Methods for Interpreting Monitoring Data Following an Accident in Wet Conditions

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ABSTRACT

Procedures for interpreting monitoring data after an accidental release have been developed primarily by considering the situations that might arise if the accident occurs in dry conditions. However, as rain is an effective mechanism for locally enhancing the deposition of material from dispersing plumes, the extent of significant deposition following an accidental release in wet conditions could be much greater than for the same release in dry conditions. In addition, rainfall rates vary in time and space, leading to the possibility of a wet deposition pattern that could vary rapidly in space.

Following an accident, monitoring would be carried out to describe the deposition pattern around the nuclear site. This is aimed partly towards estimating doses to people near the site and identifying those areas where countermeasures are required, and partly towards building up a complete picture of the consequences of the release. Simple atmospheric dispersion models can assist in building up a picture of the consequences and directing monitoring effort. However, those currently used after an accident do not include a realistic description of the effects of variations in rainfall rate on the deposition pattern.

Options and problems associated with the use of monitoring data in wet conditions are discussed with particular attention paid to the use of such data to support model estimates of accident consequences.

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EXECUTIVE SUMMARY

This report considers some of the problems associated with assessing the consequences of an accidental release of radioactivity to the environment when portions of the material released to the atmosphere are likely to disperse through an area of rain. Procedures for interpreting monitoring data after an accidental release have been developed primarily by considering the situations that might arise if the accident occurs in dry conditions. However, as rain is an effective mechanism for locally enhancing the deposition of material from dispersing plumes, the extent of significant deposition following an accidental release in wet conditions could be much greater than for the same release in dry conditions. In addition, rainfall rates vary in time and space, leading to the possibility of a wet deposition pattern that could vary rapidly in space.

Following an accident, monitoring would be carried out to describe the deposition pattern around the nuclear site. This is aimed partly towards estimating doses to people near the site and identifying those areas where countermeasures are required, and partly towards building up a complete picture of the consequences of the release. Simple atmospheric dispersion models can assist in building up a picture of the consequences and directing monitoring effort. However, those currently used after an accident do not include a realistic description of the effects of variations in rainfall rate on the deposition pattern.

This report considers ways of improving the assessment of where material will be deposited. It advocates supplementing the use of measurements of radioactive contaminants in environmental samples with information on other quantities that are related to where the enhanced deposition is likely to occur.

Immediately after an accident, there will only be a few measurements of the amount of material deposited that could be used to improve model predictions. However, the amount of material deposited at a location is likely to be highly correlated with the amount of rain falling at that location during the time a plume is overhead. Information on rainfall rates can be obtained rapidly from the network of radar sites measuring rainfall in the UK. This report considers ways of using information on rainfall to substitute for and supplement limited quantities of direct measurements of the amount of radioactive material deposited.

The report concludes that existing techniques of data assimilation should enable model predictions to be improved by combining modelling with available deposition or rainfall measurements.

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CONTENTS

1 INTRODUCTION

It is known that following an accidental release of radioactivity to the atmosphere, rainfall during the passage of the dispersing plume can have a large influence on the amount of radioactivity deposited. For example, following the Chernobyl accident heavy thunderstorms and a cold front moving northwards over the UK washed out radioactive iodine and caesium over upland areas of north Wales, north west England, south west Scotland and Northern Ireland. The deposition patterns in other parts of Europe were similarly affected by rain eg heavy rain over central Scandinavia resulted in the contamination of lichens and mosses, the main diet of reindeer (Smith, 1989). Thus, in any assessment of the immediate consequences of an atmospheric release of radioactivity, it is important to know where in the path of the plume it has rained and to have practical methods of assessing the effect of that rain on predicted levels of deposition. This study has considered a range of options that may be applicable to such an assessment.

The aims of the project were to investigate methods that could be used to include information on rainfall within data assimilation techniques, specifically covering the following points:

a Availability of rainfall data
b Likely spatial and temporal variation in rainfall in different conditions (frontal, showers, etc)
c Assimilating data on deposition in areas with similar deposition mechanisms, utilising supporting data from adjacent areas.

The work leads to a description of the way in which data assimilation methods could be extended to handle rainfall, and to provide guidance on the most appropriate monitoring strategy in the event of rain during an emergency.

The concept of assimilating measurement data with models is briefly introduced in Section 1.1 and subsequent sections then elaborate the issues and practicalities of this approach. Section 2 discusses the effect of rain on dispersing plumes, considering the relative depositions in wet and dry conditions. The section also considers the differences in interception, and in particular the short-term effects on plant surface contamination, in dry and wet conditions resulting in different uptake by plants and animals. It also considers the way in which rainfall rates vary in time and space. The remainder of Section 2 provides a link to the main discussion of data assimilation methods in Section 3. This section considers the assimilation of rainfall information as an aid in making improved assessments of the amount deposited. It indicates that some direct measurements of deposition, with an appropriate allowance for the interception fraction, are likely to improve the assessment of the spatial distribution of deposition over and above indirect assessments the effect of rainfall on radioactive deposition. Section 4 considers ways in which the monitoring programme might differ for accidents in wet or dry conditions, and how suitable information for use in data assimilation procedures might be obtained. Finally, recommendations are provided for further research and on the current practicability of assimilating rainfall information following an accidental release of radioactivity to the atmosphere.

The majority of the techniques discussed in this report can be incorporated into simple assessment procedures to provide approximate estimates of the effect of localised rain events on deposition. These not only use available data more effectively but also have the particular advantage in the case of rainfall, that information gathered independently of any radioactivity monitoring effort can be used. Section 4 considers the effective use of measurements in assessments by discussing some of the factors that should be considered when planning a monitoring programme in wet conditions.

1.1 Data assimilation

To provide a starting point for the discussion to follow it is appropriate to define, in a general way, the terminology to be used and in so doing to say what aspects of the problem will be considered. The central problem, improving knowledge of the actual deposition pattern for a release in rain, will be treated as a problem of data assimilation. This is a widely used term, which can mean different things to different authors. A simple definition could be the use of measurements to improve predictions about, or the representation of, a particular event. At the trivial level all environmental models use measurements to particularise their generic predictions e.g. the wind speed and atmospheric stability category used when running a simple atmospheric dispersion model. However, data assimilation is usually taken to mean something more substantial than that. There has been considerable work in the past on the adjustment of model parameters to achieve the best fit between the predictions of a model and actual measurements. This is a form of data assimilation but one that often exposes the limitations of the model in use rather than helping to overcome those limitations (Edwards et al 1990). The alternative more radical approach is to view data assimilation as a method of prediction that tries to be true to both the available data and general modelling considerations but that also recognises that data add information on processes not represented adequately or at all by the model. Thus, if sufficient measurements become available their influence should dominate over the predictions of the best fitting, but inherently limited, model of the physical process. The idea of the data adding information on processes not adequately represented by the process model is particularly important in the context of assimilating the effect of rainfall while relying on a simple (if robust) atmospheric dispersion model for the rapid assessment of accident consequences. The Gaussian model (e.g. Clarke 1979) is often used because of its simplicity; it can give guidance on the expected dispersion and deposition of a plume of radioactivity while requiring only limited input data. The more capable ADMS model (CERC 2002) is becoming increasingly used in assessments of the consequence of discharges. However, while more complex than older Gaussian models, it remains a Gaussian model; like other Gaussian models, it cannot describe the effects of patchy rain. Considering a model that contained sufficient physics to represent patchy rain would place considerable demands on the data required after an accident, and perhaps require the model to be linked directly to a system analysing radar measurements of rainfall or to a weather forecasting program. This has been achieved on the large scale through the use of models such as The Nuclear Accident Model (NAME) run by the Meteorological Office (Ryall 2000). NAME has a precipitation analysis package in which radar data are blended in real time with satellite observations, numerical models and conventional observations to predict deposition on a European scale (Collier et al 1989). However, the NAME model is not designed to assimilate measurements of radioactive deposition directly, nor to provide estimates of the deposition pattern over more localised areas.

Measurements will eventually dominate the results of an assimilation process, when the task of estimating a value at an unsampled location must reduce to interpolating between known measurement values. In the opposite extreme, i.e. when very few monitoring data are available, interpolation is not possible. Assimilation then reduces to the scaling of the parameters of the process model (judged to be an adequate representation of the physics) to obtain the 'best fit' to the data. In the case of assimilating rainfall information after an accidental release, the choice of approach is strongly weighted by the practicality of the options. Data are potentially available on rainfall from automatic rain gauges and radar measurements. Unfortunately, the Gaussian atmospheric model cannot accommodate such complex rain information to produce improved estimates. To effectively optimise the model representation to include new information on rain, would require a very much better process model. Thus, the approach of scaling model parameters is ruled out. However, a simple model can be used to support the interpolation of a limited number of radioactivity measurements including inferred measurements estimated from the effect of rain on the plume.

Data assimilation techniques, both model fitting and interpolation based, generally use statistical methods. These allow them to take advantage of supplementary data correlated with the primary quantity of interest (in this case radioactive deposition density). In this study rainfall is the supplementary information expected to be strongly correlated with the deposition density of radioactive material from the plume. This work considers various methods of estimating the spatial variation in deposition density arising as a result of rainfall that occurs at particular locations over the extent of a dispersing plume of pollution. It also considers the effect of an inhomogeneous rainfall field on the amounts of material continuing to travel in the plume. Several approaches to these problems offering various degrees of approximation, applicable in different circumstances and requiring very different levels of effort to implement, are discussed.

2 EFFECT OF RAIN ON DISPERSING MATERIAL

Rain has two main effects on dispersing material. First, it is an effective mechanism of removing material from the plume and depositing it on the ground. Second, the way in which deposited material is divided between the ground itself and vegetation can be very different for wet and dry deposition processes.

The simple Gaussian plume model can be modified or extended to describe the effects of rain on both activity concentration in air and deposition for a short release, as described in Jones (1981, 1986), if a number of simplifying assumptions are made. The greatest simplification amounts to assuming that rain falls at the same rate over the whole of the area covered by the plume, and for the whole time period of interest.

Two mechanisms by which rain can remove material from plumes have been considered. Washout covers the processes where the dispersing plume is entirely below the rain cloud, and material is removed by rain as it falls through the dispersing plume. It is generally assumed that washout removes material equally throughout the vertical extent of the plume, and so this process does not affect the vertical Gaussian profile of the dispersing material. Rainout covers processes occurring once parts of the dispersing material have been transported into the rain clouds themselves. However, as the rain drops fall through the dispersing material, they would further remove material by washout. Therefore this process may only have a limited impact on the vertical distribution of activity within the plume.

The rate at which material is removed from plumes by rain has been studied extensively, as reviewed in, for example, Jones (1986). There is considerable uncertainty in the most appropriate value for the removal coefficient and its variation with rainfall rate, and in some cases whether the measurements refer to washout or rainout. Some studies suggest that the removal rate is independent of the rainfall rate, while others suggest that it increases as a power law of the rainfall rate. Some of the studies carried out could not identify whether the deposition was a result of washout or rainout. The few studies where the mechanism could be clearly identified as either washout or rainout have produced similar values for the removal coefficient. It is assumed in this study that the washout coefficient is a function of the rainfall rate.

Rainout only occurs once plumes have travelled for sufficiently large distances that part of the material has been transported into the rain cloud. It is therefore of less importance than washout at the distances at which emergency countermeasures might be considered following an accidental release. Although the emphasis in this report is on removal by washout, many of the comments should be equally applicable to removal by rainout.

A recent review of the uncertainty in washout coefficient (Harper et al 1995) suggested that the washout coefficient for a 1 μm aerosol lies between about

10^{-6} and 10^{-3} s^{-1} for a rainfall rate of 1 mm h^{-1}. The relative wet and dry deposition rates for aerosols and elemental iodine are considered in Appendix A, which shows that

a Wet deposition is likely to be much greater than dry deposition for aerosols. The conditions where dry and wet deposition processes are comparable correspond to very light rain or a washout coefficient in the lower part of its plausible range.

b Wet deposition is a few times greater than dry deposition for elemental iodine other than for situations where the washout coefficient is in the lower part of its plausible range and the rain is light. There are plausible sets of values for which dry deposition is greater than wet deposition.

