ISSN 1018-5593

Commission of the European Communities

radiation protection

Radiological aspects of nuclear accident scenarios

Volume 1
Real-time emergency response systems
Post-Chernobyl action

Report

EUR 12552/1 EN

Commission of the European Communities

radiation protection

Radiological aspects of nuclear accident scenarios

Volume 1
Real-time emergency response systems
Post-Chernobyl action

Edited by:

J. Sinnaeve

Commission of the European Communities
200, rue de la Loi
B-1049 Brussels

Final report

Directorate-General
Science, Research and Development

1991

EUR 12552/1 EN

Published by the
COMMISSION OF THE EUROPEAN COMMUNITIES
Directorate-General
Telecommunications, Information Industries and Innovation
L-2920 Luxembourg

ISBN 92-826-2937-6 (Volumes 1 + 2)

Cataloguing data can be found at the end of this publication

Luxembourg: Office for Official Publications of the European Communities, 1991

ISBN 92-826-2938-4 Catalogue number: CD-NA-12552-EN-C

Printed in Belgium

Preface

The Chernobyl accident, which occurred on 26 April 1986, presented major challenges to the European Community with respect to the practical and regulatory aspects of radiation protection, public information, trade, particularly in food, and international politics. The Chernobyl accident was also a major challenge to the international scientific community which had to evaluate rapidly the radiological consequences of the accident and advise on the introduction of any countermeasures. Prior to the accident at Chernobyl, countermeasures to reduce the consequences of radioactive contamination had been conceived largely in the context of relatively small accidental releases and for application over relatively small areas. Less consideration had been given to the practical implications of applying such measures in case of a large source term and a spread over a very large area.

The Radiation Protection Research and Training Programme was influential in a number of important initiatives taken within the Community immediately after the accident. Information was collected by Community scientists and, from it, an assessment made within days of the possible consequences. This showed that the health impact on the population of the European Community was not expected to be significant. About four weeks after the accident, the Programme, together with the US Department of Energy, organised a meeting in Brussels during which the data on dispersion of radioactive material were discussed and evaluated. Several other meetings followed soon after on the transfer of radionuclides in the food chain and possible health effects. These meetings were carried out in close co-operation with the DG XI (Directorate General, Environment, Consumer Protection and Nuclear Safety) within the CEC, and, externally, with international organisations such as the International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO). In addition, the Commission convoked a Committee of high-level independent scientists to assess the scientific evidence from current research in view of recent nuclear incidences, to consider the possible implications for the Basic Standards and emergency reference levels and to advise the Commission on future action in radiological protection including research. (EUR 11449 EN).

Soon after the accident, additional research requirements were identified by the Programme; these were mainly better methods to assess accident consequences and

the further improvement of off-site accident management. Several existing contracts were reoriented and new contracts were placed; however, the financial means then available within the Programme were insufficient to fund the additional research identified as necessary. A proposal for a revision of the Programme was, therefore, elaborated in 1986. It comprised 10 specific "post-Chernobyl" research actions. This revision, with an additional budget of 10 MEcu for a period of two years, was adopted by the Council of Ministers on 21 December 1987. With the help of the Management and Coordination Advisory Committee (CGC) "Radiation Protection" a number of institutes was identified to carry out the research in a co-operative manner, and the research began in the spring of 1988.

These post-Chernobyl activities have now been completed. Detailed reports on each of these studies and an additional volume containing the executive summaries of all reports are now available.

- Evaluation of data on the transfer of radionuclides in the food chain,
- Improvement of reliable long-distance atmospheric transport models,
- Radiological aspects of nuclear accident scenarios,
  A. Real-time emergency response systems,
  B. The RADE-AID system,
- Monitoring and surveillance in accident situations,
- Underlying data for derived emergency reference levels,
- Improvement of practical countermeasures against nuclear contamination in the agricultural environment,
- Improvement of practical countermeasures against nuclear contamination in the urban environment,
- Improvement of practical countermeasures: preventive medication,
- Treatment and biological dosimetry of exposed persons,
- Feasibility of studies on health effects due to the reactor accident at Chernobyl.

The research undertaken within the "post-Chernobyl" actions has added considerably to the understanding of the basic underlying mechanisms of the transfer of radionuclides in the environment, of the treatment of accident victims and of how the environmental consequences of accidents may be mitigated. In addition, progress has been made in the setting up environmental surveillance programmes development of predictive and decision-aiding techniques, the implementation of

which will lead to significant improvements in off-site accident management. Several new ideas and lines of theoretical and practical research have originated from the post-Chernobyl research and these have already been integrated into the ongoing Community Radiation Protection Research Programme. A further important feature which should not be overlooked, is the close and effective collaboration of many institutes in the research; this has markedly strengthened the ties between Community institutes and scientists. The outcome of all of this work is that the Community and all other countries are now better prepared and co-ordinated should a significant release of radioactivity ever occur again

Further research is continuing within the current Radiation Protection Research and Training Programme 1990-1991 on a number of the "post-Chernobyl" topics; these also form part of the proposal of the specific Programme on "Nuclear Fission Safety" 1992-1993, e.g. real-time emergency management systems, development of countermeasures in the agricultural environment, treatment of radiation accident victims, etc. Moreover, the Community Programme is currently making a significant contribution to an international evaluation, being undertaken by IAEA at the request of the Soviet Government, on the consequences in the USSR of the Chernobyl accident and of the measures being taken to ensure safe living conditions for the affected populations.

S. Finzi
Director DG XII.D
Nuclear Safety Research

G.B. Gerber
Head of Unit DG XII.D.3
Radiation Protection Research

E. Bennett
Director DG XI.A
Nuclear Safety, Industry and Environment, Civil Protection

A) Real-Time Emergency Response Systems

Participating Institutions

Comitato Nazionale per la ricerca e per lo sviluppo dell'Energia Nucleare e delle Energie Alternative, Direzione Sicurezza Nucleare e Protezione Sanitaria (ENEA-DISP)
1044 Rome, Italy

R. Caracciolo, F. Desiato, M. Masone,

Commissariat à l'Energie Atomique, Institut de Protection et Sûreté Nucléaire, Centre d'Etudes Nucléaires de Fontenay-aux-Roses (CEA-IPSN)
92265 Fontenay-aux-Roses, France

N. Parmentier, D. Robeau,

Imperial College of Science, Technology and Medicine, Mechanical Engineering Department (ICSTM)
SW7 2BX London, United Kingdom

H.M. ApSimon, B.M. Barker, J.N. Wilson,

Gesellschaft fur Strahlen- und Umweltforschung, Institut fur Strahlenschutz (GSF)
8042 Neuherberg, Federal Republic of Germany

H. Müller, G.Pröhl, H.G. Paretzke.

CONTENTS

EXECUTIVE SUMMARY

As part of the post-Chernobyl programme, the need was recognised for improved capabilities for the real-time assessment of accident consequences and emergency response procedures. Whereas such emergency response capabilities had hitherto concentrated on smaller accidental releases characteristic of design basis accidents, it was recognised as important to cater for a wider spectrum of accident scenarios, including those with potential consequences on a European scale. In particular, those responsible for decision making and the introduction of countermeasures would require computer-based support systems. This project (post-Chernobyl activity 4a) has therefore worked towards the provision of key components of real-time computerised support systems, embodied in software packages to be made generally available for use in European Community countries.

These software packages include numerical models suitable for the simulation of the atmospheric transport, dispersal and deposition of a release over local (out to a few tens of kilometres at most), mesoscale (out to 100 to 200 kilometres), and long range distances (over the whole of Europe). To aid in accidents where there are large uncertainties about the source term, packages have been developed addressing the deduction of estimates of the quantities of radionuclides released, by combining measurements and model simulations and optimising the agreement between them. Finally, as a tool to aid in the assessment of doses and the efficacy of possible countermeasures, a special package has been produced for dose assessment taking into account different exposure pathways.

The context in which these various components of a real-time support system may be used will vary in different European Community countries according to the particular arrangements for nuclear accidents and emergencies, and the division of responsibility at local, regional and national levels. A generalised scheme is illustrated in figure 1, showing how the components may be linked to each other and to the relevant control centres.

In order to be able to fulfil their assessment and decision-making roles, these centres will also require access to information about the source and available radiological measurements, together with agricultural production, demographic and other relevant data prepared for such eventualities. This information is also required by the computer codes developed in this project, plus additional data, such as meteorological windfields for the atmospheric dispersion models.

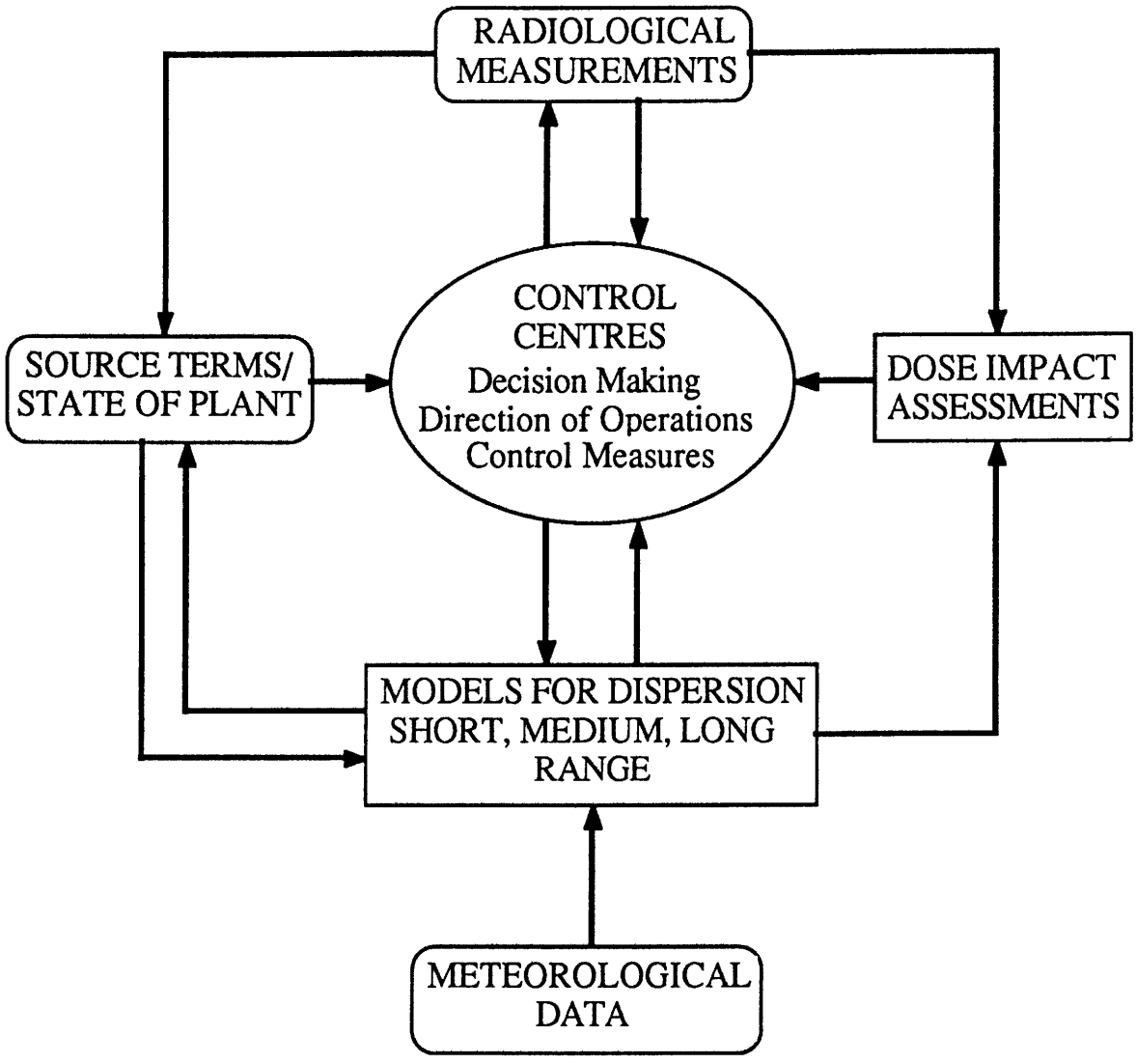

Figure 1. Generalised scheme for the structure of a real-time emergency response system.

The work has been undertaken in collaboration by four institutions:

- Comitato Nazionale per la ricerca e per lo sviluppo dell'Energia Nucleare e delle Energie Alternative, Direzione Sicurezza Nucleare e Protezione Sanitaria, Rome, Italy, who were responsible for short-range atmospheric dispersion modelling and source term assessments.

- Commissariat a l'Energie Atomique, Institut de Protection et Sûréte Nucléaire, Centre d'etudes Nucléaires de Fontenay-aux-Roses, France, who were responsible for mesoscale atmospheric dispersion modelling and source term assessments.

- Imperial College of Science, Technology and Medicine, Mechanical Engineering Department, London, UK, who were responsible for the long-range atmospheric dispersion and transport modelling.

- Gesellschaft für Strahlen- und Umweltforschung, Institut für Strahlenschutz, Neuherberg, W. Germany, who were responsible for the dose assessment modelling.

From the outset, the software packages have been developed to be compatible with each other and to take account of the information flows required between them, as well as the needs of the assessment teams and decision makers. However, each package can also be used as a stand-alone module if required; for example the short-range model might be used at a local emergency centre close to a site. To make optimum use of the modules within an overall computerised real-time support system, high quality graphics packages to produce appropriate displays and maps will also be required. However, such packages will inevitably need to be individually tailored to the different requirements of different users.

Short-Range Atmospheric Dispersion

The objective of the short-range dispersion model in the real time emergency response system is to provide a rapid evaluation for areas close to the site of the accident in relatively simple meteorological and terrain conditions. The model thus needs to be fast, and therefore relatively straightforward, and it also needs to be able to derive the necessary model parameters from few, simple input data, while at the same time maintaining flexibility with respect to the type of input data which could be available. Furthermore, the model should be suitable for use on a relatively small computer.

In order to satisfy the above criteria, a Gaussian puff model, SPADE (Sequential Puff for Atmospheric Dispersion Evaluation) has been developed. SPADE has been designed to estimate ground level air concentrations, deposition and cloud γ dose rate in flat or gently rolling terrain resulting from the dispersion of either stable or first-order decaying (e.g. radioactive) atmospheric pollutants. It is best suited for evaluation of plume behaviour out to about 20 km from the source. Model results beyond 20 km should be used with caution to 50 km, and as a screening tool for distances beyond 50 km.

The dispersing plume is simulated by a sequence of Gaussian puffs whose trajectories are determined from a single wind profile. Meteorological and source data are allowed to vary

with time and the time interval between successive sets of data is flexible. The other major features of SPADE are :

i) Atmospheric stability and dispersion parameters may be derived by different methods based on the available measurements and the site characteristics.

ii) Plume rise and buoyancy-induced dispersion are simulated.

iii) Total or partial reflection from the mixing layer top is considered.

iv) Puff number is controlled by merging adjacent puffs and deleting those away from the calculation domain.

v) The point source can be located anywhere inside the domain to optimize the extent of the useful calculation area in case of a prevailing wind direction.

vi) Dry and wet deposition as well as puff depletion are modelled.

vii) An optional cloud γ dose model is incorporated in SPADE.

SPADE requires a set of time-independent data, like geographical data (domain size and coordinates), source characteristics (time of release start, pollutant species, deposition velocities), code parameters (duration of time step, times of required output analysis) and several sets of time-varying meteorological and release rate data. The required meteorological data are principally wind speed and directions, mixing layer height, rain intensity, and additional data for the estimation of atmospheric turbulence (cloud cover, or wind direction fluctuation, or solar radiation).

SPADE calculates instantaneous and time-integrated air concentration, total deposition and wet deposition values on a 20 x 20 grid and at a maximum of 100 receptors located anywhere inside the calculation domain. The size of the grid interval is given as an input data. The ground is assumed to be level, so no topographical data are required. The output analyses can be generated any time after the beginning of the release. The absorbed dose rate in air from a γ-emitting plume can be calculated by SPADE, as an option. However, it should be done only for a limited number of receptor points due to the much longer time the code takes to calculate the γ doses compared to the dispersion calculations.

As far as the limitations of SPADE are concerned, it must be emphasised that the current version uses only one set of meteorological data at a time and so does not allow atmospheric parameters and wind field to vary spatially. Thus, it should not be applied to complex terrain or meteorological situations. Additionally, gravitational settling is not treated by the model.

Mesoscale Atmospheric Dispersion

The mesoscale atmospheric dispersion code MC31 has been developed to calculate atmospheric dispersion and deposition out to 100 to 200 kilometres from the source. Over such distances, it is necessary to allow for such complicating factors as complex terrain, urban areas, coastal regions and spatially and temporally varying meteorological conditions. To allow for such factors in simulating atmospheric dispersion, a Lagrangian approach has been adopted as the basis for the code MC31, which like the Monte Carlo methods used by Imperial College for the long range model, treats the release as an assembly of particles tracked forwards in space and time, but is more in the nature of a stochastic model. The methods are based on work performed in the Soviet Union (Khintchine, Guikman, Skorokhod, Kolmogorov et al.) and Japan (Ito). The model gives the spatial distribution of a radionuclide at specified times and accumulated deposition.

To apply the model, it is necessary to specify windfields and turbulence over a regular rectangular three dimensional grid of cells, updated at regular intervals. Within this fixed grid, each particle is followed in a series of time steps. In each time step, the particle is moved in such a way as to represent advection with the wind plus a turbulent displacement, which is prescribed statistically. By considering a large number of particles, the distributions of radionuclide air concentrations over space and time corresponding to a release in the specified windfield and turbulence conditions are well represented.

The novel aspect of the model lies in the way in which the displacement of the particles is treated. Thus the forward motion of a particle is considered in the context of a moving box aligned along the mean wind direction local to the particle. The size of the box depends upon the windspeed and turbulence and the length of the time step: the larger the timestep the larger the box, subject to the constraint that the box must be entirely within a single rectangular windfield grid cell, inside which the windfield and turbulence are constant. Additional constraints may further reduce the timestep, for example, to ensure that it does not extend beyond the specified times at which the meteorological conditions are updated, or at which results giving air concentrations corresponding to the instantaneous spatial distributions of particles are required.

The maximum length of the timestep and the dimensions of the box having been established, the next step is to consider the probabilities of the particle taking the various exit routes from the box during the time interval. More specifically, the particle may either be displaced to one of the corners of the box or it may remain at the centre, equivalent to it being advected

by the mean wind velocity alone. The probabilites of these different results/destinations are calculated as functions of the box dimensions, time interval and turbulence components. The particle is then randomly assigned to one of these positions, according to their relative probabilities.

A similar statistical approach is taken in the representation of dry and wet deposition processes in the model. During each time interval, the probability that a particle is deposited by dry deposition is determined, according to the specified dry deposition velocity. Similarly, the probability that a particle is deposited in precipitation is deduced according to the prescribed washout parameter, and the occurrence and intensity of the precipitation. The flexibility of this approach allows a variable scavenging efficiency to be attributed to the precipitation according to the height of the particle. According to the probabilities of deposition, either the particle is removed to the ground and not considered further in the simulation, or it continues airborne into the next time interval. Radioactive decay is treated in a similar fashion.

The method is thus an economical and computationally efficient approach to simulating the atmospheric dispersion of a radionuclide in non-homogeneous conditions over complex terrain. However, it does require considerable additional computing resources in comparison with the short-range model SPADE. MC31 requires as input the source as a function of time, together with the relevant nuclide characteristics. Also, as is the case with the long-range model, 3-DRAW, MC31 requires externally generated three dimensional windfields and precipitation fields to be specified over the model domain and it additionally requires turbulence fields to be similarly specified. These data can be obtained from a mesoscale forecasting model such as that operated by the French Meteorological Service.

The accuracy of the model depends on the numerical techniques used and the representativeness of the data supplied. The accuracy of the numerical technique is readily controlled by the number of particles considered (varying as $\sqrt{n}$). Thus the limiting factor is likely to be the accuracy of the meteorological data. In contrast to 3-DRAW, the simulation is restricted to consideration of nuclides characterised by a single decay constant in any one computer run.

Long-Range Atmospheric Dispersion

The program 3-DRAW has been developed to model long range atmospheric transport and dispersion in real-time and predictive modes, using output from a meteorological forecasting model. In the design of 3-DRAW, several objectives were identified. The model should be capable of identifying those regions which are likely to be contaminated following an accidental release, and also give an indication of the scale of any such contamination. In identifying the likely scale and extent of contamination following an accident, the model should only utilise standard output from a meteorological forecasting model. The model was also to be compatible with the short-range and mesoscale models also under development. In addition, the model was required to calculate quantities which correspond to those observed in the field, and also the inputs to a dose response module, that is, atmospheric concentrations integrated over sequential periods and accumulated wet deposition. Lastly, the model should be capable of considering those nuclides which could give rise to significant consequences over long distances from an accident site.

The 3-DRAW model is a 3-dimensional random walk or Monte Carlo model, which differs substantially from the mesoscale model MC31. It is capable of simulating atmospheric dispersion and transport on a continental, or hemispherical scale, according to the meteorological forecasting model output used. A release is represented by a sequence of particles, which are advected through a windfield specified by the forecasting model, with random turbulent displacements from the mean flow. 3-DRAW can treat a number of different radionuclides simultaneously. Each particle represents a given activity of each nuclide under consideration, according to the magnitude of the release. Depletion processes (radioactive decay, and dry and wet deposition, according to the radionuclide) can then be modelled by depleting these activities, while still tracking all the particles released.

This method involves the release of fewer particles than are required when particle numbers themselves are depleted. The direct calculation of atmospheric concentrations, as described below, on a grid of cells at ground level according to the length of time taken by the particle in traversing the grid cell and the nuclide activities represented by the particle, further reduces the number of particles, and thus the computing resources needed. The Monte Carlo technique also has the advantage that the results can be interpreted as an indication of the probability of a particular area being exposed as well as giving an indication of the probable magnitude of exposures. In addition, it is comparatively straightforward to distinguish the contributions to exposures from different sections of an extended release, numerical diffusion is not a problem, and the technique is also ideally suited to parallel processing.

Horizontal winds are linearly interpolated in time and space, in the upper layers of the atmosphere, while a logarithmic wind profile is fitted between the ground and the lowest forecast wind level. Vertical winds are interpolated in time and height only, as they are normally specified as mean values over the forecast model grid elements. Superimposed on the windfield is a dynamic boundary mixing layer, which varies diurnally in height according to the underlying surface and whether or not it is raining. As a default option, the diurnal mixing layer profile is currently specified externally according to latitude and time of year. Within the mixing layer, horizontal turbulent displacements are derived as a function of wind shear across the mixing layer, while vertical turbulent displacements are represented by the random reassignment of the particle height after each timestep. Above the mixing layer wind flow is assumed to be laminar, vertical turbulent displacement is ignored and horizontal turbulent displacement is assumed equivalent to that in stable air.

Exposures are accumulated on a grid which is specified independently of the forecasting model, as a function of the time spent by individual particles over each grid cell. Thus time-integrated air concentrations and total dry and wet deposition are determined rather than instantaneous air concentrations and deposition rates. Particles only contribute to the mean time-integrated air concentration for an exposure grid cell when they are within the mixing layer above the cell. Particles above the mixing layer do not contribute to the surface air concentration, and neither are they depleted by dry deposition, which is also restricted to particles in the mixing layer. Dry deposition is modelled by applying a nuclide-specific deposition velocity over the depth of the mixing layer.

The distinction between dynamic (or frontal) precipitation and convective precipitation which is normally made in forecasting models is usefully preserved in the modelling of wet deposition. Dynamic precipitation can reasonably be assumed to be uniform over the forecasting model grid and to deplete particles at all heights, with the removal of activity modelled by a washout coefficient. Convective precipitation on the other hand is non-uniform over the model grid cells, and is treated statistically in recognition of this, with particles either missing a convective cell, or entering either a low or a high rainfall area within the cell. Also only particles within the mixing layer are assumed to be depleted by convective rainfall. The extent of the areas of low and high rainfall and the rainfall rates within them are derived from the mean convective precipitation rate in the model cell. The depletion of the activity associated with particles in such systems is modelled by a washout coefficient.

3-DRAW produces mean time-integrated air concentrations, dry and wet deposition, and rainfall encountered by the release, on an exposure grid, for successive 6 hour and 24 hour periods, as well as over the entire period of the simulation. It is thus able to generate output files which may then be used as input by the dose response module. The time-integrated air concentrations may also be represented as mean air concentrations over successive 6 hour periods. In addition, particle positions every 6 and 24 hours may also be produced as output.

The most significant requirement of the 3-DRAW model is the forecast windfields and dynamic and convective precipitation fields from a forecasting model. The model is capable of operating when only horizontal windfields are supplied, as these can be pre-processed to generate mass-consistent vertical velocities. The model may be initiated either from interactive dialogue with the user, from a file of source term data which may be supplied by a source term evaluation module, or by taking a file of particle activities and positions and advecting these forwards.

A first version of 3-DRAW has been designed, developed and subjected to preliminary testing within this contract. This model inevitably has several limitations, which will require further development. The absence of a routine for the specification of the mixing layer height over the model domain is a significant limitation to the general applicability of the model. There are also several special situations which the model does not currently consider. The most important of these is the transport of a release in frontal regions, where the fixed timestep used in the model can easily result in the advection of particles through the frontal surface. The whole question of the integration of the model results with field radiological data, in order to obtain a best estimate of the pattern of exposure, has still to be addressed in any detail.

It is hoped to address these topics in future work. For example, the proposed investigations into particle transport in the vicinity of fronts will involve considering the identification of such regions from the forecasting model windfields, rainfall and available synoptic output. Then, in the light of this investigation, alternatives to the current method of linear interpolation of the windfield and advection with fixed timesteps, which are more appropriate to known patterns of atmospheric motion in frontal regions, need to be identified and developed. In addition, the applicability of the 3-DRAW model to parallel processing on a transputer-based system, which would yield a substantial saving in computer time and resources required, also warrants further study.

Source Term Estimation

In the early phase of an accident the assessment of the radiological scenario is almost completely based on the modelling capabilities. The effectiveness of this kind of evaluation, however, depends on the availability of important data, like meteorological conditions and source term, that can usually be received earlier than field measurements. As the situation evolves, this last type of data becomes available and it is very important to integrate radiometric observations and model predictions with the aim of reducing uncertainties and optimizing the assessment of the accident consequences. The complexity and effectiveness of the feed-back processes depend on the quantity and quality of measured data and on the model capability. The approach can be simplified if the attention is focused on the optimization of a subset of parameters.

Modules for the estimation of the source term can be considered a specific category of feedback models and their availability becomes very important where there is a lack of or breakdown of release monitoring instruments.

In the present research program two such modules were developed: STEP and STAR. STEP is based on a few simple considerations about the uncertainty of the concentration field produced by a dispersion model and its comparison with monitoring data available in emergency situations. Thus, after running a dispersion code with unit source rate, STEP rotates the computed concentration pattern until the best correlation between observed and calculated patterns is reached. The average ratio between observed and computed values at sample points is then the estimated source term.

STEP does not depend on the particular dispersion model adopted: it can be applied in conjunction with any model, provided its output is in the form of a matrix of concentration values on a fixed eulerian grid.

The application of STEP is limited to all the cases for which the assumption that the computed concentration pattern is similar to the measured one is reasonable, i.e. it should not be applied in very complex terrain situations or wherever some crucial input parameters of the dispersion model, like the effective source height, is very uncertain, or in rapidly varying meteorological or source term conditions.

STEP has been tested in two different ways. Firstly it has been evaluated against a set of data collected during two meteo-diffusive campaigns (1983 and 1984). The results showed

that in about 90% of the episodes the emission rates have been predicted within a factor 2 and in all within a factor 3. Secondly a study was performed, simulating a release of radioactive material and varying some meteorological input data, to investigate the STEP sensitivity with respect to the uncertainty of atmospheric stability, horizontal wind fluctuation and wind direction.

