.67E+08	983646.6	0.00E+00	983646.6
470367	123066	2.95E+07	59238.16	0.00E+00	59238.16
470467	122366	0.00E+00	29589.79	0.00E+00	29589.79
470467	122466	0.00E+00	267361.7	0.00E+00	267361.7
470467	122566	6.53E+08	3217956	0.00E+00	3217956
470467	122666	4.41E+10	1.79E+08	0.00E+00	1.79E+08
470467	122766	4.85E+11	1.87E+09	0.00E+00	1.87E+09
470467	122866	6.91E+10	2.84E+08	0.00E+00	2.84E+08
470467	122966	1.43E+09	6077089	0.00E+00	6077089
470467	123066	0.00E+00	207632.3	0.00E+00	207632.3
470467	123166	0.00E+00	29618.5	0.00E+00	29618.5
470567	122366	2.97E+07	29740.79	0.00E+00	29740.79
470567	122466	2.37E+08	414824.4	0.00E+00	414824.4
470567	122566	1.78E+09	1.07E+07	0.00E+00	1.07E+07

4.7 Calculations and output

If the calculations are measurement-based rather than source-term based, each measurement is compared to the nearest (in space and time) corresponding unit prediction in the NAME unit release calculations. One measurement may be assumed to be either one radionuclide or a sum of radionuclides in a specified ratio. If the latter, this needs to be turned into 'sub-measurements' eg half of the measurement goes to a ^{131}I calculation and the other half goes to a ^{137}Cs calculation (with the subsequent doses added together later).

For each radionuclide, on the basis of the ratio between the measured value (after the modification to take into account the assumed radionuclide split of the measurement) and the predicted value for the 'unit release' run of NAME, the remaining NAME data of activity concentrations in air and depositions for that radionuclide, both spatially and temporally, are scaled to the size of the release indicated by the comparison, to produce - again for each measurement and for each radionuclide - modified surfaces for activity concentrations in air and deposition. The dose and countermeasure calculations are undertaken on the basis of these new layers.

There will a number of alternative NAME output files produced by Met Office rather than just one, reflecting alternative weathers, release duration, and particle size and deposition velocity. This will be dealt with by a high level layering structure, with the top-most layer containing the 50 or so subdivisions for each of the Met Office assumption sets, with the subsequent measurement and radionuclide breakdowns being below these. However the layers are structured, the following dose calculations need to be done for each result set, each for a single radionuclide and spatial point.

The two dose end-points in the prototype version are:

1. The **dose from inhalation of the airborne plume**, at each location, for each radionuclide, from time 0 to the removal of the plume from that location. The committed inhalation dose is based on the NAME predictions of the total time integrated activity concentration in air applicable to that location, for each

radionuclide, and is calculated for each age group and for effective dose and three organs (lungs, thyroid and bone surface). Doses are required showing contributions to effective, thyroid, lung and bone surface dose from each radionuclide.

Calculation performed

For a particular radionuclide, I_p (the total dose from inhalation of the plume at point p in mSv) is determined by:

> time integrated air concentration of the radionuclide over the period the plume passes location p (Bq s m^{-3})
>
> x inhalation dose coefficient for the radionuclide (Sv Bq^{-1})
>
> x inhalation rate (m^3 s^{-1})
>
> x 1000 (mSv Sv^{-1})

Example calculation for ^{137}Cs:

For a release of 1 10^{16} Bq released over 1 hour, assume the time integrated air concentration at 2km is 4.1 10^{10} Bq s m^{-3} for a release 10 metres above the ground.

Multiply by the inhalation dose coefficient for a 10 year old child (3.7 10^{-9} Sv Bq^{-1})

Multiply by inhalation rate for a 10 year old child (1.8 10^{-4} m^3 s^{-1})

Hence, inhalation dose to a 10 year old child at 2km is 2.7 10^{-2} Sv, or 27 mSv.

2. The **deposited gamma dose** (whole body) at each location for each radionuclide, to a series of times. The external gamma dose arising from radioactivity deposited on the ground is calculated on the basis of the NAME predictions of the total deposited activity at that location, for each radionuclide. This calculation also includes the modelling of the subsequent environmental transport. External dose from unit deposit of a range of radionuclides is pre-

calculated using a model which represents radioactive decay, including ingrowth of daughter products, and redistribution through the underlying soil following a single instantaneous deposition (Kowe *et al* 2007); as the downward migration through soil is assumed in this calculation, the long term doses represent exposures in a rural location rather than an urban one. While distinction can be made between age group, it can also be assumed for simplicity that the external dose is the same for all organs and age groups.

Calculation performed

For a particular radionuclide, E_p the external dose integrated to time t from the deposited activity at point p in mSv is determined by:

Total predicted deposit of the radionuclide at location p (Bq m^{-2})

x external dose per unit deposit of the radionuclide integrated to time t (Sv per Bq m^{-2})

x 1000 (mSv Sv^{-1})

Example calculation for ^{137}Cs:

For a release of 1 10^{16} Bq released over 1 hour, assume the total deposition at 2 km is 4.1 10^{7} Bq m^{-2} for a 10 m release.

Multiply by external dose per unit deposit for ^{137}Cs integrated to 2 days (6.4 10^{-11} Sv per Bq m^{-2})

Hence, external dose to a 10 year old child to 2 days at 2km is 2.6 10^{-3} Sv or 2.6 mSv.

These inhalation and external doses may then be summed for each location, for each radionuclide and for the sum over radionuclides, from time 0 to a series of times. Doses can be presented showing the totals summed across radionuclides and the percentage contribution made by each radionuclide to the total.

The pathways of external dose from cloud and the inhalation dose from resuspension were not included in the prototype tool as the calculation of cloud gamma doses was not then fully incorporated into NAME, and the resuspension pathway is not of significance at short times when compared to the inhalation of the plume pathway for principle radionuclides released in a reactor accident (and in particular for ^{137}Cs and ^{131}I which are the radionuclides considered in section 3). However, a full version of the tool would include:

- Doses from gamma or beta emitting airborne radionuclides, inhalation dose from resuspension, individual doses arising from consumption of contaminated foodstuffs and doses from deposition onto the skin.
- The collective dose to the UK population for each radionuclide and for the sum over radionuclides, which can be calculated on the basis of the above doses, to a series of times. This requires the UK population data to be stored as a layer in ArcMap.
- The concentrations (peak and to a series of times) of each radionuclide in food, as a function of time after deposit. The foods to be considered will be cow's milk and leafy green vegetables, as these are the foods which require urgent consideration in terms of countermeasures. This uses the prediction of total ground deposition levels from NAME (when scaled to measurements), and pre-calculated concentrations in each foodstuff at a series of times following the release (ranging from a few days to one year) and the peak concentrations, from the FARMLAND model (Brown and Simmonds 1995), for unit deposit of each radionuclide.

All doses may be calculated and output either with or without countermeasures.

Calculations of **early emergency countermeasures** (evacuation, sheltering, stable iodine) are required at each location, based on a comparison between predicted dose and the user-selected dose criterion for each countermeasure. The dose measure used to estimate countermeasure areas in the prototype version is the sum of the predicted effective inhalation dose to a 10 year old child from the cloud and the effective external dose to a 10 year old child from deposited activity integrated to 2 days. A time period of 2 days is applied because this is a typical assumed duration of sheltering and evacuation and it therefore approximates to the dose averted by the countermeasure as currently required for comparison with a dose criterion within the ERL range (NRPB 1990, NRPB 1997b). The dose used in the prototype is the total predicted dose from time 0 to 2 days rather than the dose averted, which is the measure of dose that should be used for comparison against ERLs in emergency planning, but in emergency response the data required to start the dose integration period from the time the countermeasure actually commences are unlikely to be available on the timescale required.

If the sum of the inhalation and external doses exceeds the selected dose criterion then the countermeasure is indicated to be required at that location. This information is stored as a 0 or 1 on the spatial and temporal grid, for the particular set of assumptions. In the prototype version, the dose is compared against the criteria of the lower ERL for sheltering and evacuation (which are averted doses of 3 mSv and 30 mSv effective dose, respectively).

From the examples of inhalation dose and external dose calculated above, the sum of inhalation dose I_p and external dose E_p at the point considered is 27 mSv plus 2.6 mSv, ie 29.6 mSv. Comparing this to the lower ERL for sheltering (3 mSv) and the lower ERL for evacuation (30 mSv) it can be seen that sheltering extends beyond this point but that 2 km is about at the furthest extent of the evacuation zone (assuming the decision is made purely on the lower ERL as a criterion).

To display areas where EC Food Intervention Levels are exceeded (Council Regulation (EC) 1989), the predicted peak radionuclide concentrations in milk or leafy green vegetables at each location from the estimated total deposition, are compared with the EC intervention levels after an appropriate summation over radionuclide category. This provides an indication of the areas where food restrictions may be required. The calculation could also be done as a function of time, to indicate food restriction areas by time, but in practice such longer term decisions would be based on measurements rather than model predictions and the calculations are therefore not really required for response purposes.

The current understanding of the extent of the plume and the levels of deposition in the affected area are also of key significance to the decision maker, in addition to being input to the tool's calculations. To provide visual information on the best estimate of activity concentrations in air across the affected area, the **AM(t_x)** layers can be combined (for any specific time period) either by averaging all the predictions for each location, or by a weighted average if more credibility is attached to some measurements than to others, by weighting to a user-input confidence scale. This process can be done also for deposition using the **DM(t_x)** layers, where, in addition to the information being presented in terms of the total deposition to a specific time period, the total deposition anticipated as a result of the full release can be shown by using a NAME run for the best estimate of release duration and assuming a time a number of hours beyond this to allow for recirculation of air and longer term depositions.

Finally, the tool should have the ability to interrogate each gridpoint for detailed data by hovering over the point with the mouse; this would provide a breakdown of dose information by total, pathway, radionuclide percentage etc, with more information provided in detailed tables.

4.8 Technical issues and possible future developments

4.8.1 Discrete input parameters

The simple technique described above assumes a series of pre-specified alternatives for the parameters being varied, namely the release duration, dry deposition velocity and release height. To enable a limited number of calculations to be performed within a reasonable time, these will be discrete values rather than probability distributions on each parameter, and as a consequence the results obtained will also be discrete endpoints rather than a continuous probability distribution, of the type typically output from an uncertainty analysis which results from the sampling, in uncertainty assessments, from a distribution of possible inputs. There are several reasons for the discrete approach proposed here. Firstly, the probability distribution of the input parameter ranges, in a specific accident, is unknown, and superimposing one is likely to increase the imprecision. Secondly, the process will be more transparent in terms of the likelihoods allocated to the different input parameter options than would be the case with the use of probability distributions. Thirdly, the run times associated with sampling from multiple distributions are unlikely to be feasible at present in a system which must run rapidly.

The consequence of the use of discrete values is that the results do not fully represent the actual results distributions, as they are based on only a selection of values from the possible true range. However, if the values of the input parameters selected roughly spread across the possible ranges the discrete results will indicate the possible spread in endpoints. The user would need to ensure that the values do not just scope the spread but also include at least one intermediate value, so that the probability mappings generated do reflect the range. For example, release durations of 0.5 hours, 4 hours and 8 hours could be used rather than just 0.5 hours and 8 hours. The latter would be satisfactory if only the impact of separate options was required, but at least one intermediate value would be needed to obtain probability shadings.

There are mathematical techniques which combine and integrate multiple causes of uncertainty, for example, fuzzy sets and the Dempster-Shafer method for handling imprecise probabilities (see, for example, Ducey 2001). However, a mathematical process which results in a complex and processed result being given to the decision maker who would then be unaware of its derivation is not the transparent tool thought necessary for this application.

4.8.2 Use of monitoring data and data assimilation

It is important to be able to view the impact on the predictions of the first few key measurements – including the possible alternative radionuclide composition assumptions, if the composition is not known – individually. The use of data assimilation techniques, such as Bayesian analysis, which generate smoothed surfaces of air concentrations and depositions for input into assessments may be misleading in the early stages of an accident, as key information may be lost through over-processing of limited raw data, and incorrect information generated through inappropriate interpolation between a small number of data points. In the interim phase, once the key information from consideration of individual measurements separately is understood, these measurements can be combined into consistent sets. The remaining calculations in the early phase would then be undertaken on scaled grids of activity concentrations in air and deposition levels, averaged on the basis of the measurements in each of these sets. As the hours pass the generation of air and deposition surfaces through manipulation of a larger number of measurement data in combination with modelling results becomes more appropriate, and the approach described above can then be extended to use such surfaces.

A further extension to evaluating the implications of measurement uncertainty may be introduced by considering a probability distribution around the actual measured value, and propagating such a distribution through the calculations. This distribution may take into account the imprecision associated with the measurement itself, as a reflection of the true level of activity at that specific time and location. The measurement is imprecise due to the limitations of the monitoring equipment, localised features such as tree canopies or roads (although measurements should not ideally be taken in such locations), error by the operator, and also because there is lack of knowledge as to the radionuclide mix of the release, both in general and also at the specific location of the measurement. The distribution could also be broadened to consider the potential variation in the measurement in the local spatial and temporal fields, although an appropriate spread on this localised variation would need to be carefully established, through a research project, to avoid introducing the data assimilation problems discussed above. This use of a measurement distribution is clearly more complex calculationally than the use of single values, and would require an additional stage within ArcMap which may slow the running time of the tool when undertaken in combination with the treatment of multiple input parameters as proposed here; for this reason it is regarded as a potential future development rather than an intrinsic feature of the proposed tool.

After the first few hours following an accident, the incoming measurement information can become complex, and difficult to interpret and keep track of without the aid of a database. Even a simple GIS system will offer useful visualisation tools. A mapping system can display the available data in different ways, showing for example only activity concentrations in air, or only measurements taken in a particular time period or in a particular location. This simplification of the total information makes it easier to spot trends and inconsistencies.

4.8.3 Possible future extensions

Later developments are possible for the tool, based on developments in NAME and NWP at the Met Office. The current NAME/NWP modelling capability does not have the resolution or the urban modelling capability to predict complex urban dispersion; this is a possible refinement for the future, as is the introduction of varying deposition velocities to different surface types and resuspension processes (including modelling possible return to atmosphere and subsequent transport/re-deposition).

4.9 Section summary

This section describes the design and the methodology for the development of a new tool which links to real time plume predictions, to enable enhanced response calculations and visual display of information relevant to countermeasure decisions. This has application in UK emergency response. It also has application in UK emergency exercises and planning by enabling exercise data generation to be based on real (archived) meteorological results for the site in question, thereby increasing realism and providing enhanced site-specific details.

The tool includes a proposed approach to assessing the imprecision associated with dose and emergency countermeasure predictions in the early phase of an accident. The display of imprecision associated with the estimates of emergency countermeasure zones and on dose endpoints is a fundamental part of the new tool's design. The approach retains an essentially simple assessment capability while enabling lack of knowledge to be taken into account and reflected in the information supplied to decision makers. It will enable a range of calculations to be made based on radiological monitoring data or, when it becomes available, on source term information. A number of possible future developments and extensions to the tool outlined are also discussed.

5 VISUALISATION AND COMMUNICATION OF IMPRECISION

5.1 Introduction

The review in Section 2 concluded that the imprecision inherent in any predictions made in the early phase of a radiological emergency should be indicated in the output so that it is remembered during decision-making. The output from a response system should also be clear, unambiguous and straightforward, with the key assumptions clearly presented. The presentation of clear information regarding the imprecision associated with emergency predictions is an area where little work has been done. This section develops approaches to the display of imprecision associated with predictions from early emergency response calculations based on a limited number of off-site measurements and incomplete information about the nature of the release.