A further aspect of the greater removal rate in wet as opposed to dry conditions is the rapid plume depletion that can occur in continuous rain. The simple model assumes that the fraction of material, F, remaining in the plume following a period t of constant rainfall is given by

$$F(t) = F(0) \exp(-\Lambda t) \qquad (1)$$

where Λ is the washout coefficient. This equation shows for example, assuming rain falls continuously over the time taken to travel between the source and receptor locations, that 90% of the released material is deposited within about 6 hours of travel if the washout coefficient is 10^{-4} s^{-1}. This corresponds to a distance of about 100 km at a wind speed of 5 m s^{-1}. As noted above, there is considerable uncertainty on the value of the washout coefficient. The value used here is near the centre of the uncertainty range for a rainfall rate of a few mm per hour. The same fraction is deposited within only 10 km of the source, for the same wind speed, if the washout coefficient is 10^{-3} s^{-1}. This value is around the centre of the uncertainty range for a much higher rainfall rate of around 10 mm per hour.

These calculations assume that rain falls continuously and at a constant rate over the travel distances of interest. This is unlikely to be the case for distances corresponding to travel times of several hours. Therefore, results obtained from equation 1 will over-estimate the amount of material likely to be removed from the plume in the patterns of rainfall likely to be encountered following an accident.

The simple Gaussian plume model could be made more realistic by relaxing the assumption that rain falls at a constant rate for the whole of the time taken for material to travel from the source to the receptor point. If the plume travel period is divided into shorter periods so that the rainfall rate is constant in each period, the fraction of material remaining in the plume can be expressed as

$$F(t) = F(0) \exp(-\Sigma\Lambda_i t_i) \qquad (2)$$

This assumes that the travel period can be divided into a series of shorter periods of constant rainfall rate, including the time period over which rain does not fall, such that the washout coefficient has the values Λ_i for a time t_i. The washout coefficients in the different time periods could be different because of the assumed relationship between washout coefficient and rainfall rate.

The previous discussion assumes that rain falls equally across the whole width of the plume. This assumption may not be appropriate at larger distances from the site, as the plume width increases. The effects of this could be incorporated in a more complex model, which allows for spatial variation in rainfall, or estimated, by a data assimilation process (see Section 3.2).

Rain can affect deposition at a point in two different ways. Firstly, the amount deposited depends on the rainfall that occurs at the selected location while the plume is passing over, as this directly affects the fraction of airborne material removed from the plume. Secondly, the amount deposited also depends on the total amount of rain experienced by the plume in travelling to that point. The rain on route to the location affects the amount of deposition occurring along the plume path and hence the amount of material remaining in the plume at the point of interest.

Simple calculations of wet deposition give the total amount of material deposited to the ground and vegetation by rain passing through the plume. However, this may not be the quantity of interest, or the one available from measurements. It is often important to know how the deposited activity has been partitioned between the ground and vegetation. This partitioning depends on both the total amount of rain and the rainfall rate. It may also be affected by "clean" rain falling before or after the passage of the radioactive plume. The fraction of the deposition intercepted by vegetation depends on the total rainfall because leaves can only hold a certain amount of water, becoming saturated, with further rain rapidly running off the leaves. The interception factor also depends on the radionuclide, being particularly affected by the valence of the deposited material. This topic is discussed further in Appendix B.

2.1 Typical rainfall patterns

Common experience suggests that rain does not fall at a constant rate over long periods or large areas, but that the rainfall rate can vary rapidly in both space and time. A literature survey was undertaken to identify any information on the spatial and temporal variation of rainfall rate. Three sources of information, flooding frequencies, microwave transmission and analyses of radar rainfall data, were identified. Information on rainfall related to flooding frequencies considers situations where substantial amounts of rain might fall over wide areas. Heavy rainfall can attenuate microwave transmissions through the atmosphere, and information is available on the extent to which this might happen. Unfortunately for this context, rain only has an important effect for rainfall rates above about 20 mm h^{-1}. Therefore, neither of these sources relate to the rainfall rates most likely to be encountered following an accidental release.

Limited information on the frequency distribution of rainfall rate and the correlation between rainfall rates at points which are different distances apart is given in Jones (1986), taken from an analysis of UK radar data (taken from Smith 1983). Unfortunately, no further similar analyses could be located. Smith's analysis showed that rainfall duration is inversely related to rainfall rate. For example, a rainfall rate of 1 mm h^{-1} would be expected to continue for three hours on about 10 occasions per year while a rate of 20 mm h^{-1} would only persist for more than an hour about once per year. The analysis also showed that the rainfall rate varies more rapidly in space over a short than a long period. For example, the correlation coefficient between rain over a 15 minute period at points about 10 km apart is 0.8; the same correlation coefficient is found for rain over 6 hours at points about 40 km apart.

Unfortunately, this analysis does not provide sufficient information to estimate the likely extent of plume depletion as a function of distance from the release. An alternative method was therefore used to determine this variation, by considering records giving hourly information on wind speed and rainfall rate over a period of several years at three sites. It is plausible to assume that, statistically, the sequences of conditions measured at a site are the same as those experienced by a plume travelling in the region around the site. Therefore, quantities such as the frequency distribution of the fraction of material remaining in a plume after a particular travel time can be calculated using the frequency distribution of sequences of rainfall rate measured at the site. Using information on the wind speed for each hour enables frequency distributions of the fraction of material remaining in the plume at particular travel distances to be obtained[*]. Figure 1 shows the probability distribution of the amount of material remaining in a plume at distances of 50 and 100 km, assuming in each case that it rains for some part of the time during the travel of the plume to the respective distance. This shows that the probability of rain removing more than about 20% of the material released to the atmosphere is very small, and therefore data assimilation techniques that do not allow for plume depletion should be appropriate. These calculations assumed that the washout coefficient (in s^{-1}) is related to rainfall rate (in mm h^{-1}) by $\Lambda = 2\ 10^{-5}\ R^{0.67}$ which are the 50th percentile coefficients for aerosols given in Table A1. The washout coefficient and therefore the results will depend on the values chosen for these parameters but the general conclusion that significant plume depletion is unlikely over these distances is appropriate for a large part of the plausible range of variation of washout coefficient with rainfall rate. The results here show much lower plume depletion amounts than given above after Equation 1. Those values were calculated assuming rainfall of a few mm per hour for 6 hours, or much heavier rain for about half an hour. The values given here reflect actual patterns of rain, and are consistent with the study described in the previous paragraph.

The approach assumes that the rainfall is constant across the width of the plume, an assumption that may not be appropriate for the distances considered.

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[*] A series of random samples of rainfall rate sequences could have been drawn from the population as an alternative estimator. This would have the effect of washing out the temporal auto-correlation between rainfall rates in sequences and thereby reduce the effect of rain on the amount of material remaining in the plume.

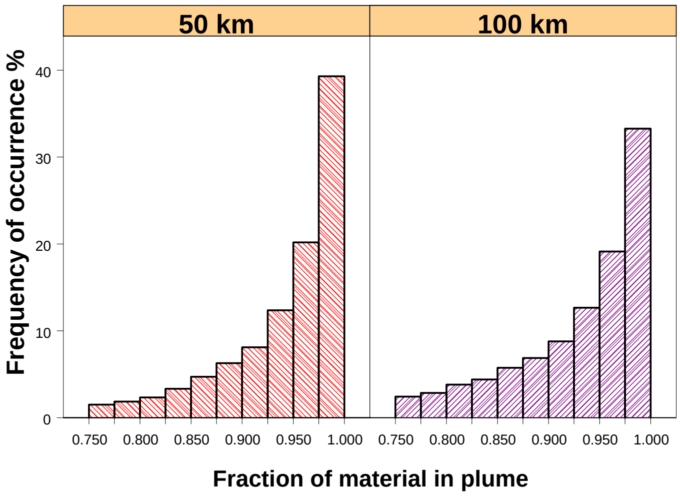
However, since the conclusion of only limited plume loss was based on measured rainfall sequences, it is unlikely that variations in rainfall rate across the width of the plume would substantially alter this. Moreover, the results in Figure 1 will be valid if used only to estimate a correction factor relating the air concentration on the plume centre line in wet and dry conditions.

2.2 Implications for assimilating wet deposition

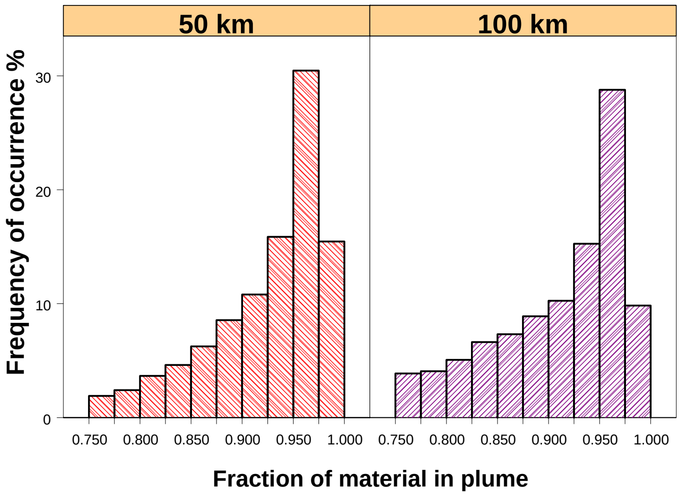
If plume depletion can be ignored which as indicated in Section 2.1 may often be the case, rainfall will only have a local effect. In this case, as the amount of dry deposition is not affected by rainfall, the assimilation of rainfall enhanced deposition data can be easily handled as a post-processing step to a model estimate derived assuming no washout. This enables the intricacies of the rain field pattern to be imposed onto the dry deposition estimate. The simplest approach is to take the expected ratio of dry to wet deposition for the appropriate conditions and use this factor to correct the local dry deposition estimates. This has the advantage of being simple and likely to give a sensible result independent of the method used to estimate the deposition if care is taken over any temporal effects that may complicate the situation (see Section 3.4).

If plume depletion is larger, due to periods of heavy or prolonged rainfall, then it may not be possible to simply correct calculations of deposition that do not consider the effects of rain. In this case, it would be necessary to use a dispersion model with an allowance for plume depletion as the basis of the assimilation procedure. This can be done, but could be rather more complex than the simple situation where plume depletion is not important. A discussion of possible approaches when plume depletion is significant is given in Section 3.7.

Honington
1970 - 1978



Squires Gate (Blackpool Airport) 1974 - 1981



Turnhouse
(Edinburgh Airport)
1973 – 1982.

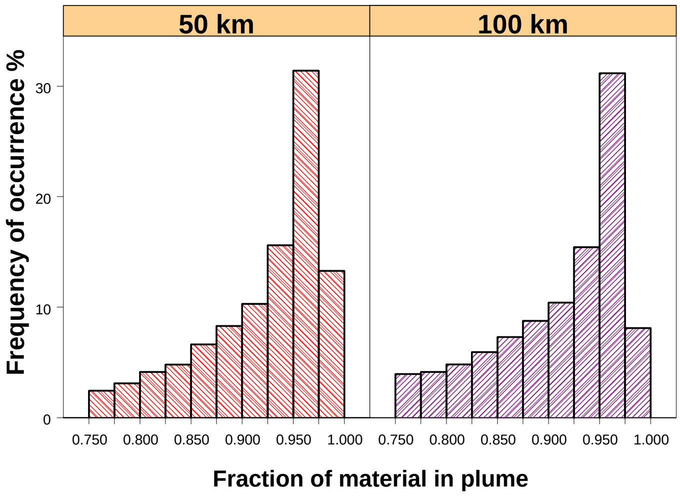


Figure 1 The probability distribution, at three example sites, of the amount of material remaining for travel distances of 50 and 100 km, assuming that it rains during the time of travel.

3 ESTIMATION METHODS

One objective of this work was to examine methods of estimating the enhanced deposition expected following the passage of a plume of pollutant through an area of rain. In the idealised situation of a non-depleting plume, a simple or complex dispersion model can be used to estimate the local concentration in air and consequent dry deposition. The ratio of dry to wet deposition can be estimated from the rainfall rate, vertical extent of the plume and the deposition parameters, as described in Appendix A. Wet deposition can then be introduced by using the calculated ratio of wet to dry deposition. One part of the task, therefore, amounts to estimating the amount of rain that falls in the different areas passed over by the plume.

Several methods are available for estimating the rainfall over an area from point measurements. However, as the UK mainland has comprehensive rain radar coverage, appropriately calibrated radar measurements could be used directly and there would seem to be little need to consider the use of point measurements from rain gauges. The following sections nevertheless discuss the use of point measurements to estimate rainfall for two reasons.

Firstly, studies have been undertaken where the rainfall at a location was calculated from information on rainfall at other locations. Techniques that can be applied to point rainfall measurements can be equally well applied to measurements of radioactive or other pollutant deposition, i.e. estimates can be made of the spatial distribution of the amount of material deposited from the plume based on a set of point deposition measurements. These studies support the use of interpolation or assimilation techniques for the applications considered in this report. As discussed in the introduction this is assimilation of radioactive deposition in the limit when model estimates are rejected in favour of an interpolation approach that implicitly includes physics that may be poorly represented by the process model. Rainfall estimation using rain gauges therefore provides a convenient surrogate problem for a range of techniques that if useful for rain are likely to be applicable to other deposits.