The results showed that STEP performance is not very sensitive to the inaccuracy in the horizontal dispersion and the average wind direction evaluations. It is sensitive to the atmospheric stability, but the results are generally still acceptable if the correct stability category is missed by one and sometime two categories. The only critical case is that of an elevated release in stable conditions. These preliminary results of the STEP test are encouraging. The model needs to be validated against further experimental data to be applied with sufficient confidence in real emergency situations within the limitations specified above.

The STAR code adopts a more global approach to the problem than the STEP code. STAR uses air concentration and deposition measurements made in a given zone to obtain best estimates of the source term, the dispersion model transfer parameters, and the overall air concentration and deposition fields.

This kind of method is fundamentally different from those approaches that assign standard values to the environmental transfer parameters and then use them with a hypothetical source, either to work out concentration fields, or in conjunction with radiological measurements to work back to an estimate of the source term. In STAR in contrast, all or part of the set of environmental transfer parameters, as well as the source term, become unknowns within the problem, as do the values of air concentration and deposition required. Only the radiological measurements and perhaps some of the environmental transfer parameters are fixed parameters.

Thus, the measurements are used as a basis for determining the values of the source term and the environmental transfer parameters, thereby yielding the best air concentration and deposition fields that are supported by the measurements made. The above objectives are typical of optimum control problems. It is known how to construct various types of models of atmospheric transfers which are sufficiently accurate when the model parameters are known well enough. However, the parameters used in the model fluctuate a great deal or are not exactly known, and it is often only possible to specify a range of values.

In order to provide an operational solution to the problem, the method proceeds by linearizing the solution of the atmospheric transfer equation with respect to the various parameters. Then a mathematical program is defined, made up of constraints on the variation of atmospheric transfer parameters and constraints which ensure that the values given by the solution of the atmospheric transfer equation lie within a range determined by the radiological measurements. The solution of the mathematical program is a set of parameters satisfying the constraints and optimizing the so-called 'economic function'. If the constraints and economic function are linearly related to the parameters, this mathematical program is termed a 'linear program'.

The so-called 'simplex' method was chosen by CEA to solve this mathematical program, now reduced to a linear program. This method has the advantage of not being limited to a simple stage of adjustment: it enables the performance of sensitivity analyses and the implementation of processes which aid decision making. It also makes it possible to pick out the most incongruous radioactivity readings or the most inadequate parameter values. But other methods of optimization can be used to solve this kind of optimum control problem.

The linearization of the solution of the atmospheric transfer equation is a problem that can be approached more or less easily, according to the method used to resolve the equation. For example, at one extreme an exact calculation of the derivative could be replaced with a finite increments calculation. In a particular study, the calculations of the derivatives of the analytical solutions to the diffusion-convection equation obtained using the Gaussian plume resolution method can be used. In this case, derivatives of atmospheric concentration are expressed with respect to the following parameters: horizontal dispersion, vertical dispersion, discharge height, height of the mixing layer, deposition rate, washout rate, windspeed, and the source term of a given radionuclide.

The wind direction can be considered as a parameter only if a plume model is used. In this case, the best fit is calculated for a given direction. The goodness of the fit is qualified by the value of the optimized economic function. A gradient method based on the decrease of the economic function in the space of parameters identifies the best fit: the minimum of parameters including the parameter 'wind direction'.

Dose Assessment

The management of the situation after a large-scale radioactive contamination of the environment requires a fast and reliable tool for the prognosis of the radiological consequences for the population concerned. For this purpose, the dose assessment program system EURALERT has been developed.

Starting from the radioactive contamination of the near-ground air and of precipitation at up to 1 000 locations, the radiation exposure at these locations is calculated. All relevant exposure pathways are considered:

i) the external exposure from radionuclides in the air,

ii) the external exposure from radionuclides deposited on the ground,

iii) the internal exposure due to inhalation, and

iv) the internal exposure due to the ingestion of contaminated foodstuffs.

EURALERT consists of two different program modules, one which allows a fast assessment of the most important doses and contamination of foodstuffs for all locations, and one which allows a more detailed calculation of these quantities at individual locations. Together, these results give an overview about the expected doses for different age groups and the importance of the pathways considered, and give a first indication about the necessity and effectiveness of countermeasures. The spatial distribution of predicted doses identifies the areas of greatest concern. Additional programs are available for considering quantitatively the potential reduction of doses by implementing different countermeasures, for example:

i) the introduction of intervention levels for activity in foodstuffs,

ii) temporary changes in human consumption rates and feeding management for domestic animals, and

iii) recommendations to the public to stay inside buildings.

EURALERT has been developed to take into account the experience obtained with the post-Chernobyl application of the radioecological model ECOSYS. The external exposure is estimated taking into account the shielding efficiency of houses and the time spent indoors and outdoors in urban and rural areas. For the inhalation dose estimation, the filtering effect of houses can also be considered.

The food chain module of EURALERT considers seventeen plant foodstuffs and sixteen animal foodstuffs. For the calculation of the initial contamination of the plant, dry and wet deposition are modelled separately taking into account the seasonally dependent development of the plant canopies. The activity concentration in plant products at the time of harvest is estimated from the loss of activity due to weathering and physical decay, the growth dilution and the transport of radionuclides within the plant from the foliage to the edible parts.

From the activity concentration in feedstuffs, those in animal products (milk, beef, pork, eggs etc.) are calculated taking into account the kinetics of the radionuclides in the animals. The loss or enrichment of activity in plant and animal products during processing and culinary preparation is considered as well as the decay of activity during storage. The ingestion dose results from the time-dependent activity concentrations in the foodstuffs and the human consumption rates; besides mean consumption habits, those of critical groups can be applied. The dose assessment is done under the assumption that food is produced locally; it is also possible to consider it being partly imported from uncontaminated areas.

For every location at which the activity in air and precipitation is given in the input file, the respective dose to an individual at this location is calculated. If a location is representative of a certain area (i.e. if the activities in air and precipitation are mean values for this area) the resulting dose is to be regarded as a mean dose of this area and, when multiplied by the number of inhabitants of this area, yields a rough estimate of the collective dose within the area. Variations in the individual doses within an area which are due to variations in individuals' consumption habits or agricultural practices etc. can be estimated by re-running the program with different values of these parameters.

The model results are written to data files which can be printed or used for graphical output (e.g. maps of contamination or doses, graphs of time dependency of activity concentrations or doses). The software to prepare the graphics has to be provided by the user.

For every location for which the dose assessment is to be performed, EURALERT requires those quantities which control the contamination of the different plant types and the soil during the deposition event:

i) the time-integrated radionuclide concentration in the near-ground air,

ii) the nuclide-specific activity deposited by precipitation per unit area, and

iii) the amount of precipitation.

These input quantities can be predicted by the atmospheric dispersion codes developed in collaboration with this module, and their output can be directly used for the dose assessment. On the other hand, if the above quantities have been measured at certain locations it is possible to base the dose predictions on these measured values.

The external γ exposure from the radioactive cloud is dependent upon the extent of the dispersion of the cloud. At small distances from the release point, assessment of the external γ exposure from the cloud requires knowledge of the cloud geometry. Consequently the absorbed γ dose in air (Gy) has to be provided by the dispersion model. An adequate model is included in the SPADE code for the short range. At larger distances this is not necessary and EURALERT calculates absorbed γ dose in air (Gy) as well as organ doses and effective dose by assuming a semi-infinite homogeneous cloud.

The simulation of the transfer of radionuclides through food chains requires plenty of parameters describing the different processes. In addition data as e.g. the habits of people staying indoors and outdoors and the shielding of γ radiation by houses are needed for the assessment of external and inhalation exposure. Many of these parameters vary to a high degree within the different countries of the European Community. Therefore the programs have been designed to be easily adaptable to the different conditions. The program system is delivered with a data base that is representative for German conditions. All model parameters are in data files which can be edited. The selection of adequate values of all model parameters has to be done by the user who applies the model to regions with different conditions. For the future it is planned to provide default values of all model parameters for all regions of the European Community.

Further future development of the EURALERT code will address the consideration of additional foodstuffs which are of importance for some regions of the European Community, and the extension of the data base for additional radionuclides.

Summary

Software packages have been developed under a collaborative project, as five major components of a computer-based support system for use in emergency response systems in European Community countries in the event of a nuclear accident. These packages incorporate numerical models to simulate atmospheric dispersion locally, near the source (SPADE), over mesoscale distances, out to a few hundred kilometres (MC31) and on a

continental scale (3-DRAW). The models reflect the particular requirements and complexities over these different distances, within the context of a nuclear accident emergency.

In addition, attention has been given to combined interpretation of radiological measurements and model estimates, particularly in those situations where there are large uncertainties in the source term and the relative quantities of different nuclides released. The modules STEP and STAR provide alternative approaches to using available measurements and model estimates to make deductions about the source term; STAR also optimises model parameter values and the agreement between the observed and estimated data.

The introduction of countermeasures and their effectiveness will depend on both the levels of the exposures and the reductions in doses that the countermeasures can achieve. A flexible module for dose assessment (EURALERT) has therefore been provided. This estimates doses from different exposure pathways based on levels of contamination in near-ground air and deposited on the ground in precipitation, which may be supplied either by the dispersion models or directly from measurements.

These packages have been developed in the overall context of an computerized real-time emergency response system, and attention has been given to making them compatible with each other. However, each package may also be used individually as appropriate; for example, the short-range model could be applied alone at a local emergency centre at the accident site. All the codes have been written in FORTRAN 77 and implemented on the same system (VAX). Detailed technical descriptions of the models, the concepts on which they are based and the computational techniques used are given in the combined project report, together with an indication of the data and computational resources required. User manuals are already available for some of the packages, although additional work would be required to make them more user friendly, a highly desirable attribute of any computer-based support system, especially those designed to provide assistance in emergencies.

Future requirements

The main limitations and uncertainties have been discussed at joint meetings during the project and have led to the identification of areas where useful improvements can be made. In addition the need for more work on model validation and testing has been recognised.

The accuracy and uncertainties in the various types of model estimates produced depend only partly on the models themselves. They are largely limited by the representativeness of the data available, which is likely to vary greatly according to the particular accident situation. How these uncertainties can be effectively communicated to the decision makers in an emergency is also a difficult problem.

Certain contributory factors can be identified where more detailed consideration and evaluation are desirable. These include, for example, topographical effects, demographic and geographical aspects and agricultural practices; also complex meteorological situations such as frontal systems, or stagnant anticyclones where wind directions are highly variable. The probable significance of such factors will vary throughout Europe. There are also several processes which are not yet allowed for, such as deposition in mist and fog, or gravitational settling and the complicating effects of buildings on the dispersion of the release close to the source.

Further attention is also required to how model components may be integrated into overall emergency response and assessment procedures. Although the interfaces between the software packages developed under this project have been defined in relation to the data transferred between them, there are further considerations. For example, there may be a step between supplying an average wet deposition value based on rainfall averaged over a grid cell in a dispersion model mesh, and the identification of potential 'hot spots' within that area which may be critical for dose impact and countermeasures assessment. Similar problems apply to the interfaces between dispersion model output and measured data.

More work is also required on the combined interpretation of radiological measurements and modelling results and the feed-back between the two, for example the updating and revision of modelling estimates of dispersion and contamination, as measurements become available. There are also major tasks involved in the provision of high quality graphics and the clear presentation of assessments according to user needs. Bearing in mind the rapid advance in computer technology it is also worthwhile considering the potential for improvements to the models that these advances will permit. Thus, parallel processing techniques could introduce significant improvements in the costs and operating speed of the Monte Carlo dispersion models.

In conclusion, in developing and expanding these software packages, it is important to lay sound foundations for the development of emergency response procedures, not just for the present but also for future decades.

1. INTRODUCTION

1.1 Scope and aims of the project

The experiences after the Chernobyl accident in 1986 have emphasized the need for rapid assessment of the levels of environmental contamination in the event of a nuclear accident. In order to facilitate decisions about possible countermeasures, knowledge of the potential radiological consequences of a nuclear accident, and the potential effects of any such countermeasures is essential. This requires the development of specific tools, including numerical models to simulate atmospheric transport and deposition over various distance scales and techniques for the estimation of the resulting doses. The aim of this joint research project has been to develop such tools, in the form of computer software packages, which will subsequently be generally available for use in European Community countries.

Thus different atmospheric dispersion models have been developed which are suitable for application in the vicinity of an accident on a local scale out to a few tens of kilometres at most, for the surrounding region out to one or two hundred kilometres - the mesoscale, and beyond this over long distances out to the continental scale covering the whole of Europe. In addition, software packages have been produced for use in conjunction with early radiological measurements for assessment of the quantities of radionuclides released in situations where on-site monitoring or other observations of the release cannot provide this information. For estimation of individual or collective doses, and evaluation of the benefits of countermeasures, a dose assessment module has been produced which can use either the results from the dispersion models, or radiological measurements from the area of interest, in conjunction with demographic and other geographical information.

The project has been undertaken in collaboration by four institutions:

- Comitato Nazionale per la ricerca e per lo sviluppo dell'Energia Nucleare e delle Energie Alternative, Direzione Sicurezza Nucleare e Protezione Sanitaria, Rome, Italy, who were responsible for short range atmospheric dispersion modelling and source term assessments.

- Commissariat a l'Energie Atomique, Institut de Protection et de Sûreté Nucleairé, Centre d'Etudes Nucléaires de Fontenay-aux-Roses, France, who were responsible for mesoscale atmospheric dispersion modelling and source term assessments.

- Imperial College of Science, Technology and Medicine (IC), Mechanical Engineering Department, London, UK, who were responsible for the long range atmospheric dispersion and transport modelling.

- Gesellschaft für Strahlen-und Umweltforschung (GSF), Institut für Strahlenschutz, Neuherberg, W. Germany, who were responsible for the dose assessment and countermeasures modelling.

1.2 Layout of the report

The generalised structure of a computerised real-time emergency response system and the role of the key components developed in the current project are given in chapter 2, while a detailed analysis of the construction and technical performance of such a system is given in appendix A. A general introduction to the atmospheric dispersion models suitable for real-time emergency response applications is given in chapter 3, along with descriptions of the three atmospheric dispersion models developed in the current study. The problems of relating early off-site measurements to the dispersion model results are addressed in chapter 4 and two complementary approaches to source term assessments are presented. The dose assessment model EURALERT which can predict individual and collective doses from all the relevant pathways using either the atmospheric dispersion model output or off-site radiological measurements if there a sufficient number available, is described in chapter 5. The conclusions and future recommendations arising from the project are given in chapter 6.

2. THE CONTEXT OF THE STUDY

In the event of an accident leading to a release of radioactivity key personnel will be alerted and emergency procedures brought into action. In some cases there may be a warning period when a potential accident situation is recognised before the release commences, and forecasts of the areas likely to be affected are required in contingency planning. In the event of an accident being of sufficient magnitude to have trans-frontier consequences in another country, an international protocol drawn up by IAEA since the Chernobyl accident provides for early notification to inform those countries.

The most urgent considerations will be those close to the accident source. Personnel and resources are likely to be limited, and there may be large uncertainties about the release and how it will continue. Rapid decisions may be necessary on such control measures as evacuation, sheltering, and the issue of iodine tablets. These will be based on assessments of inhalation doses and external irradiation to the surrounding population, which in turn depend on the air concentration and deposition over the critical period as the radioactive release disperses downwind. In this context numerical models, using local meteorological data or forecasts of the local conditions given by the meteorological services, to estimate levels of contamination in the surrounding area can be valuable tools. They can be helpful in directing and interpreting early measurements and in forecasting future developments.

In the event of a major breach of the containment of a nuclear reactor or any other accident which bypasses any release monitoring, patterns of contamination from nominal releases estimated by the models may be compared with the available measurements to give approximate indications of the magnitude of the release and the nuclides involved. The release may vary from noble gases which do not deposit significantly on the ground, to a wide range of radionuclides with differing physico-chemical characteristics, depending on their volatility. In a severe accident, deposition close to the site may be enhanced by a spectrum of coarser material subject to gravitational settling at various rates.

Within the first few hours additional resources and personnel will be available to assist, and contamination and exposure of the population at longer distances in the surrounding region may need to be considered, depending on the severity of the accident and the meteorological conditions. Again the levels of exposure will depend on time integrated air concentrations during passage of the radioactive release and accumulated deposition. The deposition will again depend on the chemical and physical form of the nuclides released, and will be greatly influenced by meteorological factors such as the occurrence of precipitation.

According to magnitude of the estimates of contamination of milk and other foodstuffs, control measures may be necessary to limit ingestion doses. The dispersal of the release over mesoscale distances (out to 100 to 200 km) will be complicated by meteorological conditions varying in time and space, and topographical features such as hills and valleys, changes in surface (grass, water, forest, urban areas, etc.). More complex numerical models are therefore required to simulate atmospheric dispersal over these mesoscale distances and to provide estimates of integrated air concentrations and deposition. The resulting exposures will also depend on the nature of the surrounding region, the agriculture, vegetation and soils, urban areas and types of housing, etc.

Methods of assessment of doses are therefore required which allow for these variations in circumstances and are capable of making predictions of individual and collective doses, based on either measurements or model estimates.

At longer distances the considerations are slightly different. In countries beyond the mesoscale range, the initial concerns will be whether significant amounts of radionuclides are likely to reach the country, and also for the welfare of nationals abroad in other countries which may be affected. For the former, model predictions based on forecasts of the evolution of the weather conditions on the relevant distance scale, from the meteorological services are required. These predictions should be capable of being updated and revised as the situation evolves. Again the consequences may be related to the estimated time integrated air concentrations and deposition during the passage of the radioactive release over the country.

As the radioactivity arrives, monitoring capabilities will be implemented, and such factors as where the material is scavenged and brought down by precipitation are important. Control measures will again depend on estimated exposures, including those potentially arising from ingestion of contaminated foodstuffs. There will also be a need to consider any regulation necessary on imports from other countries.

The manner in which nuclear accidents both those within and those outside a country are managed, are likely to differ substantially from country to country within the European Community. Some countries will rely on more centralized decision making, and others allocate more responsibility to local or regional centres. Different information will be required according to individual responsibilities, with the relevant conclusions of more detailed technical assessments of particular aspects communicated to the decision makers.

The form in which information is conveyed, the desired information flow patterns and the communications networks obviously need to be designed according to the allocation of responsibilities and emergency plans. Computer technology and computerised support aids do however, have a large role to play in storing, accessing, and interpreting radiological measurements and information on the source and release, indicating the best estimates of patterns of contamination, and identifying the resulting impacts and doses.

In this context key components of a computerised emergency response system can be identified as shown in figure 2.1.

The control centres, whether local, regional or national will all require access to information about the source and the radiological measurements assembled for the areas of concern in appropriate data bases, together with demographic and other relevant data prepared in advance for such eventualities.

Atmospheric dispersion models applicable over appropriate distance ranges, may be implemented as tools for estimating contamination of air and ground, given the necessary meteorological data and information on the release and its evolution. If necessary they may also be used, assuming nominal releases, to interpret the early radiological measurements and work backwards to the source terms.

As a basis for decision making, a flexible dose impact assessment package for estimating doses and the effectiveness of possible countermeasures provides an additional tool, which can be used with information provided in a common format by any of the atmospheric dispersion models for different distance ranges or directly with radiological measurement.

Additional requirements and considerations in designing an overall system are addressed in an appendix, including software, hardware, and transfer and display of information. Modern computer graphics and carefull planning of appropriate displays and maps with clear and unambiguous labelling are also important. Provision can also be made to record operator actions and displays requested as a contribution to the records on the management of the accident situation.

In the following chapters the modules developed for incorporation in such overall computerised systems, specifically atmospheric dispersion models appreciable over different distance scales, packages to derive estimates of the source terms, and a module for dose impact assessment, are addressed.

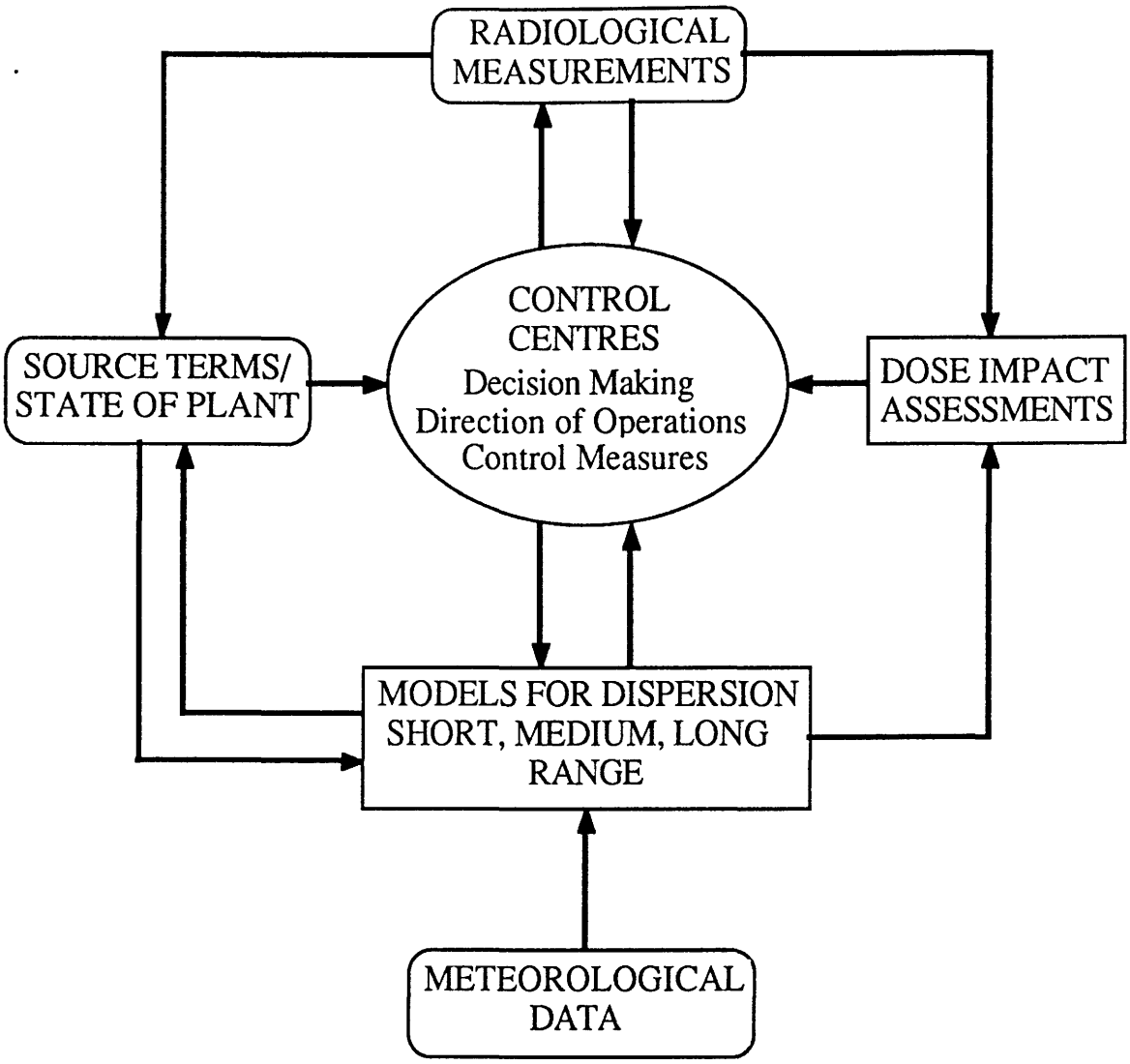

Figure 2.1 Generalised scheme for the structure of a real-time emergency response system

3. ATMOSPHERIC DISPERSION MODELS

3.1 Introduction

Numerical models simulating the dispersal of radionuclides released to the atmosphere are essential components of an emergency response system for the real-time management of emergencies. However they must be used properly, with due allowance for the uncertainties involved. It is also important that results generated by the model are presented clearly in a format that is easily understood, for example as maps or other graphical forms.

The types of control measures and corresponding time-scales for their implementation, following an accident vary with distance from the source. The requirements for atmospheric dispersion models, in the context of emergency response procedures, therefore vary accordingly over different distance ranges. This introductory section briefly reviews the types of model available over three distance ranges; close-in (within a few kilometres), the mesoscale (≈100 to 200 km) and long-range (continental scale), and considers the relative merits and disadvantages of different modelling approaches. In addition the representation of removal processes which are common to all three distance ranges, and the nature of possible links between models covering different distance ranges are considered.

3.1.1 Short range models

At distances up to a few kilometres of the plant, rapid calculations are required, indicating the areas likely to be most contaminated. It is also important to know when areas will be affected by passage of the material, a different requirement to risk studies where only the time-integrated concentrations and deposition are generally used. In addition, a short range dispersion model should be capable of calculating γ doses as activity concentrations in air near the source vary over comparable distances to the mean-free path lengths of γ radiation.

In risk studies the model most commonly used is the Gaussian plume model in which the time-integrated air concentration χ_{air} (Bq.s.m^{-3}) is related to an elevated release Q (Bq) by:-

$$\chi_{air}(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\left(\frac{y^2}{2\sigma_y^2}\right)} \left[e^{-\frac{(z-h)^2}{2\sigma_z^2}} + e^{-\frac{(z+h)^2}{2\sigma_z^2}} \right] \qquad 3.1$$

where u is the wind-speed, h the source height, and σ_y and σ_z empirically derived parameters representing horizontal and vertical spreading. Further terms may be incorporated to represent reflection from the top of the mixing layer.

The same formula also gives the instantaneous air concentration (Bq.m^{-3}) when Q is a release rate (Bq.s^{-1}). Strictly 3.1 only applies to a period over which meteorological conditions are approximately constant, a prolonged release is therefore broken up into sections with separate calculations for each section, and results then superimposed.

In emergency situations greater flexibility is provided by use of a Gaussian puff model, with an additional parameter σ_x for the along-wind spread;

$$\chi_{air}(x,y,z) = \frac{Q}{\sqrt{2\pi^3}\, u\, \sigma_x\, \sigma_y\, \sigma_z} e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} \left[e^{-\frac{(z-h)^2}{2\sigma_z^2}} e^{-\frac{(z+h)^2}{2\sigma_z^2}} \right] \qquad 3.2$$

The Gaussian puff model can produce maps of concentration for any specific time or time interval, with simultaneous contributions from a sequence of puffs representing a release varying with time. Again, further terms may be incorporated to represent reflection from the top of the mixing layer.

There are many Gaussian type models in existence, with various prescriptions for determining atmospheric stability and the horizontal and vertical dispersion parameters. Model intercomparisons have been undertaken, and validation studies made against tracer experiments. The models differ in the type of terrain to which they apply, some include schemes making specific allowance for the roughness characteristics of the terrain.

If the dynamics and magnitude of the release are not well-known, as is likely to be the case, especially in a major accident, model calculations can be used in conjunction with early radiological measurements to provide initial estimates of the source. The ability to adjust model parameters in order to minimise the differences between the model calculations and observations, is thus an important additional component of an emergency system for the short range, and this is considered further in chapter 4.

Problems with Gaussian models

Large differences between the model results and observations can occur, and can be caused by a number of reasons; for example, inadequacies in the parameterisation of the models, or in the representation of the meteorological situation, or in the mis-application of the model in a complex topographical situation. The latter two problems are considered below.

Complex meterological conditions

The Gaussian model assumes that meteorological conditions are homogeneous within model domain, although there are prescriptions for allowing changes in conditions with time. More importantly, the structure of the lowest levels of the atmosphere is assumed to be relatively simple, based on typical vertical wind-profiles. There can however, be considerable deviations from this; for example, shallow surface layers a few tens of metres deep, moving with different speed and direction from layers above (especially where the underlying surface is not level), or nocturnal jets with fast moving layers at a height of a few hundred metres. If sites are equipped to measure vertical wind and turbulence profiles, e.g. with sodar, such irregularities are revealed, giving an indication of the uncertainties involved.