The first part of this section reviews the published literature on the presentation and understanding of data in emergency response and other environmental health/pollution situations. The prototype version of the tool described in the previous section has then been used to explore ways in which imprecise or uncertain information can be presented to decision makers, considering the alternative outcomes which may arise from possible alternative weather and dispersion situations, different release types, and the use of alternative measurement information. Maps are presented showing projected countermeasure areas for combinations of possible scenarios weighted by estimated probabilities. Alternative ways in which the information can be presented visually to decision makers to illustrate the range of consequences and the associated imprecision are explored. In developing this, opinions have been sought from those with emergency response roles in HPA as to the visual approaches they find most useful.

A key reference consulted as general background to visualisation techniques has been Tufte (1983).

5.2 Review of risk communication and visualisation techniques

5.2.1 Communication of emergency information

The first aspect briefly considered has been communication of imprecise information regarding risks. A key reference for this is Lundgren and McMakin (2004). The presentation of imprecise information is an issue for areas wider than emergency response, as for example in intelligence forecasts (Dieckmann *et al* 2010); in this paper it is stated that '*How to assess and present analytic uncertainty to policymakers has emerged as an important topic in risk and policy analysis*'. This paper distinguishes between probability assessment that is based on available probabilistic input data, and 'second-order' ambiguity that is '*primarily about the weight of the available evidence and the amount of missing information that is relevant to the problem under study'.*

It is human nature to believe that visual evidence and information is reality and 'true' (see for example Gershon 1998, Mark and Csillag 1989, Lundgren and McMakin 2004). As computer graphics become increasingly sophisticated and convincing, and the associated uncertainty either ignored or hidden, there are challenges in the presentation of information and data which are imprecise and uncertain.

Mapped output is now the expected form of emergency data, as for example in the CHEMET forecasts of Met Office, which also use the predictions of the NAME model. The availability of mapping systems such as ArcGIS encourages still more use of mapped data, and there is considerably more familiarity with GIS systems now than there was 10 years ago. The previous style of radiological emergency response results, of the type of 'countermeasures extend to about 5km from the site of the release' is unlikely to be regarded as sufficient; decision makers have become used to receiving maps. However, in some ways the extent of the imprecision associated with simple statements of this type is easier to communicate than with more complex results. The level of detail provided by mapped results, presented on a grid which suggests detailed spatial resolution, implies clarity and certainty in the data that are mapped to a far greater extent than rounded numbers on a table. It is therefore necessary to present, simultaneously with the basic results, an indication of imprecision to avoid unwarranted conclusions being drawn. Although the underlying degree of precision may be similar to that presented in tabular form, I would regard the need for the representation of imprecision to be greater if a GIS system is used than it was previously when results were more simplistic, despite the degree of imprecision being much the same in both cases if the same approach to calculational endpoints such as dose is applied in both.

Methods of representing uncertainty in emergency response situations need to be clear and intuitively easy to grasp, as they will be used in pressured environments where decisions have to be taken quickly. It is therefore an important part of emergency system development that imprecision and uncertainty is displayed along with the basic results and that the decision maker understands both components, and that this is done in a way that is helpful to decision makers and not overly complicated or time-consuming as '*decision makers need to know if something is, or is not, a problem …. they have little time for pondering confidence levels in data*' (Cliburn *et al* 2002).

Uncertainty or imprecision should be displayed in a way that is integral to the results, which can be interpreted easily and clearly, and which does not allow significant misinterpretation. The users may well only see the representations intermittently (for example, in occasional emergency exercises), as real radiological accidents are very infrequent. They need, for example, to be able to appreciate that 'probability of a countermeasure being required' (for example, in 10% of the scenarios considered 100% of the population in area A need to be evacuated) is not the same as 'severity of a countermeasure' (for example, only the most vulnerable 10% in the population in area A need to be evacuated).

A key part of risk communication is pre-emergency training. Those making decisions should be aware of the general nature of, for example, the risks associated with countermeasures to avert dose as well as the risks from delivered doses, and that decisions appropriate in one accident may not be appropriate in another accident of a different scale or at a different location or in different weather conditions. For example, in small accidents countermeasures may be based on averted doses towards the lower end of the ERL scale whereas the upper end may be more appropriate in larger accidents. Education and training of decision-makers is therefore needed. The concept of the tool outlined in Section 4 is that it forms the basis for decisions. It does not provide the decision itself; for that, additional judgement and the consideration of the wider context are necessary. The need is therefore for familiarity with the underlying issues to be encouraged through training and exercises. The use of the tool in exercises would also give familiarity with the style of presentation of results in an incident.

Finally, as the output of an emergency system may be used after the event as an explanation and justification of emergency decisions, it needs to be based on the best information currently available, and produced in a rigorous and defensible way. The actions taken in response to the Icelandic volcanic ash release in Spring 2010, for example, were closely analysed by both government and those with commercial interests both during and after the release, with particular attention being focused on the dispersion predictions and the estimates of risk. It is likely that the predictions made in the event of a radiological release would be scrutinised after the event in the same way, particularly if decisions taken had significant health or economic consequences.

5.2.2 Methods to aid visualisation

There are techniques which combine and integrate multiple causes of uncertainty, for example fuzzy sets (see, for example, Regan and Colvan, 2000) and the Dempster-Shafer method for handling imprecise probabilities (see, for example, Ducey 2001). However, the difficulties arising from only having a part of the ‘true’ set of countermeasure zones, and the fact that the set which is known may not evenly represent the true set, suggest that mathematical techniques to combine countermeasure areas may be inappropriate and misleading. A combination of results which is based on the judgement of the modeller and which results in a processed result being given to the decision maker who would then be unaware of the judgements involved in its derivation is not transparent. However, a certain amount of ‘processing’ may aid the decision maker's understanding and may also be necessary to reduce over-complication and the presentation of too much information. Several studies, for example Cliburn *et al* 2002, have indicated that users find a display that becomes cluttered with uncertainty information to be counterproductive.

Fan charts can be used to demonstrate the uncertainty associated with predictions and projections into the future. They have been used to demonstrate mortality predictions and future temperature increases. The Bank of England uses fan charts to visualise the uncertainty associated with inflation in the future[1]. Fan charts show a central projection with adjacent series of prediction intervals at various levels of probability. In the case of the Bank of England charts they show predictions in intervals from 10% to 90%. The shading of the intervals reflects the confidence associated with the predictions. The charts are termed fan charts because the forecasts spread out and resemble a fan as the project extends further into the future.

The concept has been extended by Jackson (see http://www.mrc-bsu.cam.ac.uk/personal/chris/papers/denstrip.pdf) with the introduction into the fan chart of shading to represent cumulative confidence, which leads to increasingly lighter shading as the predictions extend into the future. Jackson also proposes the use of a 'density strip' for 2-dimensional presentation of uncertain information, '*a shaded strip with darkness proportional to the density*' (Jackson 2008).

Both of the above methods, the fan chart and the density strip, are of potential help in displaying the imprecision associated with tabulated or diagram-based results from an emergency assessment. However, they are not considered further here as the emphasis of this section is on the visualisation of spatial data, where they do not have an obvious application.

Developing methods to aid the visualisation of uncertainty in spatial data is a relatively new area of research; see discussions, for example, in Fairbairn *et al*

[1] See for example http://www.nottingham.ac.uk/business/cris/papers/2007-6.pdf, http://www.bankofengland.co.uk/publications/inflationreport/ir08feb.pdf, and http://www.voxeu.org/index.php?q=node/2592).

2001, MacEachren *et al* 1998, Zhang and Goodchild 2002, MacEachren *et al* 2005. It is recognised that the visualisation of uncertainty is significant in aiding the correct decisions to be made based on mapped data but also that the results of many of the possible techniques have not yet been assessed, and furthermore that it is not well understood what effects the presentation of uncertainty information has upon the recipient and how it aids (or otherwise) analysis of the data. MacEachren *et al* (2005) considers that '*we have only scratched the surface of the problem*' and '*nor do we understand the impact of uncertainty visualisation on the process of analysis or decision making*'. It is, however, clear that presenting information in a way which suggests false precision may lead to over-confidence and inappropriate decisions.

A number of possible techniques for representing uncertainty in visual data have been proposed. These include:

- Hue and saturation of colour (for example, McEachren 1992, Schweizer and Goodchild 1992, Brewer 1994). Hue is the colour category (eg, red, blue, yellow) and saturation is the amount of hue in a colour. Hue can be used to represent a type of data, and saturation used to visualise uncertainty. The more saturated (richer) the colour representing a particular type of data, the more certain the information is on that data. Hence colour can be used to represent data in two ways on the same map (Hengl *et al* 2002). Colour, including light/dark variations, has been found to be one of the most effective ways of communicating uncertainty, see, for example, Leitner and Buttenfield 2000.

- Alterations in focus and resolution (McEachren 1992), possibly including fog at varying degrees of density to obscure information which is uncertain, with the thickness of the fog representing the degree of uncertainty in that part of the map.

- Broken lines or lines of varying thickness to suggest uncertainty in contour information, or symbology (for example, the use of question marks in varying densities) (Monmonier 1994).

- Sharpness of pattern, in either areas or at boundaries, where the clarity of an area or boundary is used to define the uncertainty of the spatial data via the use of a scale of sharp patterns through to fuzzy patterns to indicate the degree of associated uncertainty (MacEachren 1992).
- Overlaying of information, where a single map can be used to show the basic information with an overlay of the uncertain information shown as texture over the top.
- Adjacent maps, one showing the basic information and another the uncertainty associated with it (McEachren 1992 and McEachren *et al* 1998). As an example, under ESRI GIS systems, a map showed on the screen can be scrolled down to reveal another map of the same area showing different details. This could, for example, show the underlying map with superimposed dose distributions, with the overlayed map showing best-estimate countermeasure areas, and further overlayed maps showing the 5% and 95% countermeasure areas.
- Animation techniques, for instance a computerised display alternating (toggling) between several possible outcomes (Fisher 1994, and Hengl *et al* 2002), or uncertain areas blinking to indicate high uncertainty. Animation can be used to show in sequence a series of alternative outcomes in a GIS framework. Such animation techniques have been used, for example in relation to meteorological forecast modelling (Fauerbach *et al* 1996). However, Aerts *et al* (2003) concluded that users have some preference for static displays rather than toggling. A particular type of animation is a draggable slider scale. The user can drag a slider across a range that can be linked to a particular parameter. In this instance, it can alter the mapped information across the uncertainty range, and the user can drag the slider to change the value of a parameter across its range, or the slider can be used to show the areas which are more uncertain by fading these out of the picture as the slider is moved to one end of the range (Drecki 2002). The central position on the slider could be the best estimate of countermeasure area,

with – for example – the extreme end at the left showing the 'uncertain – smallest areas' countermeasure information and the extreme end at the right showing the 'uncertain – largest areas'. Alternatively, the slider could be used to move the estimated countermeasure areas from those corresponding to the lower ERL to those for the upper ERL.

- Sound, where the cursor moving over the map can suggest a level of uncertainty at a particular location through variable pitch, for example a low pitch sound for low uncertainty rising to a high pitch sound for large uncertainty (Fisher 1994, Krygier 1994).
- Touch techniques for enabling interrogation of the basic data for details of supplementary data on the associated uncertainties (Fairbairn *et al* 2001).

Of the above, colour (including light/dark variations) has been found to be one of the most effective ways of communicating uncertainty (see, for example, Leitner and Buttenfield (2000)). Animation and sound/touch techniques are not the first choice for the issue addressed here, as the countermeasure maps will not always be displayed on computers; decision makers and others will need to take paper copies to meetings, for example. But other techniques may be of value in displaying particular results. For example, to view the impact on the predictions of the first few key measurements individually, a simple technique would be to view computerised visual displays of the countermeasure areas or dose zones generated on the basis of each measurement in rapid sequence (see, for example, Howard and MacEachren (1996) in which techniques for the comparison of multiple surfaces is discussed).

An alternative technique is a method demonstrated by Fauerbach *et al* (1996), in which the output of three alternative meteorological forecasting models was combined in an animated display. In this work, the uncertainty associated with the model predictions was represented by the standard deviation among the three models at each location and time. Where predictions differed considerably the uncertainty in the modelled endpoint (which in this case was forecast pressure) was large, while it was small in the areas where the models were in close agreement.

Both the UK Met Office and Professor David Speigelhalter of Cambridge University have identified the potential usefulness of relating the size of a risk to the font size used to communicate information, but a direct application for this technique in the spatial presentation of assessment results is not obvious.

5.2.3 How can spatial mapping be visualised to show uncertainty?

One option for the spatial display of probabilistic information is to augment the colour density at each location for every calculation which indicates, for example, a countermeasure at that point, by a degree which is dependent on the increased probability. The colour densities would then correspond to a legend showing the graduation of shading against probability.

ArcMap has the capability to show areas in partial shades, building up density in multiple layers. Through multiple overlays of alternative areas, colour or shade gradients can be built up for each alternative countermeasure zone, leading to increasing strength of colour/shade in those areas where the most zones coincide, hence providing a visual indicator of likelihood. Further development of this leads to alternative pictures of the countermeasure zones; for example, the ‘best estimate’, an estimate of the largest countermeasure area (for example, the area which is only exceeded in 5% of possible outcomes), and an estimate of the smallest countermeasure area (for example, the area which is exceeded in 95% of possible outcomes). This is similar to a recommendation in Lundgren and McMakin (2004), which is to make clear to decision makers the maximum action, the recommended 'middle' action and the minimum action (which can be considered as corresponding to 'you must do X, you should do Y, you can do Z'), although in this situation the smallest countermeasure zone does not correspond to the minimum possible action.

A particular aspect is the use and overlay of colour combinations. This can utilise the properties of colour combinations. For example, red, green and blue can be used to represent three alternative dimensions. Then, the areas of overlap can be illustrated using red-green (combination of red and green), purple (combination of red and blue), turquoise (combination of green and blue) and brown (combination of all three) (see for example, Goodchild *et al* 1994). The difficulty is that this approach is primarily useful for illustrating only three dimensions, as the introduction of a fourth colour such as yellow leads to a colour combination (such as green) which corresponds to more than one dimension combination.

Colvile *et al* (2002) have suggested probabilistic colour mapping as a method of presenting emergency data, in the setting of air quality management. The technique proposed is a method for describing the need for action in regard to environmental quality measured against a relevant standard, for example 'air quality objective possibly will be achieved with action' or 'air quality objective probably will not be achieved without action'. The Colvile study uses the colours red (definitely dangerous), yellow/green (possibly problematic) and blue (unpolluted). This is consistent with the view of Davis and Keller (1997) that green/red are the obvious choice of colour to represent hazard. In the context of this study, a variation on this would be to define colours on a map showing the likelihood of the need for action, for each radiological countermeasure. For example, for evacuation, and retaining here the colour choices of the Colvile study, the probabilistic colour mapping could be:

Red: evacuation almost certainly needed (probability > 90%)

Yellow: evacuation likely to be needed (probability < 90% but > 50%)

Green: evacuation may be needed (probability < 50% but > 10%)

Blue: evacuation unlikely to be needed (probability <10%).

Here, 'probability' is not exactly the 'probability of a countermeasure at that point' but shows that percentage of scenario combinations as considered in the study that indicate a countermeasure is required at that point. This is a surrogate for the probability but is not exactly the same. This option for display is explored further below.

5.3 Examples of visualisation techniques

The extent of countermeasures based on past real weather sequences from stored NWP files has been presented in Section 3. These results demonstrate the significant influence on the predicted endpoints of emergency assessments arising from the weather, which is only one element of imprecision. The visualisation of the output of emergency systems is therefore clearly important, and is likely to become still more important when further sources of imprecision are included in the analysis.