Secondly, it allows a discussion of the combined use of point measurements and a continuous, if indirect, estimate of the quantity sought. In the case of rain, the continuous estimate is from radar measurements but for radioactive deposition it could equally well (or in addition) be from a model. The relationship between radar measurements and rain gauges is discussed in Section 3.3.2.

There are a number of methods, of varying complexity, which may be used to estimate rainfall from point measurements. The simpler methods include, for example, Thiessen polygons and inverse distance weighting. The more complex methods can entail the use of a variety of geostatistical techniques but also other approaches such as basis function expansions, neural networks etc. A discussion of more complex methods is deferred to Section 3.5.

3.1 Simple methods

Many simple techniques can be used to carry out spatial interpolation. They have the advantage of speed and generally have little reliance on particular theoretical assumptions to produce their estimate. They do however make assumptions about the phenomenon that are unlikely to be true and/or require a large amount of data to derive an estimate. The two most common techniques are Thiessen Polygons and distance weighted interpolation.

Thiessen Polygons (Thiessen 1911) are used to define an area of influence around each measurement point such that each polygon contains all locations that are closer to the selected measurement point than to any other. An interpolation estimate can be made for a location by equating its value to that of the measured value within the same polygon. If there is a very dense network of measurements, or if it is known that the phenomenon only changes very slowly with distance, this method will provide a simple and reliable estimate.

Inverse distance weighted interpolation assumes that the value at a location is the weighted sum of values measured at other locations with the weighting usually assumed to be proportional to the inverse of the square of the separation distance between each measurement and the target location. This will tend to produce a smoother interpolation surface than Thiessen polygons but because it has no theoretical basis it introduces arbitrariness to the results.

3.2 Advanced methods

To estimate the amount of rainfall in a more thorough and convincing way than the simple approaches of Section 3.1 there are several improved estimation techniques that can be used. The methods generally fall into two categories: deterministic and statistical. The first form of technique generally tries to fit a surface to the limited number of measurements available (for example, by generating a polynomial surface that exactly passes through the known points). The most developed method in this category, which gets away from a simple single polynomial, is the use of thin plate splines. These interpolating splines can be viewed as minimising the flexing energy of a thin metal plate passing through the known measurement values. If the measurements have known error bounds, subsidiary smoothness conditions are generally applied to improve the behaviour of the fitting function (Hutchinson 1991)[*]. The smoothing parameter can be evaluated automatically by minimising the overall "jack-knife" error i.e. the sum of the differences between known values and the predicted values when each of

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[*] In the sense that a least squares fit is performed to estimate the smoothing parameter, this technique is also statistical.

the known values are left out of the calculation in turn. This amounts to fitting a particular form of correlation structure to the underlying data[*].

In the statistical category, the techniques of geostatistics are used. The assumption here is that the quantity of interest is a realisation of a random function and that a measure of the spatial correlation structure of the phenomena can be derived from the available measurements[†]. The measured values at different locations provide what is termed an experimental semi-variogram. This can be thought of as the inverse of a correlation function. The semi-variogram measures the dissimilarity of all pairs of points a given distance apart as a function of different distances apart. These distances are known as lags and a semi-variogram, γ, may be written as a function of the lag or separation h:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{\substack{i=1 \\ j=1}}^{N} (v_i - v_j)^2 \tag{3}$$

where v_i and v_j are the data values a distance (lag) h apart and N is the number of pairs of points with that separation. Generally, it rises from a low value for closely related measurements that are near to each other to a higher constant value for separation distances where the measurements are statistically independent. An idealised semi-variogram is shown in Figure 2 where the important attributes are identified. These are: the range R, which is the maximum distance over which data are effectively correlated; the sill, the limiting level of correlation between distant points (ie points separated by more than the range); and the nugget, which represents the unresolved variability between measurements that are close together.

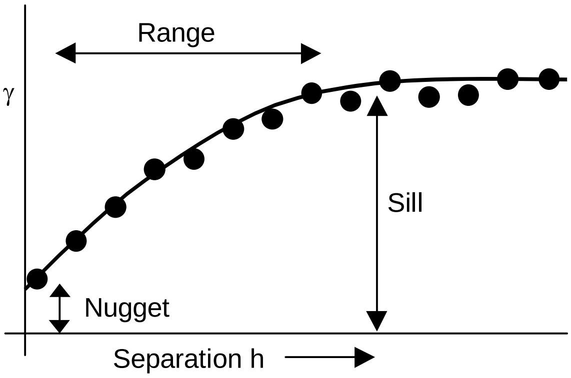

Figure 2. Typical experimental semivariogram with model semivariogram fitted.

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[*] The jack-knife predictor gives a measure of how well a point can be estimated from the data. If points can be exactly predicted, there is a deterministic relationship between the data i.e. perfect correlation.

[†] At any point the observed value is assumed to be a particular realisation from a distribution of possible values, which could be observed at that location. The values expected at a nearby locations depend on the values already observed.

Geostatistics uses a model function fitted to the experimental semi-variogram to characterise the spatial correlation. The model semi-variogram is in turn used to provide the weights used in a linear estimation procedure called ordinary kriging. Mathematically, kriging is termed BLUE because it is the Best Linear Unbiased Estimator possible. It has been shown that splines and kriging are formally equivalent. However, from an operational perspective the two approaches are different because kriging leaves open the possibility of selecting a different covariance model from the standard spline type. Not surprisingly, the techniques can achieve broadly similar results in many cases (Laslett 1994 and Hutchinson and Gessler 1994). Laslett (1994) says that kriging has the potential to out-perform splines when data are not sampled on a grid because of its ability to translate information from more densely sampled areas to more sparsely sampled regions.

There are many extensions and variants of kriging designed to tackle particular problems. Co-kriging is one such technique in which information on the quantity of interest, termed the primary quantity, is obtained with the aid of information on a secondary quantity. To apply the technique a large stock of measurements of the secondary quantity, covering the area of interest, should be available and values of the secondary quantity should be strongly correlated with values of the primary quantity. Co-kriging is a conceptually simple extension to ordinary kriging but is quite difficult to do in practice, see for example Burge et al (2002). Variograms are required for the primary and secondary data, together with a cross variogram to model the correlation between the different types of measurement. In addition, there are mathematical restrictions on the component terms, representing the cross-correlation between the two measurement types involved, which are difficult to satisfy. For this reason, techniques such as co-located co-kriging and universal kriging have been used to combine scarce primary data with plentiful secondary data. Co-located co-kriging is a simpler variant of co-kriging where measurements of the secondary quantity are available at all locations at which measurements of the primary quantity are available or are required. Universal kriging supports an ordinary kriging estimate, derived solely from the primary data (ie deposition measurements), with the provision that any trend in the mean of the primary data is provided by the secondary information. In the universal kriging system of equations, the trend is included as a deterministic change in the mean of the primary quantity over the area that is then added to the locally estimated values derived assuming a constant mean. Universal kriging and co-kriging are closely related i.e. universal kriging can be thought of as co-kriging with a deterministic secondary variable.

3.2.1 Bayesian methods

An alternative but related approach to geostatistical data assimilation is provided by the use of Bayesian techniques. A Bayesian method is currently available that will assimilate air concentration and deposition measurements (Kennedy et al 2002) with the predictions of a Gaussian dispersion model under conditions of dry deposition. The approach combines measurements of activity concentration in air and ground deposits to give predictions that go beyond the calibration of the model parameters, using the data to include the concept of ‘model inadequacy’. Model inadequacy is accounted for by a form of kriging that will eventually dominate the predictions made if the dispersion model is a poor representation of the available data. Although the technique is not tied to a particular atmospheric dispersion model, it currently has no mechanism for representing and therefore assimilating isolated rain events that occur as a plume disperses. If applied to radioactive deposition, locally enhanced by the effect of rain, the approach will discount the contribution of a poorly fitting dispersion model reliant on a single parameter to represent deposition and produce a kriging estimate. To fully utilise the approach and correctly assimilate rain data would require the Bayesian techniques to be used in conjunction with a dispersion model that supported local effects. This would allow parameters of the dispersion model to be calibrated with respect to local phenomena at particular locations or grid elements using, for example, a Lagrangian dispersion model. Bayesian methods are discussed further in Section 3.8.

3.3 The use of secondary data

Many data assimilation techniques can be used to derive information on one quantity with the aid of the data available on a secondary quantity. The ability is particularly relevant to the problem of inferring the change in radioactive deposition occurring over an area due to rainfall. Unfortunately, this particular result cannot be demonstrated directly due to a lack of the appropriate data. However, the possible success of the approach can be inferred by studying the application of assimilation techniques in other broadly analogous situations. To this end, this report uses measurements of rainfall at a point in two different contexts. For much of the report, measurements of the amount of radioactive material deposited are the primary data and measurements of rainfall are the secondary data. However, the report also discusses studies in which information on the rainfall at particular locations is derived from other quantities (altitude or radar measurements). Here measurements of rainfall at a point are the primary data while measurements on the related quantity are the secondary data.

3.3.1 Rainfall and Elevation

A comparison by Goovaerts (1999) of alternative geostatistical methods for incorporating elevation into the mapping of precipitation indicates the merits of different methods and by inference their applicability to the mapping of radioactive deposition incorporating the effect of rainfall. The comparison also included straightforward linear regression of rainfall against elevation and three univariate techniques: Thiessen polygons, inverse square distance and ordinary kriging. Goovaerts found, as expected, that for low resolution networks geostatistical methods outperform techniques that ignore spatial correlation. He also found that secondary information from the digital elevation model further improved the predictions. However, in agreement with the observation of Burge et al (2002) in their examination of co-kriging Goovaerts found that co-kriging was more difficult to use and less effective than other multivariate techniques.

3.3.2 Rainfall and Radar

Elevation data are one possible source of secondary information to supplement rain gauge data but another, radar reflectivity data, provides a more direct event specific source of secondary information. Rainfall can be measured at a limited number of locations using automatic gauges that take a reading every few minutes, or by gauges that record for longer periods. Alternatively, rainfall can be estimated every few minutes over an entire area using radar. However, what is observed by radar needs to be interpreted and calibrated to return an estimate of the rainfall over an area. It is therefore often used in conjunction with measurements at fixed locations. For example, Raspa et al (1996) proposed and demonstrated the estimation of rainfall over an area using the geostatistical technique of kriging with an external drift (universal kriging). In this case, rain gauges, providing time integrated measurements every 5 minutes, were used in conjunction with radar data recorded every 30 minutes. One-dimensional temporal kriging was used to establish the best weights to use when combining the available radar maps in estimates over different time periods. The weighted radar data covered the whole estimation area mapped out by the rain gauges and supplied local trend information to support the kriging of the rain gauge data. Creutin et al (1988) and Azimi-Zonooz et al (1989) had previously used the related, but more difficult to apply, technique of co-kriging to provide support for rain gauge data with radar information.

More information on radar measurements is given in Appendix C.

3.4 Temporal effects

Generally, there will be little interest in the temporal resolution of the amount of radioactivity deposited unless there is a strong connection between say, a storm front and the peak discharge rate occurring during an accident. However, it is important to know when the rain started and stopped in a particular area and when the dispersing plume of radioactivity passed over the area. The total predicted amount deposited is then composed of the amount deposited up to the time that it starts to rain, the corrected amount that falls during the period of rain and, if this ceases before the plume passes, the remaining dry deposition that occurs after the rain has stopped. If the plume passes before the rain ceases, unless there is sufficient temporal resolution in the rainfall data to have a measure of the amount that fell during the passage of the plume, an estimate will have to be made of the proportion that fell before the release passed[*].

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[*] Rain falling after the plume has passed may alter the distribution of contamination between vegetation and ground (and in urban areas, wash it away).

Even the comparatively simple problem, described above, of marrying the start and stop times of the rain with the passage of the plume, must be considered carefully. The simplest situation is likely to be when the rainfall period is the same over the entire area affected, and the area of rain entirely contains the envelope of the plume. Complications can arise if, during the passage of the plume, its ‘leading edge’ moves into an area of rain or its trailing edge moves out of an area of rain. This would only be an important occurrence if a substantial amount of the plume were dispersing slower or faster than the cloud cover. The plume and cloud cover might travel together, as suggested by the drop in air temperature under clouds but this will depend on the differences between wind directions and velocities at different heights. Problems could also arise if the edges of the plume move into or out of areas where rain falls.