Another factor is that Gaussian horizontal dispersion profiles are somewhat idealised. Often a cross-wind profile through a plume reveals an irregular shape, which may for example be bifurcated with more than one maxima. The size of the spread depends on the turbulence which is best indicated by direct measurements of wind fluctuations in real time conditions; for example it may vary with upwind fetch. However in predictive mode such measurements will not be available.

Effects of topography

As indicated even gentle slopes can introduce shallow drainage flows, while hills upwind can induce turbulence and larger fluctuations in wind direction. Another factor close to the site can be the influence of buildings on the initial dispersion. Changes in surface, even in a flat area, can also be important, generating internal boundary layers (inhomogeneous turbulence and dilution). In particular at coastal sites land-sea breezes may cause localised winds and circulations of limited depth, which may be further complicated by curved coastlines or cliffs. Extreme topography, such as sites placed in a narrow valley will need

special consideration. In such situations wind tunnel studies or tracer experiments may be advisable to gain insight into the windflow patterns.

3.1.2 Mesoscale dispersion

The windfield and turbulence will only be reasonably homogenous within a few tens of kilometres of the site at most, according to the complexity of terrain and the meteorological situation. However, the control measures to be introduced at such distances will generally not be so urgent as those required close to the source; consequently models can be used to simulate dispersion which can allow for the 3-dimensional windfields and spatially varying turbulence.

Thus, the first problem for a mesoscale dispersion model is to define the windfield. One possibility is the mass consistent method, where observed or estimated wind measurements within the model domain are interpolated onto a 3-dimensional grid of cells. However, the interpolated windfield is not necessarily mass consistent, so minimal adjustments are therefore made to balance the fluxes into and out of each cell. These adjustments are not unique, but may be controlled to reflect stability, using prescribed weighting functions for vertical and horizontal wind component adjustments. Alternatively, finite element methods can be used to determine the wind field on an irregular grid, if desired.

Another possibility is to use a numerical approach, integrating the primitive equations (conservation of mass, momentum, energy etc.) for the air flow over the region, in much the same way as a weather forecasting model, but with greater spatial resolution and less vertical depth. Such windfield models are in fact embedded in forecasting models covering a larger domain, in order to specify the boundary conditions. The new mesoscale forecasting models with their finer grid resolution are better for this purpose, since they make more allowance for the blocking and channelling effects of mountains. The resolution of the embedded model with its greater detail is generally of the order of a few kilometres, as for the mass consistent models described above.

Having defined the windfield the next task is to describe the turbulent dispersion of the material within it. This can also be done in a variety of ways. In 'Eulerian grid' models the advection-diffusion equation is integrated numerically over the 3-dimensional volumes of the grid-cells. However this involves the use of sophisticated techniques to overcome problems of numerical diffusion, and substantial computer resources are required.

The other categories are 'particle' models: 'particle-in-cell' models and 'Monte-Carlo' models. Both these consider the release as an assembly of particles, tracked through a series of time-steps. Since large numbers of particles are needed to represent a release statistically, the computer requirements are again considerable. In 'particle-in-cell' models the particles are repositioned during each time-step with a combined velocity representing advection and diffusion. The diffusion component is calculated by assigning the particles to grid-cells, and computing effective diffusion rates according to the concentration gradients.

In Monte-Carlo models on the other hand, particles are tracked independently. Each particle is advected by the mean wind, with random perturbations superimposed to represent turbulent displacement. Monte-Carlo models do not suffer from problems of numerical diffusion like the Eulerian grid models, but with spatially varying turbulence care has to be taken to avoid artificial accumulation of particles in regions of low turbulence. Monte-Carlo models have perhaps not been popular as advanced air pollution models mainly because it is difficult to represent interactive chemistry, however in the context of radioactive releases, where the chemistry is less crucial, they have substantial advantages. In particular it is relatively easy to distinguish different parts of the release, and revise results as source terms are re-evaluated and up-dated. They also provide good visual simulations of the movement of material when transposed onto a film or video tape. Monte-Carlo techniques have been chosen for both the medium range and long range dispersion models developed by CEA and Imperial College respectively and described in sections 3.3 and 3.4.

3.1.3 Long range models

The Chernobyl accident demonstrated the need to develop capabilities to forecast and assess the transport of radionuclides on a continental scale. In this context there is less urgency than at short distances, since measures requiring immediate implementation to control exposure such as evacuation of the local population are not involved. Only major accidents are likely to give rise to significant effects over such long distances, principally from deposited activity, either directly or through the contamination of foodstuffs. Consequently, the interaction of any precipitation with the release and the resulting wet deposition will be particularly important. The main functions of a long range model are thus, to indicate which areas may be reached by the release and the likely level of deposition, together with the likely arrival time, in order to alert monitoring services.

Over long distances out to two or three thousand kilometres, the time-scales for implementation of control measures, and the objectives of such measures are again different. Wind-fields are best prescribed by weather forecasting models (although simple geostrophic winds deduced from pressure fields can give quite a good indication of the overall patttern of dispersion). On notification of an accident, modelling will be undertaken using forecast windfields to predict future movements. Modelling simulations are then updated as forecast windfields are replaced by analysed windfields at regular intervals. (Analysed windfields are still obtained from forecasting models, but incorporate the meteorological observations up to the time of the analysis, as a starting point for forecasting yet further ahead). In forecasting mode, the further ahead the prognosis, and the longer the travel-time of the release, the greater the uncertainties in the simulation. Under many circumstances, simulations beyond 3 days or so are likely to be increasingly unreliable.

Vertical winds are either taken directly from vertical components in the forecast windfield, or advection is computed using isentropic surfaces of constant potential temperature. The fine mesh models from forecasting services over Europe, give a better spatial resolution than coarser grid models over the Northern Hemisphere.

The range of models available to simulate dispersion in such windfields includes extrapolated 'plume' models, and 'Lagrangian puff' models, as well as the Eulerian grid and particle techniques outlined above. The plume model, representing the passage of material across the map area as a plume stretched out along a calulated trajectory, has the advantage of simplicity; but it is of little use in providing a map of concentrations at a particular time due to different parts of the release, and the lateral spread of the plume can be highly variable. Although simple Lagrangian trajectory models such as MESOS provided a useful insight into the pattern of dispersal across Europe from the Chernobyl accident (ApSimon et al. 1989), they are generally limited in their 3-dimensional treatment of the windfields. Eulerian grid models which integrate the equations for advection and diffusion of material across a 3-dimensional grid of cells, can incorporate the 3-dimensional windfields, but are unable to differentiate different time-phases of the release unless these are separately calculated, but this is very demanding on computer time.

As a statistical approach the Monte-Carlo particle models have the advantage of giving some indication of the probabilities of contamination. An area reached by a large number of particle trajectories is more likely to be affected, whereas an isolated outlying particle arriving may indicate a very remote possibility. It is also easy to see where the material has divided into separate streams, moving in different air masses or layers. The techniques are

also suitable for parallel computing using for example new transputer developments. Thus the extensive computer resources required need not remain a problem.

It is also useful to have available a back-trajectory model, which, if material is observed unexpectedly, can trace backwards to indciate possible source regions. Such facilities can easily be generated using a sequence of analysed wind-fields, and working backwards in time. However allowance may have to be made for the original height of the release and other uncertainties, and ideally an envelope of the area in which the source is likely to lie should be indicated.

Once material has arrived at a distant location, then precipitation data is likely to be very important. In some countries on-line weather radar provides detailed data on precpitation, clearly showing the more intense cells and their development. Such data may even be used to indicate short term forecasts up to three hours ahead, and integrated with satellite observations. Such a system is operational at the U.K. Meteorological Office, with international exchange of radar data with other countries in north-western Europe. The alternative is rain-gauge data, but this is generally difficult to assemble in a short time from enough stations to give good spatial resolution.

If good spatial and temporal resolution of precipitation is available, then approximate deposition patterns may be estimated using a wash-out model according to where and when precipitation intercepts the airborne activity. This can help to indicate priority areas requiring monitoring, and analysis of samples. The modelling of such wet deposition patterns is described below.

3.1.4 Removal processes

Radioactive decay and transformation

During transport radionuclides may change their form. This may be due to chain decay where the quantity of a nuclide n is reduced by decay to a daughter nuclide n+1, and/or increased by decay from a parent nuclide n-1.

$$\frac{dA_n}{\delta t} = -\lambda_n A_n + \lambda_{n-1} A_{n-1} \qquad 3.3$$

Other changes may affect the behaviour of a nuclide in the atmosphere however. Isotopes of iodine will behave quite differently according to their chemical form. Methyl iodide is very inert and insoluble. Gaseous iodine however, tends to become partly attached to atmospheric aerosols; for example about 25 - 33 % of the ^{131}I released from Chernobyl was observed on aerosols. (NB This is important for monitoring, as many monitoring devices captured aerosols from the air, but did not retain the gaseous iodine which required a charcoal filter). Such nuclide characteristics are important when it comes to deposition processes. Usually it is sufficient to consider a limited number of nuclides, which have the same dispersion characteristics, but differ in their rates of deposition and decay. Over longer travel distances the number of important nuclides is relatively small, most of the shorter lived nuclides having decayed.

Deposition Processes

Activity is also lost from the atmosphere by deposition at the ground, leading to contamination of crops and pasture etc., and exposure by ingestion and direct irradiation from the ground. This can happen by several processes, which can be allowed for in models, eg by simple extension of the Gaussian plume model to calculate deposition beneath, and adjusting the flux surviving downwind.

Gravitational settling

Large heavy particles effectively 'fall' out of the atmosphere by gravitational settling. This is likely to be more important for the short range models. Each particle settles at a rate determined by a balance between the viscous drag of the air and the gravitational force (the Stokes terminal velocity, g). The settling velocity for a spherical particle of radius r and density ρ, falling through air of viscosity μ is

$$v_g = \frac{2r^2 g\rho}{9\mu} \qquad 3.4$$

As an example a 40 micron particle with density 5 $g.cm^{-3}$ has a fall speed of about 25 $cm.s^{-1}$. Gravitational settling can be modelled with a Gaussian plume by tilting the plume downwards towards the ground, so that the effective source height decreases with

downwind distance;

$$h_{\text{eff}} = h - \frac{v_g u}{u} \qquad 3.5$$

although there is some uncertainty in treating the reflection terms at the ground (see for example Underwood (198?).

Dry deposition

For smaller particle sizes, less than about ten microns, and gases, the turbulent motion of the air is more effective at transferring particulate activity down to the surface. Contaminants in the surface layers of air may then be deposited. This dry deposition is proportional to the concentrations in the surface air.

$$D_{\text{dry},n} = v_{\text{d},n} X_{\text{air},n} \qquad 3.6$$

where $X_{\text{air},n}$ is the air concentration (units.m^{-3}) of nuclide n, and $v_{\text{d},n}$ is the nuclide specific 'dry deposition velocity' with units of m.s^{-1}.

The deposition velocity depends on the turbulence in the air, and the ease with which activity is transferred down to the surface by this turbulence. It also depends on the nature of the crop canopy or other surface elements. Finally having reached the surface, the nature of the surface and the particluate activity will be important. The deposition velocity can thus be expressed in terms of a sum of resistance terms.

$$\frac{1}{v_{\text{d}}(z)} = r_a(z) + r_b + r_s \qquad 3.7$$

Here $r_{\text{a}}(z)$ is the aerodynamic resistance determined by the nature of the turbulence above the surface, r_{b} is an additional resistance operating in the laminar sub-layer adjacent to the surface or within the crop canopy, and r_{s} is the surface resistance controlled by the nature of the surface. The resistance term r_{b} depends on the nature and morphology of the surface elements. In a complicated crop canopy it can be very difficult to estimate.

The surface resistance term can vary substantially both seasonally and diurnally, and depends on such factors as stomatal opening for plant uptake. It also depends of course on whether the surfaces are wet or dry, or perhaps covered in snow, and the chemical and physical form of the pollutant. Small aerosols for example may bounce off leaf surfaces, whereas gaseous iodine may be efficiently absorbed.

It should be recognised that deposition velocities can vary considerably over a small distance, given that they are strongly dependent upon the nature of the surface cover, however, dispersion model calculations are usually based on values averaged over a variety of surfaces. As an example; average bulk deposition velocities of ^{131}I from Chernobyl were of the order of 0.3 $cm.s^{-1}$, and of ^{134}Cs and ^{137}Cs attached to micron size aerosols, less than 0.1 $cm.s^{-1}$. Reactive gases such as sulphur dioxide, with lower surface resistances would have bulk deposition velocities of the order of 1 $cm.s^{-1}$. Noble gases do not deposit to any significant extent at all, being very chemically inert. It should be noted that deposition velocities to urban surfaces are usually very small. In fact exposure in urban locations can be dominated by trees, with a high capture efficiency, rather than buildings.

Wet deposition

Particulate activity is also removed from the atmosphere by precipitation. Precipitation involves complex processes resulting from the ascent of moist air and condensation or accretion on to particles or ice crystals. Activity is incorporated in rain either in cloud during the formation of rain drops (rain-out) or are scavenged by rain drops falling through air beneath the cloud (washout). These processes lead to a wide variability in observed washout ratios (the ratio of activity concentrations in rain water to activity concentrations in (ground level) air).

Different types of precipitation have different removal efficiencies, and also transport material upwards out of the boundary layer. Thus, there are differences between the wet deposition occurring in the slow upward transport in frontal systems, and that occurring in the strong convection within thunderstorms, or the weaker convective motions of showers. There are also differences between cold cloud processes involving ice, and warm clouds with water droplets. Even in the absence of rain small droplets of mist or fog can lead to enhanced deposition. Effectively the pollutants are captured within the droplets, which have a higher deposition velocity than the dry pollutants. This can be particularly important in coastal regions with sea-fog, or over high land capped in cloud.

Thus, wet deposition is a very complex subject and not yet fully understood in terms of the implications for air pollution. However it can be important, as was evident after Chernobyl from the patchy nature of wet deposition over the upland areas of the U.K. In this context orographic enhancement is particularly significant. Deposition of fine particulates can be increased through the 'feeder-seeder' mechanism where air is forced above the condensation level, so that the small aerosols became encapsulated in cloud water droplets. The latter are far more readily captured by falling raindrops, with the result that wet deposition can be an order of magnitude higher.

In models relatively simple approximations are used based on a washout rate. This is equivalent to rain falling uniformly through a vertical column of air and depositing a fraction of the airborne pollutant on the ground beneath per unit time.

$$D_{\text{wet},n} = \Lambda_n \int_0^H X_{\text{air},n}(z)\, dz \qquad 3.8$$

H is the height of the cloud of activity and Λ_n the washout coefficient (s^{-1}). Typical values of the washout coefficient for radionuclides such as ^{131}I or ^{137}Cs are of the order of 10^{-4} to 10^{-5} s^{-1}. Often the washout coefficient is made to vary with rainfall intensity J ($mm.h^{-1}$) to some power p, with p lying between 0.5 and 1.

$$\Lambda_n = \Lambda_{n,e} J^p \qquad 3.9$$

where $\Lambda_{n,e}$ is equivalent to the effective washout rate in rainfall of 1.0 $mm.h^{-1}$ and effectively has units of $h^p.mm^p.s^{-1}$.

3.1.5 Linking the atmospheric dispersion models

If an emergency response system is to use more than one atmospheric dispersion model, then the question of how the models will inter-relate with one another needs to be considered. A system with a short range, a mesoscale and a long range atmospheric dispersion model, which are all operated independently would inevitably give conflicting results over the common areas of the respective model domains, and in an emergency such confusion would make the whole system ineffective. It is thus important to devise a system

of links between the models which removes, or reduces to acceptable levels, the potential for inconsistences between the models over their common areas.

It has not been possible within the scope of the current contracts to devise strict links between the three models that have been developed; instead, the theoretical basis on which the models can be linked together has been considered and general file structures consistent with the agreed theoretical links, have been included in each model. Strictly, the implementation of fixed links between the atmospheric dispersion models is counter to one of the objectives of the whole study which has been to provide flexible modules which can be utilised within a flexible emergency response system framework.

In general, the long range model needs to be able to continue dispersion simulations fom both the short range and mesoscale models; the mesoscale model needs to be able to continue dispersion simulations from the short range model and transfer it's simulations to the long range model, and lastly, the short range model needs to be able to transfer it's simulations to both the other models.

Possible connections between the mesoscale and long range models are perhaps easier to specify. As both are very likely to have a three dimensional model domain, one option is for the mesoscale model to supply the long range model with a three dimensional air concentration field at a given time, thus allowing the long range model to 'pick up' and continue the mesoscale model's dispersion simulation. Alternatively, it may be more straightforward for the mesoscale model to supply the activity fluxes leaving it's model domain, over given time periods.

Connections between the short range model and the other two are likely to be less straightforward, as there are likely to be greater differences in the specification of the model domain. Also, because the mesoscale and longer range models are more demanding on computer resources, it makes sense to supply them with as accurate data as possible. Thus, if possible, links between the short range model and the others should reflect the 'best estimate' of the release and it's subsequent behaviour, which may given by feedback analyses between the short range model results and any radiological observations.

3.2 A Lagrangian Short Range Model: SPADE

3.2.1 Introduction

SPADE (Sequential Puff for Atmospheric Dispersion Evaluation) is a Lagrangian, short range, sequential puff model designed to estimate ground-level concentrations, deposition and cloud γ dose rate, in flat or gently rolling terrain in the vicinity of a point source. Several co-located point sources can be considered by adding the results of the corresponding number of SPADE runs.

It is specifically designed for applications involving either stable or first-order decaying (radionuclides) atmospheric pollutants and is best suited for evaluation of plume behaviour out to about 20 km from the source. Model results beyond 20 km should be used with caution to 50 km, and SPADE can be used as a screening model for distances beyond 50 km.

SPADE is a non-stationary model, in the sense that it can accept a sequence of meteorological and source data sets and produce output analyses which take into account the evolution of the atmospheric conditions. It uses a few, simple meteorological and geographical data. Due to the short range validity of the model, it uses only one set of meteorological data at a time and does not allow atmospheric parameters to vary spatially.

The principal features of the SPADE model are;

i) Meteorological input data are grouped into data sets, one for each time of observation; meteorological data sets can be spaced at variable intervals; time variations of single variables can be taken into account by introducing a new set of data with the same values of all variables but the ones which contain the new values.

ii) The dispersing plume is simulated by a sequence of gaussian puffs whose trajectories are determined in the following way:
- firstly, a wind speed and direction profile is computed from available wind measurements;
- secondly, the 'effective' puff speed and direction are calculated at each time step by weighting the vertical profile with the vertical concentration distribution.

iii) Plume rise for buoyant plumes is computed; transitional plume rise is considered until the downwind distance to equilibrium plume height is reached by the puffs.

iv) Buoyancy-induced dispersion is taken into account.

v) Total (default) or partial puff reflection from a mixing lid is taken into account in computing ground level concentrations.

vi) If the effective puff height is greater than mixing layer height, the fraction of the plume that penetrates the lid is calculated and is not considered in computing ground level concentrations.

vii) Adjacent puffs are merged if sufficiently superimposed one to the other, and deleted if sufficiently far from the calculation domain, to avoid indefinite growing of the puff number.

viii) Atmospheric dispersion parameters are determined in the following way:
- for the horizontal, they depend on atmospheric stability category or on horizontal wind direction fluctuation measurements, if available.
- for the vertical, they depend on atmospheric stability category.

ix) Atmospheric stability index is calculated by the SPADE code based on wind speed and cloud cover (or solar radiation, if available).

x) Horizontal and vertical dispersion coefficient curves can be chosen between several sets of semi-empirical curves (for example, for urban or rural environments).

xi) A virtual source distance is introduced in case of atmospheric stability changes to avoid time discontinuities in the puff spreading.

xii) Dispersion during calm or low wind speed conditions can be simulated by SPADE, using dispersion coefficients dependent on time, instead of on the distance from the source usually used by plume models.

xiii) Dry deposition is calculated by introducing a proper deposition velocity for each released pollutant.

xiv) Wet deposition is calculated by introducing a washout coefficient dependent on rain intensity, which is assumed, as the other meteorological variables, uniform over the domain but variable in time.

xv) Plume depletion due to both wet and dry deposition is taken into account.

xvi) Cloud γ dose rate from selected radionuclides can be optionally calculated for a limited number of sample points by use of a finite cloud model incorporated into SPADE.

xvii) Output analysis, which consist of instantaneous and integrated concentrations, and ground deposition values, can be required any time after the beginning of the release.

SPADE uses the following input files:

i) A file containing time-dependent data: geographical data (domain size and co-ordinates), source characteristics (time of release, pollutant species, etc.), and code parameters (duration of time step, times of required output analysis, etc.).

ii) A file containing time-variable data, grouped in small datasets, one for each time of observation: meteorological data (mixing layer height, wind speed and direction, etc.) and source terms for all the species.

iii) An optional file containing the coordinates of receptors locations where output concentrations and depositions (in addition to the standard grid points) and eventually cloud γ dose rates must be computed.

iv) A library file for cloud γ dose rate calculation containing, for each nuclide, the energies and the corresponding branching ratios of the γ rays.

The execution of the SPADE code produces a series of disk output files and a printout of the following data:

i) Grid values of the following analysis: ground level instantaneous concentration, ground level integrated concentrations, total ground deposition, wet deposition.

ii) Receptor values of the same data as above and of cloud γ dose rate.

Gridded values contained in the output files produced by SPADE can be displayed and analysed using a graphic post-processor that plots the isopleth pattern of required concentration or deposition levels.

3.2.2 Mathematical formulation and model parameters

Model domain

SPADE calculates concentration and deposition values at the points on a 20 x 20 grid and at a maximum of 100 receptors located anywhere inside the calculation domain. The size of the grid interval is given as input data. The ground is assumed to be flat, so no topographical data are required.

The point source can be located anywhere inside the domain, to optimize the extent of the useful calculation area in case of a prevailing wind direction. A release can be comprised of up to five radionuclides or pollutant species in the present version of SPADE, although this limit can be easily changed depending on the computer power.

Advection

Puff trajectories are computed by SPADE based on wind speed and direction measurements at various heights. As a minimum SPADE requires at least one measurement near the ground (usual ground level anemometers) and one upper-air measurement, although the latter can be an estimate. In this way wind data coming from different kind of instruments (ground stations, meteorological towers, sodar, pilot balloon, radio-soundings) can be used to determine the vertical wind profile, $\underline{v}(z)$ that is input to the model, providing of course, that all the measurements are representative of the same time interval and of the same area.

Windspeed in the surface layer whose depth is taken to be $^1/_{10}$th of the boundary mixing layer, is assumed to follow a power law profile;

$$u(z) = u_0 \left(\frac{z}{z_0}\right)^p \qquad 3.10$$

where z_0 = the reference height at which windspeed u_0 is measured (m)
p = power function dependent upon atmospheric stability

Wind direction within this surface layer is assumed to be constant. In the outer boundary layer, the windspeed and direction are linearly interpolated from the available data.

Then, at each time step the advection $\underline{v}_p$ for each puff is computed from

$$\underline{v}_p = \frac{\int_0^{z_p} \underline{v}(z)\, \chi_{air}(z)\, dz}{\int_0^{z_p} \chi_{air}(z)\, dz} \qquad 3.11$$

where $\chi_{air}(z)$ = the gaussian vertical concentration distribution of the puff at the start of the timestep (Bq.s.m^{-1})
z_p = the height representative of the upper limit of the layer affecting the ground level concentration (m)

and $z_p = h_s + k\, z_s$

where k = von Karman constant (0.4)
z_s = a scale height representing the vertical extent of the plume; $z_s = 2\sigma_z$ (m)
h_s = the source height (m)

The method described above is an attempt to take into account the effect of wind shear in the determination of an effective puff trajectory, based on the assumption that ground level concentrations are affected by air mixing between the ground and a vertical scale height.

Dispersion

In SPADE, the pollutant plume is simulated by a sequence of Gaussian puffs which are released from a point source at time intervals sufficiently short to avoid discontinuities inside

the plume and consequently in the ground concentration field. Thus the ground level air concentration from each puff $\chi_{air}(x,y,0)$ is derived as follows;

$$\chi_{air}(x,y,0) = \frac{Q}{\sqrt{2\pi^3}\,\sigma_x\sigma_y\sigma_z} e^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right)} \left[e^{-\frac{z_0^2}{2\sigma_z^2}} + e^{-\frac{(2h-z_0)^2}{2\sigma_z^2}} + e^{-\frac{(2h+z_0)^2}{2\sigma_z^2}}\right] \quad 3.12$$

where $\chi_{air}(x,y,0)$ = air concentration at a point x,y,0 ($Bq.m^{-3}$)
Q = activity contained in the puff (Bq) (given by release rate/no. of puffs released per time interval).
σ_x, σ_y, σ_z = standard deviations of the gaussian distribution in the x, y and z directions (m).
x_0, y_0, z_0 = coordinates of puff centre (m)
h = mixing layer height (m)

Only the first two terms representing puff reflection from the top of the mixing layer are considered; vertical puff spreading is also limited by the condition $\sigma_z < h$. The time integrated air concentration over each timestep $\Delta t = t_f - t_i$, centre on t_m is then

$$\chi_t(t_f) = \chi_t(t_i)f + \chi(t_m)\,\Delta t \quad 3.13$$

Where f is a factor representing the decay process. The time integrated air concentration at ground level at a receptor point or grid point is the sum of the individual puff time integrated air concentrations at the point for all the puffs comprising the release.

The total number of puff is controlled over each timestep by two different mechanisms; merging adjacent growing puffs, and deleting puffs transported far away from the calculation domain (Ludwig et al, 1977). At each timestep, pairs of successive puffs are merged, in the sense that they are deleted and a new one is created if the distance between the puffs is less than their average σ_x.The activity content of the merged puff is the sum of the two and all other parameters (coordinates, dispersion coefficients) are a weighted average of the two. Puffs are purged at each timestep, if they are located at a distance greater than half domain size from the nearest domain boundary, due to their negligible contribution to the concentrations inside the domain.

In SPADE, σ_y and σ_z may be derived by a number of different methods. This flexibility is maintained to allow the most appropriate dispersion coefficients for the physical characteristics of the release, like source height, roughness height, etc. to be used. The

horizontal dispersion coefficients must be derived for sampling times comparable with time intervals between successive wind data. Plume meandering and dispersion due to turbulent motions with longer time scales than the intervals between successive meteorological data sets are implicitly modelled in SPADE by the variations in the puff trajectories, while dispersion due to turbulent motions with shorter time scales will be described by the expansion of the puffs.

The use of dispersion coefficients derived for sampling times longer than the average time interval between wind measurements would lead to underestimated maximum ground level concentrations and to overestimation of the extent of the area with significant ground level concentrations, while the opposite would occur if dispersion coefficients derived for sampling times shorter than the average time interval between wind measurements were used.

The hierarchy in which available meteorological data is used in calculating the horizontal dispersion coefficient σ_y is as follows. If horizontal wind direction fluctuation measurements σ_θ are available, then σ_y is given by;

$$\sigma_y = \sigma_\theta x \ f(\frac{t}{t_L}) \qquad 3.14$$

where x = distance from the source (m)
t = elapsed time from the release (s)
t_L = Lagrangian time scale (s)

The form of the function f (t/t_L) is taken from Draxler (1976), (see also Irwin, 1982);

$$f(\frac{t}{t_L}) = [1 + 0.9 \sqrt{\frac{t}{1000}}]^{-1} \qquad 3.15$$

If σ_θ data are not available, σ_y values are computed from a set of dispersion coefficients dependent on the atmospheric stability category and are power laws of the distance from the source:

$$\sigma_y = A\, x^B \qquad 3.16$$

The following sets of dispersion coefficients can be selected:

i) Pasquill-Gifford curves modified for stable classes to take into account the increasing spread due to plume meanders (Pasquill, 1976; Start and Wendell,1974).

ii) Original Pasquill-Turner curves for rural environment and 10 minutes sampling period (Turner, 1969).

iii) Coefficients derived by Smith (1968), who summarizes the Brookhaven National Laboratories formulas, based on hourly average measurements of a non-buoyant plume released from 108 m height.