To illustrate alternative visualisation techniques, an example emergency assessment has been undertaken using the prototype system outlined in Section 4. To examine the doses and countermeasure predictions for a hypothetical release in 'real weather' meteorological conditions, the NAME model has been run at the Met Office for three sets of real NWP data from 2007 and 2008, obtained from the Met Office archives. The NAME runs were undertaken specifically for this study. In these three weather sequences, the stability category is Category D with a wind speed between 4.5 - 5.5 m s^{-1} throughout the time period of interest. The period was defined as up to 12 hours after the start of the release, to permit the plume to leave the area potentially affected by countermeasures.

All three weather sequences have some degree of rainfall at some location during the period of plume dispersion, ranging from very light to heavy. For each of these weather sets NAME was run to predict the dispersion of a plume of ^{137}Cs from a 10m release height. The initial wind direction in all three sequences was constrained to be from 270º, ie towards due East, with a possible variation of up to 10 degrees either side. The NAME runs were repeated with three alternative release durations (of 1 hour, 4 hours and 8 hours) and two alternative dry deposition velocities (of 1 10^{-3} m s^{-1} and 1 10^{-2} m s^{-1}). There were therefore 18 sets of calculations undertaken, for all combinations of 3 weathers, 3 release durations and 2 dry deposition velocities. Variations in weather conditions (eg rainfall rate, atmospheric stability) were included through the use of the three real alternative weathers sets.

For simplicity here, only a single instantaneous measurement of activity concentration in air was considered. This was assumed to be 2.6 10^5 Bq m^{-3} at 5km due east of the release point, measured 1 hour after the start of the release; the NAME results were all scaled to show this value at this time and location. Table 5.1 summarises the furthermost predicted extent of the sheltering countermeasure, determined on the basis of the lower ERL of 3 mSv effective dose, for each of the 18 sets of calculations.

Table 5.1 Furthermost extent of sheltering for the 18 combinations

Description	Furthermost extent of sheltering, km[1]
Weather 1 (mostly dry), release duration 1 hour, deposition velocity 10^{-2}	4.6
Weather 1 (mostly dry), release duration 4 hours, deposition velocity 10^{-2}	11.4
Weather 1 (mostly dry), release duration 8 hours, deposition velocity 10^{-2}	17.9
Weather 1 (mostly dry), release duration 1 hour, deposition velocity 10^{-3}	3.0
Weather 1 (mostly dry), release duration 4 hours, deposition velocity 10^{-3}	8.0
Weather 1 (mostly dry), release duration 8 hours, deposition velocity 10^{-3}	13.6
Weather 2 (rain), release duration 1 hour, deposition velocity 10^{-2}	2.6
Weather 2 (rain), release duration 4 hours, deposition velocity 10^{-2}	8.3
Weather 2 (rain), release duration 8 hours, deposition velocity 10^{-2}	14.3
Weather 2 (rain), release duration 1 hour, deposition velocity 10^{-3}	1.7
Weather 2 (rain), release duration 4 hours, deposition velocity 10^{-3}	5.1
Weather 2 (rain), release duration 8 hours, deposition velocity 10^{-3}	9.9
Weather 3 (very wet), release duration 1 hour, deposition velocity 10^{-2}	3.7
Weather 3 (very wet), release duration 4 hours, deposition velocity 10^{-2}	8.5
Weather 3 (very wet), release duration 8 hours, deposition velocity 10^{-2}	18.7
Weather 3 (very wet), release duration 1 hour, deposition velocity 10^{-3}	2.6
Weather 3 (very wet), release duration 4 hours, deposition velocity 10^{-3}	6.5
Weather 3 (very wet), release duration 8 hours, deposition velocity 10^{-3}	17.6

[1] For all combinations, the instantaneous activity concentration in air at 5km due east at 50-60 minutes after the start of the release is 2.6 10^5 Bq m^{-3}

The results presented in the figures below show the areas in which the sheltering countermeasure is predicted to be required. Overlaid on the maps is a 30º sector centred towards 90º (due East), with distances from the point of release shown for scale.

Figures 5.3a – 5.3c show results for the three alternative weathers as summarised in Table 5.1, namely ‘mostly dry’, ‘rain’, ‘very wet’. For each weather, the sheltering areas are illustrated using a different set of colours. Within each figure, the same alternative release durations and deposition velocities are included. It can be seen from Figures 5.3a – 5.3c that there are significant differences between the predicted sheltering zones. The most significant influence here is the duration of the release and the variation in wind direction through the period of plume travel, although other factors also affect the predictions.

Figure 5.3a Sheltering areas; weather 1 (‘mostly dry’), 3 alternative release durations and 2 deposition velocities

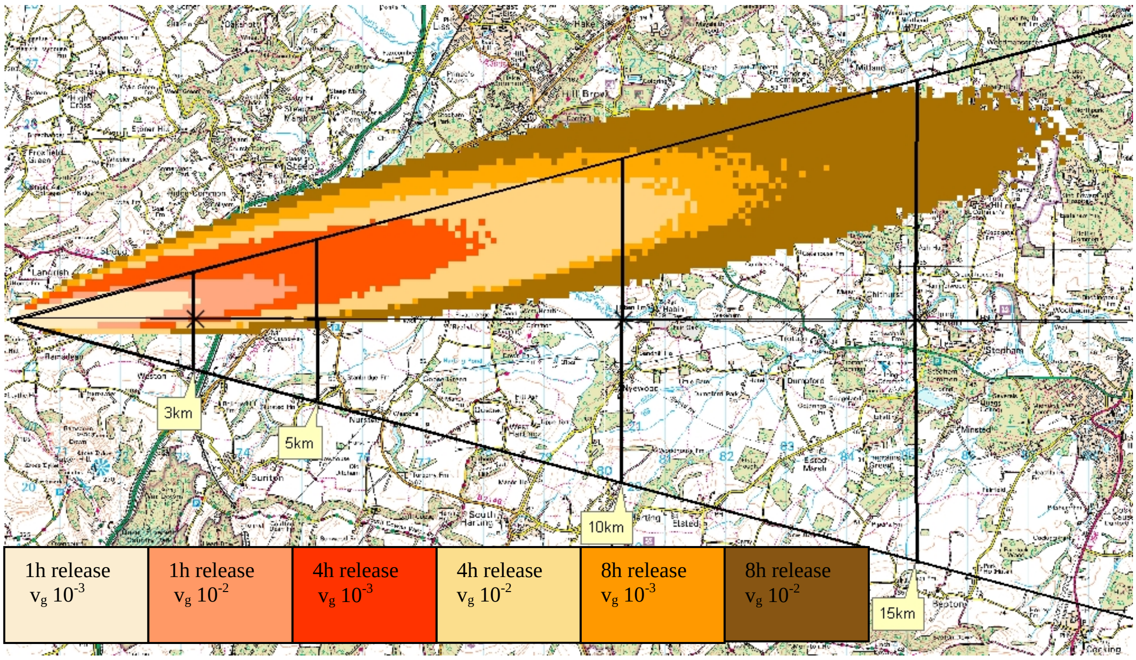


Figure 5.3b Sheltering areas; weather 2 ('rain'), 3 alternative release durations and 2 deposition velocities

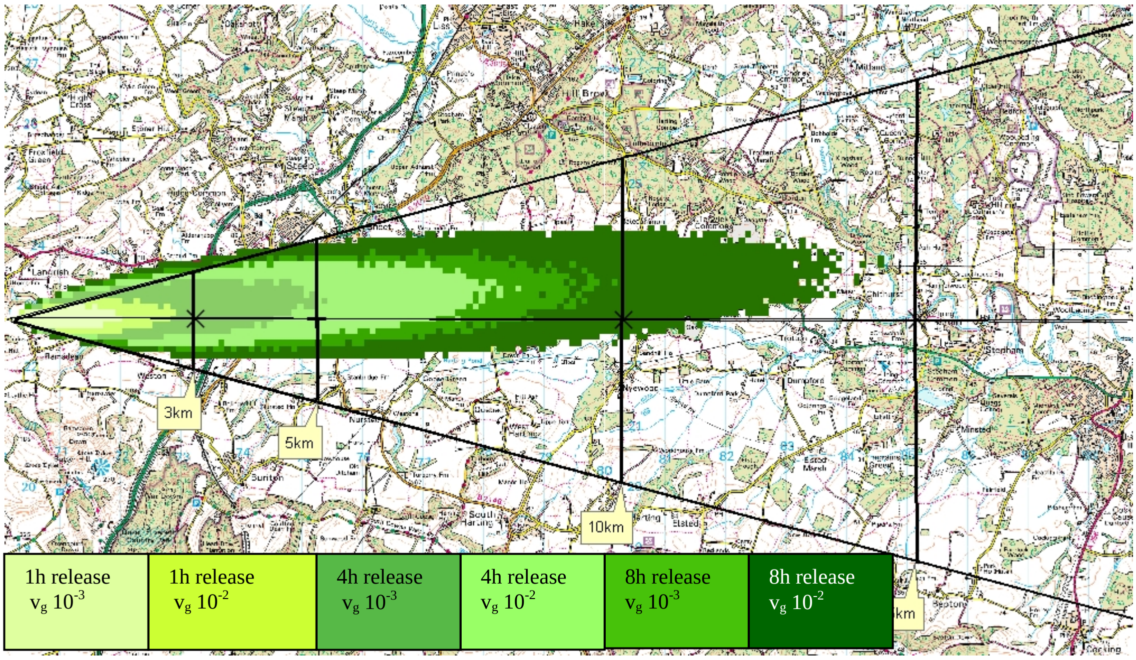
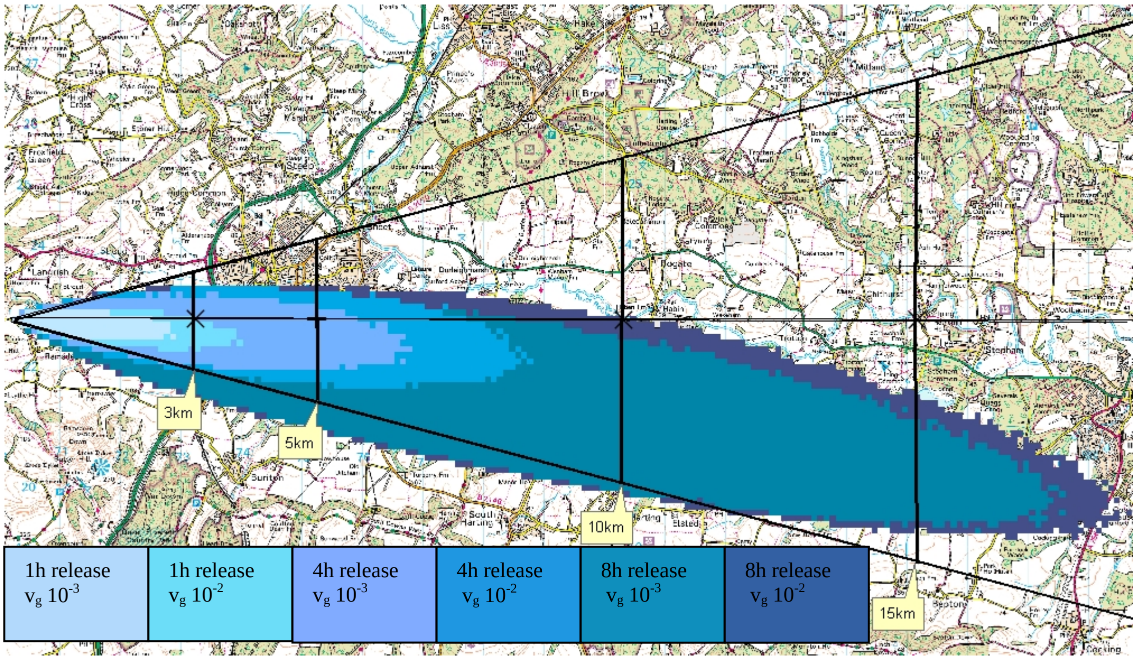


Figure 5.3c Sheltering areas; weather 3 ('very wet'), 3 alternative release durations and 2 deposition velocities



It is interesting to note in Figure 5.3c that there is little difference between the predicted sheltering areas for the long release duration for the lower and upper deposition velocities. This is due to the influence of plume depletion, which is modelled in NAME but not in R91. Bedwell *et al* (to be published) show that plume depletion reduces the time integrated air concentration by a factor of 2 or more from about 10 km downwind for a rainfall rate of 10 mm h^{-1}. A lower rainfall rate of 4 mm h^{-1} was shown to reduce the TIAC by a factor of 2 or more from about 20 km downwind.

Figures 5.4a – 5.4e illustrate more clearly the relative importance of the release duration and deposition velocity variables. Figure 5.4a shows the area covered by sheltering if the release duration is predicted to be 1 hour, retaining the three alternative weathers and two deposition velocities. Figure 5.4b shows the area covered by sheltering if the release duration is predicted to be 4 hours, retaining the three alternative weathers and two deposition velocities. Figure 5.4c shows the area covered by sheltering if the release duration is predicted to be 8 hours, retaining the three alternative weathers and two deposition velocities. Figure 5.4d shows the area covered by sheltering if the deposition velocity is 10^{-2} m s^{-1}, retaining the three alternative weathers and three release durations. Figure 5.4e shows the area covered by sheltering if the deposition velocity is 10^{-3} m s^{-1}, retaining the three alternative weathers and three release durations.