Methods for incorporating temporal effects into the assimilation process are discussed in Section 3.8 following the discussion on depleting plumes of Section 3.7.

3.5 Comparison of Methods

Several techniques have been used to estimate rainfall, often with restricted amounts data with respect to the complexity of the task. This section will illustrate some of these techniques and their practicability in accident conditions where there is likely to be the greatest demand for a mechanism to deal with the effect of rain on pollutant transport. Of particular interest in this regard are the results of an inter-comparison exercise on rainfall in Switzerland (Dubois et al 1998). Rainfall measured at 100 rain gauges distributed over the whole of Switzerland was used to estimate the rainfall at a further 367 rain gauge locations. The participants were also supplied with a digital elevation model with a resolution of about 1 km x 1 km although this was not used by every group (Dubois et al 1998).

Following the discussion of Section 3.3.2 the techniques may not appear to be directly applicable to the estimation of enhanced radioactive deposition due to rain. For example, the use of radar rainfall estimates is likely to be a more readily available source of rain data than rain gauge measurements. However, as discussed in Section 3.6 the techniques discussed are directly applicable to the estimation of radioactive deposition using as a starting point a few deposition measurements or estimates and the linking of these with rainfall estimates.

The modelling approaches of the inter-comparison were compared on a number of grounds, in particular the root mean square errors (RMSE), the mean absolute error (MAE), the maximum (MAX) and minimum (MIN) predicted values and the mean absolute error of the highest 10 values. The results of the intercomparison are shown in Table 1 ordered by the magnitude of the RMSE. However, one or a combination of other error measures could have been chosen. Indeed for radiation protection purposes it could be argued that the technique that can successfully predict the highest values to within a reasonable approximation would be the best one to use after an accident. Table 1 is based on the results of a single trial, with all participants using the same set of 100 values as their starting point, for estimating the amount of rain from a particular rainfall event. In this case it is likely that a more robust requirement would be to seek the technique that displayed the greatest fidelity to all the measurements and therefore scored well against all the measures of error.

Table 1 Summary Results of Intercomparison (units 0.1 mm)

Method	RMSE	MAE	MIN (0)	MEAN (185)	MAX (517)	MAE Highest 10
Multiquadric functions[1]	53.1	36.7	17	183.4	476	?
Ordinary Kriging linear S-V[2]	54.6	37.5	15.4	182.8	485.7	118.1
Neural Network Residual Kriging[3]	56.342	39.38	0	181.45	514.1	?
IRF-K[4]	57.41	39.806	0	182	486	53
Ordinary Kriging Gaussian plus spherical S-V[5]	59.7	41.0	-27.92	181.87	510.67	103.15
Indicator Kriging[5]	60.0	42.6	29.549	186.91	489.63	102.78
Kriging Robust variography[6]	62.0	32.0	14	171	433	146.72[##]
Adaptive Kernel Estimator[7]	64	47	35.9	192	400	175[*]
Multidimensional Smoothing Splines[8]	65.21	47.8	0	184	497	120.4[**]
Locally Weighted Polynomial[9]	67.85	45	0	181	501	123
Kriging with Relative Variogram[10]	68.6	50.8	16.16	175.21	435.38	?
Surface under Tension[2]	71.0	47.9	-40.4	185.7	666.7	141.6
Fuzzy B-Splines[11]	71.78	50.82	0	165.54	435.05	153.5
Artificial Neural Networks[12]	78.65	55.9	3	182	522	8.14[##]

[1] Thieken 1998
[2] Saveliev, Mucharamova et al 1998
[3] Demyanov, Kanevsky et al 1998
[4] Bruno and Capicotto 1998
[5] Atkinson and Lloyd 1998
[6] Genton and Furrer 1998
[7] Ali A 1998
[8] Wendelberger 1998
[9] Rajagopalan and Lall 1998
[10] Raty and Gilbert 1998
[11] Gallo, Spagnuolo et al 1998
[12] Lee, Cho et al 1998

[*] Based on the top 5 measurements [##] Based on 7 values [**] Based on 9 values

The first thing to note is that the exercise, inferring the rainfall over Switzerland on a particular day from a few[*] randomly distributed measurements, was an extreme test of any interpolation routine. The interpolation was carried out without the assistance of any physical model of the processes involved and generally without the help of the available terrain information as authors failed to find an overall correlation between height data and measured rainfall. It is therefore encouraging that the results had such a small overall margin of error. In the less rugged UK environment with the possibilities of radar rain information

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[*] The number of measurements is small in comparison to the area represented.

and some insights from the modelling of a dispersing plume these or similar techniques should provide a useful method of assessing the amount of radioactivity deposited. The particular problem experienced by the techniques in the trial was their inability to reproduce the small-scale variability to be expected in the data. The trial data were sampled from the measurements of an inhomogeneous network of rain gauges. These measurements provided some data characterising small-scale variability but localised to particular areas. The trial requirement to assess the errors in predicting the ten highest (or lowest) measurements was therefore a particularly demanding test of any technique. Although, as commented on by many of the contributors, the performance of a technique under these particular conditions is unlikely to be a fair measure of how well it might perform with different data, the statistic does provide some evidence to help choose between the techniques.

The sections below provide some additional information on the more successful methods employed in the trial. They also discuss the applicability of the various techniques in a UK setting.

3.5.1 Multiquadric functions

Like splines, multiquadric functions are a form of radial basis function. Basis functions are simple functions of the separation distance, corrected for anisotropy, between the observed and target locations modulated by a smoothing parameter. The estimated rainfall at a location is calculated from a weighted sum of the basis function terms where the weighting factors are found by solving a system of linear equations. The smoothness parameter is left undetermined by the fitting procedure. As with splines, interpolation with multiquadric functions is a form of kriging with a prespecified generalised covariance function (Borga and Vizzaccaro 1996). Although the technique produced good measures of the overall error the author felt that the technique failed and that in particular the performance of the technique at reproducing the highest levels of precipitation was poor. Borga and Vizzaccaro (1996) compared the technique with kriging by estimating rainfall using varying numbers of simulated rain gauge readings obtained from radar rainfall estimates. They found that kriging resulted in lower errors in sparse networks.

3.5.2 Artificial Neural Networks

Neural networks were employed twice in the trial, most successfully in terms of overall error when the approach was combined with kriging. However, the approach achieved a remarkably small error for the largest rainfall estimates when applied unsupported although at the expense of a large overall error.

A neural network is composed of a set of inter-linked ‘neurones’ that each receive inputs and send outputs to the nodes they are connected to. The inputs and outputs are weighted by different amounts for each node. There is generally an input layer of neurones, which in this case are supplied with the input locations, and an output layer, which predicts the rainfall. There are in addition a number of hidden layers connecting the input to the output. Neural networks have to be 'trained' i.e. the weights connecting neurones are adjusted until the inputs generate the observed outputs. The training is organised as a global optimisation problem with the optimisation objective of minimising the output errors[*]. The number of hidden layers is an important consideration, if there are too many the network will capture specific features of the training set that may not be representative of the data as a whole[†]. Neural networks have a mysterious air to them with hidden layers and the use of training regimes. However, the process employed can, at least in the limit, be fully described in Bayesian terms (see Sections 3.2.1 and 3.8) i.e. a Gaussian process is like a neural network with an infinite number of nodes (Radford 1999).

The technique of neural network residual kriging uses the neural network to estimate the global trend and ordinary kriging to model the remaining correlated residuals. The difficulty, as with all techniques that try to separate global behaviour and local variability, is to achieve the successful separation of a deterministic trend.

3.5.3 Adaptive Kernel Estimator

This nonparametric spatial interpolation method does not assume that the underlying stochastic process is stationary. This is in contrast to the conventional assumption of kriging, which assumes a weakly stationary process i.e. one with a constant mean and the covariance between samples only depends on their separation distance. Kernel estimators are weighted moving averages over an appropriate area. The kernel function is usually chosen to be a symmetric probability distribution and acts as a weight function.

3.5.4 IRF-K Approach

This is an extension to the conventional kriging approach that does not require an assumption of a stationary random function. The approach assumes that the phenomenon can be represented by an intrinsic random function of order k and introduces the concept of a generalised covariance. The formulation allows the drift in the mean of the random function to be represented by a k^{th} order polynomial. The technique can be viewed as an extension of universal kriging in that an IRF-k function that possesses a covariance (or variogram) function in addition to the generalised covariance of the approach will produce an identical result to universal kriging with that covariance function. It can be argued that this technique had the best overall performance with both moderate overall errors and moderate errors in predicting the 10 maximum rainfall amounts.

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[*] Global optimisation is a potentially difficult task that is usually tackled by a mixture of a local optimiser (e.g. a gradient method) and simulated annealing to prevent the optimiser from being trapped by a local minimum.

[†] The familiar analogy would be to the use of a high order polynomial that is faithful to the data.

3.6 Application in the UK

A large variety of the techniques applied to the estimation of rainfall in Switzerland are likely to be applicable to the estimation of rainfall and or radioactive deposition over a local area in the UK if sufficient data are available. In the UK the number of synoptic stations reporting hourly rainfall data seem quite dense on a national scale but would provide relatively sparse coverage for a dispersing plume originating in the UK. The plume would therefore need to extend over a considerable distance before it encompassed many of the rain gauge stations. Thus, as already stated in Section 3.3.2, if rainfall data are to be used they require the use of the Nimrod radar system (Harrison et al 2000) which will provide rainfall information with a 2km resolution over most of the UK.

The above interpolation techniques using point measurements are still applicable if deposition measurements are considered directly. Measurements of deposition will become available after an accidental release of radioactivity in areas near to the site. Although only a small subset of the total amount of data available were employed in the Swiss study, the one hundred rain gauge measurements used in the trial assessment are likely to represent more measurements than would be available shortly after an event beginning in the UK. However, studies of the application of geostatistics to nuclear accident data have demonstrated that adequate variograms can be produced if between 30 and 40 measurements (Charnock et al 1999, Burge et al 2002) are available[*]. The exact number required will depend on many factors, including the particular arrangement of the sampling locations. In the case of Charnock et al (1999) it was found that simple geostatistical methods, ie ordinary kriging, had difficulty estimating the deposition because of the strong trend imposed on the amount deposited by the dispersing plume of radioactivity. Nevertheless, improvements over simple dispersion modelling were achieved by combining a Gaussian dispersion model estimate of the trend with measured results. The implication is clear, this approach can be extended to supplementing measurements of radioactive deposition with radar rainfall estimates. References have already been discussed where point measurements of rainfall have been used in conjunction with radar data. Thus, it is likely that the techniques discussed above, or variants thereof, can be applied to radioactivity deposition measurements in the UK in areas of rain. The techniques chosen should allow radar rainfall estimates and, if required, trend estimates of the mean deposition from a dispersing plume, to support the calculation.

There is an important imperfection in the analogy that implies that techniques applied to point rainfall estimates should also work with radioactive deposition estimates. Radioactive deposition measurements are partially correlated with the amount of rainfall estimated by radar or rain gauge. Including rain information should allow the deposition to be modelled more effectively and the different scale dependence of the two phenomena (i.e. the rain and the dispersing plume) to be better accounted for. However, although, for example, co-kriging can be

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[*] This is likely to be a higher density of measurement than the Swiss study.

used to estimate the rainfall using point and radar measurements, difficulties arise when the objective is to calculate the enhanced deposition of radioactivity directly. If deposition measurements in areas where it has rained are being used then the technique of co-kriging will be useful if the deposition is significantly under-sampled in comparison to the rainfall data*. However, if mixtures of deposition data representing measurement in wet and dry areas are available great care will have to be exercised in determining the appropriate correlation functions. The fundamental assumption of kriging is that measurements that are in close proximity to one another are more similar than those further apart. This assumption will break down if some measurements are made in dry areas and others in wet areas. A discontinuous change of this form will also affect the use of Universal and IRF-K kriging. This point should be considered further in subsequent work.

3.7 Depleting Plumes

The analysis has so far considered only the case where plume depletion is small. This assumption is thought likely to be adequate in the majority of cases, i.e. when the rain event is of limited effect or duration, as shown in Figure 1. However, there will be rain events when this assumption is not valid. In this situation there are two possible approaches, the first of which is a continuation of the existing data-driven approach and the second which requires more complex modelling of the dispersing plume. It has already been alluded to above that a dispersion model can be used to provide only trend information i.e. no source term needs to be specified (Charnock et al 1999). The kriging of ground measurements with their correlation represented by a variogram of the residual de-trended measurements supported by radar rainfall data can then be carried out. This is likely to be a difficult calculation to carry out during an emergency without significant preplanning and automation of the procedure. However, there is no reason why, given sufficient preplanning, it should not be a practical approach. The disadvantage of the method is that it requires sufficient deposition data to be available for kriging to be carried out (see Section 3.9).