Due to the difficulty of the measurement and consequently the general unavailability, of the vertical component of turbulence intensity (σ_ϕ), σ_z values are computed by using a power law of the distance from the source;

$$\sigma_z = C\, x^D \qquad 3.17$$

The following sets of dispersion coefficients can be selected:

i) Pasquill-Gifford curves as used for Gaussian particle dispersion in the ADPIC model (Lange,1978).

ii) Coefficients determined for emission height 50 m and major ground roughness types by Vogt (1977), see (IAEA, 1982).

iii) Coefficients derived by Smith (1968).

If atmospheric stability changes at any time, then the 'virtual source' model is used whereby the current values of σ_y and σ_z are maintained, but their subsequent rate of change is determined from the appropriate curve for the new stability category.

In calm or low wind speed conditions, 3.16 and 3.17 are substituted by

$$\sigma_y = A\,(t\,u)^B \;, \qquad \sigma_z = C\,(t\,u)^D \qquad 3.18$$

with u = 1 $m.s^{-1}$, or an equivalent 'virtual' velocity.

Thus, in low winds, the dispersion coefficients are transformed from distance-dependent to time-dependent, to allow a realistic treatment of puff spreading. For a more proper use of the model in this case, a special set of dispersion coefficients empirically derived for calm conditions should be used, if available.

The stability category is computed by SPADE for each meteorological data set, based on a radiation index. The radiation index is determined from the angle of elevation of the sun (which is in turn derived from the date and hour of the SPADE simulation), cloud cover and wind speed, following a method developed by Turner (1964) and revised by Cagnetti et al. (1981). For sites where solar radiation data are available a different algorithm for the calculation of stability category based on solar radiation data is used. In this case the solar radiation intensity instead of cloud cover must be included into the meteorological input file.

Another important input parameter for the dispersion calculation in SPADE is the mixing layer height h. The following hierarchy of alternative methods for evaluating the mixing layer height is suggested. If temperature soundings data are available, the base of the inversion layer or of an elevated stable layer should be used as mixing layer height. Alternatively, the following equations could be used for the neutral and the stable cases respectively, for example (Van Ulden and Holstlag, 1985);

$$h = \frac{0.2\, u_*}{f} \qquad 3.19$$

and

$$h = 0.4 \sqrt{\frac{u_* L}{f}} \qquad 3.20$$

where f = the Coriolis parameter (s^{-1})
u_* = the fricton velocity ($m.s^{-1}$)
L = the Monin-Obukhov length (m)

No adequate diagnostic equations exist for the unstable case. Instead, rate equations are available (for example Carson, 1973) which depend on several atmospheric variables that could be not routinely measured. Alternatively, in absence of vertical temperature data, the depth of the mixing layer can be roughly evaluated by using nomograms (Underwood et al. 1984) relating h with other variables (stability, wind speed, etc.) in standard climatological conditions. This is an aspect of dispersion modelling in which further development is needed over this and other distance scales.

Specific processes

Plume rise

In the SPADE model, plume rise, or more precisely, puff rise, is calculated using the Briggs' plume rise equations (Briggs 1969, 1973, 1975). Both transitional and equilibrium plume rise are calculated. Each puff is positioned, in the vertical, at an 'effective stack height' which is the sum of the actual stack height h_s and the plume rise Δh_s.

For unstable and neutral conditions (stability classes 1, 2, 3 and 4), plume rise above the stack is given by:

$$\Delta h_s = \frac{1.6 \sqrt[3]{F x^2}}{u} \qquad \text{if } x < 3.5\, x_* \qquad 3.21$$

$$\Delta h_s = \frac{1.6 \sqrt[3]{12.25 F x_*^2}}{u} \qquad \text{if } x \geq 3.5\, x_*$$

where F = the buoyancy flux of stack emissions ($m^4.s^{-3}$)
x_* = the downwind distance at which atmospheric turbulence dominates entrainment in plume rise (m)
($x_* = 34\, F^{2/5}$ if $F > 55.0$; $x_* = 14\, F^{5/8}$ if $F < 55.0$)
$3.5\, x_*$ being the appropriate downwind distance at which the plume levels off

and

$$F = g\, v_e\, d^2\, \frac{(T_s - T_a)}{4 T_s}$$

where v_e = exit velocity ($m\ s^{-1}$).
d = stack diameter (m).
T_s = stack temperature (°).
T_a = ambient temperature (°).

For stable conditions (stability classes > 4);

$$\Delta h_s = \frac{1.6 \sqrt[3]{F x^2}}{u} \qquad \text{if } x < 2.07\, u \sqrt{s} \qquad 3.22$$

$$\Delta h_s = 2.6 \sqrt[3]{\frac{F}{u\, s}} \qquad \text{if } x \geq 2.07\, u \sqrt{s}$$

where s is an stability parameter based on atmospheric lapse rate:

$$s = (\frac{g}{\Theta})(\frac{\partial \Theta}{\partial z})$$

and $\partial\Theta/\partial z$ is the rate of change of potential temperature with height.

For low wind speeds, the plume rise is given by

$$\Delta h_s = 5\sqrt[8]{F^2 s^{-3}} \qquad 3.23$$

For stability class 5 (weakly to moderately stable), s = 0.0003 and for stability class 6 (stable), s = 0.001.

Buoyancy enhanced dispersion

For buoyant plumes, the entrainment of ambient air, induced by the vertical motion of the plume relative to the ambient air, contributes to their growth as they rise to stabilization height. This enhanced plume growth is modelled in SPADE by the following relationship (Pasquill,1976);

$$\sigma_b = \frac{\Delta h_s}{\sqrt{10}} \qquad 3.24$$

This formulation of plume enhancement is applied to both σ_y and σ_z in the same way. The resultant values of σ_y and σ_z can be expressed as the square roots of the sum of the squares of the ambient turbulence component and the plume buoyancy component, σ_b.

Partial plume penetration of an elevated inversion

Most present gaussian air quality models treat the stable stratification above the mixing layer as either a perfect reflector or perfect absorber of a growing and rising plume. This binary mode of modelling of plume behaviour is not a very realistic approximation and in some cases can lead to serious errors in concentration predictions.

SPADE allows for the simulation of intermediate situations with the introduction of a partial plume penetration factor, (REFL in the input file SOURCE) ranging from 0 to 1, which multiplies the last two terms of the exponent in 3.12. The default situation is total reflection (REFL = 1). Different values of REFL can be chosen based on information about the strenght and the height of the upper stable layer limiting the vertical spread of the puff. For buoyant, rising plumes, the effective plume height computed using 3.20 and 3.21 can be higher than mixing layer height. In this case the plume rise is recalculated using the Briggs (1975) option for plume rise penetration in an elevated stable layer. The effective plume height z_e is given by;

$$(\frac{z_e}{h})^3 - (\frac{z_e}{h})^2 - (c - \frac{4}{27}) = 0 \qquad 3.25$$

where

$$c = \frac{2F}{0.16\, u\, s\, h^3}$$

with the same notation for F and s as in 3.22.

Only the fraction of the puff that is within the mixing layer is assumed to contribute to ground level air concentrations from that puff.

Dry deposition

In SPADE dry deposition is modelled by the method referred to in section 3.1.4 and equation 3.6. Nuclide deposition velocities are specified as input data, the effects of aerodynamic, crop canopy, and surface resistance (equation 3.7), thus need to be taken into account when selecting appopriate deposition velocities.

Wet deposition

Wet deposition is modelled in SPADE by the method referred to in section 3.1.4 and equations 3.8 and 3.9. SPADE assumes that the washout rate (Λ) is a linear function of rainfall rate, i.e. p in 3.9 is unity. Again, the effective washout coefficients are specified as input data, while the rainfall rate is one of the required meteorological input variables. Rainfall rates are assumed constant over the whole computation domain.

Radioactive decay

Radioactive decay is considered by SPADE with the following method. Each puff is depleted for an amount that, at each time step, is given by

$$Q_2 = Q_1 \, e^{-\lambda_D (t_2 - t_1)} \qquad 3.26$$

where Q_1, Q_2 = activity within a puff at times t_1 and t_2 (Bq)
λ_D = decay constant (s^{-1})

The decay constant is specified for each nuclide as input data.

Plume depletion by dry and wet deposition

Plume depletion by dry and wet deposition is taken into account by SPADE by computing, at each cycle, the decrease of the amount of pollutant contained in each puff. For dry deposition, the puff depletion in a time step is given by;

$$Q_2 = Q_1 \sqrt{\frac{\pi}{2}} \, v_d \, (t_2 - t_1) \, \frac{e^{-\frac{z_0^2}{2\sigma_z^2}}}{\sigma_z} \qquad 3.27$$

with the same notation as above, while for wet deposition, puff depletion is given by;

$$Q_2 = Q_1 \, e^{-\Lambda (t_2 - t_1)} \qquad 3.28$$

where Λ has the same meaning as in 3.9.

Cloud gamma dose rate

SPADE incoroporates a module for the estimate of the absorbed dose rate in air from a γ emitting plume. Use of the semi-infinite cloud model for γ dose calculation can lead to

considerable error close to the source and also at a distance for points not close to the plume centerline, particularly for elevated releases. For this reason, a finite cloud model is used in SPADE, integrating over all the emitting sources, i.e. over the puffs.

The absorbed dose rate in air is obtained as the product of the effective γ flux and the absorbed dose rate in air per photon per unit area (Jones, 1980). The effective γ flux,F, from a plume with a air concentration C per unit volume v is obtained by the use of a multiple scattering build up factor and is given by;

$$F = \int_{v} \frac{f\,C\,B(E,\,vr)\,e^{-vr}}{4\,\pi r^{2}}\,dv \qquad 3.29$$

where f = branching ratio to the specified γ energy,
B = the energy deposition build-up factor,
E = the γ ray decay energy,
v = linear attenuation coefficient.

The build-up factors are parameterized by

$$B(E,\,vr) = 1 + avr\,e^{bvr} \qquad 3.30$$

where a and b are are functions of energy.

The integral in 3.30 is evaluated numerically in SPADE using spherical polar coordinates with the origin at the point where the dose is calculated.

The gamma dose rate calculation is an optional output from SPADE, but it takes far longer than the dispersion calculations. It is therefore recommended that SPADE is run first without calculating γ doses and then repeating the run but calculating γ doses at a limited number of sampler points.

3.2.3 Results

Code testing

The SPADE computer code has been tested by simulating a wide variety of meteorological and source conditions, i.e. by varying over wide but realistic ranges the values of each individual variable of the SOURCE and METEO input files (see SPADE User's Guide). However, it must be stated that the code testing performed cannot be considered comprehensive particularly when the number of possible combinations of the input values is practically infinite; besides, the software is a research product, not an operational engineering product, and it is currently non-optimized and potentially affected by errors.

In particular, the γ dose rate evaluation module has been implemented very recently and it must be emphasised that the present version is a preliminary attempt to integrate a γ dose module within the dispersion module. A much more limited number of tests have been performed for the γ dose than for the dispersion module.

As far as model validation is concerned, SPADE has been compared with the analytic solutions in the cases of constant wind and stability and calm conditions. The conclusion from this study is that SPADE can calculate the simple Gaussian solution to within 5% of the concentration values.

As far as the γ dose is concerned, it has been verified that SPADE estimates by use of the finite cloud model are in agreement (within a factor of 1.05) with the infinite cloud model for receptors located well inside the plume, near the plume centerline. It can be shown that the accuracy of the dose rate estimate is largely dependent on the space integration step which can be adequately changed as a function of the computer power (see SPADE User's Guide).

A model evaluation study with several set of experimental data collected during meteorological and tracer campaigns is currently outstanding. Two data set are presently under consideration: the sea breeze campaign carried out at Montalto di Castro in 1983 and 1984 (Cagnetti et al., 1984), and the SIESTA campaign, originally designed for low wind speed dispersion investigation, over the Swiss plateau (Gassmann et al., 1986).

Preliminary results show that the decoupling of the horizontal and vertical diffusion parameters in SPADE is very effective in simulating the actual dispersion conditions; the

most important parameter affecting the model performance is the wind direction: if an error of 10° or less in the plume centerline trajectory is taken into account, more than 80% of the calculated concentrations arewithin a factor of 5 of the observations.

SPADE generates output files suitable for use by a dose assessment module, such as that described in chapter 5. In addition, output can be graphically represented as isopleth maps either on colour videographic terminals or on a plotter. Examples of isopleth plots from a typical SPADE run are illustrated in figures 3.1 - 3.4 and the input files for these plots are given in tables 3.1 and 3.2 (see the user guide for definitions of the variables).

XUTM	1800.0	IDELT	5
YUTM	4500.0	MESTR	60
CELSIZ	1.0	ELEM	XXXX, YYYY
XEST	1.0	IDOSE	1,0
XNRD	19.0	VDEP	0.0, 0.01
NUMKAL	2	WASH	0.0001
KALTT	60, 120	THALF	9999999.0, 9999999.0
IMON	03	HSOUR	10.0
IDAY	01	DIA	0.0
IHOU	08	REFL	1.0
IMIN	00	IDIFY	1
ISTOP	120	DIFZ	1

Table 3.1 Sample source input file for SPADE.

MH	8	MM	0
SRATE	1.0, 1.0	RAIN	0.0
MCL	6	MTOP	500
IHG	10, 100, 500	POWER	0.0
VEL	3.0, 5.0, 6.0		
DIR	300.0, 330.0, 340.0		
MH	9	MM	0
SRATE	1.0, 1.0	RAIN	0.0
MCL	2	MTOP	700
IHG	10, 100, 500	POWER	0.0
VEL	2.0, 3.5, 4.0		
DIR	320.0, 350.0, 350.0		

Table 3.2 Sample meteorological input files for SPADE.

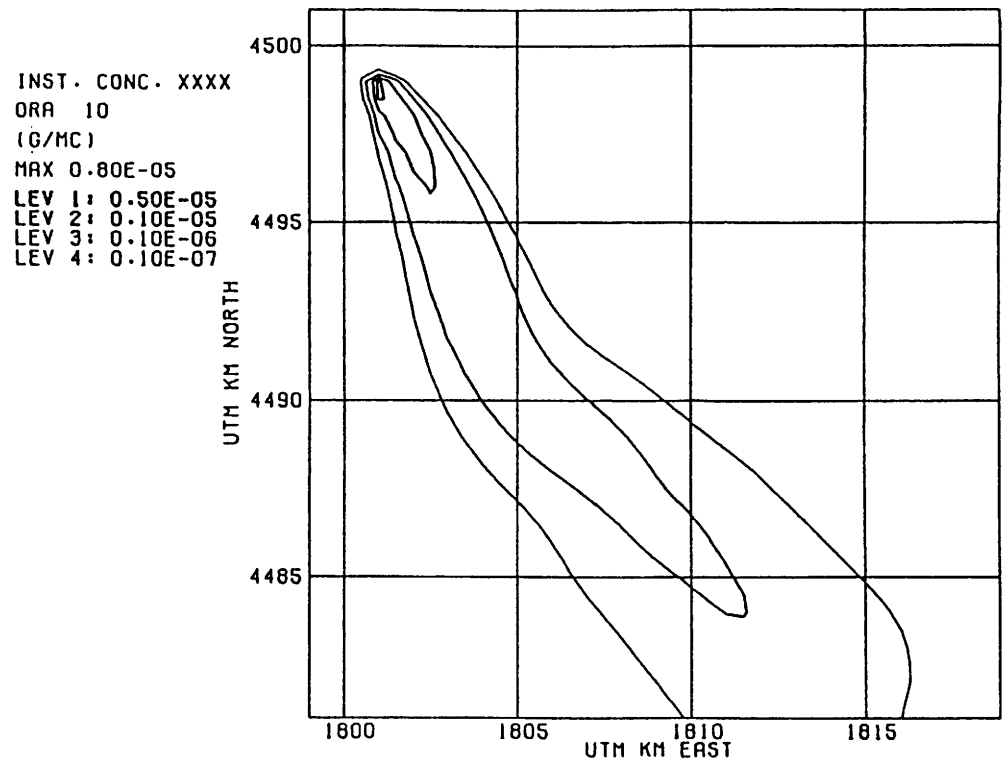

Figure 3.1 **Instantaneous air concentration XXXX after two hours.**

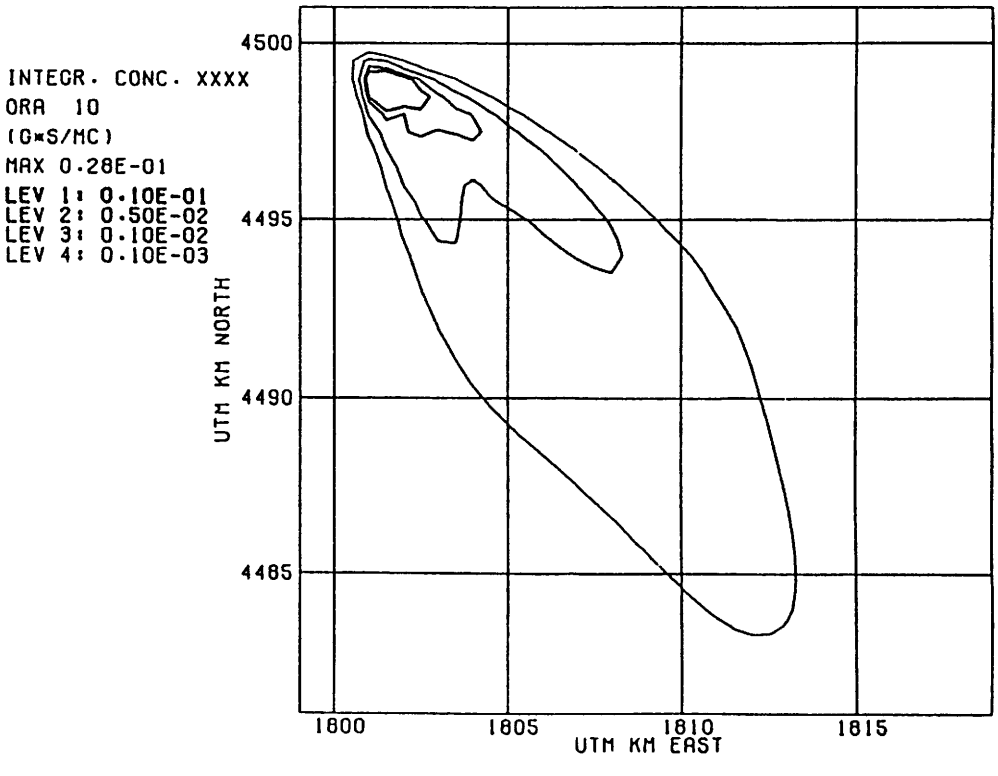

Figure 3.2 **Integrated air concentration XXXX after two hours.**

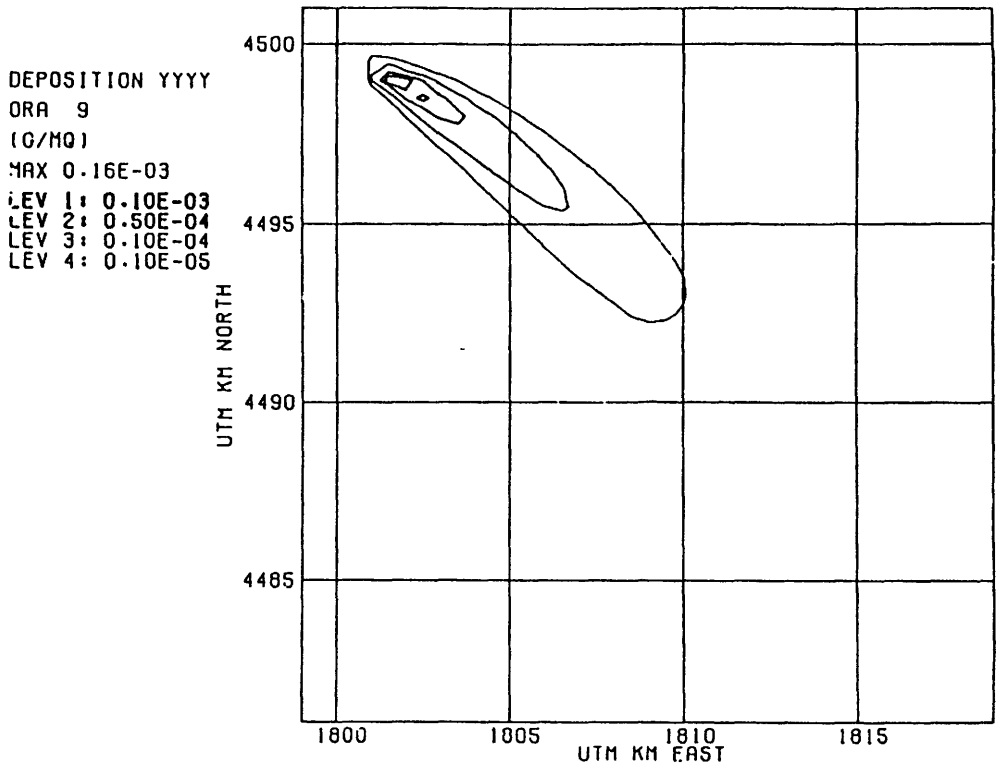

Figure 3.3 Total deposition YYYY after one hour.

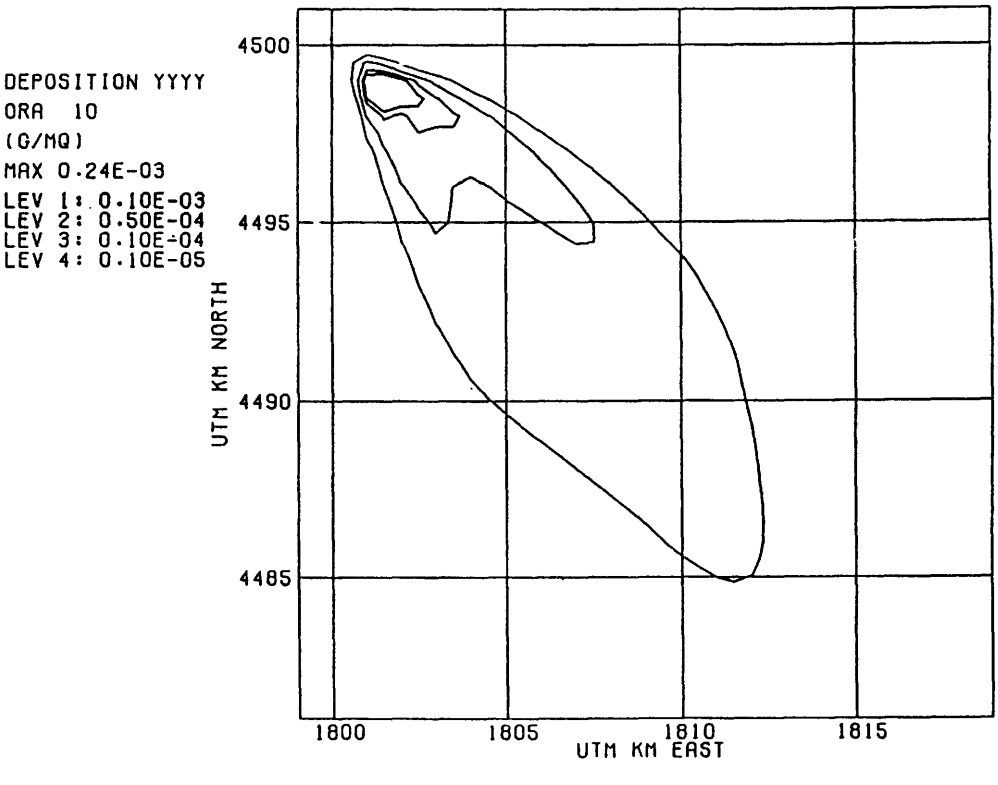

Figure 3.4 Total deposition YYYY after two hours.

3.3 A Mesoscale Dispersion Model: MC31

3.3.1 Introduction

MC31 calculates concentrations of atmospheric pollutants in complex situations, such as as hilly terrain, urban areas, and coastal regions with a high spatial and temporal numerical resolution and a detailed description of the studied domain. In the mesoscale, these situations have to be taken into account and the calcu lation of atmospheric concentrations up to 100 or 200 km away from the source should be carried out with a code which allows meteorological conditions to vary in both space and time.

The dispersion-advection equation is resolve numerically using a Lagrangian Monte-Carlo method. This method is based on work performed by the Soviet mathematicians Khintchine, Guikman Skorokhod and Kolmogorov (1972, 1980) and the Japanese mathematician Ito. An advantage of this resolution method is that it provides useful analytical results, i.e.

- a value representing the probability of a particle, located at any given point in a medium, exiting that medium,
- values characterising a distribution of the departure time from the domain, and the moments, of any order, in this distribution.

Thus, the trajectory of a particle can be simulated, and the equation resolved in any medium by using a number of simulations.

The method used describes the chaotic movement of a particle in suspension in air as a random progression. The particle moves under the advective action of the fluid, and under the chaotic action of the same fluid. The route followed by a particle can therefore be described as a sequence of straight line segments, each segment being taken at random according to a probability law which is dependent on the medium, and on the stochastic process that describes the movement of the particle. A large number of these random progressions are simulated on a computer, and the temporal and spatial distributions of the particles are calculated. If there is a sufficient number of random progressions, the temporal and spatial probability distributions of the presence (or transition) of a particle are clearly described, and are a close representation of the exact solution to the diffusion-advection equation.

The heterogeneous two or three dimensional medium is defined by a physical grid which can, in principle, be of any shape. Average characteristics of the medium are defined for

each grid cell. For example, in a two-dimensional domain, the following are defined for each cell:

- an x component of the advection vector : a_x
- an y component of the advection vector : a_y
- a diffusiveness, such that:
- this grid defines a fixed system of carterian co-ordinates, called the physical grid.

The resolution of the diffusion-advection equation is carried out using the successive random progressions of particles in the medium concerned. At different time steps in the simulation, spatial statistics of the particles are produced for each cell of the grid describing the medium.

Throughout its' trajectory, a particle is associated with a rectangular cell called the 'mobile cell'. This mobile cell is defined in a Cartesian or Eulerian co-ordinate system, with axes, whose directions corresponds to vectors which are co-linear with, and perpendicular to, the wind advection vector. The lower left hand corner of the mobile cell is at the origin of the co-ordinate system, and the upper right hand corner is a point whose co-ordinates are defined in the Eulerian co-ordinate system. The particle is located in the centre of this rectangular cell.

The simulation an atmospheric release consists of successsively firing particles, each one being followed by a rectangular moving cell centred around it. The dimensions of the mobile cell cannot exceed the size of the physical cells for the problem considered. The duration of the time step is controlled by an iterative system which determines the size dimensions of the mobile cell, and therefore the time step, as functions of the wind velocity and the eddy diffusivity.

It is then necessary to calculate the distribution of the first particle exit from the mobile cell and to derive a random exit time according to this probability law. The inverse operation is equivalent, namely, calculation of the exit probability for an arbitrarily chosen time. This technique would be the most strict and the most representative of the method developed, however, it is not very realistic. It would be impractical to calculate a new probability law at each time step, assuming that the physical characteristics of the medium change each time. Such a calculation would require a particulary complex series to be computed, and its' convergence would imply the calculation of a fairly large number of terms.