Figure 5.4a Sheltering area; 1 hour release duration, 3 alternative weathers and 2 deposition velocities

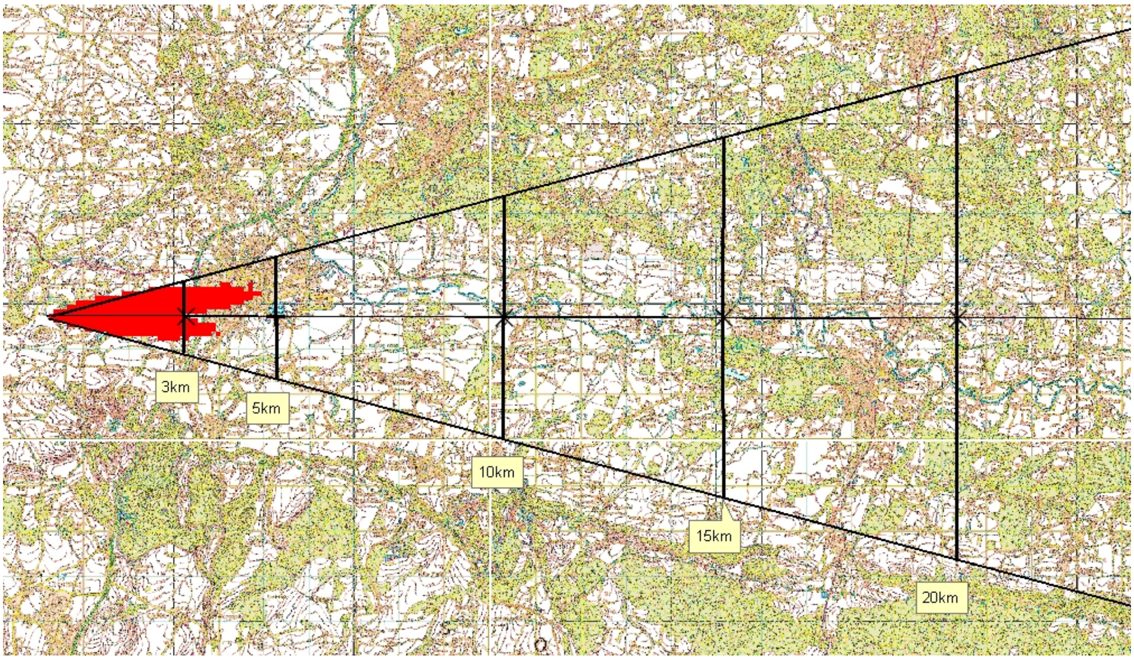


Figure 5.4b Sheltering area; 4 hour release duration, 3 alternative weathers and 2 deposition velocities

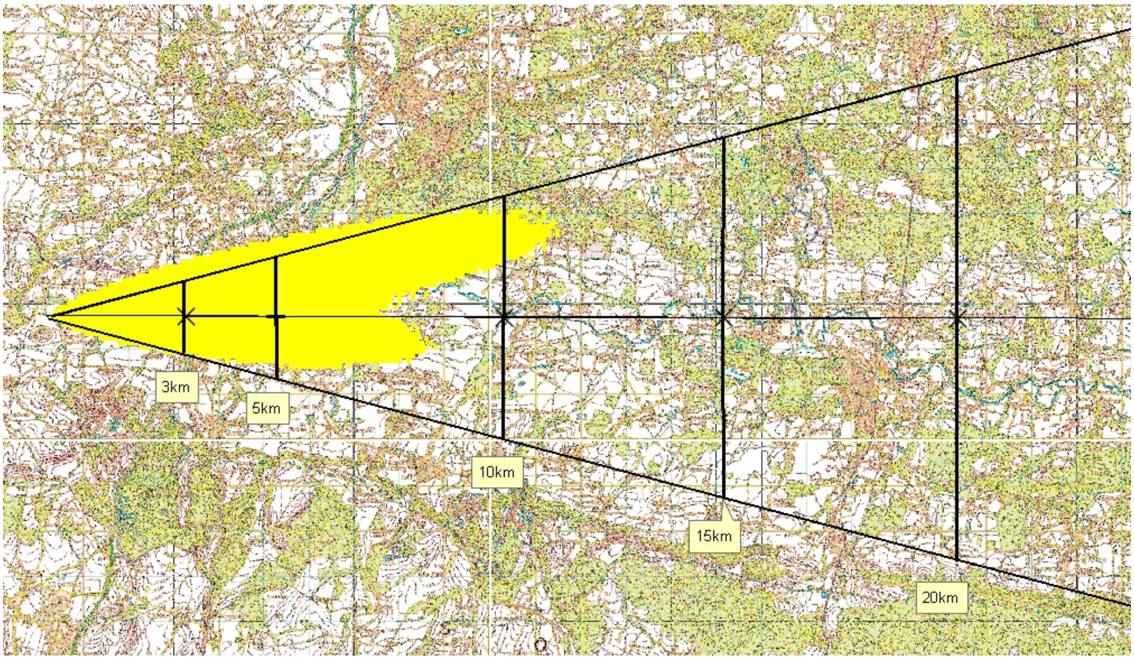


Figure 5.4c Sheltering area; 8 hour release duration, 3 alternative weathers and 2 deposition velocities

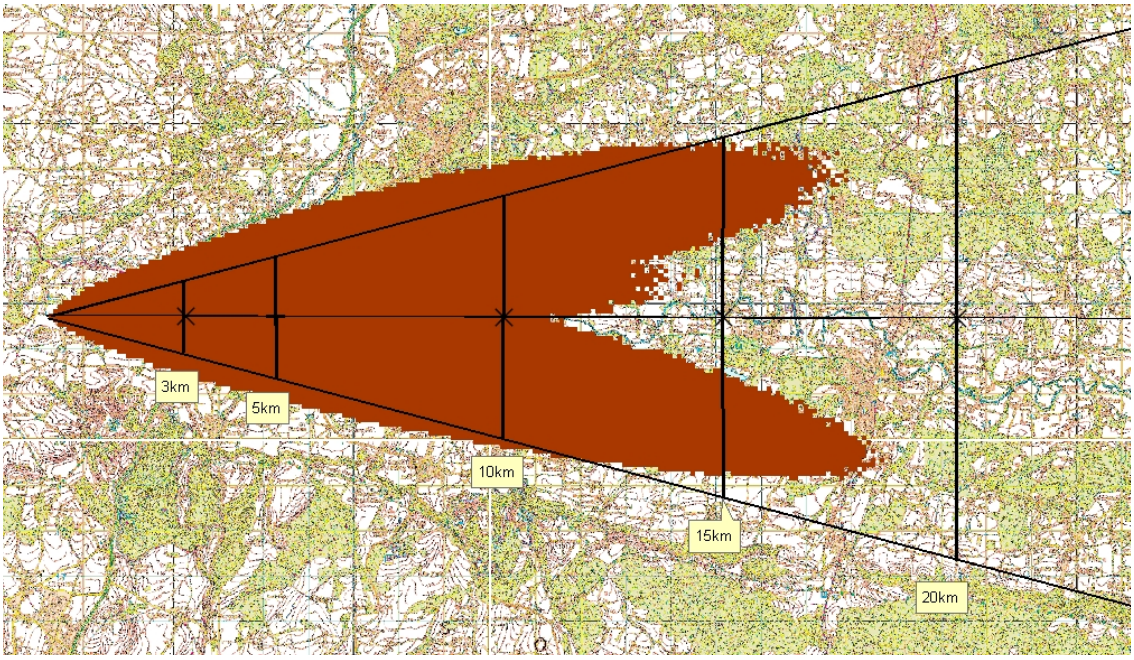


Figure 5.4d Sheltering area; 10^{-2} m s^{-1} deposition velocity, 3 alternative weathers and 3 release durations

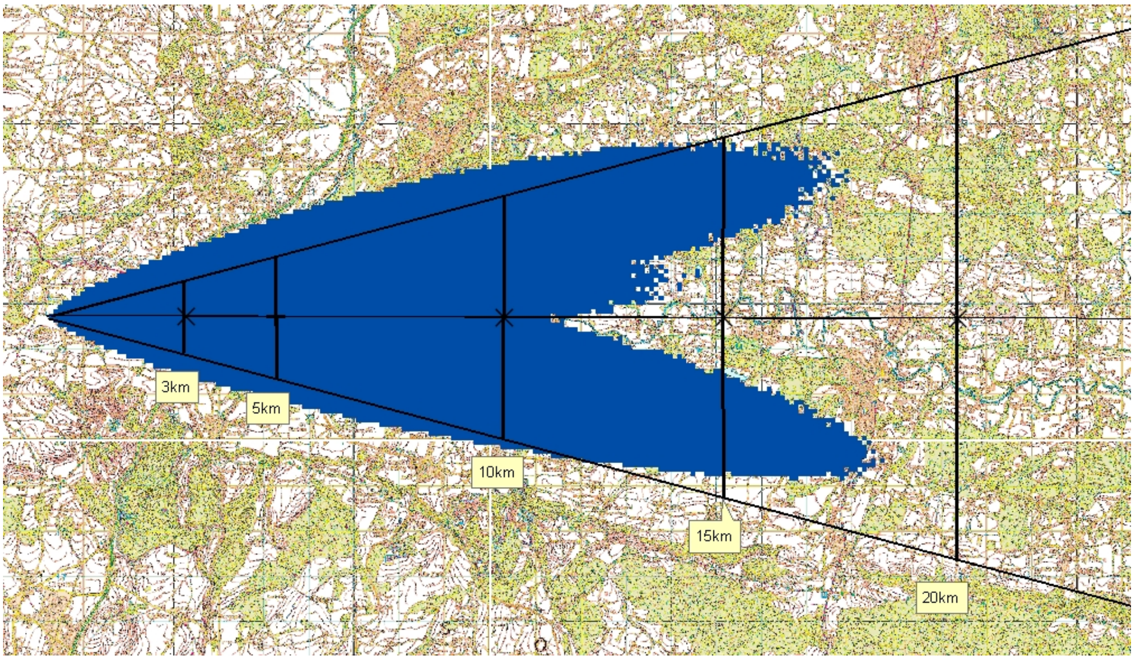
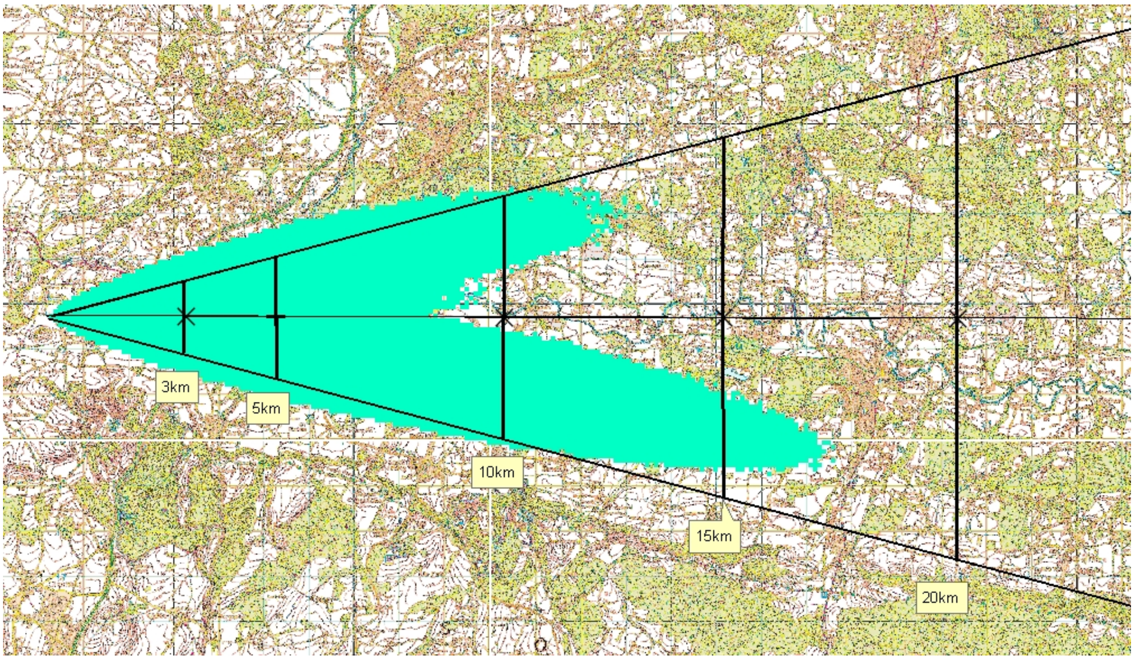
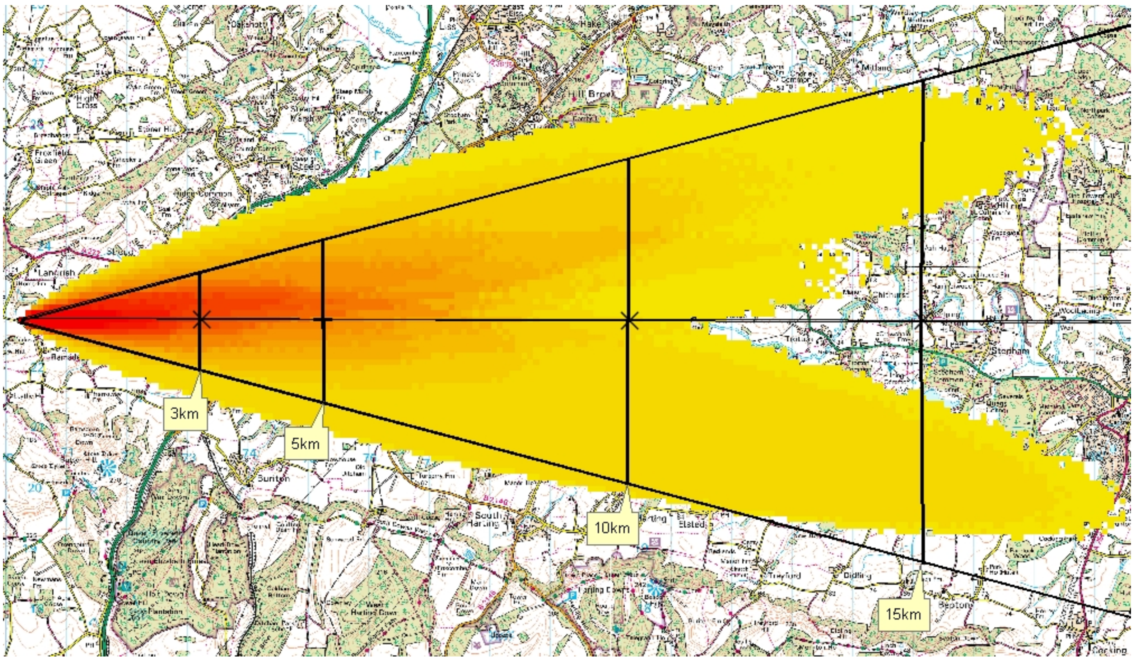


Figure 5.4e Sheltering area; 10^{-3} m s^{-1} deposition velocity, 3 alternative weathers and 3 release durations



In this example, as shown in Figures 5.3 and 5.4, there are 18 alternative sheltering zones, arising from all combinations of three weathers, three release durations and two deposition velocity alternatives. How can this information best be presented to those who have to make decisions on the sheltering areas? Assuming first that all 18 possible outcomes are regarded as equally possible (which is an unlikely situation, in reality), a colour saturation map (see Figure 5.5a) can be produced. This overlays all the sheltering countermeasure areas, and the density of colour indicates the probability of the countermeasure being required (in terms of a total dose, as defined above, of 3mSv being exceeded). The darkest shade, red, corresponds to the areas most likely to require sheltering, and yellow shows the least likely. It can be seen that while the sheltering areas do overlay to some extent there are areas which only feature with lower likelihood.

Figure 5.5a Sheltering area; 3 weathers, 3 release durations, 2 deposition velocities: colour density

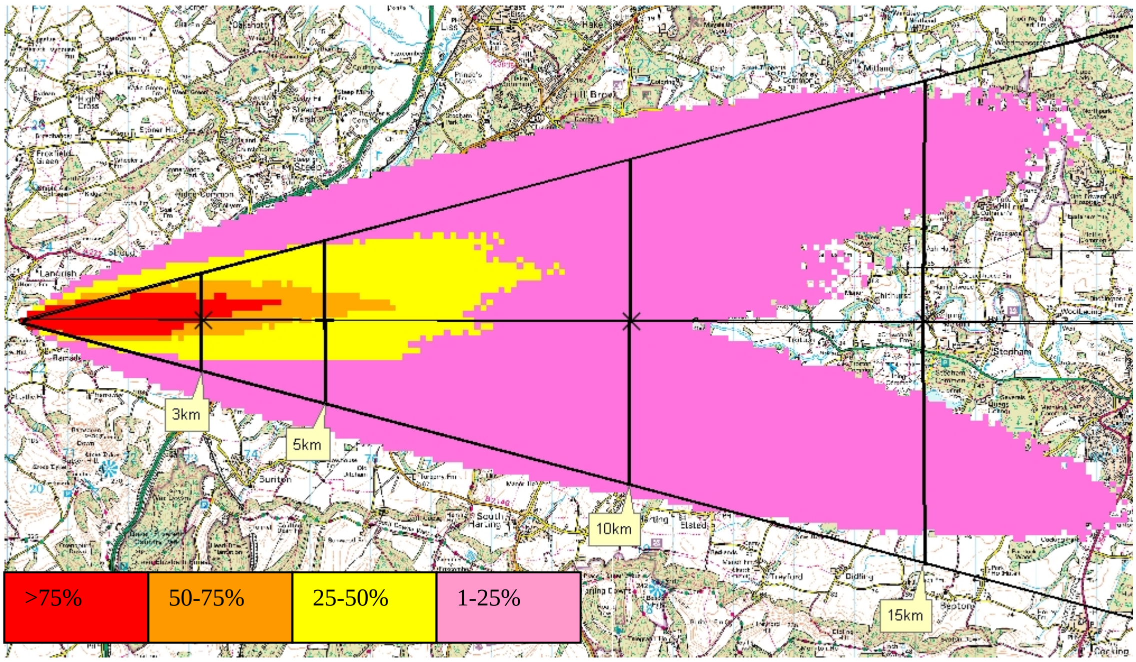


An alternative presentation of the same information, again assuming that all the weathers, all the release durations and both the deposition velocities are equally likely, is shown in Figure 5.5b. Here the information presented in Figure 5.5a is categorised. Figure 5.5b shows as red the areas where sheltering is predicted with more than 75% likelihood (here, in more than 13 out of the 18 runs), orange where sheltering has 50% - 75% likelihood, yellow where sheltering has 25% - 50% likelihood, and pink where sheltering has 1% - 25%

likelihood. Although, as discussed above, Colvile *et al* (2002) and Davis and Keller (1997) have suggested the use of red, yellow/green and blue as colours to present emergency data, in the present context pink is suggested as being preferable to either green or blue. Green and blue may mistakenly give the impression of an area which is ‘safe’ or ‘unpolluted’; additionally, green and red may be difficult to differentiate for those who are colour-blind.