An alternative approach to the problem, which partly preserves the simplicity of a Gaussian model, is to iteratively estimate the plume depletion. Rain estimates from radar would indicate areas of enhanced deposition on the ground, the amount of which can be easily estimated assuming no plume depletion due to rain (see Appendix A). To improve this estimate the enhanced plume depletion that occurs when the plume meets the observed area of rain can be approximately accounted for by reducing the source term. This will in turn reduce the estimated deposition further downwind. The final deposition estimate is then composed of a set of simple Gaussian dispersion estimates, each of which will only be valid over a small range of downwind distances. This approach

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* If the deposition is not under sampled these measurements will provide sufficient information on their own without the support of other correlated data.

clearly assumes that rain is occurring over the entire crosswind extent of the plume at approximately the same rate. But it has the advantage that it should be relatively easy to implement and quick to run.

A more soundly based approach can be achieved using a Lagrangian formulation to follow tracers from the source to different target areas. However, the knowledge of the flow field that is required to run this sort of model will generally make it impracticable for accident work.

3.8 Space time methods

If plume depletion is likely to be important, a requirement to calculate changes to the amount remaining in the plume and being deposited as a function of both time and space will greatly increases the complexity of the assimilation problem. An iterative approach similar to that described in Section 3.7 could be considered or a technique applied that considered time explicitly. If, in considering time, the objective is to move away from interpolation and use model results to extrapolate in time and space a more complex dispersion model will be required together with an alternative statistical approach.

3.8.1 Space-time kriging

Kriging is based on the theory of regionalised variables (Journel and Huilbregts 1978) and for the linear theory the supplementary assumption of stationarity. To a large degree, this can be fulfilled in the spatial domain. However, as discussed in Section 2 the problem of deposition and rainfall is potentially non-linear even without the added complication of plume depletion. Time can be regarded as another dimension and kriging can proceed without difficulty but only if it is reasonable to assume that the process is approximately stationary (Rouhani and Myers 1990). This restriction will also apply to a co-kriging formulation where spatial values at different times are represented by distinct but correlated random functions (Papritz and Fluhler 1994). As the phenomenon of interest is unlikely to be stationary (i.e. both the release rate and the rainfall rate are likely to fluctuate) a more comprehensive formulation is required.

The application of kriging techniques when the process is not stationary in time or space is difficult. There are two approaches that might be considered. One is the use of a kriging update model using a Kalman filter to learn about the changing correlations as time progresses. The other is the use of kriging with Bayesian maximum entropy. Both of these techniques apply Bayesian learning methods to account for the change in the dispersion of the plume with time.

Kalman filtering methods are very widely used in many areas of research and have been applied to the problem of assimilating environmental data for some time (French and Smith 1992, Smith and French 1993). They are generally applied to solely temporal series (Meihold and Singpurwalla 1983) but are applicable more widely. For example, Kerwin and Prince (1999) have developed a universal kriging formulation with a recursive update in the form of a Kalman filter. This however reduces to the kriging of the data available at each time step if there is no measurement noise. It also requires at least some of the measurements at different times to be made at the same locations. As might be expected for a method based on kriging interpolation it is not appropriate for forecasting.

A more comprehensive approach to the problem of space-time kriging, that claims to offer the potential of temporal prediction, has been put forward by Christakos (2000). This develops the concept of spatio-temporal kriging using a Bayesian maximum entropy approach*. It has been used for example in the dynamic estimation of solute concentrations in river catchment areas (Christakos and Raghu 1996).

3.9 Timescales when assimilation can help

Assimilation by its very nature requires measurement data, generally of the quantity of direct interest i.e. the amount of radioactivity deposited by a passing plume. It clearly takes time to obtain the density of measurements of radioactivity required before they can be used to improve estimates from models. Thus there is a limitation to the benefits possible from this form of assimilation in the very early stages of an accident. Even if a Bayesian procedure is used that can begin a process of assimilation from the arrival of the first few measurements little is gained initially as each measurement only provides information on the area immediately surrounding its location. The major benefit in this case is the scaling calibration of the model estimates provided by the first few measurements, but as it is difficult even under ideal conditions to locate the plume centre line, initial scaling corrections will be very approximate. The predictions of a dispersion model will initially provide the best estimates at the vast majority of locations simply because there is no alternative. The practical potential of assimilating measurements of radioactive deposition has been explored in great detail by Burge et al (2002). They found that providing the measurements were spaced sensibly (to prevent redundancy because measurements were too close together or so far apart that except for any trend they were uncorrelated) interpolation could be effective with a few tens of measurements over the area where countermeasures might be expected.

In distinction from the limitations of assimilating direct measurements of radioactive deposition, radar rainfall measurements if available, can be used from the start of an accident as discussed in Section 3.7.

The time scale for implementing assimilation clearly depends on the approach under consideration. A data driven approach relying on the kriging of radioactive deposition measurements supported by radar rainfall information may take some

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* Maximum entropy is used as a method of determining a Bayesian prior based on initial ‘objective’ information. It is a theoretically contentious area, which has not yet been fully resolved (Bernardo and Smith 1994).

time to prepare. However, this is predominately a problem of linking software and not one related to the techniques. Variograms can be estimated automatically and even modelling by eye would not take very long if the data were received automatically for display, manipulation and calculation within a Geographical Information System (GIS). The initial exploratory data analysis and variogram fitting would be the most time consuming aspect of any procedure. It is important to gain an understanding of the data and get a feel for any deviations from simple model estimates but once this is achieved calculations would only take a few minutes at most. The key to a practical implementation is therefore agreement on the form and type of data required and the provision of the necessary software to use and manipulate it easily.

4 IMPLICATIONS OF RAINFALL FOR MONITORING PROGRAMMES

This section briefly introduces some of the considerations that are likely to be important in modifying a monitoring programme developed primarily for dry conditions for use when rainfall has occurred after an accident. An effective monitoring programme will enable the knowledge gained of the distribution of radioactivity in the environment to make a timely contribution to the decision making process. In the first instance, effort will be directed to the protection of the population. Activity concentration in air decreases rapidly as distance from the site increases, but the extra deposition caused by rain could counter-balance this decrease, possibly leading to deposition levels many tens of kilometres from the site which are comparable to, or greater than, those found in the dry region near the site. In this case, the monitoring programme would need to be modified to enable data to be obtained to determine whether countermeasures would be required near the point where the plume first encounters rain and to obtain sufficient information to enable the deposition patterns to be reconstructed. Subsequently, monitoring will help people to resume their lives and the affected area to be restored or managed appropriately to minimise any long-term consequences. In the short term, the key constraints on sampling are likely to be the need for speed, the closely related requirement that sampling locations are easily accessible and, most importantly, are concentrated near inhabited areas. Until sufficient monitoring has taken place to characterise the effect of the accident near inhabited areas, or countermeasures are in place which minimise the immediate risks, other factors will have much less influence on the selection of sampling locations. However, multiple agencies contribute to the monitoring response and some, such as the Food Standards Agency, the Department for Food and Rural Affairs and the Environment Agency are charged with responsibilities that require them to consider a more general perspective from an early stage.

The effect of rain on the sampling undertaken after an accident may vary with time after the event. For example, the location of the rainfall and the initial responsibilities of the monitoring organisation will influence by how much and at what stage the predicted consequences of rainfall on deposition and uptake perturb the monitoring programme being implemented. Although not generally considered in this report rain occurring after the passage of the plume of radioactivity over the area could also influence the monitoring subsequently undertaken. Directing the monitoring programme should be done mainly on the basis of rain that falls during, rather than before or after, the passage of the plume. Section 4.1 discusses some general ideas about locating environmental samples and Sections 4.2 and 4.3 then discuss how these might be applied in an accident situation, while Sections 4.4 to 4.6 discuss the likely influence of rain on the programme.

It is worth noting that there are no experimental data that can be used either to test data assimilation procedures in wet conditions or to check the effectiveness of modifications to normal monitoring programmes. For example, most of the data for the UK following the Chernobyl accident gives deposition by county, rather than the detailed information required to test data assimilation procedures. Advice on these issues must, therefore, be based on experience in dry situations and the perceptions of the problems and differences likely to be created by rain.

4.1 Pre-selection of monitoring locations

Before designing a sampling programme, it is important to determine why the monitoring is being undertaken. For example, the average dose rate or activity concentration over an area might be sought. Alternatively, finding hot spots of activity or threshold boundaries delineating areas where action needs to be taken might be the objective. These different requirements will, in general, require different monitoring strategies. If, for example, a limited number of field measurements are to be used to characterise the expected deposition over a sample area then the measurements must be representative of the area as a whole. This generally requires a carefully designed sampling scheme. For example Rodriguez-Iturbe and Mejia (1974) discuss the design of rainfall networks at regional and local levels. More generally Gilbert (1987) discusses basic concepts of pollution monitoring[*]. Many of these ideas are appropriate for fixed networks and are unlikely to fit within the constraints imposed by an evolving accident situation. However, it is appropriate to review briefly the design of simple monitoring approaches as it serves to illustrate the difficulties of gaining a representative sample during an actual event.

There are several conventional approaches to sampling within a region that are commonly considered and these are discussed in turn below.

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[*] There are some elementary errors in Gilbert e.g. that the simple mean of sample values is an unbiased estimator of the population mean for spatially correlated samples.

a Simple random sampling selects sampling locations by drawing them independently from a uniform distribution. For example, a random number table could be used to select the required grid co-ordinates.

b Stratified random sampling divides the area of interest into a set of distinct regions and then simple random sampling is carried out within each region. For example, McArthur (1987) demonstrated that concentric circular or rectangular rings of increasing size would be an appropriate choice for estimating the amount of pollutant concentrated around a point source where the concentration is expected to decrease with distance from the site.

c Systematic random sampling involves specifying an initial sampling location at random and then specifying the remaining points in a regular pattern. If the initial location is not chosen at random then the sampling is simply termed regular[*]. The most popular regular patterns adopted are a rectangular or a triangular grid with the latter often being the most efficient (McBrateny et al 1981).

If, for example, a study of contaminated land were being conducted it is likely that one of the above methods would be used initially to provide trial data which would then be used in the selection of further sampling locations (see Section 4.3). This can involve complex calculations but they will allow an efficient site assessment to be carried out by indicating the best locations and the number of measurements required to meet the desired quality objective.

4.2 Preferential sampling

In general in a post accident situation the sampling data are neither regularly spaced nor randomly distributed over the study area. This occurs for a number of reasons, for example, fields bordering roads are easier to reach or it is thought important to make more measurements in areas of high deposition or near settlements. However, these choices will have an impact on the sample statistics collected (Goovaerts 1997). For example if the average deposition over a particular area is required then it is likely that some form of de-clustering procedure will need to be applied. This will help to ensure that measurements in the more heavily sampled areas are given less weight than measurements in less densely sampled areas. The simplest of these procedures is the use of Thiessen polygons (see Section 3.1). This involves summing a weighted contribution of each measurement to give an average where the weights used are the proportional areas of influence of each point with respect to the total area under study. Another phenomenon that needs to be considered when sampling predominately from high deposition areas is hetroscedasticity i.e. the change in the variability of sample values across the area under study. This is often manifested through the so-called proportional effect where the local

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[*] These sampling plans are different if expectation values are calculated from the sample values.

variance is related to the local mean. Thus, for positively skewed data the variance increases as the local mean increases. The implication is that a small number of measurements in an area of high deposition could be more misleading than the same number of measurements from an area of lower deposition. However, high values are context dependent e.g. whether concern is centred on external dose from deposited radioactivity or on concentrations in food exceeding the EU intervention levels. In the former case it is likely that measurements would be concentrated within the confines of complex built environments whereas in the latter they may be required over larger areas of the countryside.

Rainfall will contribute to the problems of preferential sampling by introducing changes to the amount deposited, which may or may not coincidentally relate to areas where sampling is concentrated. To capture some of the effects of rain some sampling may be redirected to areas of high rainfall in the expectation that these will be areas of high deposition. However, the scope for redirecting monitoring to areas of expected high deposition will be no greater than that available or utilised in dry conditions. The difference is that in dry conditions areas of high deposition are inferred from simple dispersion models and previous measurements while in wet conditions knowledge of where it rains will also help to define areas of interest. The variance behaviour in areas of rainfall is also likely to be different than that observed in dry areas even if the areas had similar mean amounts of deposition.