The exact calculation of this probability distribution can reasonably be replaced by the reconstruction of the diustribution from the first moments, which are fairly easy to calculate, particularly if the mean time is used (i.e. the case of uniform distribution).

To carry out the spatial resolution, we have retained the method which uses centred finite differential discrete substitution, which is a correct approximation. The approximation permits the particle to exit from the corners of the mobile cell, giving 4 possible exits for a 2-dimensional case, and 8 for the three-dimensional case. In addition, different limit conditions can be taken into account in the random progression method described above, although this method involves complex calculations in the latter case.

The zero entry current condition has no influence on the trajectory of the particles, since they simply pass through the limit of the domain; any particle which leaves the domain cannot return into it. The flow condition causes a reflection on the limit of the domain; this reflection can be total, or partial if there is an albedo condition.

In order to characterise the particle, it is necessary to define a radioactive yield coefficient, which is translated into the probability of a particle disintegrating after a transfer time T. The source is defined in the Cartesian co-ordinate system of the physical grid. A block of data enables the vector fields associated with the medium to be defined, each vector is centred on a mesh of the physical grid. The source of radioactivity released into the atmosphere is thus defined by the co-ordinates of its emission point, and by the radioactive yield constant. A further data block defines the observation steps; these are marked periods, counted from the instant when the particles are temitted, when the distribution of particles in the domain is output in the form of a table.

The program, without its graphics module, is entirely written in Fortran, and does not call upon any specific mathematical library, consequently it is totally portable.

The medium through which the release is dispersed is described by a regular two- or three-dimensional Cartesian grid. Eight parameters are associated with each cell of the grid:

- An axial turbulence coefficient.
- A transverse turbulence coefficient.
- A vertical turbulence coefficient.
- An absorption coefficient which takes various processes into account, such as changes of phase or wash-out by rain. This coefficient is then translated into a probability term. Thus

the speed of deposition of the particles on the ground, from the lower layers of the atmosphere, becomes the probability of a particle being deposited on the ground when it arrives there, i.e. the probability of it being retained, especially if the ground is rough.

- Four coefficients showing the behaviour of the particle when it crosses one of the sides of the rectangular cell, or six coefficients showing the behaviour of the particle when it crosses one of the faces of the rectangular parallelipiped-shaped cell in a three dimensional situation. Each coefficient represents the albedo as a probability β between 0 and 1. Thus the particle has a probability β of passing through the face or side of the cell, and a probability $(1-\beta)$ of being reflected. One coefficient is defined per side or face of the cell.

- One field of vectors is associated with the medium. A two or three-dimensional vector is associated with each cell. This vector is defined by its components in the fixed Cartesian coordinate system defined by the two- or three-dimensional grid. The origin of this vector is located at the centre of each of the cells.

Together, these parameters define the wind field. By defining a medium in terms of the above parameters, it is possible to consider any one- two- or three-dimensional medium. It is therefore easy to define a medium using, for example, three types of cell:

- A 'ground' type cell, whose coefficients of turbulence, absorption, and advection are defined for the lowest level of the atmosphere.

- An 'air' type cell, whose coefficients of turbulence, absorption and advection are defined for the corresponding layers of the atmosphere.

- An 'inversion limit' type cell, whose coefficients of turbulence, absorption and advection are defined for the highest layer of the atmosphere.

In theory, this model has no limits. It is icapable of describing complex media at different scales (macro, meso and micro) with various conditions at the different limits (absorption - total or partial reflection with albedo, on one of the faces of any cell used to describe the medium). The only limits to the model are either program-included and/or linked with the capacity of the computer in which the model is running, for example, the number of cells used to described the medium, or power of the computer used.

3.3.2 Physical and mathematical aspects of the model

Stochastic formulation of the diffusion-advection equation

The diffusion-advection equation is the solution of a stochastic differential equation representing a random Markov process with continuous values. A process occurring in a physical system is said to be a Markov process if, at each instant, the probability of any given state in the future depends only on the state of the system at the current instant t_0, and

has no relation to the system which caused it to be in this state. A simple example of a random Markov process follows:

A particle moves randomly along the abscissa OX. At instant $t = 0$, the particle is located at the origin of the system (x_0), and remains there for one second. At the end of this second, the particle has a probability of $^1/_2$ of moving one length-unit towards the right, and a probability of $^1/_2$ of moving one length-unit towards the left. One second later, a further random movement is made according to the probabilities described above. The random movements of the particle constitute a discrete-time random process with countable states. The possible transitions involved in this process can be represented thus:

$$x_{-n} \ldots . <=> \; x_{-2} <=> x_{-1} <=> x_0 <=> x_1 <=> x_2 \ldots . <=> x_n$$

This is very similar to a diffusion diagram and clearly represents a Markov process. For example, at time t_0, the state of the system, i.e. the position of the particle, is x_1, one distance unit from the origin of the co-ordinate system. During the next second, the particle has equal probabilities of $^1/_2$ of moving either to position x_0 or to position x_2; after two seconds, the particle will be in position x_{-1}, x_1 or x_3 with respective probabilities of $^1/_4$, $^1/_2$ and $^1/_4$, and so on. Thus all the probabilities depend on the position of the particle at instant t_0, and are independent of how the particle got there.

If at timet_0, the system is in an x_K state, the probability of any given event in the future is independent of the history of the process, and the probability of a particle leaving state x_K for a period of time Δt is independent of the time the particle spent in that state. Consequently, the probability of the particle changing to state x_K will follow an exponential curve. When the process occurring in a continuous-time physical system with countable states is Markovian, it can be described by means of ordinary differential equations in which the unknown functions are the probabilities of different states occurring.

General formulation

The following transport equation:

$$\frac{1}{2}b^2 \frac{\partial}{\partial x^2}[\varphi(x,t)] + a(t)\frac{\partial}{\partial x}[\varphi(x,t)] + \frac{\partial}{\partial t}\varphi(x,t) = 0 \qquad 3.31$$

is solved using a stochastic differential equation method. N.B. this solution to the equation is the transition probability of the Markovian process which describes the diffusion-advection phenomenon. It can be replaced by the following hyperbolic equation:

$$\frac{1}{2}\frac{\partial}{\partial x^2}[b^2\varphi(x,t)] + \frac{\partial}{\partial x}[a(x,t)\ \varphi(x,t)] = 0 \qquad 3.32$$

whose solution is the transition probability density. The distribution of the time of the first exit is obtained by solving the following differential equation:

$$\frac{1}{2}\frac{\partial}{\partial x^2}[b^2\ v_\lambda(x)] + \frac{\partial}{\partial x}[a(x,t)\ v_\lambda(x)] - \lambda v_\lambda(x) = 0 \qquad 3.33$$

and then carrying out the inverse Laplace transformation of $v\lambda(x)$ in relation to t.

Consider a finite, homogeneous, one-dimensional medium. This medium is a segment (α, β) of the Δ_x segment; it has a constant advection vector a and a constant dispersion b^2. A particle is located inside this segment, at point x. We will now determine:

- the probability of a particle exiting at α,
- the probability of a particle exiting at β,
- the time distribution of the first exit of the particle from segment (α, β),
- and, the first moments of this distribution.

Care should be taken to ensure that the established formulae remain valid in the absence of any advection, i.e. for a pure diffusion process. Thus, we solve the following hyperbolic partial differential equation:

$$\frac{1}{2}b^2\frac{\partial^2}{\partial x^2}\varphi(x) + a\frac{\partial}{\partial x}\varphi(x) = 0 \qquad 3.34$$

with the following limit condition: $\varphi(a) = 0$.

We can then obtain the probability density for the transition of a particle from x to α or from x to β.

$$\varphi(x) = -\frac{b^2}{2a} e^{-(\frac{2a}{b^2}(x-\alpha))} - 1 \qquad 3.35$$

Equations programmed into the calculation code, and algorithms used

The following is a detailed explanation of the numerical resolution method chosen to solve the diffusion-advection equations in any given medium that is finite, one- two- or three-dimensional and non-homogeneous.

Description of a one-dimensional random progression

We will first describe a random progression in an homogeneous one-dimensional medium, Δ, which can be represented by a straight line. Let (α, β) be a segment of straight line Δ. The medium Δ has a velocity field a and a coefficient of diffusion b^2. We will assume that the particle is located in the centre of segment (α, β), and postulate $h = X - \alpha = \beta - x$. Taking the results obtained in the previous section, we can calculate $P(\beta)$, the probability of transition of the particle to β.

If $\varphi(X)$ denotes the probability density of the presence of a particle at point X, and $\varphi(\beta)$ the probability density of the presence of a particle at β, then:

$$\varphi(X) = P(\beta)\ \varphi(\beta)$$

Where $\varphi(X)$ is given by 3.35, and

$$P(\beta) = \frac{e^{-\frac{2ah}{b^2}} - 1}{e^{-\frac{4ah}{b^2}} - 1} \qquad 3.36$$

The probability of transition to α, called $P(\alpha)$, is written:

$$P(\alpha) = 1 - P(\beta)$$

If the particle is initially located in $x = {}^{h}/_{2}$, the first moment of the time distribution of the first exit of the particule from (α,β) is:

$$T_x = -\frac{h}{a}\left[1 - \frac{2}{e^{-\frac{2ah}{b^2}} - 1}\right] \qquad 3.37$$

Using these three simple results, it is possible to effect a random progression by proceeding as follows:

i) The particle is at X, in the centre of an interval (a,b)

ii) draw a random number between 0 and 1
- If this number is greater than $P(b)$, the particle goes to a, and therefore $X = X - h$
- If it is less than this number, the particle goes to b, and therefore $X = X + h$

iii) the time is incremented by T_X

iv) return to i)

It is clear that this simple calculation process does not assume that a and b^2 are constant in either space or time, and is therefore sufficient to solve the diffusion-advection equation in a finite, heterogeneous and one-dimensional medium. It does this in a very straighforward manner, and is very fast.

Two-dimensional random progression

Consider a finite, heterogeneous two-dimensional medium defined by a grid which can, in principle, be of any shape.The mean characteristics of the medium are defined for each grid cell as follows:

- an x component of the advection vector: a_x
- a y component of the advection vector: a_y
- a diffusiveness a, such that:

$$b_x^2 = 2\,|\alpha|\,a_x$$
$$b_y^2 = 2\,|\alpha|\,a_y$$

The resolution of the diffusion-advection equation is carried out using the successive random progressions of particles in the medium concerned. At different time steps in the simulation, spatial statistics of the particles are produced for each cell of the grid describing the medium.

Description of a two-dimensional random progression

By definition, a random progression is a sequence of segment trajectories, whose length and direction are defined on an elementary basis by solving locally the diffusion-advection equation. Consider a fixed Lagrangian system of Cartesian co-ordinates in which the grid defined earlier is defined. This system of coordinates is defined by the O_tX_t and O_tY_t axes. Now consider a particle located at point M, whose coordinates are (x_t, y_t), at time T.

We will now associate the particle, throughout its' trajectory, with a rectangular mobile cell. This mobile cell is associated with a Eulerian system of Cartesian co-ordinates defined by the O_AX_A axis, whose direction corresponds to a vector which is co-linear with the advection vector a, and by the O_AY_A axis, whose direction corresponds to a vector which is perpendicular to the advection vector, and is such that (O_AX_A, O_AY_A) is direct.

The mobile cell is defined by the axes of the Eulerian co-ordinate system; the lower left-hand corner is the origin of the coordinate system, and the upper right-hand corner is the point with Eulerian co-ordinates (X_A,Y_A) in Eulerian co-ordinates. The particle is located in the centre of this grid cell: at ($X_A/2$,$Y_A/2$), as shown in figure 3.5.

Local resolution of the diffusion-advection equation

The diffusion-advection equation is solved within the mobile cell using the following method.

To carry out the spatial resolution, we have retained the method which uses centred finite differential discrete substitution. As we have seen from the one-dimensional random

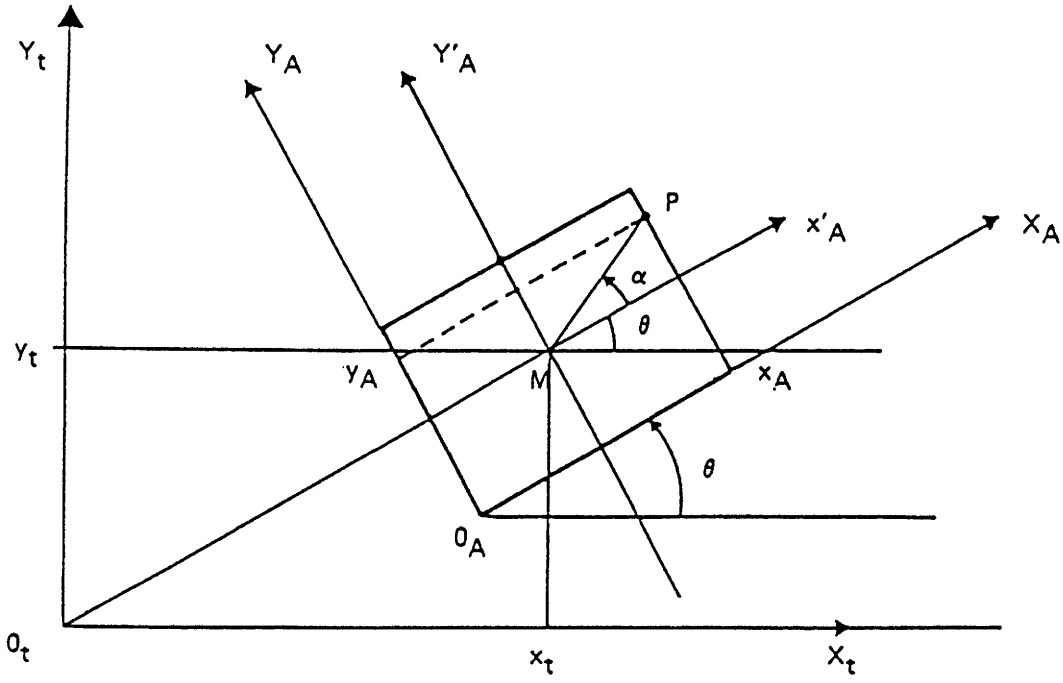

Figure 3.5 Illustration of the Lagrangian and Eulerian co-ordinate systems for the two dimensional case.

progression case, this is is a correct approximation. The equation is as follows:

$$\frac{1}{2}b_x^2\frac{\partial^2\varphi(x,y)}{\partial x^2}+\frac{1}{2}b_y^2\frac{\partial^2\varphi(x,y)}{\partial y^2}+a_x\frac{\partial\varphi(x,y)}{\partial x}=0 \qquad 3.38$$

which after discrete substitution, becomes:

$$\frac{1}{2}b_x^2\frac{\varphi(x+h,y)-2\varphi(x,y)+\varphi(x-h,y)}{h^2}+$$

$$\frac{1}{2}b_y^2\frac{\varphi(x,y+p)-2\varphi(x,y)+\varphi(x,y-p)}{p^2}+$$

$$a_x\frac{\varphi(x+h,y)-\varphi(x,y)}{h}=0 \qquad 3.39$$

in which

$$h=\frac{X_A}{2} \quad \text{and} \quad p=\frac{Y_A}{2}$$

If we rearrange this equation in terms of probability, then if the points A, B, C, and D have the following co-ordinates: $(x\text{-}h, y)$, $(x, y+p)$, $(x+h, y)$, $(x, y-p)$ respectively, and $p(A)$, $p(B)$, $p(C)$, $p(D)$ represent the probabilities of a particle exiting at A, B, C or D, when its' original position was at M, in the centre of the rectangular cell, then:

$$\varphi(x) = P(A)\ \varphi(x-h,y) + P(B)\ \varphi(x,y+p) + P(C)\ \varphi(x+h,y) + P(D)\ \varphi(x,y-p)$$

with:

$$P(A) = \frac{b^2 x}{2h^2 D} \qquad 3.40$$

$$P(B) = \frac{b^2 y}{2p^2 D} \qquad 3.41$$

$$P(C) = \frac{b^2 x + 2axh}{2h^2 D} \qquad 3.42$$

$$P(D) = \frac{b^2 y}{2p^2 D} \qquad 3.43$$

and

$$D = \frac{b^2 x}{h^2} + \frac{b^2 y}{p^2} + \frac{ax}{h}$$

Until now, neither x_a, nor y_a, nor even h and p have been determined. Indeed, in both the one-dimensional random progression case and the previous sections, the first moment in the exit time distribution, i.e. the mean time, is dependent on the size of the domain. We therefore use an arbitrarily specified time pitch (or step) to define the size of the mobile cell, and vice versa. In order to solve the problem with respect to time, we project the above equation on the x-axis and calculate the mean exit time, i.e. the first moment from 3.38.

The value of T_x will enable the size of the grid cell to be determined. If we project the diffusion-advection equation onto the y-axis, we can also calculate the mean exit time; this is given by the following relationship:

$$T_Y = \frac{p^2}{b^2 y} \qquad 3.44$$

If we take any grid cell, it is possible to calculate the spatial exit probabilities of the cell, as shown earlier. It is merely necessary to calculate the distribution of the first particle exit, and to derive a random exit time according to this probability law. The inverse operation is equivalent: calculation of the exit probability for an arbitrarily chosen time (for example the mean time T). In the latter case, we no longer add 1 into the cell containing the particle, but its probability of presence instead.

Again, although this technique is the strictest and the most representative of the methods we are developing, it is not very realistic. The exact calculation of this probability distribution can however be reconstructed from the first moments, which is a fairly easy calculation, as we saw earlier.

Simulation method

The simulation consists of successively releasing particles, each one being followed by a rectangular mobile cell centred around it. The X-axis of this cell is parallel to the direction of convection, and the Y-axis is perpendicular to the X-axis, both axes are defined positive.

Calculation of mobile cell dimensions

The dimensions of the mobile cell cannot exceed the size of the physical grid cell of the problem considered. The size of T_x is given by the iterative system, which manages the value and succession of the time steps. This value enables the size of the mobile cell to be determined along the X-axis, by solving 3.38. h is the unknown quantity in this equation, which we solve using Müller's method. Once we have determined the value of h, it is merely necessary to calculate the values of p which solve the following trivial equation:

$$T_x = \frac{1}{b^2 y} p^2 \quad \text{i.e. } p = \sqrt{b^2 y T_x} = b\sqrt{y T_x}$$

Probability of the particle exiting the mobile cell

The previous calculations give both the mean time to exit the grid cell and the dimensions of the cell, i.e. h and p. We now call a random number; according to this random number, the particle will leave the cell through one of the points A, B, C or D. The iterator then calculates the co-ordinates of the exit point in the fixed Lagrangian co-ordinate system, using standard transformation formulae.

Formula for switching from Eulerian to Lagrangian co-ordinates

The calculations are actually carried out in the Eulerian co-ordinate system of the $Y_A\, O_A\, X_A$ mobile cell. It is therefore necessary, at each stage, to return to the Lagrangian co-ordinate system $Y_t\, O_t\, X_t$. We begin by switching from the $Y_A\, O_A\, X_A$ co-ordinate system to the $Y'_A\, M\, X'_A$ co-ordinate system, through the following transformation:

$$x'_A = x_A - h$$

$$y' = y_A - p$$

The angle φ is determined by the following relationships:

$$\varphi = \text{Arc cos} \frac{x'_A}{x'^2_A + y'^2_A} \quad \text{if } y'_A > 0$$

$$\text{or } \varphi = \text{Arc cos} \frac{x'_A}{x'^2_A + y'^2_A} \pi$$

We can therefore switch from the $Y'_A\, M\, X'_A$ co-ordinate system to the co-ordinate system $Y_t\, O_t\, X_t$.through the following transformations:

$$x''_t = x_t + [x'^2_A + y'^2_A] \cos(\theta + \varphi)$$

$$y''_t = y_t + [x'^2_A + y'^2_A] \sin(\theta + \varphi)$$

Introduction of an absorption term into the equation

In this case, the equation is written:

$$\frac{1}{2}b_x^2\,\varphi'_x + \frac{1}{2}b_y^2\,\varphi'_y - a_x\,\varphi''_x - T_s\varphi_x = 0 \qquad 3.45$$

where T_s is the particle absorption rate at point $(x+h, y+p)$. In order to re-write the entire system of exit probabilities, we can postulate:

$$D = \frac{b^2x\,(h+h^*)}{2h^2h^*} + \frac{b^2y\,(p+p^*)}{2p^2p^*} + \frac{ax}{h^*} + T_s \qquad 3.46$$

The probabilities of the particle leaving the cell; $p(A)$, $p(B)$, $p(C)$, and $p(D)$ are modified accordingly.

$$P(A) = \frac{b^2x}{2hh^*D} \qquad 3.47$$

$$P(B) = \frac{b^2y}{2pp^*D} \qquad 3.48$$

$$P(C) = \frac{b^2x + 2a_xh^*}{2hh^2D} \qquad 3.49$$

$$P(D) = \frac{b^2y}{2pp^*D} \qquad 3.50$$

We can deduce the probability of absorption of the particle in the cell from these. Ifhe theorem of composed probabilities is be applied to the case studied earlier, we can write:

Probability of the particle leaving the cell at X = (Probability of the particle leaving the cell at X/Sub-condition that the particle is not absorbed) x probability of non-absorption of particle Q.

This can be expressed mathematically in the following simplified case where $h = h^*$, $p = p^*$, and $b^2_x = b^2_y = b^2$, and as a further simplification, let us calculate the value of Q for $h = p$.

$$Q = \frac{2b^2 + ah}{2b^2 + ah + T_s h^2} \qquad 3.51$$

the unit of T_s is now equal to [T^{-1}]. Conversely, we could deduce T_s from Q.

$$T_s = (\frac{2b^2 + ah}{h^2})(\frac{1 - Q}{Q}) \qquad 3.52$$

$(1-Q)$ is therefore the probability per m^2 and per s, of a particle being deposited.T_s represents the fraction of the particle deposited per s and is equivalent to the deposition rate. The general form of this is written as follows:

$$T_s = (\frac{b^2 x}{h^2} + \frac{b^2 y}{p^2} + \frac{ax}{h} + \frac{1 - Q}{Q}) \qquad 3.53$$

Limit conditions

We also need to take the different limit conditions into account in the random progression method described above. This method is described for a two-dimensional medium, but is identical for one- or two-dimensional media although it involves more complex calculations in the latter case.

Zero entry current condition

This condition has no influence on the trajectory of the particles, since they simply pass through the limit of the domain: any particle which leaves the domain cannot return into it.

Flow condition: reflection on the limit of the domain

This condition causes a reflection on the limit of the domain; this reflection can be total, or partial if there is an albedo condition.

Total reflection condition

Let AB be a straight line segment which is a part of the frontier; take a particle located at point C, whose trajectory hits frontier AB at a point I, reflects off it, and goes to position M as illustrated in figure 5.6. We will calculate the co-ordinates of point M, taking into account the c-oordinates of A, B, C and D, the latter being the virtual point where the particle would be located if it had not rebounded off the frontier. Point D is symmetrical to M with respect to the line D to which segment AB belongs.

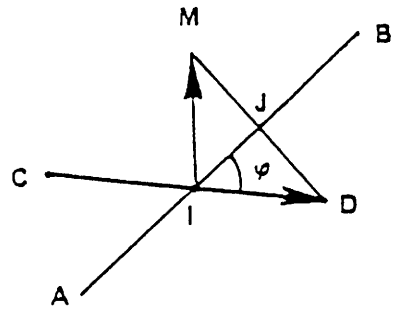

Figure 3.6 Illustration of the total reflection condition

Condition of partial reflection

The condition of partial reflection does not entail any further calculation because, due to the definition of the albedo, the particle has a probability b of being reflected and moving to M, and a probability (1 - b) of being transmitted.

3.3.3 Description of the computer code.

The computer code embodying this model is written in FORTRAN; it consists of one main program and thirteen sub-routines. As the code does not call upon any specific mathematical

libraries, it is totally portable. During a calculation, there is no Input/Output action, which means that the program code and tables are resident in the main memory during execution.The required memory space is almost entirely taken up by the space reserved by three tables:

- A first table containing the data of the wind field at different time steps after emission of the particles. This table therefore contains as many elements as the number of grid-cells, multiplied by the number of wind fields, and multiplied by the number of wind vector components.
- A second table contains the description of the medium. It has as many elements as there are grid-cells.
- A third table contains the vector of the number of 'mother' particles present in a cell at a given time step. It also has as many elements as the number of cells, multiplied by the number of given 'steps'.

This third table can be larger if:

. the user requires results on a finer grid than the one used to describe the medium;
. the user requires an additional table showing the value of the number of 'daughter' particles created by radioactive depletion, present in a cell at a given time step. The table created in this way will be of the same size as the third table.

Execution time

The execution time cannot be specified, as it depends to an enormous extent on the machine used. Execution time depends on two factors:

- the maximum observation time: the greater this time is, the longer the particles will have to be followed,
- the number of particles whose history needs to be followed: the greater the number of particles followed, the more accurate are the results. Indeed, if N is the number of particles emitted, the precision will be in $1/\sqrt{N}$,

The tracking of 10 000 particles thus gives a precision of 10^{-2} , which means that the third decimal in the calculation will be meaningless, however, the calculation times for 10 000 particles and a few hours of simulation will, on most mini-computers, take only a few minutes.

Description of the physical grid system and the parameters associated with each cell

The medium studied is described by a regular two- or three-dimensional Cartesian grid.

Eight parameters are then associatedwith each grid cell:

- An axial turbulence coefficient.
- A transverse turbulence coefficient.
- A vertical turbulence coefficient.
- An absorption coefficient which takes various processes into account, such as changes of phase or wash-out by rain. This coefficient is then translated into a probability term. Thus the speed of deposition of the particles on the ground, from the lower layers of the atmosphere, becomes the probability of a particle being deposited on the ground when it arrives there, i.e. the probability of it being retained, especially if the ground is rough.
- Four coefficients showing the behaviour of the particle when it crosses one of the sides of the rectangular cell, or six coefficients showing the behaviour of the particle when it crosses one of the faces of the rectangular parallelipiped-shaped cell in a three dimensional situation. Each coefficient represents the albedo as a probability β between 0 and 1. Thus the particle has a probability β of passing through the face or side of the cell, and a probability (1- β) of being reflected. One coefficient is defined per side or face of the cell.
- One field of vectors is associated with the medium. A two or three-dimensional vector is associated with each cell. This vector is defined by its components in the fixed Cartesian coordinate system defined by the two- or three-dimensional grid. The origin of this vector is located at the centre of each of the cells.

These parameters together define a windfield.

Construction of a medium

The technique for defining a medium described above enables any one- two- or three-dimensional medium to be defined. It is therefore easy to define a medium using, for example, three types of cell:

- A 'ground' type cell, whose coefficients of turbulence, absorption, and advection are defined for the lowest level of the atmosphere, and whose faces representing the ground are assigned with the total reflection limit condition (β=1). The other faces of the cell must be assigned with a total transmission limit condition.
- An 'air' type cell, whose coefficients of turbulence, absorption and advection are defined for the corresponding layers of the atmosphere; in this case, all the faces of the cells are assigned with a total transmission limit condition.
- an 'inversion limit' type cell, whose coefficients of turbulence, absorption and advection are defined for the highest layer of the atmosphere, and whose topmost face is assigned with a ß albedo transmission-reflection type limit condition. All other faces of this cell are assigned with total transmission limit conditions.

Figure 3.7 illustrates a simple two-dimensional relief situation with an inversion surface.