HPA staff with roles in emergency response, when presented with the alternative presentations, have thought the colour classification as shown in Figure 5.5b to be clearer and more informative than the colour density approach in Figure 5.5a.

Figure 5.5b Sheltering area; 3 weathers, 3 release durations, 2 deposition velocities: colour classes



The areas shown in Figures 5.5a and 5.5b assume all permutations are equally likely. In reality, it is to be expected that certain alternatives will be thought more likely than others. To illustrate the influence of this, the sheltering areas in this example have been re-assessed, giving more weight to weathers 2 and 3 than to weather 1 (ie it is thought more likely to rain than be dry), and also greater weight to the longer release durations. Weights have been associated with the results of the basic 18 individual runs to reflect this. The weights applied are shown in Table 5.2. Only the colour classification presentation is shown here, in Figure 5.6, with the colours showing the same percentages of likelihood as in Figure 5.5b.

Table 5.2 Weightings applied to the 18 combinations to reflect increased probability of rain and long release durations

Description	Weighting factor[1]
Weather 1 (mostly dry), release duration 1 hour, deposition velocity 10^{-2}	1
Weather 1 (mostly dry), release duration 4 hours, deposition velocity 10^{-2}	2
Weather 1 (mostly dry), release duration 8 hours, deposition velocity 10^{-2}	5
Weather 1 (mostly dry), release duration 1 hour, deposition velocity 10^{-3}	1
Weather 1 (mostly dry), release duration 4 hours, deposition velocity 10^{-3}	2
Weather 1 (mostly dry), release duration 8 hours, deposition velocity 10^{-3}	5
Weather 2 (rain), release duration 1 hour, deposition velocity 10^{-2}	2
Weather 2 (rain), release duration 4 hours, deposition velocity 10^{-2}	4
Weather 2 (rain), release duration 8 hours, deposition velocity 10^{-2}	10
Weather 2 (rain), release duration 1 hour, deposition velocity 10^{-3}	2
Weather 2 (rain), release duration 4 hours, deposition velocity 10^{-3}	4
Weather 2 (rain), release duration 8 hours, deposition velocity 10^{-3}	10
Weather 3 (very wet), release duration 1 hour, deposition velocity 10^{-2}	5
Weather 3 (very wet), release duration 4 hours, deposition velocity 10^{-2}	10
Weather 3 (very wet), release duration 8 hours, deposition velocity 10^{-2}	25
Weather 3 (very wet), release duration 1 hour, deposition velocity 10^{-3}	5
Weather 3 (very wet), release duration 4 hours, deposition velocity 10^{-3}	10
Weather 3 (very wet), release duration 8 hours, deposition velocity 10^{-3}	25

Note:
1. Contributory weights are ‘mostly dry’ = 1, ‘rain’ = 2, ‘very wet’ = 5, release duration 1h = 1, release duration 4h = 2, release duration 8h = 5.

Figure 5.7 shows a different split of likelihood areas, which decision makers may find helpful. Here, the pink area represents a ‘less than 10% chance of sheltering being required’ and the red area is ‘a greater than 90% chance of sheltering being required’. The two yellow zones show the 10% - 90% region, with the division in yellow tone marking the 50% boundary.

Figure 5.6 Sheltering area; rain and longer release durations preferentially weighted: colour classes

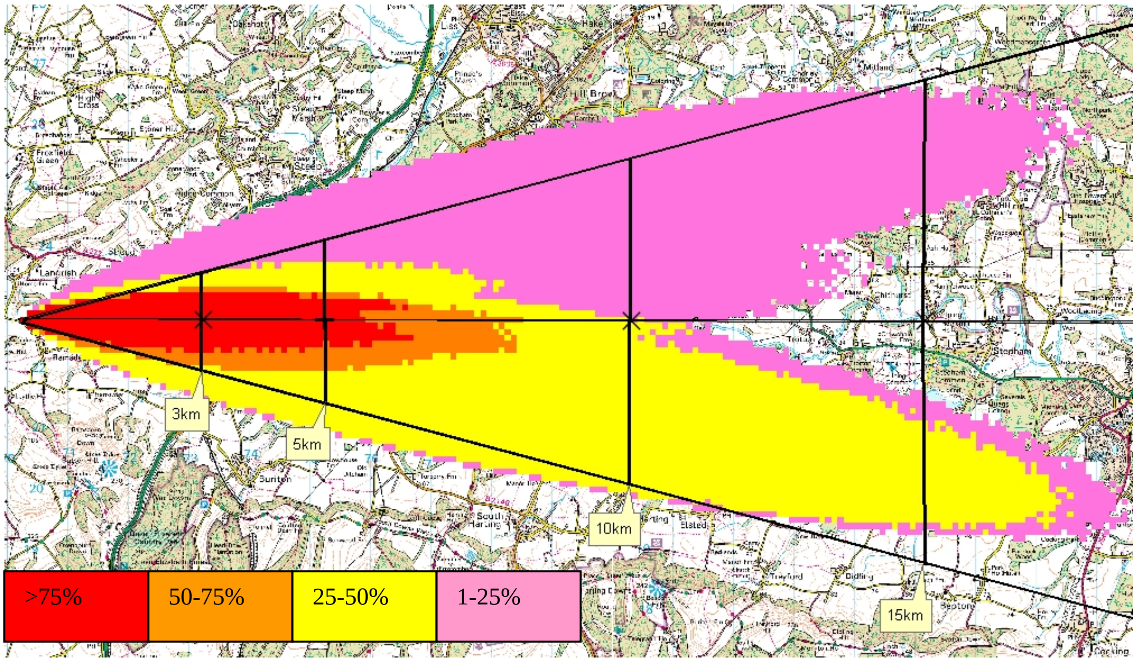
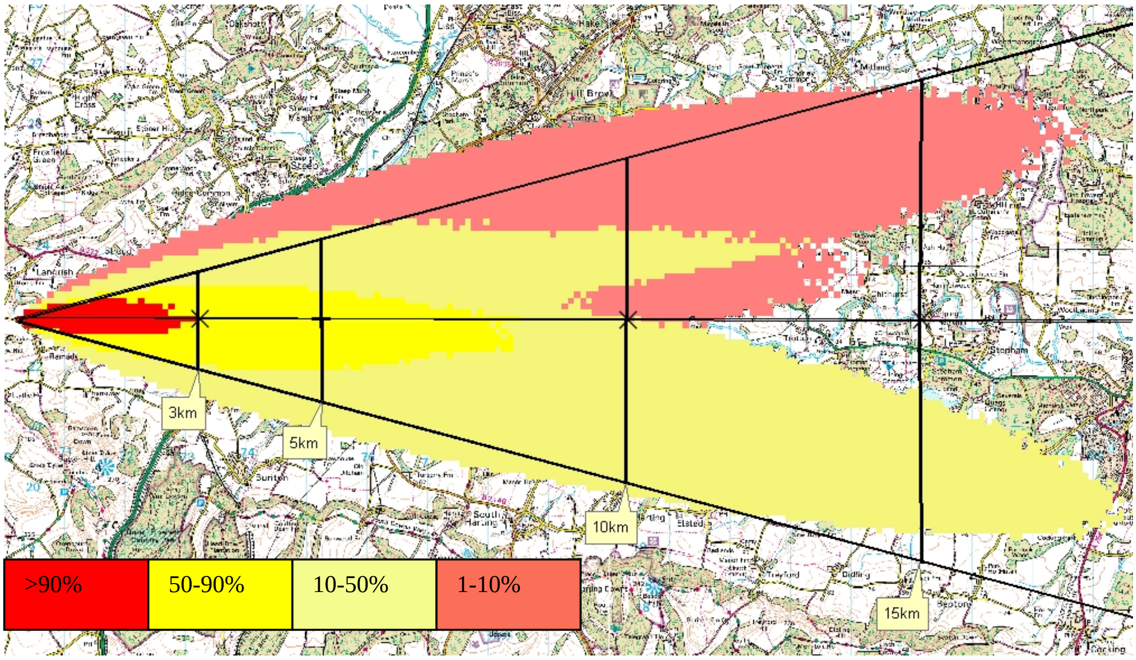
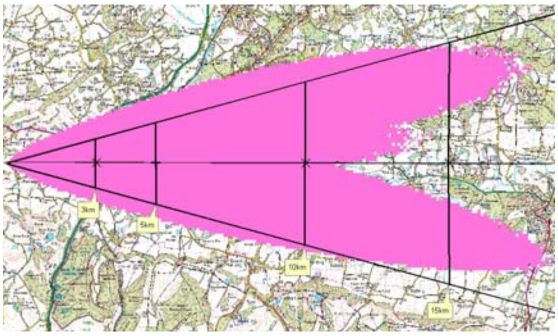


Figure 5.7 Sheltering area; rain and longer release durations preferentially weighted: colour classes

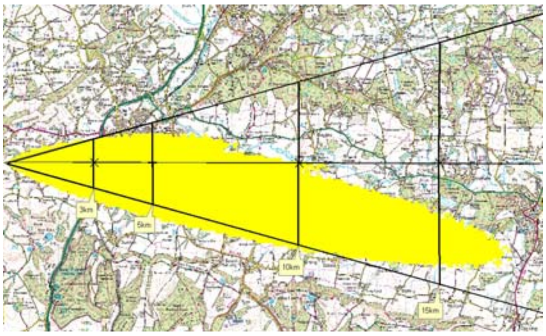


A presentational option for computer display is the draggable slider scale. For example, by sliding across a scale showing likelihood of outcomes, the user can move the areas shown from the full probability range, for example all sheltering zones with a greater than 1% probability, to those areas where there is at least a 75% chance of sheltering being required. An example of this is shown in Figure 5.8 below, which shows the same information as that presented in Figure 5.6, but in a sequential format. Alternatively, the slider could move along a scale showing the influence of changing the intervention criterion (for example from the lower ERL to the higher ERL). Techniques such as a slider scale may temporarily remove parts of the overall picture, such as the areas where there is a low chance of a countermeasure being needed, for example; it is important that misunderstandings do not arise from selective presentation of data.

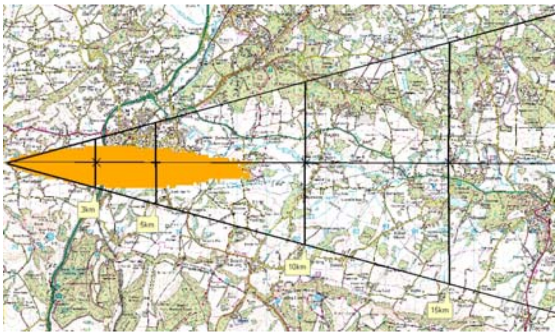
Figure 5.8 Sheltering areas; likelihood slider scale from >1% to >75%



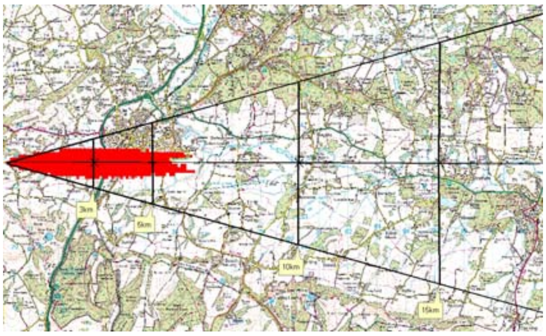
Sheltering: >1% likelihood



Sheltering: >25% likelihood



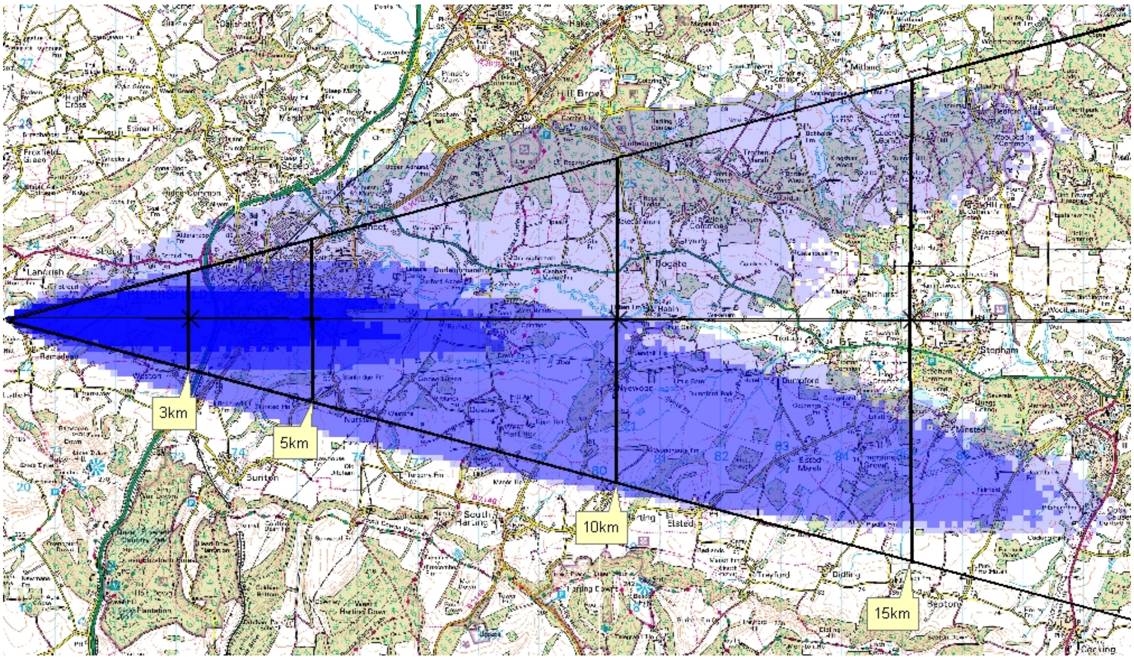
Sheltering: >50% likelihood



Sheltering: >75% likelihood

An alternative feature is the use of transparency. It has been suggested that greater transparency can be used to indicate areas of higher uncertainty or lower likelihood. This is shown in Figure 5.9, which presents the same information as Figure 5.6 but with the use of a single colour combined with degrees of transparency ranging from 5% (nearly all solid colour) for the areas most likely to require sheltering to 80% (mostly transparent) for the areas least likely to require sheltering. HPA emergency staff considered that some degree of transparency was helpful as it enables the underlying map details to be viewed, but it was not considered particularly effective when the degree of transparency varies from one part of the zone to another. The optimum presentation for clarity would therefore seem to be combining colour classification with semi-transparency. Figure 5.10 is a modified version of Figure 5.6, using 30% transparency throughout.