4.3 Optimal sampling

The problem of designing a monitoring programme that improves the effectiveness and efficiency of data assimilation is a natural extension of the assimilation process itself. In this view future monitoring should change, in the light of existing findings, to optimally reduce the uncertainty in the current predictions. This form of monitoring programme is therefore adaptive allowing a constant interplay between model predictions and future sampling priorities. However, many other factors will play a role in the selection of sampling locations and the programme is likely to be always sub-optimal when judged solely in terms of assimilation. The key constraints in this respect are likely to be time and practicality. Section 4.4 discusses the practical application of optimal sampling ideas and the particular influence of rain on the programme.

Optimisation is a mathematical task that is commonly akin to maximising a function subject to some constraints. Clearly the function must represent a measure of the information recoverable from a particular conformation of sampling locations. The optimum function will then be the most efficient arrangement for recovering information about the expected deposition at any location within the area of interest using a given number of samples. For accident response purposes, an optimal estimate of the deposition at any location is not required: the primary concerns are establishing where the areas of highest deposition are likely to occur, the radiation levels in areas where people live and work, and transition regions defining boundaries between action and no action. Depending on the countermeasure under consideration, these last may represent a relatively low deposition level.

Kriging provides two pieces of information. It provides a best estimate of the deposition likely to be found at unsampled locations and, through the kriging variance, an estimate of the uncertainty in deposition estimates predicted by kriging. The kriging variance differs from a true variance in that it is independent of the sample values and depends solely on their relative locations. However, knowledge of the kriging variance does require a variogram model and therefore an initial sample data set. The kriging variance can be used to indicate where more measurements are required to reduce the uncertainty in estimates but it does not discriminate between uncertain low values and uncertainty in the estimation of high values. However, the kriging results can be used to prioritise subsequent measurements with respect to the relevant absolute criterion. For example, food restrictions imposed at the level set by the European Council of Ministers are likely to enclose a much greater area than restrictions imposed to protect the public from external exposure from deposited material or doses from resuspension of radionuclides. Thus, additional measurements to refine the location of the boundaries between areas where countermeasures are taken and those without are likely to be required in very different places for each of the range of concerns. If monitoring effort is limited it must be clear which priorities should dominate so that resources can be directed to the right areas.

One obvious way of selecting a sampling plan is to minimise the mean square prediction error (the kriging variance) at all locations in the area under investigation with respect to the set of possible measurement locations[*]. This calculation is perhaps easier to visualise if the locations of the possible measurements are confined to points on a fine grid. In this discrete analysis the optimal locations of a selected number of additional measurements are found by sampling all possible combinations of grid locations for that number of additional samples. The configuration with the lowest kriging variance can then be selected. This is a combinatorial problem and the naïve approach of exhaustive enumeration would be impractical. For example, if the area of interest covered 100 km^2 and the fine grid had a resolution of 0.5 km then in selecting the location of the next 5 samples more than $8\ 10^{20}$ possibilities would need to be considered. Fortunately, there are techniques that make the problem tractable, such as employing the methods of integer programming (Garside 1971), simulated annealing (Van Groenigen 1997) and genetic algorithms (Goldberg 1989).

The optimal sampling problem described above can be extended to give the number of measurements required to meet an imposed accuracy constraint on the acceptable size of the optimal kriging variance. The calculation above is

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[*] Previous sampling may identify several areas or regions of interest. These may be considered separately but using a common variogram or, if there is sufficient data, separately with individual variograms for each region.

simply repeated with an additional sampling point on each cycle until the predicted kriging variance satisfies the accuracy constraint. Further refinement is possible by restricting the underlying grid points to those that are practical to reach. For example, a GIS can select all those points within a few hundred metres of the roads and tracks covering the area. However, it may be difficult to combine this limitation to a potential sampling region with a demanding accuracy constraint, while still allowing a feasible solution to be found.

There are alternatives to optimising sample selection through the minimisation of the overall kriging variance that may be applicable at different stages in the evolution of the event. For example, sample selection could be designed to optimise the estimation of the experimental variogram. This criterion demands that the point pairs are distributed over the distance and direction lags according to a pre-specified distribution (Warrick and Myers 1987).

Another alternative is to minimise the mean of the shortest distances between sampling locations (Van Groenigen 1997). This will require them to be evenly spread out over the area of interest ensuring that unsampled locations are never far from a sampling point. As discussed in Section 4.1 the equilateral grid is almost optimal (McBratney et al 1981) but this is based on the assumption that the area of interest is a contiguous, continuous, infinite plane. In the field situation there will always be boundary effects, which will be increasingly important as the complexity of the area under examination increases. It is also likely that the area of study will be composed of several non-contiguous regions with complex boundaries and it is important to take full advantage of existing sampling when deciding where to sample next. This latter optimisation is only determined by the geometry of the sampling area and can be carried out as a preparatory step before an accident occurs as part of an emergency planning programme.

A final alternative is to tie down the area bounded by a given criterion by using kriging to produce a contour at that value and the kriging variance to estimate bounding contours of plus or minus one standard deviation on either side of the central estimate. Additional sampling can then be targeted at locations that will reduce the estimation error of that contour in particular, a process termed chasing the action line (Myers 1997).

These techniques are applicable in both dry and wet conditions. However, in wet conditions radar information, with ~2km resolution, will additionally supply approximate boundaries between wet and dry areas. Depending on the location of the rain affected areas with respect to the dispersing plume these boundaries may correspond to significant changes in the amount of radioactivity deposited. It is therefore likely that additional sampling will be sought in the boundary regions between definitely wet and definitely dry areas. This is an extension of the constrained sampling discussed above. The simplest way of handling this complex task would be through the use of a GIS to supply the necessary spatial constraints on the areas of interest and the use of a series of variograms which become more specific to the regions of interest as further measurement data become available. There is no specific information on the consequences of using a poor variogram as an input to deciding where next to sample although it is known that a kriging estimate is only weakly dependent on the variogram used. Trials and analyses would be required to establish guidance on when to recalculate a variogram or to use a poorly defined variogram for a specific area instead of a better defined variogram representative of a larger area. Section 4.4 provides simple practical advice on selecting monitoring locations that avoids the complexity of trying to do it formally.

4.4 Monitoring programmes in wet conditions

This section considers the ways in which monitoring programmes might be modified if an accident were to occur in wet weather, with particular emphasis on methods of obtaining results that would most easily help a data assimilation process.

Rain during the passage of a plume, as has already been discussed, will increase deposition over the area where it rains and, particularly for heavy rain, reduce deposition in areas further downwind. If the rainfall is very localised it may be appropriate to modify the sampling plan to accommodate this effect. This could only be considered for rain that is known to be falling within the potential sampling region i.e. the area over which practical sampling can take place. This is likely to be a very limited ribbon of land, near roads and farm dwellings in the countryside and in streets, parks and possibly gardens within settlements. If the rain occurred elsewhere, e.g. on surrounding hills, then any enhanced deposition in those locations is likely to remain unsampled in the short term. If rain is more widespread the sampling should carry on as before as there is less likelihood of isolated rain induced hot spots.

In the case of isolated rain events, it is unlikely that there will be sufficient knowledge from other measurements taken in contiguous rainfall areas to consider the use of a variance approach to selecting sampling locations. The simplest compromise is therefore to constrain some measurements to be made in the areas within the potential sampling region that are subject to rainfall and adjust the location of other samples to accommodate the change. The other locations may be determined in part by variance optimisation or by the equal spacing rule, which does not require any existing measurement information other than the boundary conditions. The person taking the sample should record whether the ground was wet or dry, and whether it was raining at the time of taking the sample.

4.5 Monitoring when rainfall is uniform

If the rainfall rate is essentially uniform over the region covered by the dispersing plume, then data assimilation techniques developed for use in dry conditions should be applicable and there should be little difference between suitable monitoring programmes in wet and dry situations. However, rainfall is unlikely to be absolutely uniform over the area covered by the plume, and there will be some variation in the deposition levels at different points caused by the spatial variations in rainfall. The likely magnitude of such variations could be determined from analyses of the spatial and temporal variation of rainfall rates obtained from the weather radar data. Most such analyses have been undertaken for rainfall rates that occur typically once a year or less (i.e. sufficiently heavy that there is danger of flooding), but have not been undertaken for the more frequent rainfall rates that are of interest in dispersion modelling. One study at rainfall rates of interest is described in Jones (1986), and summarised in Section 2.1.

4.6 Monitoring when rainfall is not uniform

There are potentially problems in assimilating data from different regions with very different rainfall rates, particularly across the boundaries between such regions. The monitoring programme should be extended to identify such regions and boundaries, based on available information on the likely or actual rainfall patterns. This information could be obtained from a variety of sources, with different information available during and after the release, such as

a Weather forecasts, as given on TV or radio (i.e. information such as "showers this afternoon in S England"), or information on the current weather conditions at a distance from the site, expressed at a similar level of detail.

b Detailed output from the forecasting programs (i.e. predicted rainfall rates by time and grid element).

c Detailed results from the NAME model (Ryall 2000), giving deposition at particular points rather than simply trajectory and activity concentration in air.

d Real time radar data, giving the current rainfall rate on a grid spacing of a few km. This could be used to provide information on the total rain over the previous n hours,

e Rain gauge data.

It seems unlikely that monitoring in the immediate vicinity of the site would be very different for wet or dry conditions during the accident. The spatial variation of rainfall rate within a few kilometres of the site is unlikely to be large, particularly if averaged over a period of a few hours, corresponding to likely durations of accidental releases. Although variations in rainfall rate will produce variations in deposition, it is likely that any data assimilation procedure would be able to handle all measurements made within the immediate vicinity. Section 2 gives information on the relative amounts of wet and dry deposition for different rainfall rates. This shows that rain falling at the site during the release period would considerably increase the deposition levels close to the site, compared to those expected for a release of the same size in dry conditions. This could mean that countermeasures (such as food restrictions) might be required for smaller releases in wet than in dry conditions.

The following sub-sections consider the ways in which the different sources of information might be used to inform and adapt monitoring programmes, and the timescales over which it would become available.

4.6.1 Using qualitative information from forecasts

Weather forecasts would indicate if the plume is likely to move into an area, at some distance from the site, where rainfall is expected. Information from weather forecasting would provide time to direct monitoring teams to locations where higher deposition levels would be expected, so that measurements could be made to enable countermeasures (especially food restrictions) to be implemented on a suitable timescale.

4.6.2 Using information from quantitative forecasts

The MO's weather forecasting programs give information on the expected rainfall rates at particular times and locations. This information could be used in a similar way to that suggested above for the more qualitative forecasts, but taking advantage of the more detailed predictions on where, when and how heavy the rainfall would be. The information would be used in much the same way whether it was obtained from the weather forecasting programs or the NAME model. The PACRAM system enables information on atmospheric conditions near nuclear sites to be extracted from the forecasting programs and provided to the emergency controllers.

4.6.3 Using information from the radar network

The radar network gives information on the current rainfall rate on a grid with a spacing of a few kilometres. The data could also be combined to give information on the total rainfall over any period for which information is required. The main effect of rain is to increase deposition at those points where rain occurs while the plume is overhead. Therefore it seems reasonable to suggest that data from the radar network should be processed to give information on the total amount of rain that has fallen while material from the plume was likely to be present at each grid point considered. This information could be used to provide correction factors to estimate the likely deposition at each grid point using relatively simple dispersion models. This information could be used to direct the monitoring programme in two ways.

First, it would allow measurements of deposition to be made at those locations where countermeasures might be appropriate at distances away from the site. The use of radar data will enable the "hot spots" to be located more precisely than could be done using forecast information. This would be used during and immediately after the release.

Second, it would more clearly delineate those areas within which the rainfall was moderately uniform and help to identify the boundaries between such regions. This would enable measurements to be made in sufficient suitable locations that the deposition pattern over the whole region could be reconstructed following the accident.

It should be noted that radar data refers to past or (possibly) current conditions rather than to a forecast of the situation. Radar data, on its own, would not enable monitoring teams to be directed to areas where rain was expected to fall.

4.6.4 Using information from rain gauges

Information from rain gauges is more likely to be useful in the period after the accident than during the emergency phase. As noted in Section 3.3.2 rain gauge data can be used to calibrate the radar measurements, and so such data would help in building up a complete picture of the deposition pattern produced by the accident. However, it is unlikely that sufficient data would be available from rain gauges on a timescale to enable calibration procedures to be undertaken on the day of the accident, and therefore such data are unlikely to be useful in the period during which the release was continuing.