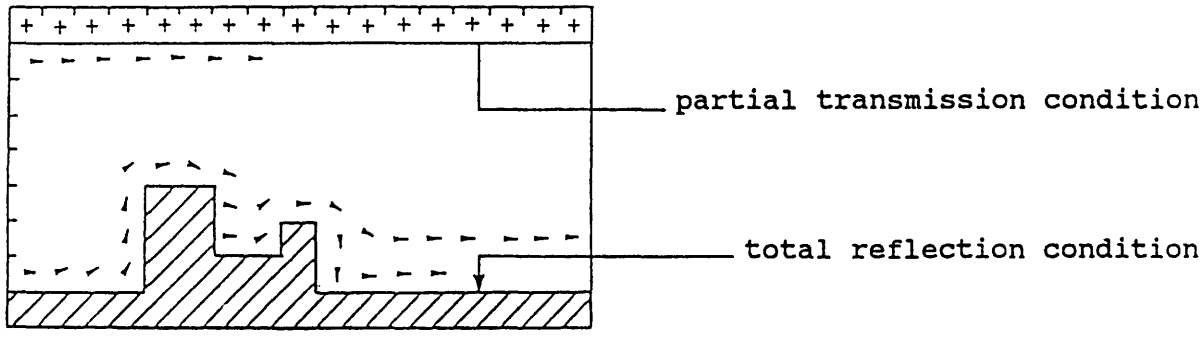

Figure 3.7 Illustration of a simple 2-D representation of relief.

The unfilled cells represent the atmosphere (air cell); the hatched cells represent the ground (ground cells), and the cells containing a cross represent the inversion surface.

Characterisation of the particles

In order to characterise the particle, we define a radioactive depletion coefficient for the particle. This coefficient is also translatable into a probability, i.e. the probability of a particle becoming disintegrated after a transfer time T.

Definition of the source

The emission point is defined by its co-ordinates in the Cartesian coordinate system in which the grid is defined.

3.3.4 Data Input

The data necessary for the calculations are input in the form of a sequential file. Successive

blocks of data define the following groups of model variables:

i) the reference physical grid for the medium

ii) the exit grid

iii) the different media

iv) the parameters connected with each type of cell

v) the vector fields applied to the medium.

vi) the source of radioactivity released to the atmosphere

vii) the observation steps

3.3.5 Output of Results

The results are output in the form of particle concentrations in each of the cells of the output grid: ratio between the number of particles present in a cell, determined at an observation step T, and number of particles thrown out by the source. Output records are written for all cells in which there is at least one particle. Cells which are not identified in the output file do not contain any particles, and are associated with a zero concentration.

As an illustration, a horizontal section of a wind and topography field is shown in figure 3.8, and a vertical profile with a cross section through a release is shown in figure 3.9

3.3.6 Conclusions

Our work has made it possible both to obtain interesting results on the diffusion-advection equation, considered in a stochastic differential form, and to write a computer code which solves the diffusion-convection equation in the most general cases. The primary interest of the proposed method is based on the modicity of the data processing resources required at the end. The resolution code for the diffusion-advection equation in a two-dimensional case, comprising 1 500 grid points, requires:

- less than 60 Kbytes of memory assigned to the program,
- no input-output during the resolution of the equation.

The calculational codes produced using this type of method therefore seem particularly well

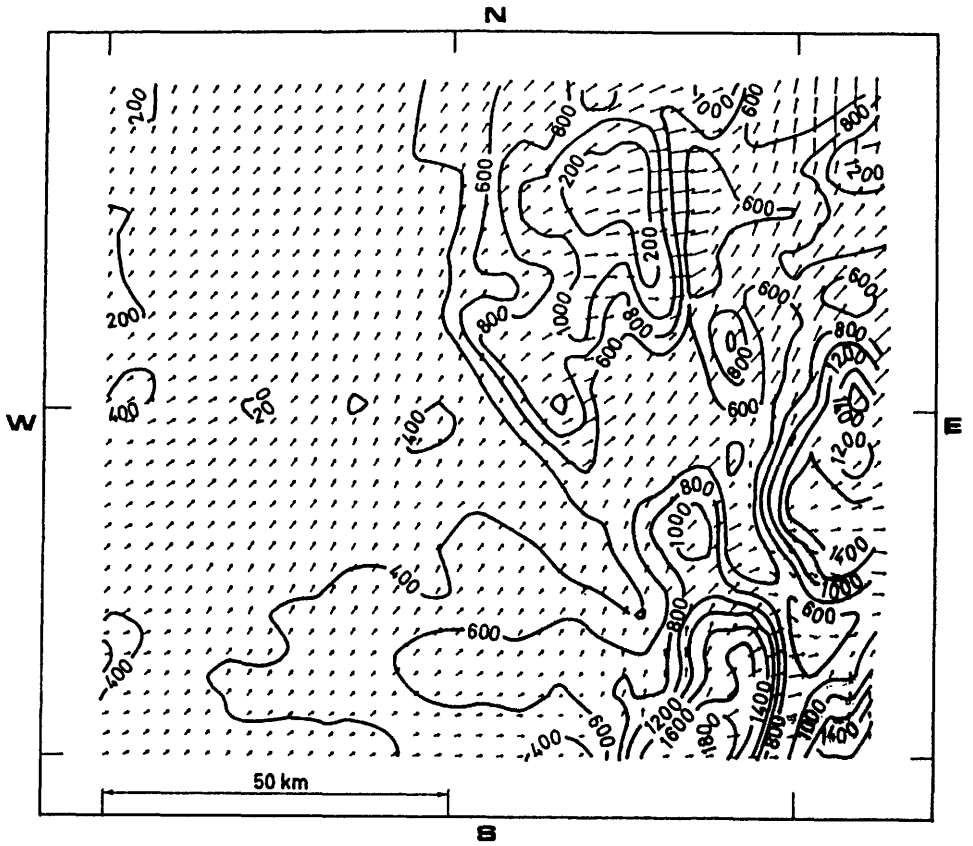

Figure 3.8 Windfield on a parallel surface 54m above the relief (horizontal section)

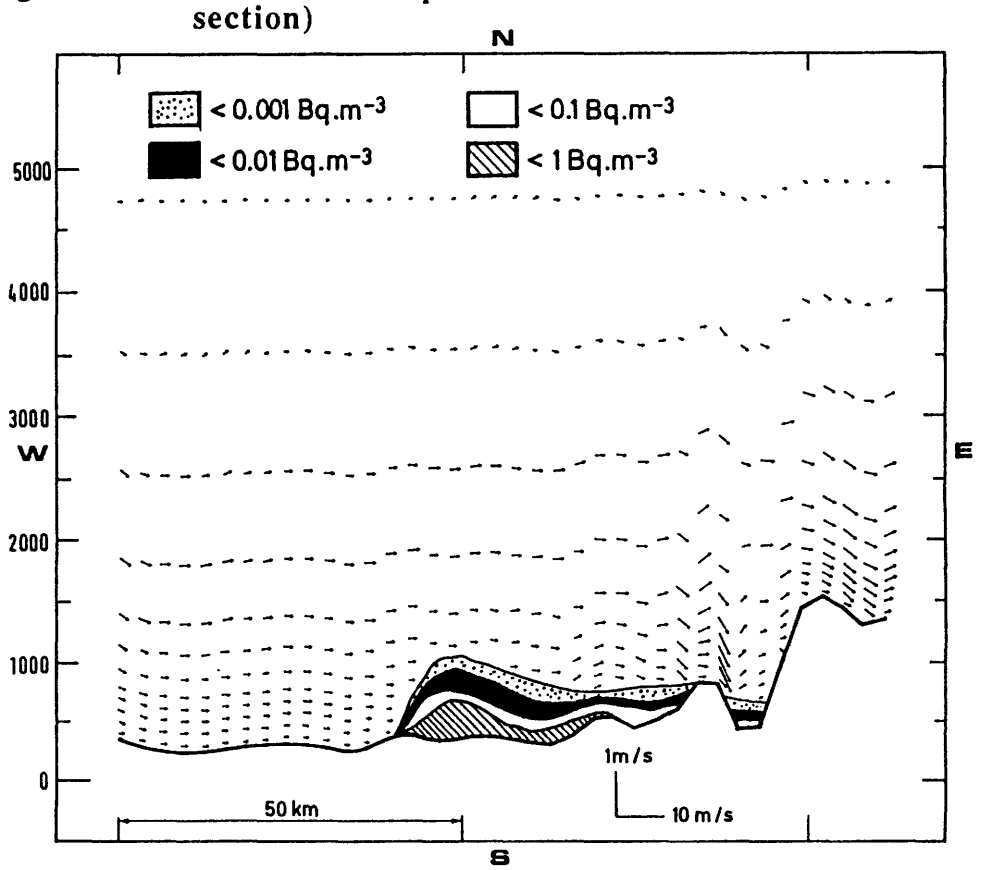

Figure 3.9 Windfield (U, ω) and release at J=14 (vertical section).

adapted to a fairly wide range of mini- and micro-computers. They provide the possibility of processing complex cases, in terms of both the media description (relief, cell heterogeneity) and the limit conditions.

Even without new calculation code developments, many improvements can be made to the atmospheric transfer simulation. It is recognised that the use of a simple wash-out coefficient is a very simple representation of the process of wash-out by rain, on radioactive or non-radioactive particles contained in the atmosphere. The model presented here enables atmosphere wash-out to be represented as absorption, whose intensity can vary with altitude. This type of model representation, based on experimental observations, should provide a better estimation of humid radioactive particles on the ground.

It is also recognised that the use of a constant rate of deposition does not provide a correct micro-scale representation of the deposition of radioactive particles contained in the atmosphere. Here again, the model simulates particle deposition as an interaction with the ground, involving a roughness factor and therefore takes surface conditions into account.

In general terms, the superiority of the resolution in the diffusion-advection equation that we have put forward resides in its ability to solve, at each time interval and at the same time as the transfer equation is solved, one or several equations describing phenomena which are remotely associated with the transfer but which can have an effect on the result of the simulation. For example, it is fairly easy to incorporate an equation into the model to describe the elevation of the particles above the emission zone, if the emission involves the release of heat.

Finally, there are several developments proposed for this code. The main difficulty resides in the generation of a coherent data set: it is not particularly easy make up the medium to be studied using a stack of cells of different types. A first development, which is currently in progress, consists in writing software that will carry out this task on the basis of a description of the relief identified by a range of points, each of which is associated with an altitude. A second development, also in progress, will allow the user to simulate a radioactive source that is more complex than a an instantaneous point source, i.e. a source that can be spread out over time and space. A third development, which should make the calculation code more interesting to use, will allow particles of different types to be traced simultaneously (different radioactive decay characteristics, ground sedimentation speeds, etc), and will also allow 'daughter' particles, produced by radioactive decay, to be traced.

3.4 A 3-Dimensional Long Range Dispersion Model: 3-DRAW

3.4.1 Introduction

The program 3-DRAW has been developed to model long range atmospheric transport and dispersion in real-time and predictive modes. It was decided that an entirely new model should be produced adopting a statistical approach. This was based on the following requirements:

i) The model should use standard data available to EC member states from forecasting facilities, principally forecast windfields specified at known pressure levels in the lower atmosphere and forecast precipitation fields (or actual precipitation fields as these become available).

ii) The model should produce as output, to be displayed in the form of clearly labelled maps, estimates of integrated surface air concentrations and total deposited activity arising during consecutive time intervals (typically 3 - 6 hours), within a user specified grid of cells capable of covering all of Europe.

iii) In addition, the model should produce output files for direct use as input to the dose response module developed by GSF for assessment of exposure, contamination of food-chains, and other effects.

iv) The model should be compatible with the short- and intermediate-range models developed in parallel by ENEA and CEA respectively. In particular it should have options to accept source terms giving the variation in release of specified nuclides over time as deduced by these models and transmitted in a fixed format, and to accept files giving estimated fields of contamination of air over a sub-region of the model domain.

iv) The model should consider a limited selection of key nuclides, namely those capable of contributing significantly to effects arising over longer distances.

v) The model should be capable of updating results in the light of revised estimates of the release and scenarios for its control, monitoring data, and updated windfield and precipitation forecasts.

vi) The model should as far as possible indicate which areas might become contaminated, not just concentrate on the most likely areas. This is necessary to alert intensified monitoring procedures. In addition, it may be required to identify regions where contamination is most likely to exceed prescribed thresholds for these nuclides. In this context the treatment of wet deposition is particularly important.

To alleviate the model's computing requirements, the whole path of each particle is used to generate exposure fields, a technique adopted from the mesoscale WAFT/TOMCATS Monte Carlo models for complex terrain (ApSimon et al. 1984), instead of just the positions at specified times, which are frequently used in Monte Carlo models. This is fully consistent with the objective of calculating time-integrated air concentrations and deposition over consecutive time periods, and reduces substantially the number of particles required to

represent the release. In addition each particle represents a number of nuclides, each with an activity at the time of release which is subsequently depleted during transport according to the nuclide-dependent probabilities of deposition and decay. The simultaneous treatment of different nuclides also reduces the number of particles which have to be tracked in the simulation. It is also consistent with the use of grey-scale maps or colour displays for the exposure fields, rather than scatter plots of particle positions which are not very satisfactory in reproducing a large range of concentrations spanning several orders of magnitude.

It has also been borne in mind that the introduction of parallel computing techniques using transputers is eminently suitable for Monte Carlo simulations, treating batches of particles simultaneously. At a later stage of development these techniques can be profitably introduced to provide an efficient and economical system for emergency assessment for a modest outlay.

Although the current model has been designed to be capable of using output from a number of forecasting models, it has been developed using output data from the U.K. Meteorological Office 'fine mesh' forecasting model. The relevant output from this model is therefore briefly described below. The model is described in section 3.4.2, while the user input required, and the output that may generated are briefly described in sections 3.4.3 and 3.4.4.

The U.K. Meteorological Office 'Fine Mesh' Forecasting Model

The 'fine mesh' model of the U.K. Meteorological Office, covers the North Atlantic and most of Europe, from 80.625° W to 40.3125° E and from 30° to 79.5° N, with 129 x 67 grid points at intervals of 0.9375° longitude (≈ 90 km at 30° N and ≈ 20 km at 78.75° N) and 0.75° latitude (≈ 83 km). The model can give forecasts, up to 72 hours ahead or analyses of historic meteorological data relayed to the Met. Office through the W.M.O. network. In both cases output data sets are generated at six hour intervals (0 h, 6 h, 12 h and 18 h).

The horizontal components of the windfield are calculated on a 'wind' grid offset half a cell from the above 'model' grid (i.e. 125 x 65 grid points spanning 80.16625° W - 39.94375° E and 30.375° - 79.125° N). Conversely, vertical wind velocities, surface winds, rainfall, surface temperature, cloud cover, and heights and several other data are calculated on the 'model' grid. The horizontal wind velocities are computed at twelve 'idealised' pressure

levels; 950 mb, 850 mb, 700 mb, 500 mb, 400 mb, 300 mb, 250 mb, 200 mb, 150 mb, and 100 mb.

The data set used in developing the 3-DRAW model covers the period of the Chernobyl accident, from 25.04.1986 to 15.05.1986, and comprises the horizontal wind data and dynamic (frontal) and convective rainfall data.

3.4.2 Model description

It is assumed in the model that the winds are fully 3-dimensional, varying in space and time as specified by their horizontal and vertical components in the windfield data. In addition there is assumed to be a boundary layer of variable depth in space and time in which the air is relatively turbulent and well mixed, and above which flow is almost laminar. In this mixing layer, dispersion is dominated by advection and wind-shear effects, apart from vertical extrusions exporting material aloft in precipitation systems. The model calculates integrated atmospheric concentrations and accumulated deposition for both dry and wet weather conditions, over specified time intervals, for a 2-dimensional array of grid cells at ground level.

The model is designed to be flexible in such aspects as the map area covered, the specification of the exposure grids, and the windfield, precipitation and other data used. Default options are given for many of these aspects, which may be replaced if additional data are available to specify them, or if other values are required. The default options are described below together with the assumptions made and the numerical techniques used.

Windfields and Advection

Data Requirements

The minimum windfield data required by the model are the horizontal components of the forecast windfields. These data are to be specified on a regular latitude and longitude grid, at a number of vertical levels (currently up to a maximum of seven) and at regular intervals of at most every 6 hours. When using the output windfields from the 'fine mesh' model, the offset 'wind' grid of the 'fine mesh' model becomes the 3-DRAW 'model' grid. The vertical dimensions of the windfield data are to be measured in 'idealised' pressure co-ordinates

(950 mb, 800 mb etc.) rather than in sigma co-ordinates.

When no vertical wind data is available, an external routine may be used to deduce the vertical windfields on the basis of mass-consistency, but this must be done in advance to prepare a complete input file of windfields. The routine generates mean vertical winds over the grid cells rather than on the horizontal wind 'model' grid, and at intermediate vertical levels. When vertical windfield data is available, the model therefore requires it to be offset half a cell relative to the 'model' grid, so that the data may be taken as mean values for the 'model' grid cells. The vertical wind data need not be at intermediate vertical levels to the horizontal wind data.

The external routine deduces vertical winds on the basis of conservation of mass for air flowing into and out of each grid cell, starting with the ground level grid cells and working upwards through higher levels. Orographic features will therefore complicate this assessment of vertical winds and produce false values if not allowed for. The routine currently assumes a uniform surface at a height of 1000 mb (approximately 130 m). The extent of the false vertical velocities arising from this assumption and the degree to which orographic features can be allowed for are under consideration.

Windfield profile

With the exception of the vertical profile between the ground and the lowest pressure level of the horizontal wind grid (950 mb in the 'fine mesh' forecasting model), horizontal winds are assumed to vary linearly in time and space between the elements of the windfield data. Thus the u component of the windfield at grid point (i,j,k) in the horizontal wind grid at time t between two successive sets of data t^- and t^+, Δt hours apart is given by;

$$u(i,j,k,,t) = u(i,j,k,t^-)\,(1-\frac{t}{\Delta t}) + u(i,j,k,t^+)\,\frac{t}{\Delta t} \qquad 3.54$$

where Δt is the interval between successive sets of data, 6 hours in the case of the 'fine mesh' model output. The mean $\bar{u}$ component of the horizontal wind advecting a particle at a point (x,y,p) at time t, where (x,y,p) is within the grid element bounded by the points (i,j,k), $(i,j+1,k)$, $(i+1,j,k)$, $(i+1,j+1,k)$, $(i,j,k+1)$, $(i,j+1,k+1)$, $(i+1,j,k+1)$, $(i+1,j+1,k+1)$, as illustrated in figure 3.10 is given by;

$$\bar{u}\,(x,y,p,t) = \Big[(u(i,j,k,t)\,(1-\tfrac{x}{\Delta x}) + u(i,j+1,k,t)\,\tfrac{x}{\Delta x})\,(1-\tfrac{y}{\Delta y}) +$$
$$(u(i+1,j,k,t)\,(1-\tfrac{x}{\Delta x}) + u(i+1,j+1,k,t)\,\tfrac{x}{\Delta x})\,\tfrac{y}{\Delta y}\Big]\Big[1-\tfrac{p}{\Delta p}\Big] +$$
$$\Big[(u(i,j,k+1,t)\,(1-\tfrac{x}{\Delta x}) + u(i,j+1,k+1,t)\,\tfrac{x}{\Delta x})\,(1-\tfrac{y}{\Delta y}) +$$
$$(u(i+1,j,k+1,t)\,(1-\tfrac{x}{\Delta x}) + u(i+1,j+1,k+1,t)\,\tfrac{x}{\Delta x})\,\tfrac{y}{\Delta y}\Big]\,\tfrac{p}{\Delta p} \quad 3.55$$

where Δx, Δy and Δp are the relevant grid intervals in the zonal, meridional and vertical (measured in 'idealised' pressure co-ordinates) directions respectively, for the horizontal wind data. Similar equations describe the derivation of the mean v component of the horizontal wind above the lowest horizontal wind data level.

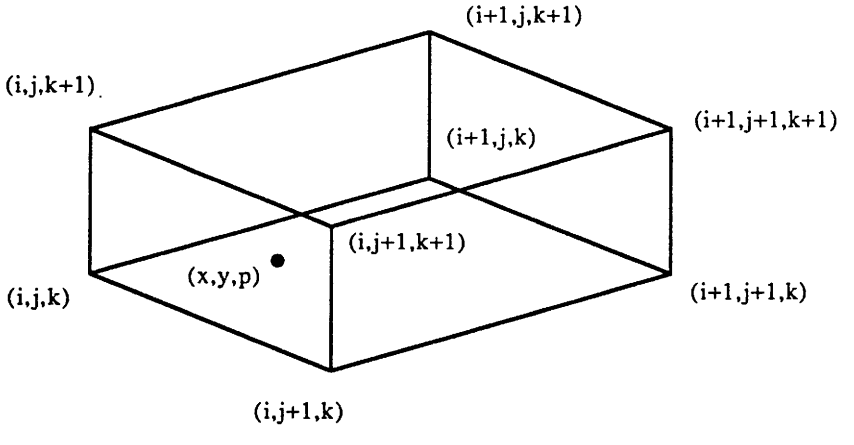

Figure 3.10 Illustrated particle position within the wind grid.

The horizontal wind profile within the lowest layer of the atmosphere is assumed to have a power law relationship to height, with the wind at 10 m reduced in strength and backed at an angle relative to the 950 mb wind, according to the underlying surface, as in the MESOS model (ApSimon et al. 1985). Over the land the 10 m wind is assumed to be 0.5 times the 950 mb wind velocity and is backed by 25°, while over the sea the 10 m wind is assumed to be 0.85 times the 950 mb wind velocity and is backed by 10°.

The vertical wind velocities are assumed to vary linearly with time and with height only, the data being the mean over each 'model' grid cell. Thus the w component of the windfield for the grid cell (i,j,k) at time t between two successive sets of data t^- and t^+, Δt hours apart is given by;

$$w(i,j,,k,t) = w(i,j,k,t^-)\ (1- \frac{t}{\Delta t}) + w(i,j,k,t^+)\ \frac{t}{\Delta t} \qquad 3.56$$

and w, the mean vertical component of the wind advecting a particle at the point (x,y,p) at time t is given by;

$$\overline{w}\ (x,y,p,t) = w(i,j,k,t)\ (1- \frac{p}{\Delta p}) + w(i,j,k,+1,t)\ \frac{p}{\Delta p} \qquad 3.57$$

where Δp is the relevant vertical interval in the vertical wind data grid. When interpolating vertical wind velocities between the ground and the lowest level of vertical wind data (900 mb in the dataset generated from the UK fine mesh model horizontal data), the vertical velocity at the ground is assumed to be zero.

Thus, the mean vertical and horizontal components of the windfield advecting a particle are determined at the beginning of each timestep and these conditions are assumed to remain constant during the timestep of one hour. Particles are then subjected to a random perturbation about the windfield of differing magnitudes depending on whether or not the particle is within the mixing layer.

Turbulent displacements

The random perturbation of the windfield represents partly the small scale turbulence and sub-gridscale wind fluctuations, as well as the effects of vertical wind-shear as material changes height in the mixing layer. The magnitude of the turbulent displacements is dependent on effective diffusivities. Again, these may be prescribed but default values are provided as described below.

Vertical turbulent displacement

When tracking particles over long distances, the timesteps are long compared with the

vertical diffusion times through the full depth of the mixing layer. This simplifies the situation, as the mean vertical velocity of particles within the mixing layer may be ignored and the particles randomly reassigned to new heights within this layer during each time step. Above the mixing layer vertical turbulence is greatly reduced, and in 3-DRAW it is ignored. Transfer between turbulent and non-turbulent conditions takes place as the mixing layer depth changes. Particles in the layers above the mixing layer are entrained in the mixing layer when it expands, and may remain in newly formed upper layers as the mixing layer declines. Particles are also transferred to the layers above the mixing layer through the expulsion of particles from the upper levels of precipitation systems.

Horizontal turbulent displacement

Within the mixing layer, horizontal spreading is generally dominated by wind-shear effects and the formula derived by Saffman (1962) is used for this. Thus the root mean square lateral displacements σ_y or σ_x (m) in a time interval δt for a particle within the mixing layer is given by

$$\sigma_y^2 = 2 D_y \delta t \qquad 3.58$$

where

$$D_y = K_y + \frac{\Delta V^2 H_{mix}^2}{120 K_z} \qquad 3.59$$

with similar expressions for σ_x^2 and D_x. ΔV (m.s^{-1}) is the wind-shear between the 10 m wind and the top of the mixing layer at height H_{mix} (m). If H_{mix} is below the height of the 950 mb pressure level (500 m), ΔV is determined from the assumed profile of the horizontal wind velocity in the lowest layer of the atmosphere. When H_{mix} is above the height of the 950 mb pressure level (500 m), ΔV is determined from the assumed horizontal wind profile between 10 m and 950 mb, together with the shear between 950 mb and the top of the mixing layer. K_y and K_x are horizontal diffusivities (m^2.s^{-1}) and K_z is the vertical diffusivity (m^2.s^{-1}). The vertical diffusivity is referred to as K_z rather than K_p, as it is defined in terms of the mixing layer height measured in metres, rather than the 'idealised' pressure used in the windfield data. In the lowest levels of the atmosphere pressure falls very nearly linearly with height and the model assumes that 10 m is equivalent to 1 mb.

The horizontal diffusivities K_y and K_x and the vertical diffusivity K_z, are strongly correlated with the mixing layer depth. An approximate description which fits well with more complex specifications is to scale them according to the square of the mixing layer depth;

$$K_z = \left(\frac{H_{mix}}{I}\right)^2 \qquad 3.60$$

where I = 300 $s^{1/2}$, while

$$K_y = K_x = \beta K_z \qquad 3.61$$

where β is about 1.5. Thus in a well developed day time mixing layer K_z is about 10 $m^2.s^{-1}$, whereas with a shallow mixing layer of about 100 m or so in stable night time conditions K_z is only 0.1 $m^2.s^{-1}$.

Above the mixing layer perturbations are very small and

$$\sigma_y^2 = \sigma_x^2 = S\delta t \qquad 3.62$$

where S = 0.2 s, corresponding to stably stratified flow.

Specification of the mixing layer depth

The model requires the change in the mean mixing layer depth for each of the model grid cells to be specified hourly. This information may be specified externally, for example from radiosonde data, in which case interpolation to give diurnal development at hourly intervals is required. Alternatively the evolution of the mixing layer over each grid cell may may be estimated within the model using a similar approach to that in the MESOS model,where appropriate data is available.

In the latter option the depth of the mixing layer over land during the day depends (Carson, 1973) on the season and time of day through the integrated insolation and associated heat input, allowing for cloud cover. At night the depth of mixing over land depends on the windspeed and blanketing effect of cloud. Over the sea the depth of the mixing layer may be derived from the windspeed and differences between temperatures of the sea and the overlying air. This option thus requires surface temperature and cloud cover data from the

forecasting model. However, as these are not included in the dataset used in the development of the model, this option is not available in the current version of the model.

The model thus requires mixing layer profiles to be preset externally. Specimen mixing layer profiles have therefore been generated externally, using the same approach as in the MESOS model, for dry and wet conditions over land and over the sea, typical of the time of year of the dataset used in development,

Simulating particle trajectories

Each particle is initiated with an array of the activities of each radionuclide it represents from the prescribed release. Thus if N particles are released over a time interval δt in which an activity A_n of nuclide n is released, each particle has an activity $A_{n/N}$ of nuclide n. The present code releases 1 000 particles per hour up to a maximum of 24 hours, and allows up to 6 nuclides to be represented by each particle. A release is treated in hourly intervals and the release rates of each nuclide may be varied from hour to hour. The effective release height must also be given. Alternatively, the model can read a file of particle positions and activities, generated by a mesoscale model, and continue the simulation of a release into the larger model domain.