Figure 5.9 Sheltering areas; rain and longer release durations preferentially weighted: transparency 5% - 80%

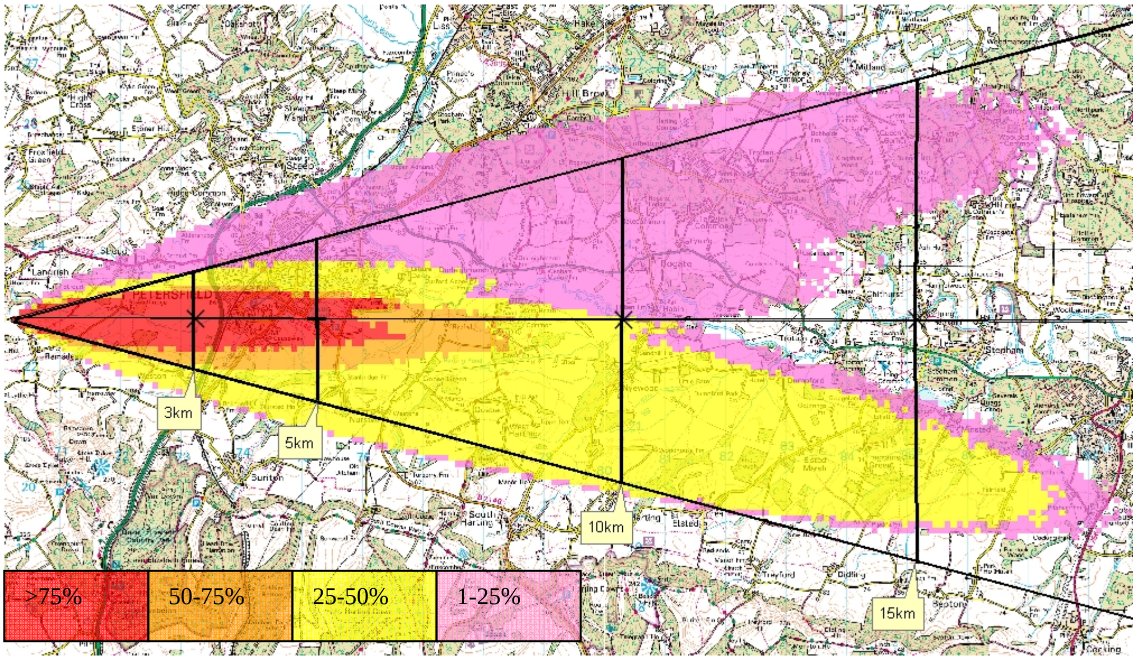


5.3.1 Presenting doses on maps

The presentation of predicted doses, which can either be done for a single exposure pathway, or a sum over all pathways, can be made by using a similar colour coding to that discussed above, to represent the percentage of model runs which show a dose in excess of a user specified dose level. A slider scale could be used for this endpoint. The slider could run across probability (from 0 to 1) with the mapped information showing as colour density the magnitude of dose, at each location, which corresponds to the level of probability shown on the slider scale. Alternatively, the scale on the slider could show the range of dose magnitude (either from 0 to the highest identified in the accident options considered, or across a user-specified range) and the colour density can represent the probability at each location of that dose occurring. Doses can also be represented simply by the percentage of model runs showing a dose in excess of a user specified dose level.

The calculation of doses in conjunction with probabilities requires some care as in combining severity of effect with probability of occurrence, different combinations can give rise to the same value. For example, a dose of 10 mSv with a probability of 0.3 gives the same value as a dose of 5 mSv with a probability of 0.6. This would lead to loss of information if the dose/probabilities are simply summed, and care would be needed to undertake the calculation in a way which avoids this.

Figure 5.10 Sheltering areas; rain and longer release durations preferentially weighted: colour classes, transparency at 30%



5.4 Discussion and possible future developments

As was suggested in Section 4, the user should ensure that the input values chosen do not just scope the spread but also include several intermediate values, so that the probability mappings generated do reflect the range. The use of discrete weather evolutions present a slightly different problem, as illustrated by the results presented in this section. This is likely to be partly a consequence of the archived weather sequences used here for illustrative purposes, which although based on very similar meteorology were not obtained from adjacent time periods. These examples should therefore not be taken to indicate that alternative weather evolutions developed by Met Office in real weather conditions on a particular day will diverge very significantly. It does, however, remain a possibility that the alternative plume patterns will show some discreteness, representing a genuine distinction due to the different weather possibilities. It is unrealistic to expect the Met Office to produce a continuum of weather possibilities at present, as their modelling capability is also based on discrete choices of input parameters as is the tool proposed here. Hence several alternative plume patterns will be received from Met Office, and it is reasonable to surmise that any apparent ‘gaps’ between these in the results obtained by the tool will also have a probability of being affected by the accident but the discrete nature of the results presented will not fully show this. Given current computer power limitations, the work-around solution is to remind users and decision makers of the discrete nature of the results, and that any edge effects of the discrete plumes should be treated with a degree of caution; the actual probabilities are likely to be rather blurred representations of those shown in the results. In practice, decision makers are likely to treat the results with flexibility in any case, marking delineation lines of countermeasures along suitable county boundaries, for example, or along geographical lines such as rivers or roads, and any degree of false discretisation in the results is unlikely to be very significant.

An additional presentational technique which could be considered is one in which the shading used represents the overall impact of the emergency action rather than just the likelihood of the action being required. For example, the likelihood of evacuation being required can be combined with information on the density of the population in the immediate area. An area where there is a medium risk of evacuation being required but which has a high population density could be shown with the same shading as an area with a high risk of evacuation being required but a medium population density. This information gives an indication of the potential problem represented by each zone, and the degree of preparation potentially required. However, the composite parts of the information (in this case, the likelihood of evacuation being required and the population density) would be vital to avoid the situation being misunderstood. This approach would need more investigation to determine whether it has potential value, or whether it is too likely to result in confusion.

5.5 Section summary

Alternative methods of presenting assessment endpoints in a way that clarifies their associated lack of precision have been illustrated. A preferred approach for the presentation of spatial results has been identified which uses colour classification in combination with a uniform degree of transparency. This approach is particularly suitable to the display of potential countermeasure areas, incorporating information on the associated imprecision. The presentation of predicted doses can also use a similar colour classification, representing the percentage of model runs which show a dose in excess of a user specified dose level. A slider scale could be used for both countermeasure and dose endpoints. Alternative presentations of dose information using a slider scale are possible; the slider can represent probability (from 'very low' to 'almost certain') with the corresponding mapped information showing with colour density the magnitude of dose at each location for that probability, or alternatively the slider can move across dose magnitude, with the colour density representing the probability at each location of that dose occurring.

It is intended to apply the approach in a new HPA emergency response assessment tool, currently under development. It should be noted that although the display options present results in a clear and transparent manner, an expert user is required to provide the estimated likelihoods of the various imprecision parameters considered and to apply the tool in a way appropriate to the circumstances of the emergency. While the new tool, with the spatial displays outlined here, is intended to be essentially simple in its assessment capabilities, its application in an emergency is not intended for the inexpert user.

6 CONCLUSIONS

6.1 What problem does the study attempt to solve?

This thesis describes work which was undertaken to investigate the extent and the causes of imprecision in emergency response assessments and to find better ways of including it in assessments and representing it in assessment results.

The background to the work is the risk and consequences of the accidental release of radionuclides to the environment through accidents arising in the nuclear fuel cycle or other uses of radioactivity, or from deliberate releases. As environmental radioactivity may cause injury to people, emergency response assessments are important so that decisions on actions such as the introduction of countermeasures to protect human health can be made rapidly and appropriately. As countermeasures can only influence the radiation dose that will be received in the future, only predicted future doses are relevant to such decisions, and as future doses cannot be measured there must therefore be a modelling component in their assessment. These predictions of dose will inevitably be imprecise due to lack of knowledge about the nature of the release and the weather, and also due to measurement inaccuracy.

The significance for emergency decisions of such imprecise or incomplete knowledge of the emergency situation in the early stages of a release, and the current lack of capability to adequately characterise the extent and the significance of the consequences of this lack of knowledge, was the reason for undertaking the work described here. There has been no other comprehensive study of the key causes of imprecision in the predictions output by emergency assessments. Although it is often surmised that weather parameters are among the most significant in estimating the radiological consequences of releases in emergency response, with a correspondingly significant impact on the decisions regarding early countermeasures in the local affected region, this conclusion has not been clearly demonstrated by a modelling study considering the imprecision associated with a wide range of input parameters. Further, there is no tool which currently incorporates these elements of imprecision comprehensively and presents imprecision information to decision makers.

6.2 What steps have been taken to solve the problem?

The work started in **Section 1** with an overview of early emergency response assessments and a summary of several major international emergency response systems. The section ended with a discussion of the implications of imprecision in emergency response predictions, and a review of relevant published literature. It was concluded that it is vital, when decisions are being based on assessment results in emergencies, for the decision maker to be fully aware of any significant imprecision or uncertainty associated with the results.

The work continued with a review phase (**Section 2**). The aspects reviewed were:

- what radiological emergency response assessment tools do, and what tools are currently available,
- what the key exposure pathways and the basic dose calculations are in an emergency response assessment,
- what assessment models and data are currently available,
- what the current basis is, in the UK, for countermeasure decisions, including the ERL system.

The work then moved on, in **Section 2**, to identify the causes and extent of the imprecision in input parameter values. The first step to this was to examine the values taken by parameters in emergency dose assessments, and then to develop ranges for the possible variability of key parameters in a typical accident scenario. A specific accident scenario was assumed as the aim was to estimate the impact of the imprecision associated with predictions based on a few off-site measurements at early times, by considering the range of values each parameter may take, within the context of an example emergency. The features of the accident scenario chosen included commonly occurring weather conditions, so that the results would have the widest possible applicability. Off-site measurements were taken as the starting point of the assessment, as this is the most likely early information on which an emergency assessment would be based; the simulation of an actual emergency assessment, as the basis for the imprecision estimate, was the aim.

Using the parameter ranges derived in **Section 2**, the extent and sources of the imprecision associated with emergency response calculations in the first few hours of a release was explored through two sensitivity studies, as described in **Section 3**. The first of these used a simple Gaussian dispersion model, and the second used a complex dispersion model, the Met Office's Langrangian model NAME. Each parameter was in turn varied to its plausible minimum and/or maximum by considering the range of values the parameter may take within the context of a 'baseline' accident scenario (ie, not the full range of values the parameter may take in any accident). The effect of these variations on the predicted extent of countermeasures was calculated, as the focus was on the imprecision associated with assessment support for decisions on countermeasures in the area beyond that covered by the emergency planning zone (ie extendibility). Two radionuclides were considered, ^{137}Cs and ^{131}I, to represent two significant radionuclides in potential accidental releases, which have differences in their modelling and data requirements.

The results summarised in **Section 3** identified the key parameters contributing to imprecision in emergency response assessments. These were essentially the same regardless of whether the simple or the complex dispersion model was used. They were factors relating to the release, and factors relating to meteorology and dispersion/deposition, namely the release duration, wind direction (in assessments where an assumed plume centre line wind direction is required), enhanced deposition velocity and rainfall, and a significantly elevated release height. The results demonstrate the importance of a radiological emergency assessment tool being linked to an appropriate real-time weather/dispersion prediction tool, and in particular for UK application with the Met Office's NAME/NWP models. Furthermore, the influence of real weather conditions on the predicted results was also demonstrated in **Section 3**, which linked NAME plume predictions with real meteorological sequences from 2007/2008 to show the predicted extent of countermeasures. This visually demonstrated the potentially very significant impact of variation in weather on the estimated location and extent of sheltering areas, even for weather conditions which are similar, and confirmed the importance of real-time weather predictions being used in assessments.

The next stage of the work, in **Section 4**, built on the results obtained in **Section 3**. As a system to comprehensively evaluate the extent of imprecision in emergency assessments does not yet exist, and is clearly of importance in deriving information for decision makers, a new calculational approach was developed. The aim was to enable the key causes of imprecision, as identified in **Section 3**, to be represented and carried through the calculations into the assessment results; this includes the effect of weather uncertainty and also the lack of knowledge on other key parameters. **Section 4** describes a proposed new tool which would link radiological emergency assessment models to the predictions of the UK Met Office's NAME dispersion model.

The aim of the tool is to minimise lack of knowledge of the significant weather-related parameters through using the best and most up-to-date dispersion predictions available, and also to take into account any lack of knowledge in the key non-weather parameters, by reflecting the significance of possible variation in these on the endpoints produced. A key element is that the main causes of imprecision each have several associated likely values, and the probabilities associated with these are carried through the calculations into the assessment results. The method proposed is consistent with the suggestion by Dieckmann *et al* 2010, that '*a forecaster could vary assumptions about the reliability of the evidence and the structural model of the situation to see how these changes affect the assessed probability of different outcomes*'.

The tool predicts countermeasure extents and other radiological endpoints, with visual display in a spatial format using the ArcMap system as developed by ESRI(UK). ArcMap can combine calculations with map-based displays and also show features in the affected area such as population, schools, hospitals and roads, in addition to the assessments endpoints.

The calculational structure developed, as described in **Section 4**, indicates the imprecision associated with the results through incomplete knowledge, but also retains a simple and transparent assessment capability. It was concluded in **Section 1** that for decision making in the UK in the very early stages of an emergency it is important that the tools used are transparent, ideally based on simple calculational assumptions which would permit approximate checking to be feasible through hand calculations. This is considered to be an important factor in quality assurance in emergency assessments, and also in being able to present and explain assessment results to senior decision makers such as those on government emergency committees, as was for example required of HPA during the incident in November 2006 when Alexander Litvinenko was poisoned with ^{210}Po. The tool outlined requires real-time input from dispersion and weather prediction systems. In the UK, such input is obtainable from the Met Office.

The tool outlined in **Section 4** clearly has application in UK emergency response. However, it also has application in UK emergency exercises and planning by enabling exercise data generation to be based on real (archived) meteorological results for the site in question, thereby increasing realism and providing enhanced site-specific details.

A prototype version of the tool was then created using spreadsheets in conjunction with ArcMap, and this was used to produce example results. These results have been used in the final stage of the work, presented in **Section 5**, which explores alternative ways in which imprecise information in radiological assessment results can be presented to decision makers. Alternative methods of presenting assessment endpoints in a way that clarifies their associated lack of precision have been illustrated. A preferred approach for the presentation of spatial results has been identified which uses colour classification in combination with a uniform degree of transparency. This approach is particularly suitable to the display of potential countermeasure areas, incorporating information on the associated imprecision. The presentation of predicted doses can also use a similar colour classification, representing the percentage of model runs which show a dose in excess of a user specified dose level. A slider scale could be used for both countermeasure and dose endpoints. For countermeasure areas the slider can move across a scale showing likelihood of outcomes, with the mapped information showing the corresponding extent of the countermeasure zone. Alternative presentations of dose information using a slider scale are possible; the slider can again represent likelihood of outcomes with the corresponding mapped information showing with colour density the magnitude of dose at each location for that probability, or alternatively the slider can move across dose magnitude, with the colour density representing the likelihood at each location of that dose occurring. In addition, the tool as proposed offers the possibility of rapidly viewing the influence of specific input parameters on the results. For example, it can easily be spotted if the results obtained for a single weather option are inconsistent with those resulting from other weather options. This provides some warning of possibly significant developments; if one weather development was to have a more significant health impact than others, any increase in the likelihood of the weather evolving towards it could be watched for and precautionary protective actions prepared. Similarly, measurements which are inconsistent to the majority of the other measurements can easily be identified

The work undertaken has been in a logical flow, where each section was dependent on the results obtained previously. The culmination of the work, the development of presentational techniques, could theoretically apply to the presentation of results regardless of the way in which the results were derived. They could, for instance, be used to reflect only limited elements of the imprecision, such as that deriving from alternative weather evolutions but not considering other issues such as an uncertain release duration. However, as presented here the techniques can be used to indicate the complete picture to those taking decisions on public protection. In this, the work has required all of the proceeding steps; the review of pathways and parameters, the analysis of the key sources of imprecision in early assessments, the development of the structure of a new tool which takes all the key elements into account and propagates the imprecision through to the results, and finally the development of techniques for demonstrating the imprecision visually.