A further possibility would be to collect rainwater at the location of the rain gauges (either by collecting the water from the gauges themselves or by using a separate collector), and to measure the activity in the rainwater. The measured activity, if combined with information on the amount of rain falling while the plume was over the collector and the predicted activity concentration in air at the same location, would give information on the relationship between deposition and rainfall, though there could be considerable uncertainty in the calculation. This could be used to improve the predictions of deposition at other locations where the rainfall is known.

5 DISCUSSION

The report has reviewed the state of knowledge in the difficult area of assimilating the effect of rain on a dispersing plume. It is clear that the areas where deposition from the passing plume is likely to be elevated due to rain can be predicted with the help of rain gauge measurements and, more generally, radar information. The time and distance scales over which such predictions may be practical will depend on the monitoring network in place. If automatic rain gauge data were to be used on its own there would be a minimum size of contaminated area that could be detected (as the area with rain must include at least one rain gauge) whereas radar can provide coverage that is more complete. It is also likely that the scale of enhanced deposition can be predicted reasonably well over an area providing the rainfall producing the enhancement has not made a significant change to the amount of pollutant being transported by the plume. If the amount of material being transported by a plume is changed significantly by passing though a belt of very heavy rain, less straightforward methods exist which could take this into account when mapping radioactive deposition. Estimates are likely to be more consistent within dry or wet regions than across boundaries and rain gauge and radar information will allow ground survey measurements to be easily zoned. This should give improved estimates of the amount deposited for a given number of measurements. The problem of fully accounting for the effect of rain on a dispersing plume without any or at least a substantial number of deposition measurements depends on the use of a model that can cope with strongly spatially dependent deposition. This is not true of simple atmospheric dispersion models that might be used after an accident (e.g. Gaussian plume models) or of more complex models that could be considered for use after an accident (e.g. ADMS). It is, in any event, likely to be inappropriate for an immediate emergency response tool as the data requirements of the model are likely to be difficult to meet if they are not routinely available. In the UK the NAME model of the Meteorological Office is an exception. It can be run quickly and has access to the radar, satellite and numerical weather models of the Meteorological Office. However, the model does not generally provide sufficiently detailed results to be of immediate use in the detailed assessment of consequences in the area around the affected site.

5.1 Future Work

The work has summarised and reviewed the opportunities and problems likely to arise when trying to assimilate rainfall information. This has highlighted a number of areas where further investigations would be useful. In particular the elementary process of assimilating the effect of enhanced radioactive deposition due to rainfall has been suggested but not demonstrated due to a lack of data. Although there is no convenient source of information on the dispersion of a radioactive plume after an accident that could be used in a study of dispersion models and rainfall, Chernobyl data measured in this country combined with contemporaneous radar data should enable the basic geostatistical approaches to be tried out. This would have several beneficial effects, in particular it would allow an examination of the role and significance of discontinuities i.e. the boundaries between areas of rain and no rain.

In additional to this fundamental work the practicality of the task could be investigated. For example, it would be useful to demonstrate if there are any difficulties with the form and processing tools available to use and manipulate the data for the calculations required.

6 CONCLUSIONS

This brief review of the complex problem of accounting adequately for rain following an accidental release of radioactivity into the atmosphere has highlighted the potential to apply some comparatively simple corrections to model estimates. These will not work in all circumstances and will only provide an approximate correction for the effect of rain. It seems reasonable to assume that the methods proposed here will work in a fairly wide range of situations likely to occur. Testing the methods requires detailed information on deposition patterns following a short release; such information is not currently available.

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APPENDIX A

Equations for Deposition Rainfall Rates of Interest

A1 Introduction

This appendix summarises relationships between air concentration, wet and dry deposition, and the fraction of the material remaining in the plume as a result of wet deposition. The equations presented are such that they predict either air concentration and deposition rate or the time integrals of these quantities, depending on whether they are used with the release rate or the total release. The implications of the different units are considered. This leads to the identification of where the equations refer to rainfall (or rainfall rate) at a particular point and where they refer to the total amount of rain experienced by the dispersing material during its travel to the point of interest.

There is uncertainty on the variation of washout coefficient with rainfall rate, which also complicates the use of the equations and affects the extent to which they can be used with the rainfall rate or total amount of rain. The implications of this uncertainty are also considered.

A2 Uncertainty on the variation of washout coefficient with rainfall rate

Information on the variation of washout coefficient with rainfall rate, and its uncertainty, can be taken from two sources. NRPB-R198 includes details of a review of information on the variation of washout coefficient with rainfall rate. This report was written in 1986, but there has been little further work on this topic, and the results given there are generally still appropriate. This report reviewed a number of experiments in which the variation had been measured. Some experiments found that there was no variation with rainfall rate. Others found that the variation could be expressed as a power law,

$$\Lambda = a\,R^{b} \qquad 1$$

where R is the rainfall rate in mm per hour and a, b are constants. R198 suggests that the value of Λ lies between about 3 10^{-6} and 10^{-4} for a rainfall rate of 1 mm h^{-1}, and that "b" lies between 0.5 and 1.

The uncertainty on the variation of washout coefficient with rainfall rate was also considered in the analysis of the uncertainty on the COSYMA predictions. The results from the expert judgement studies for washout of aerosols and elemental iodine are summarised in the Table A1.

Table A1 Uncertainty Ranges of washout parameters

Quantity	5th percentile	50th percentile	95th percentile
A for aerosols	$1.4\ 10^{-6}$	$2.0\ 10^{-5}$	$1.3\ 10^{-3}$
B for aerosols	0.21	0.67	2.2
A for iodine	$1.9\ 10^{-6}$	$2.1\ 10^{-4}$	$5.8\ 10^{-4}$
B for iodine	0.23	0.77	1.9

A3 Equations for air concentration and deposition

The basic equation for air concentration (simplified by not including the terms describing reflection of the plume from the top of the mixing layer) is

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

where C is the air concentration or its time integral, Q is the release rate or its time integral, σ_y σ_z are the standard deviations of the horizontal and vertical plume size and h is the release height. The equation can be interpreted in different ways, depending on the exact quantity represented by Q.

a If Q is the average release rate over a period, then C is the average concentration over that period. It gives the actual concentration over any period for which the release rate can be considered to be constant.

b If Q is the total amount of material released, then C is the time integrated activity over the complete period of the release. This relationship holds even if the release rate is not constant over the period considered.

A slight complication to using equation 2 with different time periods is that σ_y depends on the averaging time, because of the variation of wind direction over periods of time.

The basic equation for dry deposition is

$$D_d = V_g\ C \qquad 3$$

where D_d is the deposition and V_g is the deposition velocity.

This equation gives deposition rate or total amount deposited, depending on whether C is the air concentration or its time integral.

The basic equation for wet deposition is

$$D_w = \Lambda\, Q\, (\sqrt{2\pi}\, u\, \sigma_y)^{-1} \qquad 4$$

where D_w is the deposition Λ is the washout coefficient (fraction of material removed per unit time). This equation gives the deposition rate or total amount deposited, depending on whether Q is the release rate or the total amount released, and on the variation of washout coefficient with rainfall rate.

a If the rainfall rate is constant, then this equation can be used to give deposition rate or total deposition, irrespective of the variation of washout coefficient with rainfall rate.

b If b = 1, then the equation relates average deposition rates, release rates and rainfall rates over a period.

c In all other situations, the equation can be used by summing over time periods for which the rainfall rate can be regarded as constant.

If the equation is used to give deposition rate averaged over some period (with release rate averaged over the same period), then the rainfall rate (used to determine Λ) must also be averaged over the same period.

Equation 4 gives the wet deposition (or rate) at a point in terms of the total rainfall (or the rainfall rate) at the same point. Variation of rainfall (or rate) in time and/or space will be reflected in variations of washout coefficient in time and/or space, and equivalent variations of deposition (or deposition rate) over the region of interest.

The fraction of the original material remaining in the plume as a result of wet deposition (F_w) is given by

$$F_w = \exp(-\Lambda\, t) \qquad 5$$

This equation is generally applied to rain falling at a constant rate throughout the period taken by the plume to travel from the source to the point of interest. In that case, t is the travel time (= x/u). However, a slightly modified version of the equation can be used with rainfall rates which vary over the time or distance of interest, by summing over periods in which the rainfall rate is constant, when it can be expressed as

$$F_w = \exp(-\Sigma\Lambda_i t_i) \qquad 6$$

or

$$F_w = \exp(-\Sigma\Lambda_i x_i/u_i)$$

where the summation is over time periods or travel distances where the rainfall rate can be considered to be constant.

A4 Ratio of wet to dry deposition

The ratio of wet to dry deposition can be obtained from the equations above as

$$R_{w/d} = \Lambda\, Q\, (\sqrt{2\pi}\, u\, \sigma_y)^{-1} / [\, V_g\, Q\, (2\pi\, \sigma_y\, \sigma_z\, u)^{-1} \exp(-h^2/2\sigma_z^2)\,]$$

or

$$R_{w/d} = \Lambda\, (\sqrt{2\pi}\, \sigma_z) / [\, V_g \exp(-h^2/2\sigma_z^2)\,] \qquad 7$$

This shows that the ratio of wet to dry deposition, for the same rainfall rate, depends on the vertical extent of the plume at the point of interest, and so varies over the region likely to be contaminated after an accident. We must therefore assume values for σ_z, h, Λ (or a and b) and V_g in order to determine the relative importance of the two deposition processes.

In most cases of interest, material will be released from a point on or very close to the reactor building, at a height of a few tens of metres. In those atmospheric conditions where rain is most likely and for the distances of interest, $\sqrt{2\pi}\, \sigma_z$ could lie between about 100 m and 1000 m (at 900 m and 40 km respectively from a point source in category D). Air flow around and over the reactor building will act to bring part of the plume material nearer to the ground and to enhance the vertical extent of the plume.

Therefore $h^2/2\sigma_z^2 << 1$

$$\exp(-h^2/2\sigma_z^2) \sim 1$$

and $R_{w/d} = \Lambda\, (\sqrt{2\pi}\, \sigma_z) / V_g$ 8

at most distances of interest.

The rainfall rates to give selected ratios of wet to dry deposition rates are given by

$$R = [V_g\, R_{w/d} / (a\, \sqrt{2\pi}\, \sigma_z)]^{1/b} \qquad 9$$

Two spreadsheets have been written to provide tabulations of results from equations 5, 8 and 9 for different values of the various parameters involved. The results show the following:

a About 90% of the released material is deposited within 100 km of the source if the washout coefficient is 10^{-4} s^{-1}.

b About 90% of the released material is deposited within 10 km of the source if the washout coefficient is 10^{-3} s^{-1}.

c Wet deposition is likely to be much greater than dry deposition for aerosols. The conditions where dry and wet deposition are comparable correspond to very light rain or washout coefficient in the lower part of its plausible range.

d Wet deposition is a few times greater than dry deposition for elemental iodine other than for situations where the washout coefficient is in the lower part of its plausible range and the rain is light. There are plausible sets of values for which dry deposition is greater than wet deposition.

APPENDIX B

Wet Deposition and Interception

B1 Introduction

Estimates of the amounts of radioactive material to be found on soil and vegetation following an accidental release to the atmosphere in wet weather will improve if rainfall information can be assimilated effectively. If, in addition to rainfall estimates, measurements of radioactivity are available it is likely that a more complete and robust assessment can be made. Models predict the total amount of material deposited at a point, while measurements would normally give the amount deposited on vegetation on the surface. Therefore, if measurements are to be combined with estimates of enhanced deposition due to rain it is important to be able relate measurements in different media made under different conditions to the estimates. In particular the relative amounts deposited to a surface or crop canopy compared to the ground will differ in wet and dry conditions. If the difference in deposition and interception can be quantified, then measurements made in an area where it rained during the passage of the radioactive plume can be related to others in areas where it remained dry and *vice versa*. This information may be used to improve predictions of both the levels of deposition and the amount on or taken up by plants in each location. This latter point is of particular interest in that the same level of total deposition may result in food contaminated below the level at which restrictions are required in dry conditions but above the threshold in wet conditions, for the same release, stability category and wind speed.

The amount of material lost from a plume due to rain has been considered by Underwood (2000) in his review of dry and wet deposition. However, this review does not consider the partitioning of this material between soil and plant, which may be relevant to any consideration of where monitoring resources should be directed or where countermeasures should be introduced after an accident. One of the potential advantages offered by assimilation procedures is that they will be able to identify areas of risk where further monitoring or countermeasures need to be implemented. If there is an understanding of how radioactive deposition is partitioned under conditions of non-uniform rainfall then this can influence the assessed risk.