The particles are released at constant intervals during the release, and the first advection timestep after release is smaller for each successive particle in a 'batch', so that all particles are tracked to the end of that hour. Successive timesteps are then a uniform hour, the particle being tracked over a specified maximum number of time steps, or until it leaves the map area. In each time step the horizontal displacement is a combination of the advection term and the turbulent displacement term,

$$x(t + \delta t) = x(t) + u\,(x,y,p)\;\delta t\; + \Delta x \qquad 3.63$$

$$y(t + \delta t) = y(t) + v\,(x,y,p)\;\delta t\; + \Delta y \qquad 3.64$$

$u\,(x,y,p)$ and $v\,(x,y,p)$ being the horizontal wind components, and Δx and Δy the random perturbations depending on whether the particle is currently within or above the mixing layer. No allowance is made for a correlation between Δx or Δy in successive time steps, since the times of travel over the long distances, and hence the time steps δt, are long compared with the Lagrangian time scale over which such correlations persist. In this

respect a Monte Carlo simulation applied over long distances is simpler than that for short or mesoscale distances.

In the case of vertical displacements the treatment is slightly different. If the particle is above the mixing layer then the displacement is purely advection and

$$p(t + \delta t) = p(t) + w\,(x,y,p)\,\delta t \qquad 3.65$$

Within the mixing layer there are two additional considerations: first the random effect of vertical motion and secondly the possibility that the particle has been carried aloft in a convective storm system without subsequent deposition (to either height $p(H_{\text{storm1}})$ or $p(H_{\text{storm2}})$). Thus if $p(t) < p(H_{\text{mix}})$ then

$$p(t + \delta t) = \begin{cases} p(H_{\text{mix}}) + R\,(\,p(H_{\text{mix}}) - 1000.0) \\ p(H_{\text{storm1}}) \\ p(H_{\text{storm2}}) \end{cases}$$

where R is a random number between 0 and 1, and $p(H_{\text{storm1}})$ and $p(H_{\text{storm2}})$ are described in more detail below in the section on precipitation and wet deposition.

Calculating air concentrations

During each timestep a particle is assumed to follow a path along a straight line segment between its initial and final positions. This means that it may move between exposure grid cells, in which case the proportion of time spent in each grid cell is taken as proportional to the fraction of the line segment lying within that grid cell. Integrated air concentrations at ground level are accumulated over sequential 6 hour time periods by adding up the contributions from each particle within the mixing layer, for a fixed grid of cells prescribed by latitudes and longitudes. The default grid is a map area of Europe based on a CEA scheme (Garnier and Sauve, 1981), extending from 10.5° west to 39° east in 1.5° intervals and 35.15° to 69.03° north in increasing intervals to give a constant cell area of 10^4 km^2.

Thus if a particle has associated with it, activity A_n of nuclide n ,which in turn has a 'net depletion rate' (radioactive decay, dry and wet deposition) of λ_n, and the particle spends a fraction f_{ij} of the timestep δt within the mixing layer over the ground level cell indexed (i,j), then it contributes an amount

$$\chi_{\text{air},n,ij} = \int \left(\frac{A_n e^{-\lambda_n t}}{H_{\text{mix}} a_{ij}}\right) f_{ij} \, \partial t \qquad 3.66$$

which after integration is equivalent to

$$\chi_{\text{air},n,ij} = \frac{A_n (1 - e^{-\lambda_n f_{ij} \delta t})}{\lambda_n H_{\text{mix}} a_{ij}} \qquad 3.67$$

to the integrated air concentration in cell (i,j) over the corresponding time interval, where a_{ij} is the area of the grid cell.

Dry deposition

Dry deposition is calculated over the same grid of ground level cells, and accumulated over the same 6 h intervals as the integrated air concentrations. A mean deposition velocity is required for each nuclide. Strictly this will depend on the turbulence as well as the nuclide characteristics and surface resistance, but this is ignored as unimportant compared with the other uncertainties, however, the choice of the deposition velocity should be consistent with the range of surface dependent deposition velocities used in the dose response system, EURALERT. Typical values of deposition velocity will vary from zero for an inert gas such as xenon or krypton to about 1 $cm.s^{-1}$ for elemental iodine vapour. Over long distances most nuclides apart from the inert gases will probably be transported as fine particulates whose deposition is relatively inefficient in dry conditions. The exception is iodine, which unless released as inert methyl iodide, is more volatile and will only partly adhere to aerosols.

In each timestep, dry deposition leads to an increment in deposited acivity of nuclide n in cell (i,j) corresponding to the contribution to the integrated air concentration for the same grid cell

$$\chi_{\text{dry},n,ij} = \frac{v_d A_n (1 - e^{-\lambda_n f_{ij} \delta t})}{\lambda_n H_{\text{mix}} a_{ij}} \qquad 3.68$$

Wet deposition

The calculation of wet deposition is dependent on data prescribing the occurrence of rainfall. If the model is being used in forecasting mode then the precipitation is likely to be defined using the same horizontal grid as for the windfields. This does not necessarily coincide with the grid cells for which deposition is assessed, so that some spreading of the wet deposition may result. In hind-casting mode (or for very short term forecasts), more detailed resolution of rainfall in space and time may be available (as for example under development within the U.K. Meteorological Office capabilities for nuclear emergencies based on the COST73 co-ordinated weather radar network and satellite data, as in the FRONTIERS system).

The difficulty with the wet deposition is that it is highly variable in space and time. For example, even after 7 days' travel an hour or so difference in time of arrival in the UK of Chernobyl material would have made quite a difference to which areas were contaminated most. There will also be a tendency for deposition to be greater over land at higher altitudes, due both to enhancement of rainfall and increased efficiency of deposition. However, such factors cannot be resolved in long-range modelling on a European scale.

The traditional method of incorporating wet deposition is to use a washout coefficient. The probability of wet deposition is then dependent on the amount of rainfall encountered and material at all heights is equally likely to be scavenged. Some methods distinguish between washout and rainout, but this is rather artificial and does not reflect the dynamical nature of storm systems. In the 3-DRAW model a slightly different approach in areas of precipitation is adopted, which as well as allowing material to be deposited also allows material to be projected to a higher level in the atmosphere. Since forecasting models such as that of the UK Meterological Office differentiate between convective and frontal rain, this distinction is usefully preserved in the 3-DRAW model.

Thus, for convective rain it is assumed that storms or showers draw on air from the mixing layer, and that material entrained at higher levels into the rising storm column contributes less efficiently to wet deposition. Consequently, only the mixing layer air is significantly depleted by the storm scavenging. Separate, more detailed dynamical models of storm scavenging are being used to parameterise this. Some allowance is also made on a simple statistical basis for the fact that convective precipitation will be very patchy, so that some areas within the system may be completely dry whereas others may experience intense rain.

By contrast, frontal systems lead to more widespread and prolonged rainfall, albeit with

more intense cores arising from regions with stronger updraughts. The material is carried aloft above the frontal surface sometimes over quite long distances in a long conveyor belt ascent before being subject to deposition. In such situations deposition may bear little relation to air concentrations at ground level. Further research is still in progress on the parameterisation of wet deposition to make optimum use of the available data in these different situations, and special emphasis will be placed on better treatment of the trajectories of material through frontal systems. In the meantime some simpler parameterisations have been incorporated in the present model.

Convective precipitation

The parameters used to define the deposition in convective precipitation are the average convective precipitation rate in each time-step in each model grid-cell, J_c, and the depth of the convection systems (deduced for example from height of cloud tops). All precipitation is assumed to be in the form of rain, and the model grid-cell is assumed to contain area of heavy rainfall, light rainfall and a dry area such that

$$J_c = P_l J_l + P_h J_h \qquad 3.70$$

where the probabilities of being dry, in light rain and in heavy rain sum to unity

$$P_{dry} + P_l + P_h = 1 \qquad 3.71$$

and J_l and J_h are the rainfall rates associated with light and heavy rainfall. The convective precipitation system can then be specified in terms of a minimum value of P_{dry} (the probability of the particle missing the rain system) a ratio P_l/P_h, and minimum values of J_l and J_h. Each particle beginning a timestep within the mixing layer in a cell with convective precipitation, is assigned to one of the three areas, high rainfall, low rainfall and dry, according to their relative probabilities of occurrence, and the rainfall rate recorded.

In addition, if the particle is assigned to either of the areas of rainfall, it has a further probability of being ejected from the precipitation system, at the pressure levels $p(H_{storm1})$ and $p(H_{storm2})$, for the areas of low and high rainfall respectively. At the end of the time step the particle is thus assigned either the pressure at which it exits from the top of the relevant storm area, or a random height within the mixing layer, according to their relative probabilities of occurrence.

Frontal precipitation

Frontal precipitation is assumed to deplete the activity associated with particles both above and within the mixing layer, furthermore the mean precipitation rate is assumed to apply uniformly over the model grid cell and all precipitation is assumed to be in the form of rain.

Calculation of wet deposition

Wet deposition from both frontal and convective rainfall is calculated by the application of an effective washout coefficient $\Lambda_{we,n}$ to the relevant rainfall rate for the position of the particle.

Thus the wet deposited activity from a particle which spends a fraction f_{ij} of the timestep δt within the mixing layer over the ground level cell indexed (i,j) and has associated with it, activity A_n of nuclide n ,which in turn has a 'net depletion rate' (radioactive decay, dry and wet deposition) of λ_n, is given by

$$\chi_{wet,n,ij} = \frac{\Lambda_{we,n} J^p A_n (1 - e^{-\lambda_n f_{ij} \delta t})}{\lambda_n a_{ij}} \qquad 3.72$$

where J is the sum of the convective and frontal rainfall rates for the particle during the timestep, the default value of the exponent being 0.8. Similarly the wet deposited activity from a particle above the mixing layer over the same cell, is given by

$$\chi_{wet,n,ij} = \frac{\Lambda_{we,n} J^p A_n (1 - e^{-\lambda_n f^*_{ij} \delta t})}{\lambda_n a_{ij}} \qquad 3.73$$

where f^*_{ij} is the fraction of the timestep δt that the particle spends over the cell (i,j) while above the mixing layer and J is the frontal rainfall rate alone. In this case the λ_n, the 'net depletion rate' of A_n, the activity associated with the particle is the sum of the rates of wet depsition and radioactive decay alone, there being no dry deposition from particles above the mixing layer.

3.4.3 Input for 3-DRAW

In addition to the wind-field and mixing layer height related data described in the previous sections, 3-DRAW requires additional input from the user to initiate it . This may be in one of three forms in order to provide links with the short range and mesoscale models, as well as allowing 3-DRAW to be run independently:

i) A file containing all the required source information listed below (output from the short range model source term analysis).

ii) A file containing particle positions and any associated activities for each particle at a particular given time (produced by the mesoscale model).

iii) An interactive dialogue at which the user is asked to provide all the source information listed below.

The required source information is as follows:

i) Location of the source.

ii) Time of start of the release and duration.

iii) The height of the release, including any plume rise.

iv) For each hour of the release, the release rates of up to six fission products from a library of 39 (those fission products with a half-life of more than twelve hours).

v) The washout coefficient and dry deposition velocity, if different to the default values for each chosen nuclide.

3.4.4 Output from 3-DRAW

A range of different results may be produced by 3-DRAW, with the choice again made interactively by the user. Air concentrations, deposition and particle positions are may be output for every 6 hour period, for every day from 00 00 h to 00 00 h, and for the duration of a 3-DRAW release simulation (with the exception of the particle positions), in addition to a EURALERT input file which may be output every 6 hours, giving a total choice of up to nine output files;

i) Mean air concentration for each 6 hour period ($Bq.m^{-3}$).

ii) Time integrated air concentration for each day ($Bq.s.m^{-3}$).

iii) Time integrated air concentration for the duration of a 3-DRAW simulation ($Bq.s.m^{-3}$).

iv) Total deposition during each 6 hour period ($Bq.m^{-2}$).

v) Total deposition during each day ($Bq.m^{-2}$).

vi) Total deposition during the complete 3-DRAW simulation ($Bq.m^{-2}$).

vii) Particle positions after each 6 hour period (x and y co-ordinates only).

viii) Particle positions and activities associated with each particle at the end of each day.

ix) Rainfall, time integrated air concentration and wet deposition during each 6 hour period (input for EURALERT).

Output is only generated for those cells on the exposure grid with non zero results for the relevant time period, to save on storage.

Effort has been put into producing high quality greyscale maps fro the above results, using up to six levels of shading, and capable of good reproduction by photocopying. Colour maps are less useful in this respect. The concentration ranges corresponding to the various lavels of greyness may be specified as desired or automated according to the range of values calculated. This can be set either by dividing the range between some specified minimum and the highest values calculated into equal ranges, or by defining levels to pick out the most contaminated say 15% of the map area, the next most contaminated 15% and so on. Plots of some of the types of output available from 3-DRAW are illustrated in figures 3.11 - 3.14. The figures were produced from 3-DRAW output for a run simulating the first three hours of the Chernobyl accident. 1.5×10^{15} Bq of ^{137}Cs were released each hour from Chernobyl between 21.00 and 24.00 on 25.04.1986 at a height of 1 000 m.

Although times of arrival in specified grid squares are also potentially available, the air concentration maps can effectively prescribe this with sufficient definition. No facility is currently provided for contamination at higher levels in the atmosphere, although of course this could be useful for checking against aircraft data and picking out areas where wet deposition could result despite low concentrations at ground level. It may therefore be desirable to provide a snapshot dot printout of the particle positions at different levels at selected times, either in horizontal or vertical cross-sections, to cover this. Also colour dot prints can be useful in distinguishing different parts of the release, which is helpful in revising and correcting the predictions.

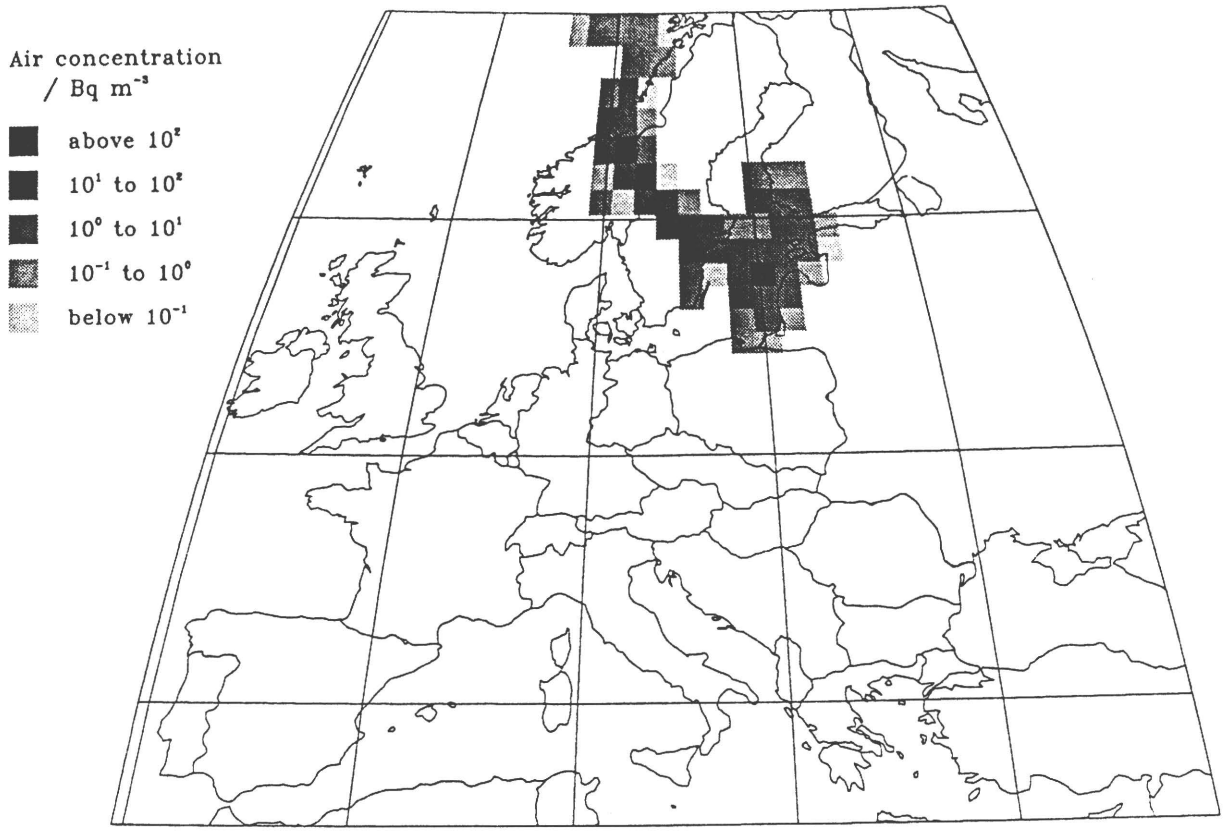

Figure 3.11 Mean ^{137}Cs air concentration 18.00 29.4 - 00.00 30.4.86.

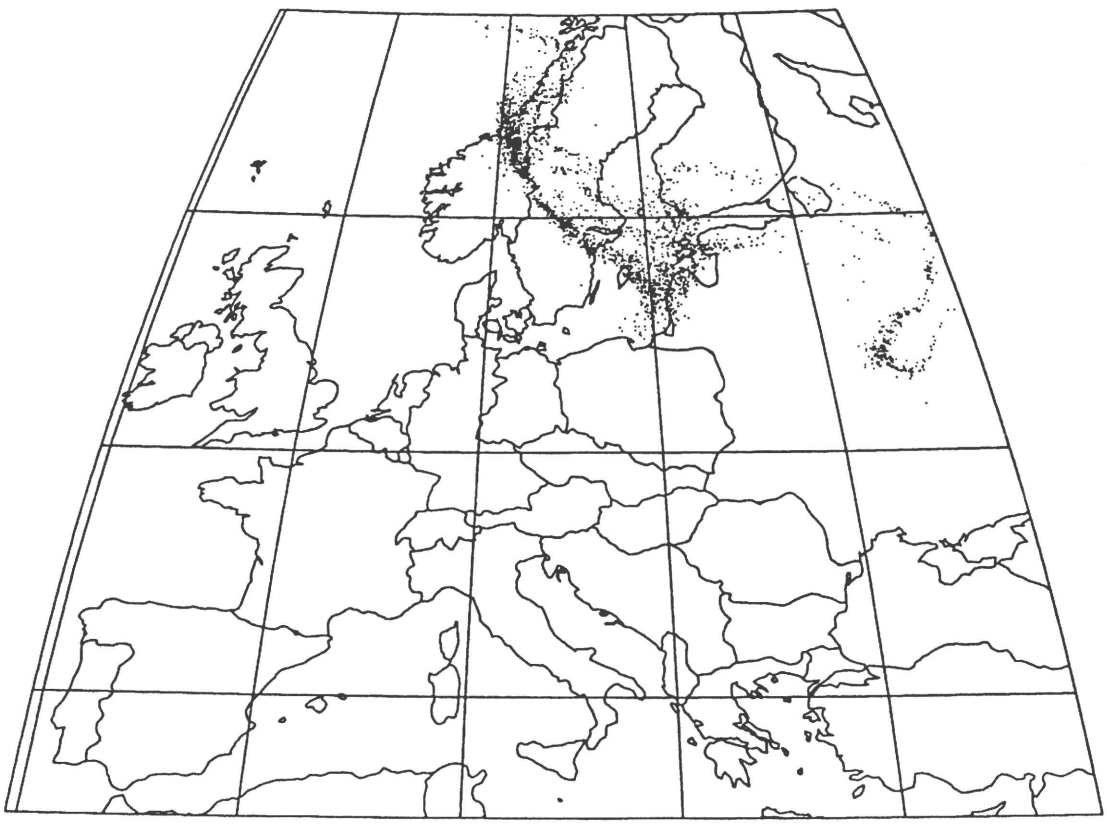

Figure 3.12 Particle positions at 00.00 30.4.86.

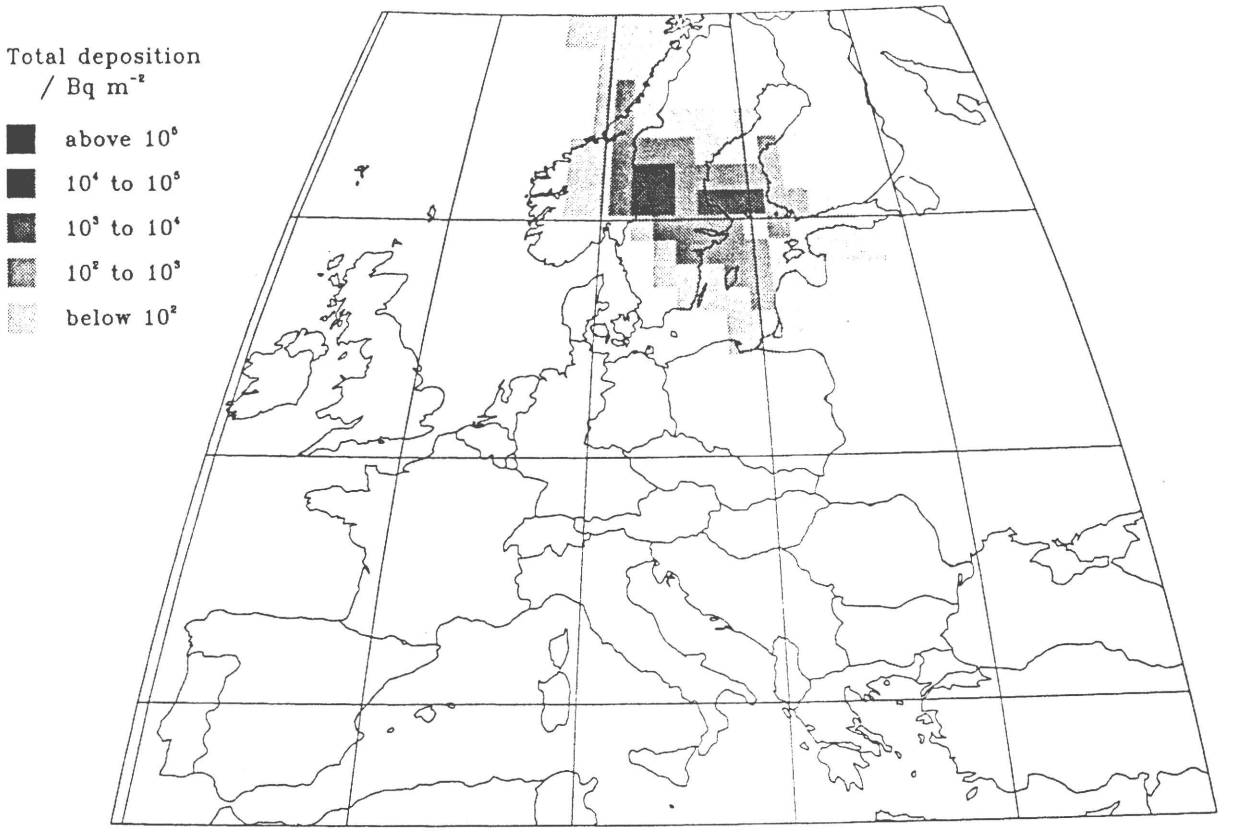

Figure 3.13 Total ^{137}Cs deposition from 00.00 29.4 to 00.00 30.4.86.

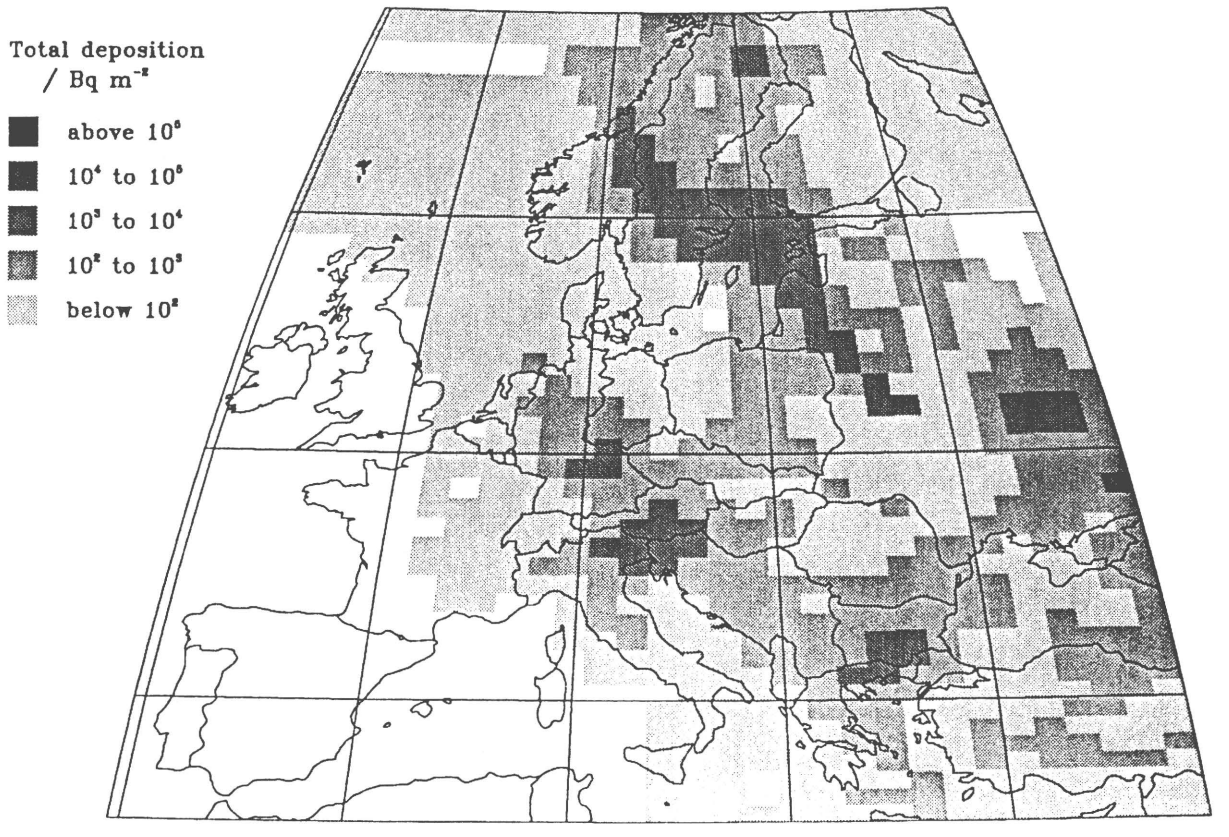

Figure 3.14 Total ^{137}Cs deposition from 21.00 25.4 - 00.00 07.05.86.

4. ESTIMATION OF THE SOURCE TERM AND FEEDBACK BETWEEN MEASUREMENTS AND MODEL OUTPUT

4.1 Introduction

Many nuclear installations (power reactors, nuclear fuel reprocessing plants) are likely, in the case of an accident or an incident, to release radioactive gases and aerosols into the atmosphere. Past experiences have shown that it is difficult to determine the source term quickly. Here, the source term comprises:

- the chemical nature of the radionuclides released,
- the time distribution of material of each radionuclide released,
- and eventually the physical state of the various radionuclides released - gaseous, aerosol, organic or inorganic vapor.

Typically, radiation counters in the outlet ventilations stacks measure total β and α radioactivity, external irradiation of gases and eventually radioactive Iodine, which are the quantities used for gauging the magnitude of the source term, but they cannot be used to determine all the components indicated above. Besides, they would only be of use in an accident if the radionuclides were discharged from the stack and the counters were still in correct working order.

Accidental situations can in fact be divided into two phases; the phase preceding discharge, and the phase including and following discharge. Conventionally, during the second phase, the best information in sought on the actual conditions of the discharge, such as its height, prevailing weather conditions, the composition of the discharge and its activity level, along with the magnitude of parameters governing the deposition process (deposition velocity, washout coefficient) and this information is used to estimate air concentrations and ground deposition, utilising atmospheric transfer models of varying degrees of complexity.