6.3 What is original in the work?

It has been argued by others that the complicated tools and models developed for emergency response in the last 10 years or so do not adequately reflect or represent the uncertainty associated with their predictions, and that the appearance of apparent sophistication and complexity in the newer tools can lead decision-makers into over-confidence in the model predictions. The inherent uncertainty in complex decision support systems has been described as '*grossly underestimated*' (French and Niculae 2005). In a more recent paper the same authors ask whether the uncertainties associated with the predictions of large models are understood, and question whether capability since the Chernobyl accident has actually improved because of this, despite the '*enormous amount of research and development that has occurred since 1986*' (French *et al* 2007).

As an example of the problems this may lead to, the tabling of several different dispersion model predictions by different organisations at the COBR meetings held during the Buncefield fire incident in 2005 led to confusion among government decision makers, as all of the model results were presented as the 'true' picture, and yet appeared to be inconsistent with each other. The presentation of the imprecision associated with each, together with greater clarity as to what was actually being presented, would have aided the decision makers and avoided at least some of the confusion. In the context of radiological emergencies, the lack of this capability and the need to undertake research to develop an improved capability, is the basis for originality in the thesis.

The work described here has therefore tackled two key areas where the current state of knowledge and availability of tools is lacking:

- there has been no study of the key causes of imprecision in the predictions output by emergency assessments,
- there is no tool which currently incorporates these elements of imprecision comprehensively and presents the resulting imprecision information to decision makers.

None of the radiological emergency response systems summarised in Section 1 include all significant sources of imprecision and most do not include any. The consequences of possible alternative weather evolutions are incorporated in the most complex systems (RODOS, ARGOS and possibly HPAC) through the use of real-time weather predictions and the optional use of 'ensemble' dispersion modelling, but non-weather sources of imprecision can only be represented through a series of alternative runs, by varying input parameters. Towards the end of this study, the EURANOS research programme which concluded in 2009 incorporated a research package which was presented at the EURANOS final contractors meeting in June 2009 but which does not appear to have been otherwise published. This considered the communication of uncertain results to the decision maker arising through uncertainty in the source term and the wind direction, and represented the results of example calculations on a shaded map but did not include the other possible sources of imprecision. This suggests that there is a perceived need for the work described here, although the EURANOS research only covered a limited aspect of it.

The original aspects of the study are summarised below:

1. *Investigation of the variability of the key input parameters to emergency response assessments, and estimation of the values they may potentially take in a particular emergency*.

   The derivation of the values each parameter may take in the baseline accident considered has not been done before. The values were derived from the literature specifically for this application. In general, there has been no comprehensive development of imprecision ranges for emergency response calculation parameters. One previous study has produced ranges for certain atmospheric parameters, but not in the context of emergency response, other studies have considered uncertainty in probabilistic accident assessments but again not in emergency assessment systems.

2. *Exploration of the sensitivity of the predictions of emergency response calculations to variations in key input assumptions and parameters.*

   The analysis using the R91 and NAME models of the significance of key parameters, and the conclusions drawn are original. This has been reflected by the two papers summarising this work being published in a peer reviewed international journal (Haywood 2008, Haywood *et al* 2010).

3. *Outline of a new method for assessing radiological consequences, to be used in conjunction with real-time weather prediction and dispersion tools, to improve early phase response to future emergencies by estimating the consequences of lack of knowledge.*

   The proposed tool is an original development. Current radiological emergency assessment tools use similar formulae for the calculation of (for example) inhalation dose and external dose, as these are standard methods used internationally, as recommended by IAEA for example. The originality of the tool lies in the proposed combination of calculations, using multiple values for the key parameters identified in the earlier part of the study. By associating a probability with each parameter value, likelihoods can be associated with each calculated result. This results in a system which presents more useful information to decision makers than the current systems which essentially present single value outputs resulting from single value inputs on most if not all of the parameters. One complex system is thought to present apparent ‘probabilities’ with its predictions (the US system HPAC) but this is misleading because of the restricted nature of the uncertainties considered, which are specific aspects of meteorology and dispersion only.

4. *Development of new ways in which imprecise information, in particular that resulting from alternative weather outcomes and different radiological measurements, can be presented to decision makers and demonstration of these using example results.*

   The originality of the work continues in the presentational features of the proposed tool, in the planned mapping of doses linked to a probability range and countermeasure areas shaded to show the likelihood of a countermeasure being required at each point. This provides decision makers with more relevant and comprehensive data on which to form decisions on actions. The shading of map areas to illustrate the degree of likelihood in different zones is not in itself original, as several authors referred to in Section 5 have applied similar approaches, but the proposed use here in a radiological emergency response context is an original application. The work proposes a number of alternative methods of visualisation and concludes with a preferred approach (transparent colour classification for spatial data, and slider scale presentation of probability-linked dose information) which is an original development. The work outlining the new tool and describing the approach to visualisation was submitted to a peer reviewed international journal in June 2010 (Haywood, 2010), and has been accepted subject to minor modifications in August 2010[1]. A further paper focussing specifically on the presentation of imprecise information to decision makers is planned, for likely submission to the international Risk Analysis journal.

The need for the work undertaken in this study has been partially driven by the increased use of spatial data, as output by Geographical Information Systems (GIS). Mapped output is now the expected form of emergency data. Plume dispersion data is prepared by Met Office, and is rapidly available via web-sites

[1] Published December 2010, J. Radiol. Prot. 30 (2010) 673-685.

such as the BBC, as seen for example during the Icelandic volcanic ash release in 2010. Mapping systems such as ArcGIS are readily available and are in widespread use commercially and increasingly by government. There is considerably more familiarity with GIS systems now than there was 10 years ago. Old-style emergency results, typically of the form 'countermeasures extend to about 5km' are no longer sufficient. However, the need for associated imprecision estimates is increased by the use of mapped data. The level of detail provided by mapped results, presented on a grid which suggests detailed spatial resolution, implies clarity and certainty in the data that are mapped to a far greater extent than rounded numbers on a table or textual statements. It is therefore necessary to present, simultaneously with the basic results, an indication of imprecision to avoid unwarranted conclusions being drawn.

Finally, a contribution to originality comes from the linking together of a series of separate aspects in this study. Section 6.2 above describes how the work was undertaken in sequence, with each part building on the preceding parts. The combination of identifying the sources of imprecision, developing a new approach to calculating the imprecision, and then developing alternative ways in which the imprecision associated with the endpoints can be visualised, creates in composite a significant new approach to radiological emergency response assessments.

6.4 What are the key contributions to knowledge?

These can be summarised as:

- Identification of the key causes of imprecision in the predictions output by emergency assessments.
- Identification of the extent of imprecision in the predictions output by emergency assessments, for a representative accident scenario.
- Identification of the potential impact of real weather scenarios on the extent of countermeasures and the distribution of doses.

- Creation of a new calculational approach to incorporate these elements of imprecision comprehensively in an emergency assessment system.
- Through the use of a prototype system, the development of novel ways of visualising information on the imprecision in radiological emergency response assessments for decision makers.

The work has also led to further investigation and analysis of the reasons for differences between the R91 Gaussian dispersion model and the Met Office's Langrangian model NAME. This work has involved other staff at HPA and at the Met Office.

6.5 What is the potential practical application of the work?

To illustrate the potential practical application of the tool and mapping system developed, it is worth summarising what would have been the approach up to now, and how the new developments will provide better information.

Currently available tools will typically produce a best estimate calculation of dose, at a particular location, which is based on the user's choice of the most likely values for input parameters. As an example, assume an accident scenario where a standard assessment of the current type produces a best estimate of dose (to 2 days, at a particular location) of 2.8 mSv. If a decision on the appropriateness of the sheltering countermeasure at this point was required, this dose of 2.8 mSv would be compared to a dose criterion for sheltering of 3 mSv, and it could be concluded that the countermeasure was not required at that location.

The tool outlined here would undertake a series of calculations of dose at the point, based on alternative input values. These could, for example, be 2 possible weather evolutions, 3 release durations, and 2 deposition velocities, and therefore 2 x 3 x 2 = 12 dose calculations are undertaken for the location. If we imagine these 12 calculated doses at the location to be 0.5, 0.5, 1, 2, 2, 2.1, 2.7, 2.7, 2.7, 2.8, 3.5, 4, and 7.1 mSv, the average dose (assuming all the alternatives are equally likely) is 2.8 mSv but the spread is 0.5 mSv to 7.1 mSv.

In 25% of these calculational combinations, sheltering would be required. There is also a 1 in 6 chance that the dose is around 0.5 mSv and a 1 in 12 chance that it is around 7 mSv. All of this information is of more value to a decision maker than a single dose value and single on/off countermeasure indicator. The ability to incorporate estimates of likelihood into the possible inputs, which are then taken through the calculations into the outputs, is a further refinement.

It would be interesting to explore the implications of such calculations and increased knowledge of the spread of possible doses with decision makers, and to discuss with them how such information would influence their decisions. HPA is starting a series of stakeholder meetings in 2011, as part of a revision of emergency advice, and such discussions will now form a part of these discussions. There are psychological and social science aspects to the impact of increased information on decision making, for example some decision makers will be more risk averse than others and more inclined to take decisions at the lower end of the ERL scale, and to attach greater weight to more pessimistic outcomes. Factors that are specific on the day of the accident, such as ease of implementing countermeasures, and the scale of the area affected, will also have an impact.

This is only one example of the additional information available, to decision makers and others, as an outcome of the work. Endpoints other than dose may be estimated, for example activity concentrations in air, depositions on the ground, and the extent of foodchain restrictions may be calculated. The scope of the work is also not restricted to emergency response assessments, but also has application in emergency planning and training. These aspects are discussed further below.

6.6 What are possible future developments from the work?

There are a number of developments possible on the basis of this work:

- The full tool would have application in emergency preparedness, planning and exercises, in addition to its use in emergency response. For example, mapped predictions of activity concentrations in foodstuffs could be used in emergency exercises to present alternative developments, and the concepts of risks and likelihoods, to those taking decisions on the need for food countermeasures. This would require the pre-exercise generation of weather scenarios for the exercise by the Met Office, but this is feasible as they already have a role in emergency exercise data preparation.

- Applications in emergency training are also possible. The results have demonstrated the substantial influence of real weather conditions on the predicted extent of countermeasures, which can be very variable in location and extent even for weather conditions which are similar. A general extension of the study could usefully consider more widely varying weather conditions sourced from historical weather records, to analyse more fully the impact of weather evolutions which have actually occurred. Analysis on a site-specific basis would also be useful. This could produce illustrative results for use in emergency response training for site personnel, enabling exercise data generation to be based on real meteorological results for the site in question.

- The results presented in Section 3 on the varying spatial distribution of doses in different real weather conditions suggest that useful insights can be gained through the tool on the cross-wind spread of an affected area. There is a common view that plumes, and hence affected regions, may extend to long distances but are unlikely to be wide. This is partly a consequence of the common past use of Gaussian plume modelling, which does often result in quite narrow plumes. As a consequence there is a tendency for planners to plan for emergency countermeasures affecting only a few radial segments around the site. This work suggests that real weather sequences have the potential to produce wide plumes, and also that plume width, and hence the area affected by the release, increases with increasing release duration. A comprehensive review of past weather conditions around a selection of UK nuclear sites, using NWP data held by Met Office, in conjunction with dispersion predictions and radiological assessments, would indicate what crosswind spreads in contaminated areas are plausible. This could have significant implications for emergency planning in the UK.

- Directly measurable action levels (for example, a dose rate or a concentration in air) are used in the UK nuclear industry to indicate when a particular emergency action or actions should be taken. For example, a total beta and gamma activity concentration in air of 10^5 Bq m^{-3} is commonly regarded as being a level at which evacuation may be triggered. The results of this work suggest that a wide spread in possible countermeasure extents may correspond to a single measured activity concentration in air at a particular location. This aspect may warrant further study, to determine whether conclusions on the meaning and application of action levels can be drawn.

- It would be interesting to investigate what doses and potential countermeasure areas would be suggested by measured data from actual dispersion tracer experiments in the open air. Unfortunately, data for this appear to be currently lacking. I have consulted Met Office (2010) and they have been unable to identify a suitable dataset for the purpose. NAME has been subject to intercomparison exercises using tracer data, but the step further required here to extend the results to radiological dose estimates needs more data than are collected on a sufficiently fine resolution in tracer experiments. A good spatial and temporal coverage of 'instantaneous' air concentrations, total depositions and time integrated air concentrations would be needed. Most short range field experiments record only total air concentrations from a short puff, and often only the maximum on an arc. Deposition is almost never measured. However, should a suitable tracer data set come to light, or result from a new experiment, the assessment of simulated doses and countermeasure areas resulting from the release would be of interest.

- Once a full tool is created, fuller experimentation together with consultation with a wider range of users, including decision makers in government (for example in Dept of Health) would be possible. A particular focus of this could be further developing the presentation of dose and risk information to meet the needs of decision makers. This could, for example, investigate the potential use of the micro-mort (1 in 1 million risk of death) as proposed by Professor David Spiegelhalter of Cambridge University to convey health risks. This could be a useful way of presenting the effects of alternative emergency actions on possible health outcomes, for example the generation of a map showing the risk of death or other health impact from 2 days exposure without countermeasures.
- Finally, an alternative angle is to contrast the results suggested by presentation of positive outcomes against negative outcomes, for example a 5% chance of sheltering being required at a particular location is also a 95% chance of it not being required, and it is not clear whether the perception of the two alternatives is equal and whether decision makers would gain the same amount of information from both.

6.7 Conclusion

The purpose of this study was to fill a gap in radiological emergency response capability by identifying the sources of the imprecision potentially associated with the predictions of assessment support tools for assisting early phase off-site countermeasure and public health protection decisions, considering the implications of this imprecision for decision making and developing improved techniques for early phase assessments, including the visualisation of the results. This thesis summarises the steps undertaken, the results obtained, and the originality of the work undertaken. Possible future developments of the work are identified.

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APPENDIX A Differences between the R91 and NAME models

This appendix contains more discussion and explanation of differences between the UK Met Office's Numerical Atmospheric-dispersion Modelling Environment NAME III (referred to as NAME in the remainder of this Appendix) and the 'R91' Gaussian plume model. These models were used in the calculations undertaken as described in Section 3, and the differences between the models explain the differences seen in the results. The key differences are therefore of interest in this thesis. Only the differences which are particularly significant to the work undertaken in Section 3 in terms of the impact on the imprecision analysis are discussed in this Appendix. The work supporting the conclusions presented here has been undertaken as a result of this thesis. It has involved not only myself but also staff at HPA and at the UK Met Office to resolve the details of the differences between the models. The work is summarised in the report Bedwell, P, Wellings, J, Haywood, S M and Hort, M C (to be published).