B2 Wet deposition and interception

Most environmental models assume 20 - 25 % of the activity in wet deposition will be intercepted and initially retained by the edible portions of pasture vegetation (Hoffman *et al.*, 1992). However, as found by Hoffman *et al* (1992), this assumption stems from experiments with unrealistic rainfall simulations. In addition, the experiments undertaken did not fully account for other important parameters such as the plant species, stage of plant development, amount of rainfall or the ability of the radioactive element to be fixed to the leaf (Muller and Prohl, 1988).

Current research has shown that the total amount of rainfall is generally more important than the rainfall intensity in determining both the total amount of deposition and how it is finally shared between the ground and the plant. For example, little difference could be identified between rainfalls of differing intensities, for simulated rain of the same droplet size distribution (Hoffman *et al*., 1992; Kinnersley *et al*., 1997a)[*]. The distribution of activity between the plant and the ground could also be affected by "clean" rain falling before or after the passage of the plume. Kinnersley *et al.* (1997a) found that contamination levels for wheat and beans increased, as total rainfall and corresponding surface water storage increased. However, once the maximum surface storage capacity had been reached, further precipitation would run off the plant surface. This concurs with observations of ^{131}I interception and initial retention on pasture plants by Hoffman *et al.* (1992). They found that for simulated convective storms the interception fraction was an inverse function of the total rainfall amount i.e. as the rainfall amount increased beyond the storage capacity the interception fraction decreased. Furthermore, if the interception fraction was normalised to account for the biomass of the pasture plants then the mass interception factor for ^{131}I was found to depend almost exclusively on the amount of rain[†]. However, both Hoffman *et al.* (1992) and Kinnersley *et al.* (1997a) found the situation was more complicated when cations were involved.

B2.1 Radionuclide dependence

Following the Chernobyl accident, the highest radionuclide depositions in the UK were found in areas where the passage of the plume coincided with heavy rainfall. However, the proportion of contaminant intercepted depended on the radionuclide e.g. ^{137}Cs interception was much higher in areas of wet deposition than dry whereas interception of ^{131}I was comparable under the two conditions (Clark and Smith, 1988). Furthermore, different chemical species of the same radionuclide may also behave differently during dry and wet deposition e.g. elemental, organic and particulate iodine radionuclides (Kohler *et al.*, 1991).

Several investigators have suggested that the valence of the radionuclide is an important factor in determining the initial amount retained after wet deposition. This is thought to be a consequence of the negative charge on leaf surfaces. The interception factors for cations have been found to be approximately 3 - 5 times greater than those for anions (Prohl *et al.*, 1995). In addition, experimental

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[*] As indicated in Section 3.3.2 under natural rainfall conditions the droplet size distribution will change with rainfall intensity.

[†] Differences in vegetation type were statistically significant but it was not a major controlling variable.

results by Hoffman *et al.* (1992) and Kinnersley *et al.* (1997a) suggest that cations are adsorbed by the leaf surface.

Kinnersley *et al.* (1997a) showed that levels of caesium contamination increased rapidly before reaching a plateau after which further increases occurred only slowly with time. This is consistent with the idea of the leaf surface being negatively charged. Thus, the specific activity of the leaf surface continued to increase after the surface water storage capacity had been reached. The slow increase in caesium adsorbed on to leaf surfaces (i.e. that retained after washing) was dependent on the time the leaf was exposed to the surface solution and the concentration of the solution on the surface. It was shown to follow a power-law where the exponent controlling the accumulation of adsorbed caesium approximately doubled for each order of magnitude increase in the concentration of the solution. The influence of the charge state on the behaviour of cations has been taken further by Prohl *et al.* (1995) who concluded that bivalent cations are adsorbed more strongly than monovalent cations.

B2.2 Vegetation

Hoffman *et al.* (1995) compared the interception and initial retention of several radionuclides (^{109}Cd, ^{7}Be, ^{51}Cr, ^{85}Sr, ^{35}S and ^{131}I) on several kinds of vegetation, including a conifer, a broad-leafed tree and several herbaceous species. It was found that there was a greater range in mean retention values among radionuclide types than among plant species, indicating that the type of radionuclide is likely to be of more significance in determining retention than the type of vegetation.

Kinnersley *et al.* (1997a) also showed contamination levels correlated well with leaf area. The leaf area index[*] may be estimated from the herbage density (Muller and Prohl, 1988). However, it should be remembered that during the first part of the growing period the exposed leaf area increases in proportion to the standing biomass whereas during the second part of the growing period the biomass still increases whilst the leaf area begins to decrease (Prohl *et al.*, 1995).

B2.3 Summary of interception of wet deposited material

The factors influencing interception and initial retention have been divided into two components (mechanical and chemical) by Kinnersley *et al.* (1997a). The mechanical component is defined by the water storage capacity of a plant, where;

mechanical component = volume of retained water x *concentration of contaminant.*

Wind effects may reduce the water storage capacity.

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[*] The leaf area index (LAI) is the ratio of the leaf area to the ground area below the plant.

The chemical component is a function of the contaminant concentration in water, the length of time of exposure to the solution and the valence (i.e. affinity to the plant's surface) of the contaminant. Kinnersley *et al.* (1997a) demonstrated that caesium accumulation at a plant surface could be modelled by a simple power law where the exponent controlling the accumulation rate was determined by the concentration of the solution.

The important observation from the above review is that the amount of radioactivity expected on vegetation in wet conditions can saturate as the storage capacity of the leaves is exceeded. If the rain continues after the plume has passed radioactivity may be lost from the plant into the soil. This behaviour cannot be represented by the conventional washout coefficient approach used in simple atmospheric dispersion models but will require an additional step to partition the total deposition appropriately by integrating over the rainfall history from the start of the release.

B3 Dry deposition and interception by crops

To complete the discussion it is appropriate to briefly mention dry deposition and interception. A much fuller discussion of dry deposition is given by Underwood (2000). As a mechanism dry deposition is generally less effective at removing material from a passing plume than wet deposition and results in a different partitioning between material intercepted by plants and depositing onto the soil. There are two general approaches to modelling dry deposition and interception in the literature. Both approaches use the dry deposition velocity (the ratio of surface flux to air concentration) to quantify dry deposition and each are based on the time-integrated air concentration using a deposition velocity that depends on the plant type. The mechanisms for dry deposition vary between two extremes, the direct sedimentation (deposition as a result of gravity) of large particles (>100 µm diameter) and Brownian diffusion of very small particles (<0.1 µm). Air movements affect intermediate particle sizes, i.e. those no longer in the sedimentation-dominated regime, and their deposition rate is larger than would be expected from just sedimentation for a particle of that size. This is because of the additional processes of interception and impaction with the canopy. Thus the deposition rate also becomes dependent on mean and fluctuating wind velocities and the effectiveness of the canopy structure (e.g. leaf distribution, shape) at removing particles from the air stream. For yet smaller particles the elevation of the deposition velocity above that predicted by sedimentation alone decreases, as the effectiveness of the canopy at removing particles becomes less. A minimum deposition velocity typically occurs between 1.0 and 0.1 µm diameter before it increases again as a result of increasing Brownian diffusion. This results in a characteristic U-shaped curve for deposition velocity with respect to particle diameter (Kinnersley *et al.*, 1997b).

Interception describes the partitioning of all the material deposited from the plume between the vegetation and the underlying ground surface. The deposition velocities discussed above are for the entire canopy, including the ground cover and the underlying surface. Thus an interception fraction must be used to estimate the proportion of total deposition which directly contaminates the vegetation. The simplest approach is probably that taken by Kinnersley *et al.* (1997b) who propose that a fixed value of 0.74 ± 0.32, represents a best estimate based on experimental results for a large range of crops, including wheat at several stages of development.

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APPENDIX C

Radar and Rainfall

C1 Introduction

The complex task of calibrating raw radar rain data in the UK, is carried out by the Meteorological Office (MO) and will not generally form a part of the process of assimilating information on radioactive deposition. The MO provides processed results from its Nimrod radar network that have been corrected to provide rainfall estimates directly (Harrison et al 2000). However, it is appropriate to understand some of the factors that need to be considered and the accuracy of the estimates produced. It is important to recognise that radar provides rainfall estimates and not a direct measure of rainfall. If possible, error bounds on the estimated rainfall should be considered when using the data to assimilate radioactive deposition estimates, noting particularly that the error is likely to change with location.

Harrison et al (2000) list some of the problems related to the use of radar. For example, Harrison et al (2000) state that stable modern hardware is likely to introduce an estimation error in the precipitation rate that is within 36%. However, as some parts of the UK network are up to 20 years old, the error introduced by hardware is likely to be significantly larger. A number of problems are also created by geography. At their simplest, these involve missing some or all of the precipitation due to the elevation angle of the radar and the curvature of the earth. More complex factors that affect a radar signal, are ground clutter and anomalous propagation*. The former is generally largely resolved through the use of a map of known ground clutter locations except under conditions of anomalous propagation. As well as stray reflections obstacles also cause problems by attenuating the power of the radar beam beyond the obstacle. Rain itself attenuates the beam sufficiently that in the case of heavy rain the entire signal may be lost.

C1.1 Rain drop size distribution

The relationship between the measured radar reflectivity (Z) and the precipitation rate (R) depends on the raindrop size distribution. The reflectivity and precipitation rate are each independently complex functions of the particle

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* Changes in the refractive index of the atmosphere of only a few parts per million can effect on the propagation of microwaves. The refractive index of the atmosphere is a function of temperature, pressure and water vapour, hence as atmospheric conditions change so does the way in which the waves propagate (the radar equivalent of an optical mirage).

diameter and consequently the distribution of raindrop sizes. Z is proportional to the sixth power of the particle diameter and the rainfall rate is determined by the distribution of raindrop volume with due account being taken of terminal velocities and the minimum drop size to reach the ground before evaporating. The drop size distribution is often represented by an exponential distribution commonly referred to in the literature as a Marshall-Palmer distribution function. However, other distributions such as gamma and lognormal are used. For example, it has recently been observed by Zawadzki et al (1994) that the Marshall-Palmer distribution of raindrop size at low rain rates is not valid for warm rain but is consistent with melting snowfall. Sempere-Torres et al (1994) have shown that all the various forms of drop size distribution can be written in terms of the general formulation shown in Equation 4

$$N(D,R)=R^{\alpha}\, g(DR^{-\beta}) \qquad (4)$$

where N(D,R) is the number of drops per unit of air volume in the size range D to $D+\Delta D$, α and β are constants and g is a function independent of R. The self consistency requirement that the rain rate derived from (4) should be equal to R together with an assumed relationship between terminal velocity and particle diameter implies that $\alpha = 1-4.67\beta$. Sempere-Torres et al found that their results were well represented if g was proportional to a simple exponential function.

The relationship between Z and R is generally represented by an empirical relationship of the form $Z=AR^{b}$ as proposed by Marshall and Palmer (1948) where A and b depend on the type of precipitation occurring. The multiplicative factor A may range from a few tens to several hundreds (Battan 1973) while the power factor b is limited to $1 \leq b \leq 3$ (Smith and Krajewski 1993) with typical values ranging between b=1.2 and b=1.8. In the particular case of the UK Nimrod system A and b are assumed to have fixed values (A =200 and b=1.6) applicable to stratiform rain (Marshall et al 1955). Raindrop growth in a stratiform cloud is slow, so its rain consists of small drops. Convective rainfall on the other hand is heavier and the drops are larger. Convective rainfall is also characterised by sharper spatial and temporal intensity gradients (high summer downpours). Radar reflectivity can be used to diagnostically separate areas of convective and stratiform precipitation (Steiner and Houze 1997) which is clearly important considering the different Z R relationships applicable. For example, Salles et al (1999) found convective storms in Marseille to have a reflectivity rainfall relationship of the form $Z=528R^{1.42}$ while stratiform events were characterised by $Z=216R^{1.6}$.

C1.2 General weather effects

The radar reflectivity is also affected by precipitation growth, evaporation, melting of ice and snowflakes and wind shear. Changes in reflectivity are particularly pronounced when melting occurs producing a phenomenon called bright band in the reflectivity signal. If uncorrected this can produce an error up to a factor of 5. Orographic enhancement can also cause problems as rain falls through low level cloud or fog to increase deposition (Hill et al 1981).

Harrison et al (2000) report comparisons of the effectiveness of the corrections applied to the Nimrod data to account for the above phenomena. Generally, these corrections reduce the errors in the predicted precipitation. However, case studies show that the rainfall rate in convective storms can be underestimated by a factor of 2. However, it maybe expected to be less than this value under the most common rainfall conditions. Notwithstanding the likelihood of improved performance, within the context of predicting radioactive deposition from a dispersing plume, a factor of 2 error in the rainfall estimate is likely to be a relatively small component of the overall error expected in estimating the amount of radioactivity deposited.

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