Table A1 shows the instantaneous (time-averaged) plume centre-line activity concentrations in air obtained from R91 and NAME, for a release of 1 10^{16} Bq of ^{137}Cs, for the baseline scenario described in Section 3. A release duration of 1 hour and a release height of 10 m were assumed, together with Pasquill meteorological stability category D, a wind speed of 5 m s^{-1} and no rain; the terrain assumed is typical rural land with a roughness length of 0.3 m and no significant features to influence the dispersion.

NAME models explicitly the time taken for the plume to reach each grid point, and the instantaneous activity concentrations in air from NAME given here are those predicted to occur 50-60 minutes after the start of the release; the values are the time-averaged concentrations over this 10 minute period. In contrast, R91 as applied in this study calculates the total eventual time integrated air concentration (TIAC) at each point, and the instantaneous activity concentrations in air from R91 given in Table A1 are obtained by dividing the TIAC by the numbers of seconds in one hour; these therefore represent an average over the total time of plume passage. Because of the explicit modelling in NAME of the time taken for the plume to reach each grid point, as opposed to the calculation in R91 that assumes instantaneous travel, the NAME results show a source-to-measurement dependence on distance that means that measurements at different distances reach a steady-state at different times. For example, the average activity concentration in air at 20km in the period 50-60 minutes after the start of the release is not yet a steady-state value; the air concentration predicted by NAME is about a factor of 50% lower than the levels reached about 20 minutes later.

It can be seen from Table A1 that for the same source term NAME predicts instantaneous time-averaged activity concentrations in air which are somewhat smaller than those predicted by R91 but the difference decreases with distance (a factor of about 4 at 1km, 3 at 2 - 5 km, and less than 2 at 10 - 20 km). There is less difference if the time integrated concentrations are considered. Very similar results were also obtained for the same release of ^{131}I, but are not presented here for brevity. It can be seen that a scaled release of 3 10^{16} Bq of ^{137}Cs would result in NAME predicting an instantaneous activity concentration in air of approximately 1 10^{7} Bq m^{-3} at 2km on the plume centre line, for the 50-60 minute 'measurement' period; the value used in the R91-based study as the baseline 'measurement', at the same location was 1.1 10^{7} Bq m^{-3}. Similarly, for ^{131}I, an instantaneous activity concentration in air of 1.1 10^{6} Bq m^{-3} at 2km on the plume centre line, for the 50-60 minute 'measurement', would be predicted by NAME from a release of 3 10^{15} Bq of this radionuclide.

Table A1 Instantaneous and time-integrated activity concentrations in air predicted by R91 and NAME

	Instantaneous activity concentrations in air at specified down-wind distance on the plume centre line, for a release of 1 10^{16} Bq of ^{137}Cs over 1 hour (Bq m^{-3})				
	1km	2km	5km	10km	20km
R91	4 10^7	1 10^7	3 10^6	9 10^5	3 10^5
NAME[1]	1 10^7	4 10^6	1 10^6	5 10^5	2 10^5
	Time integrated activity concentrations (TIAC) in air at specified down-wind distance on the plume centre line (Bq s m^{-3}) over total time of plume passage				
	1km	2km	5km	10km	20km
R91	1 10^{11}	4 10^{10}	9 10^9	3 10^9	1 10^9
NAME	4 10^{10}	2 10^{10}	5 10^9	2 10^9	8 10^8

Note:
1. The activity concentration in air in NAME given here is that predicted to occur 50-60 minutes after the start of the release.

The reasons for differences between NAME and R91 are complex, being due to the way in which the two models apply meteorological data and the different approaches to modelling plume dispersion. In general, while R91 considers each input parameter independently (for example, atmospheric stability and wind speed are incorporated in separate parameters with no dependency or inter-relationship upon one another), in NAME the impact of one parameter on another is accounted for (for example, atmospheric stability impacts on wind speed). Factors which particularly differ between the models are wind speed, the cross-wind and vertical plume profiles, and the treatment of an elevated release height. These aspects are discussed further below.

A1 WIND SPEED

The treatment of wind speed with height above the ground is different in the two models. R91 assumes a single wind speed, typically at 10m above the ground, whereas NAME considers multiple wind speeds and wind directions at multiple levels within the boundary layer, enabling the modelling of turbulence and mixing. Because of this wind profile, the wind speed in NAME typically increases with height as a result of the decreasing influence of the earth's surface; the overall effect is to reduce the air concentrations at ground level, unlike in R91 where air concentration is proportional to the inverse of the wind speed at about 10m. Bedwell *et al* (to be published) have demonstrated the influence on the R91 results by using a single modified wind speed in R91 based on the mean wind speed across the boundary layer, and so simulating the value in NAME; improved agreement was seen with increasing distance (from about 5 - 10 km), demonstrating that at these distances this is a significant component of the differences between the models.

A2 CROSS-WIND AND VERTICAL PLUME PROFILES

In the calculations underlying Section 3, it was noted that if the plume centre line is +/- 10º from the baseline direction, the source term predicted by NAME is about 2 times greater than that predicted by R91, reflecting the underlying model differences. For the greater difference of a change in the plume centre line of +/- 20º from the baseline direction, the source term predicted by NAME is about 3 times *smaller* than that predicted by R91.

The difference is due to the NAME plume being significantly wider than the R91 plume at 2 km, but of a more comparable width at 5km. The spread of the plumes is illustrated in Table A2. At 2km, R91 predicts a ratio between the 20 degree air concentration and the plume centre line air concentration of 300 whereas NAME predicts a ratio of 40, a difference of a factor of 8. This difference of a factor of 8 explains the reduction of the NAME source term from 3 times greater than the R91 source term in the baseline case, to 3 times less here. At 5km, R91 predicts a ratio between the 20 degree air concentration and the plume centre line air concentration of 500 whereas NAME predicts a ratio of 250, a difference of a factor of 2.

The wider width of the NAME plume at 2km downwind in comparison to R91 is due to a greater degree of horizontal mixing in NAME than in R91 at around 2km. This decreases with increasing downwind distance such that by 10km the degree of horizontal mixing in R91 is greater than that in NAME. At 10 degrees off axis, in this baseline calculation, the 2 km and 5 km receptors are some distance from the ‘edge’ of the plume whereas at 20 degrees off axis, the 2 km and 5 km receptors are relatively close to the ‘edge’ of the plume in R91 although still well within the NAME plume.

In R91 the cross-wind spread of the plume is described by the standard deviation of the cross-wind plume profile (σ_y), which is based on a turbulent diffusion term from empirical data and a wind direction fluctuation term also from empirical data. The standard deviation of the vertical spread of the plume in R91, σ_z, is based on the atmospheric stability, downwind distance and ground roughness. The horizontal and vertical spread of the NAME plume includes the flow and turbulent motion of the particles. To investigate the contribution σ_y and σ_z make to the difference in the predictions of NAME and R91, a modified R91 run using the σ_y and σ_z derived from NAME output in the baseline calculation was undertaken by Bedwell *et al* (to be published). The differences in TIAC between this run and the NAME baseline run are less than a factor of 2.5 at all distances downwind when the modified σ_y is used, and are less than a factor of 2 at all distances downwind when the modified σ_z is used. The improved agreement between NAME and R91 suggests that the different method used in the two models to describe the cross-wind and vertical spreads of the plume is partially but not entirely responsible for the differences in the observed model output.

A3 COMBINED IMPACT

As the cross-wind and vertical spreads of the plume, and the wind speed all have impacts on the output of the NAME and R91 models, Bedwell *et al* (to be published) have considered their cumulative effect. This has shown that the NAME and R91 TIACs are within a factor of 1.4 at all distances up to 40km if the R91 parameters used are modified to simulate the NAME values. Within a few kilometres of the release point the agreement is very close, and suggests that these parameters almost entirely explain the difference.

Table A2 Instantaneous activity concentrations in air at 2km and 5km for a release of 1 10^{16} Bq of ^{137}Cs over 1 hour (Bq m^{-3}) on plume centre line and at +/- 20º off axis

Instantaneous activity concentrations in air at specified down-wind distance, for a release of 1 10^{16} Bq of ^{137}Cs over 1 hour (Bq m^{-3})	R91[a]	NAME[b]
On plume centre line at 2 km	1 10^7	4 10^6
At +/- 20º from plume centre line and 2 km from release point	3 10^4	1 10^5
Ratio between plume centre line at 2 km and +/- 20º from plume centre line	300	40
On plume centre line at 5 km	3 10^6	1 10^6
At +/- 20º from plume centre line and 5km from release point	6 10^3	4 10^3
Ratio between plume centre line at 5 km and +/- 20º from plume centre line	500	250

Notes:

a. Time average activity concentration in air over time of plume passage.

b. The activity concentration in air predicted by NAME to occur 50-60 minutes after start of release.

A4 ELEVATED RELEASE HEIGHT

For the elevated release height considered in Section 3 (200m), the sheltering predicted by both R91 and NAME extends to beyond 30km but for NAME the extent is only just beyond 30km while for R91 the actual extent is predicted to be about 80km. The reason for this difference is that, for the same release, the TIAC at 2km predicted by NAME is three times greater than the TIAC predicted by R91, but that at distances beyond a few kilometres the TIACs from the two models are very similar. Hence if the values are normalised at 2 km by reducing the NAME source term by a factor of 3, the doses beyond a few kilometres estimated on the basis of the NAME predictions are smaller than those predicted by R91 by about a factor of 3, which reduces the extent of countermeasures considerably. Also, at distances less than 2km the TIACs predicted by NAME are considerably greater than those predicted by R91 for the same source term.

Table A3 shows the time integrated activity concentrations in air for ^{137}Cs and ^{131}I for the results normalised to 1.1 10^7 Bq m^{-3} at 2km on the plume centre line for ^{137}Cs, and 1.1 10^6 Bq m^{-3} at 2km on the plume centre line for ^{131}I, and also the time integrated activity concentrations in air for ^{137}Cs and ^{131}I for the results normalised to 2.6 10^6 at 5km on the plume centre line for ^{137}Cs, and 2.6 10^5 at 5km on the plume centre line for ^{131}I. These more detailed results show where the predicted doses fall below the 30 mSv (evacuation) and 3 mSv (sheltering) countermeasure criteria assumed. The key difference is that whereas in R91 the peak activity concentrations in air and hence in dose occurs at about 5km, in NAME the peak occurs at around 2-3 km. Normalising results to a measurement at 2km leads to differences at greater distances of about a factor of 3, because the R91 results continue to increase beyond 2 km. Normalising to a measurement at 5km leads to very similar predictions beyond that point, as the models demonstrate a similar fall-off pattern. Also, R91 predicts low concentrations at around 1km, and the results are therefore very sensitive to the precise locations in this region.

Table A3 Time integrated activity concentrations in air (TIACs) for ^{137}Cs and ^{131}I from R91 and NAME for a 200m effective release height, for baseline measurement at 2km and 5km

Release scaled such that instantaneous air concentration at 2km is 1.1 10^{7} Bq m^{-3} ^{137}Cs						
	1km	2km	5km	10km	20km	30km
R-91 TIAC on plume centre line (Bq s m^{-3})	3 10^{8}	4 10^{10}	1 10^{11}	6 10^{10}	3 10^{10}	2 10^{10}
Total effective dose (mSv)	0.2	30	76	45	20	12
NAME TIAC on plume centre line (Bq s m^{-3})	2 10^{10}	4 10^{10}	3 10^{10}	2 10^{10}	9 10^{9}	6 10^{9}
Total effective dose (mSv)	14	30	23	14	6	4
Release scaled such that instantaneous air concentration at 2km is 1.1 10^{6} Bq m^{-3} ^{131}I						
R-91 TIAC on plume centre line (Bq s m^{-3})	3 10^{7}	4 10^{9}	1 10^{10}	6 10^{9}	3 10^{9}	2 10^{9}
Total effective dose (mSv)	0.2	27	68	40	17	11
NAME TIAC on plume centre line (Bq s m^{-3})	2 10^{9}	4 10^{9}	3 10^{9}	2 10^{9}	8 10^{8}	5 10^{8}
Total effective dose (over 3 hours)	12	27	21	12	5	3
Release scaled such that instantaneous air concentration at 5km is 2.6 10^{6} Bq m^{-3} ^{137}Cs						
	1km	2km	5km	10km	20km	30km
R-91 TIAC on plume centre line (Bq s m^{-3})	3 10^{7}	4 10^{9}	9 10^{9}	6 10^{9}	3 10^{9}	2 10^{9}
Total effective dose (mSv)	0.02	3	7	4	2	1
NAME TIAC on plume centre line (Bq s m^{-3})	5 10^{9}	1 10^{10}	9 10^{9}	6 10^{9}	3 10^{9}	2 10^{9}
Total effective dose (mSv)	4	9	7	4	2	1
Release scaled such that instantaneous air concentration at 5km is 2.6 10^{5} Bq m^{-3} ^{131}I						
R-91 TIAC on plume centre line (Bq s m^{-3})	3 10^{6}	4 10^{8}	9 10^{8}	6 10^{8}	3 10^{8}	2 10^{8}
Total effective dose (mSv)	0.02	3	6	4	2	1
NAME TIAC on plume centre line (Bq s m^{-3})	5 10^{8}	1 10^{9}	9 10^{8}	5 10^{8}	2 10^{8}	2 10^{8}
Total effective dose (over 3 hours)	4	8	6	4	2	1

It cannot be argued on the basis of these results that NAME predicts the plume to come to the ground nearer to the source of the release than is the case in R91, as there are considerable uncertainties in the predictions of R91 at such close distances. However, NAME's turbulent mixing scheme is clearly enhancing ground deposition in the region 1 - 2km in comparison to that predicted by R91; in general, there is greater vertical mixing of the plume in NAME than in R91 at all distances up to 20km, as discussed above, as the R91 values of σ_z are lower than the values implied by the NAME results up to this distance. One consequence of this is that the R91 plume will require a greater distance downwind to reach ground level.

A5 CONCLUSION

The overall conclusion from the above discussion is that fundamental differences between the two dispersion models lead to differences in their predictions, but that these are largely understood. They are primarily due to differences in the approach to modelling the standard deviation of the cross wind plume profile (σ_y) and vertical plume profile (σ_z), resulting depth and spread differences within the first 20km. The spread parameters in R91 are based on empirical data, unlike the particle random-walk techniques in NAME, and are known to become less sound with increasing distance from the release point, at distances further than those from which the empirical data were derived. The particular case of elevated release heights also shows the differences between the models, again being fundamentally due to the different approach to vertical mixing. The differences in the models explain the differences in the results of the calculations based on R91 and NAME in Section 3. Despite the differences, the conclusions from the two parts of the study remained the same, in terms of the most significant parameters for imprecision, and it is concluded that the differences between the models, while of considerable interest, do not in themselves impact on the conclusions of this study.

The contribution of analyses by Pete Bedwell (HPA), Joe Wellings (HPA) and Matt Hort (Met Office) to determine the reasons behind R91 and NAME differences is gratefully acknowledged, as is the preparation of the report Bedwell *et al* (to be published) by all the authors.

Reports referred to in the Appendix (also included in the full reference list):

Clarke R H 1979 A model for short and medium range dispersion of radionuclides released to the atmosphere NRPB-R91 (Chilton: NRPB)

Jones, A, Thomson, D, Hort, M and Devenish, B 2007 The UK Met Office's next generation atmospheric dispersion model, NAME III. Air pollution modelling and its application XVII, edited by C Borrego and A-L Norman, Springer

Bedwell, P, Wellings, J, Haywood, S M and Hort, M C (to be published) Intercomparison of the R91 Gaussian Plume Model and the UK Meteorological Office's Lagrangian Particle Model NAME III. Joint HPA and Met Office publication in the Met Office's Hadley Centre Report series.