In the event of an accidental release of radioactivity from a nuclear facility, the emergency response system should assess the radiation dose received by the affected population centres. The dose assessment may be based on radiological measurements at specific sites or atmospheric dispersion modelling calculations. By combining the measurements with the model predictions, one may derive a more accurate estimate of the dose distribution than is possible when using either set of data independently. However, it must be kept in mind that the effectiveness of the optimization process will be limited by the quantity and quality of the measurements and the adequacy of the model's capabilities for simulating the relevant

atmospheric dispersion processes. In the event of large disparities existing between the model predictions and the radiological measurements, or insufficient measurements being available, this optimization process becomes ineffective and a different analysis process is required. This may include the utilization of a more complex model or acquiring additional measurements.

In developing the optimization process great care should be taken to properly balance model sophistication, data quality and timing, response time, and data-model integration schemes. This last aspect could involve the application of automated, real-time regression schemes to obtain a 'best set' of model parameters according to monitoring data. However, the computer codes devoted to this task are generally time consuming and there is considerable uncertainty as to the best mathematical treatment of the problem.

The model input parameters which could typically be adjusted by regression techniques are wind direction, wind speed, effective source height, dispersion parameters, and the source term. Within the present contract, two distinct approaches to the problem of the integration of model calculations and field data have been developed.

In the first, only a limited aspect of the integration between model calculations and field data has been addressed, namely the possibility of estimating the source term when on-site release monitoring instrumentation is unable to provide such information. As discussed in chapter 3.1 the estimated source term is an appropriate means of utilising the results of the short range model to initiate the mesoscale and long-range transport models in an emergency response system.

A code (STEP), for estimating the source term based on the regression of output data from an atmospheric dispersion model onto appropriate field measurements has been developed. For the model to give the nuclide specific source terms, it obviously requires monitoring data for the relevant nuclides. In general it's application should be limited to the cases where the computed concentration pattern is not affected by a large error, except for the errors induced by a poor estimate of wind direction as input to the dispersion model. The STEP code is described in section 4.2.

In the second approach, a method (STAR) for the evaluation of model parameters based on the mathematical solution of the atmospheric transfer equation has been developed. STAR is a model for using the results of air concentration and deposition measurements made in a given zone in order to obtain the best estimates of the source term and the transfer

parameters of the overall air concentration and deposition fields, and thereby, the best estimate of the dose to people, and the best preparedness of countermeasures and eventually medical rescue. The method used in the STAR code is described in section 4.3.

4.2 STEP Source Term Evaluation Program

4.2.1 Introduction

The STEP code attempts to link the output data of atmospheric dispersion models with field measurements to give an estimate of the source term. Because of the possible lack of information about the source term, due to either the absence of, or malfunction of, on-site monitoring instruments capable of measuring the release, this is an important application of real-time dispersion models, especially during the first stage of an accident, when a rapid but careful assessment of the situation is required.

STEP does not depend on the particular dispersion model employed; it can be applied to any model, provided its output is in the form of a matrix of concentration values on a fixed Eulerian grid. The actual pollutant is generally a mixture of gases or particulates with different physical, chemical or radiological characteristics. If the cloud composition is not known in advance, STEP can calculate an estimated source term for all nuclides comprising a release for which sufficient monitoring data is available.

For example, if ^{131}I air concentrations are measured during an accident, it is possible to estimate the ^{131}I released by coupling these data with computed ^{131}I concentration values obtained from a dispersion model with a unit source as input. If more than one nuclide contributes to the measured quantities (e.g. if measurements of exposure rates are available) the source term for each individual nuclide cannot be obtained unless the relative composition of the mixture which gives rise to the measurements is assumed in advance.

The STEP model is based on few, simple considerations about the uncertainty of the concentration field computed by a dispersion model and its' comparison with monitoring data available in the emergency situations. Thus, after running the dispersion model with unit source rate, STEP rotates the computed concentration pattern, until the best correlation between observed and computed patterns is reached. The average ratio between observed and computed values at sample points is then the estimated source term.

The application of STEP is limited to all the cases for which the assumption that the computed concentration pattern is similar to the actual one is reasonable. Thus, it should not be applied in very complex terrain, or whenever a crucial input parameter of the dispersion model, like the effective source height, is very uncertain, or in rapidly evolving meteorological or source term conditions.

4.2.2 Model Description

The simplest and most straighforward method for linking a dispersion model with a set of monitoring field data for a source rate estimate is to use the model with unit emissions as the input source term data, and then compare the computed concentration values at the sample points with the measured ones; the average ratio between them would give an estimate of the actual source.

During the early stages of an accident, in particular, the available off-site radiological data is likely to be very sparse. The amount of radiological data that is useful may be reduced further in order to be compared with computed concentration values for particular time interval.The radiological data should thus be collected in a time interval short enough to justify the hypothesis of steadiness of the meteorological situation and of the pollutant release in that interval. In addition, the dispersion model calculations will generally be affected by errors due to the limitations of the model itself and the inaccuracy in the evaluation of some input parameters, like the atmospheric stability category or the average wind direction.

For these reasons, a simple comparison between computed concentration values obtained from the model with unit source rate as input, and the available measured concentration data, could lead to a source rate estimate that would very inaccurate and of little use.

A few model validation studies (for example Rodriguez and Rosen, 1984; Desiato, 1985) show that the main cause of error in the comparison between observed and calculated concentration values is the deviation of the computed plume centerline from the observed one. Even when the main features of the concentration pattern are well reproduced by the model, an error of $\Theta = 5°$ or $10°$ in the plume centerline direction can cause errors of two or three orders of magnitude in the concentration values as illustrated in figure 4.1.

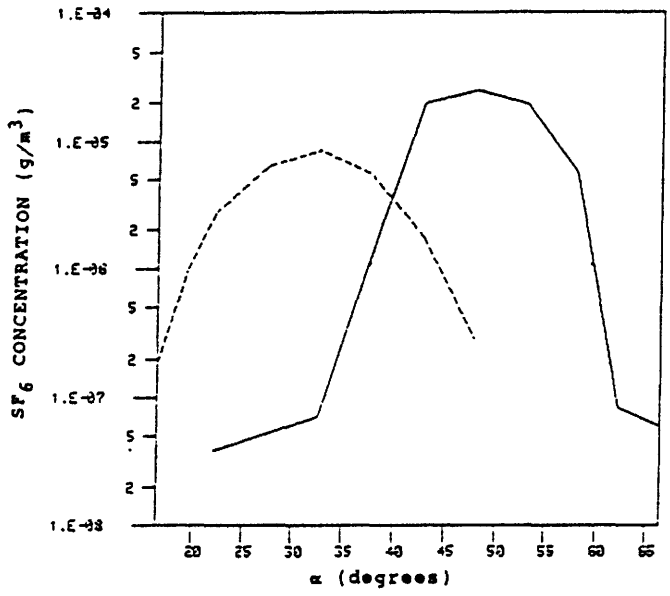

Figure 4.1 **Observed (solid line) and computed (dashed line) SF_6 concentrations on 2nd sample arc, 26.6.84 Montalto tracer experiment. α is the polar coordinate with the release point as the origin. In this case $\Theta \approx 15°$.**

Once the computed plume centerline is shifted by the angle Θ, so that the best correlation between the observed and the calculated pattern is reached, the main source of errors is eliminated and the concentration values agree satisfactorily as illustrated in figure 4.2. The angle Θ is generally dependent on the distance from the source, due to the model inaccuracy in reproducing the space and time variability of the wind field.

STEP thus performs the following operations:

i) The available monitoring data are divided into a certain number of groups, depending on the distance of the sample points from the source.

ii) For each group of sample points, the calculated concentration pattern is rotated by successive angles Θ, until the best correlation between observed O and computed C (Θ) concentration values is reached;

$$r(\Theta) = \frac{\overline{(C(\Theta) - \overline{C(\Theta)})\,(O - \overline{O})}}{\sigma_O\,\sigma_C} \qquad 4.1$$

σ_O and σ_C are the standard deviations of the observed and computed concentrations respectively. A possible range for Θ is $-30° + 30°$.

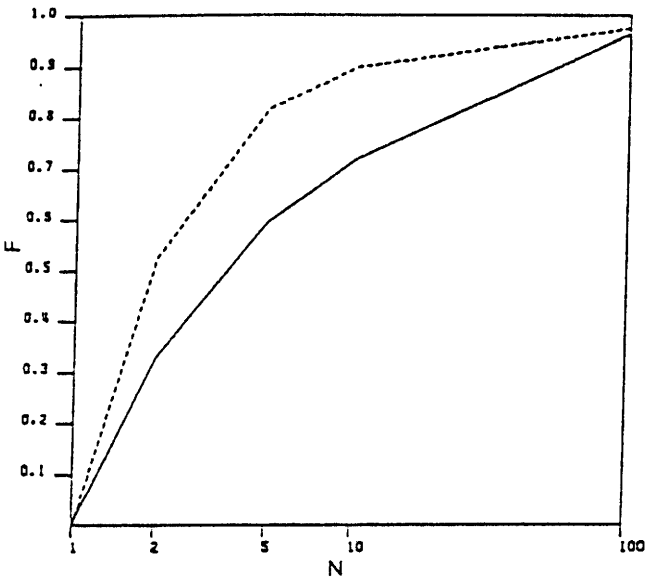

Figure 4.2. Fraction of samples *F* with SPADE computed concentration within an factor *N* of the observed value. Montalto tracer experiments; all samples. Solid line = first evaluation; dashed line = angle corrected evaluation.

The rotation process finally gives a set of $C(\Theta_m)$ from the diffusion code run with unit source rate corresponding to the maximum correlation $r(\Theta_m)$. The $C(\Theta_m)$ values can be plotted against the O values on an x-y plain. The estimated source emission E is then given by

$$E = r(\Theta)\frac{\sigma_O}{\sigma_C} \qquad 4.2$$

and is represented by the angular coefficient of the regression line of the points ($C(\Theta_m)$, O). Using a bi-logarithmic representation E is given by the y value of the intersection of the regression line with the y axis as illustrated in figures 4.3 and 4.4.

STEP has been tested in two different ways. Firstly, it was validated against a set of tracer data collected during two meteorological and diffusion campaigns carried out in June 1983 and June 1984 at the coastal site Montalto di Castro, about 100 km North-West of Rome, where a power plant is under construction (Cagnetti et al., 1985). The diffusion model

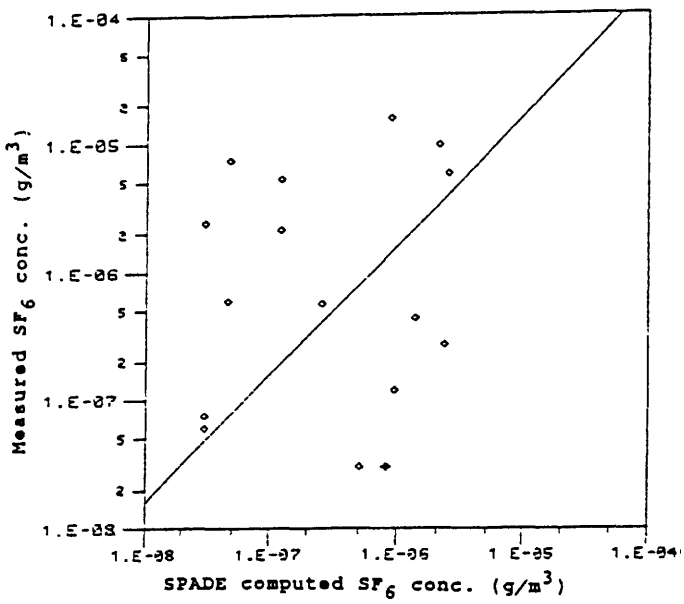

Figure 4.3 Scatter diagram of computed versus observed concentrations for 25.6.84, Montalto tracer experiment.

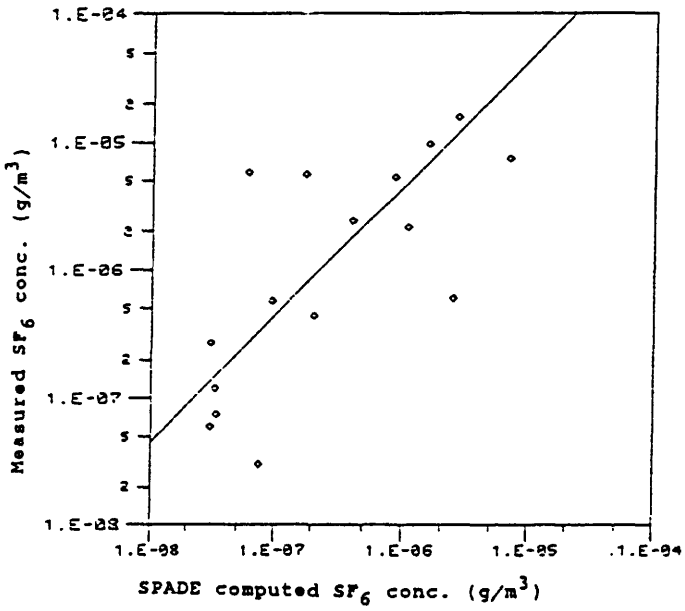

Figure 4.4 Same as for figure 4.3 but after the STEP rotation process. The source rate estimate is given by the y value of the intersection of the regression line with the Y axis divided by the x value of the origin: $E \approx 5$ g.s^{-1}. The actual source rate was 6.2 g.s^{-1}.

employed is the real-time sequential puff model SPADE developed at ENEA-DISP (see ch. 3.2).

STEP estimated the source term for all the sampling periods of the diffusion experiments, and the possibility of using it in a real situation was investigated by evaluating its' performance after varying the number of sample data available.

The results show that in about 90% of the episodes the emission rates are predicted within a factor 2, and all are predicted within a factor 3. When the number of sample data is progressively reduced through a random process of elimination, the results show that with five non-zero concentration samples emission rates are predicted within a factor 2 in more than 80% of the cases.

Secondly, a sensitivity study with STEP was performed. For this purpose, a release of radioactive material into the atmosphere at the Caorso nuclear power plant site, in the Po valley, was simulated.

The SPADE model simulated the diffusion of a radioactive cloud for a standard meteorological situation. It provided the concentration values at the points where radiological data should be available starting from a couple of hours after the beginning of the accident. These values were used as observed concentration data for STEP. Then, the SPADE code was run again several times to calculate the concentration pattern after varying some meteorological input data. STEP was then run with original and modified SPADE data sets to provide source rate estimates affected by a certain error. In this way, the sensitivity of the STEP code to the uncertainty of atmospheric stability, horizontal wind fluctuation and wind direction, was investigated.

The results show that the STEP performance is not very sensitive to the inaccuracy in the horizontal dispersion and the average wind direction evaluations. It is sensitive to the atmospheric stability, but the results are generally still acceptable if the correct stability category is missed by one and sometimes two categories. The only critical case is that of an elevated release in stable conditions.

4.3 STAR Source term and transfer parameter evaluation

4.3.1 Introduction

The method used in STAR is fundamentally different from those approaches that assign standard values to the environmental transfer parameters and then uses these either with a hypothetical source either to work out concentration fields, or in conjunction with radiological measurements to work back to an estimate of the source term. In the proposed approach, in contrast, all or part of the set of environmental transfer parameters, as well as the source term, become unknowns within the problem, as do the values of air concentration and deposition required. Only the radiological measurements and perhaps some of the environmental parameters are fixed parameters.

4.3.2 Model description

The code STAR uses measurements as a basis for determining the values of the source term and of the environmental transfer parameters, thereby yielding the best air concentration and deposition fields that are supported by the measurements made.

The objectives set out in the previous paragraph are typical of optimum control problems. It is known how to construct various types of models of atmospheric transfers which are sufficiently accurate when the model parameters are known well enough. However, the parameters used in the model fluctuate a great deal or are not exactly known, and it is often only possible to specify a range of values.

Past experience has shown that experts are not able to specify closely the isotopic composition, the activity or the height of a release either during or after an accident. Radiological protection experts therefore have to use ranges of values which are then reduced over time according to the measurements of radioactivity made in the environment.

The problem can therefore be summed up as follows :

i) The atmospheric transfer parameters of the problem may vary within specified ranges.

ii) It is required to obtain the distributions of air concentration and ground deposition using parameter values that lie within a prescribed variation interval and which provide the best possible fit to measurements made in the field.

The source term evaluation must be independent of the type of atmospheric transfer model adopted and of the way the equations used to construct the model are solved. The CEA has developed a method to solve the atmospheric transfer equation subject to a number of constraints. Firstly, the atmospheric transfer parameters are defined to lie within certain ranges, and secondly, a function is devised such that its control will yield the best possible fit to the measurements made in the field.

In order to provide an operational solution to the problem, the method proceeds by linearizing the solution of the atmospheric transfer equation with respect to the various parameters. Then a mathematical program is defined, made up of constraints on the variation of atmospheric transfer parameters and constraints which ensure that the values given by the solution of the atmospheric transfer equation lie within a range determined by the radiological measurements. The solution of the mathematical program is a set of parameters satisfying the constraints and optimizing the so-called 'economic function'. If the constraints and economic function are linearly related to the parameters, this mathematical program is termed a 'linear program'.

The so-called 'simplex' method was chosen by CEA to solve this mathematical program, now reduced to a linear program. This method has the advantage of not being limited to a simple stage of adjustment: it enables sensitivity analyses to be performed and the implementation of processes which aid decision-making. It also makes it possible to pick out the most incongruous radioactivity readings or the most inadequate parameter values. Other methods of optimization can also be used to solve this kind of optimum control problem.

The linearization of the solution of the atmospheric transfer equation is a problem that can be approached more or less achieved easily according to the method used to resolve the equation. We may be tempted at first to replace an exact calculation of the derivative with a finite increments calculation. In a particular study, the calculations of the derivatives of the analytical solutions to the diffusion-convection equation obtained using the Gaussian plume resolution method can be used. In this case, derivatives of atmospheric concentration are expressed with respect to the following parameters: horizontal dispersion, vertical dispersion, discharge height, reflexion level, deposition rate, washout rate, windspeed, and the source term relating to the activity of a given radionuclide.

The wind direction can be considered as parameter only if a plume model is used. In this case, the best fit is calculated for a given direction (the goodness of the fit is qualified by the value of the optimized economic function). A gradient method based on the decrease of the

economic function in the space of parameters is used to obtain the best fit: i.e. the minimum of the optimized values of economic function in the space of parameters including the parameters 'wind direction'.

The STAR model is best illustrated by considering the linear programs that are used to derive a source term from various sets of radioactive measurements:

i) The radioactive atmospheric aerosol contains only one kind of radionuclide (A) and one measurement of atmospheric radioactivity has been made.

The source-term S1 (Bq), the measurement M1 ($Bq.m^{-3}$), and the atmospheric transfer coefficient ATCA1 ($s.m^{-3}$) are given. The atmospheric transfer coefficient represents the atmospheric radioactivity in $Bq.m^{-3}$ arising from the relevant atmospheric and release conditions, corresponding to a release rate of 1 $Bq.s^{-1}$. The atmospheric transfer coefficient is integrated over the period of measurement. The linear program to be resolved is as follows:

$S1 * ATCA1 - dR1 < M1$

$S1 * ATCA1 + dR1 > M1$

Minimize dR1

ii) The radioactive atmospheric aerosol contains only one kind of radionuclide (A). One measurement of atmospheric radioactivity and one measurement of deposited activity have been made at the same point.

The source-term S1 (Bq), the atmospheric measurement M1 ($Bq.m^{-3}$), the deposition measurement D2 ($Bq.m^{-2}$), and the atmospheric transfer coefficient ATCA1 ($s.m^{-3}$) are given. The atmospheric transfer coefficient is integrated over the period of measurement and takes into account the deposition. The linear program to be resolved is as follows, with the deposition velocity at the point denoted as v_g:

$S1 * ATCA1 - dR1 < M1$

$S1 * ATCA1 + dR1 > M1$

$vg * S1 * ATCA1 - dR2 < D2$

$vg * S1 * ATCA1 + dR2 > D2$

Minimize dR1 + dR2

iii) The radioactive aerosol is composed of two radionuclides (A and B). Atmospheric external gamma irradiation measurements have been made at two different points.

The source-terms SA and SB (Bq), the external gamma irradiation measurements M1 and M2 ($Gy.s^{-1}$), and the atmospheric transfer coefficients ATCA1, ATCA2, ATCB1, and ATCB2 ($s.m^{-3}$) are given. The atmospheric transfer coefficients are integrated over the period of measurement. The linear program to be resolved is as follows:

$$SA * ATCA1 * FA + SB * ATCB1 * FB - dR1 < M1$$

$$SA * ATCA1 * FA + SB * ATCB1 * FB + dR1 > M1$$

$$SA * ATCA2 * FA + SB * ATCB2 * FB - dR2 < M2$$

$$SA * ATCA2 * FA + SB * ATCB2 * FB + dR2 > M2$$

$$\text{Minimize } dR1 + dR2$$

FB and FA are conversion factors from atmospheric concentrations of the nuclides A and B to external radiation, such as those given by semi-infinite or finite cloud models.

With functions of this type and with a number number of radioactive measurements, it is possible to construct a lot of mathematical programs in order to derive the source-term. Additional work could include the introduction of a program enabling the management and homogenisation of all radiological measurements performed around the nuclear power plant - such as deposition on soil, external irradiation, atmospheric radioactivity - and the computerized creation of a mathematical program to determine the set of parameters essential for the estimation of a radiological situation such as windspeed, wind direction, source-term and deposition velocity. Also the mathematical program could be modified to take into account other types of radiological data such as β–activity measurements of gaseous effluents passing through the stack or external irradiation measurements performed inside the nuclear power plant. Such measurements complement to some extent those performed away from the site: the external irradiation inside the plant and the gross β measurements from the stack are typically dominated by noble gases and iodine. Consequently, these data would allow a better estimate of these components of the release, to be made.

Another possibility is the construction of mathematical programs for determining the kinetics of the radioactive release, if the time development of the radiological measurements is sufficiently consistent. In practice, if the measurements give the integrated activity from time t1 to time t2, it will be impossible to resolve the behaviour in time of the release between t1 and t2. The source-term between these two times has to be considered constant. But if the mathematical program is given a set of measurements of radioactivity performed at a series

of times t1, t2, ..., tn, it would be possible to calculate the radioactivity released within times intervals. In other cases, interpolation of these measurements with time is needed.

A major advantage of this kind of method, is the possibility of adapting it to a large inhomogeneous set of radiological measurements, thereby allowing the possibility of modifying the size of the intervals of variations of constraints, i.e. the difference between calculations and measurements, the identification of inconsistent measurements and the setting of bounds on the differences between measurement and calculation.

5. THE DOSE EVALUATION MODEL EURALERT

5.1 Introduction

The assessment of the radiological impact of a contamination of air and precipitation with radionuclides (processes considered by the models described in chapter 3) requires the application of computer models considering:

i) The external exposure from radionuclides in the air and those deposited on the ground and on other surfaces.

ii) The internal exposure from radionuclides incorporated by inhalation.

iii) The transfer of radionuclides through the different food chains and the subsequent internal exposure of man by radionuclides incorporated with foodstuffs (ingestion).

It was the aim of project 4 to develop a program system which performs such calculations within short times to allow it to be used as a real time assessment system. Moreover this system should be able to predict the effect of several types of possible countermeasures in order to facilitate decision making with regard to appropriate countermeasures.

For this purpose the dose assessment code EURALERT has been developed on the basis of the radioecological model ECOSYS taking into account post-Chernobyl experiences in the field of radioecology. The main features of the methods applied in this model are described in section 5.3.

Different constraints which are partly contradicting had to be considered during the development of the program system:

i) The model has to start from quantities which can be predicted by the dispersion models.

ii) The assessment of the radiological impact has to be done for a lot of locations (up to about 1 000).

iii) The model has to be easily adaptable to the different radioecological conditions in the different regions of the countries of the European Community.

iv) The dose assessment shall be capable of simulating different countermeasures e.g. changes of the feeding practices or of the human diet for certain time intervals.

v) The amount of output data has to be restricted to that which can reasonably be 'processed' by the user in the form of tables or graphics.

vi) The calculation times shall be short enough to use the model as a real time system.

To meet all these requirements a program system was designed to permit dose assessments to be done, either with high spatial resolution but in reduced detail, or considering all possible feed and foodstuffs at a single location with full resolution in time. The radionuclide transfer through the food chains is pre-calculated for unit deposition in order to reduce the required computing times in the case of emergency application. An overview of the design of the program system is given in section 5.4. A more detailed description of the programs, data files and their application is given in the EURALERT User's Guide (Müller et al., 1990).

The program system is written in FORTRAN 77, so there should be no problems in transferring the programs to other computers. Of course, certain machine specific functions will have to be adapted. Details of the program installation and the necessary adaptions are described in the User's Guide.

5.2 Model input

5.2.1 Interface to atmospheric dispersion models

The starting point for the subsequent assessment of the radiation exposure of the public are the results of the atmospheric dispersion calculations described in chapter 3. The interface between the amospheric dispersion programs and the dose assessment programs is a file containing the following data, for every location up to a maximum of 1 000 locations, for which dose assessments are to be made:

i) The time-integrated radionuclide concentration in the near ground air ($Bq.s.m^{-3}$).

ii) The nuclide-specific activity which is deposited per unit area by precipitation ($Bq.m^{-2}$).

iii) The amount of precipitation (mm).

iv) The absorbed cloud γ dose in air (Gy) for each nuclide (required from the short range dispersion program only, where the activity in the air cannot be assumed to be homogeneously distributed).

There are no restrictions on where these locations are situated, for example it is not necessary that they are on a regular grid. The locations may be chosen as representative of political units (countries, departments, counties, communities etc.), since data on population and food production are normally available for those units.

5.2.2 Model parameters for dose evaluation

The model is designed to be applicable in a very general way for different regions in Europe and with a wide range in the size of the areas represented by each location. It is therefore necessary to consider the very different radioecological conditions of these locations, define different regions in which the radioecological conditions can be assumed to be uniform, and classify every location for which a dose assessment is required as one of these regions.

All those model parameters which can vary from one region to the other have to be given for each region. The selection of adequate values of these parameters is the responsibility of the user; it is not the task of this project to supply all these values for all regions of Europe.

The most important of these region specific data are:

i) Living habits of the population: times staying outdoors, dietary habits.

ii) Constitution of houses: shielding of external radiation, ventilation.

iii) Growing of plants: times of sprouting and harvest, intensity of growth.

iv) Agricultural practices: intensity of farming, feeding of animals.

For some regions it will be necessary to include additional plant species to those considered presently in the model (e.g. rice and citrus fruits which are of concern in Southern Europe). This is a task which will be addressed in the future.

Several model parameters describing the transfer in foodchains and the exposure on the different pathways can be assumed to be independent of the region; so they can be adopted from the existing data files. In addition to the region dependent, and region independent radioecological model parameters which are required, the model also requires two location specific parameters: the radioecological region to which the location belongs, and the number of inhabitants of the region.

A detailed description of all input parameters and the format in which they have to be provided in the data files is given in chapter 4 of the User's Guide.

5.3 Methods applied for dose evaluation

The assessment of radiation exposure in the EURALERT code is based on the dynamic radioecological model ECOSYS (Pröhl et al.,1988). The methods of calculating deposition and interception as well as the activity transfer in foodchains are described in detail elswhere (Pröhl, 1990), therefore only a brief description is given here. Most of the parameters used below depend on the radionuclide, however this dependency is not indicated explicitly in the following equations in the interests of clarity.

5.3.1 Deposition and interception

The first step of the assessments is to calculate the amount of activity which is deposited by dry and wet deposition on the different types of plants and on the soil.

For dry deposition the amount of radionuclides deposited onto a certain surface (i.e. the leaves of a plant species or the soil) is given by;

$$A_{d,i} = v_{d,i}\,\chi_{air} \qquad 5.1$$

where $A_{d,i}$ = activity deposited onto surface type i (Bq.m^{-2})
$v_{d,i}$ = deposition velocity for surface type i (m.s^{-1})
χ_{air} = time-integrated activity concentration in air (Bq.s.m^{-3})

The calculation of dry deposition onto the different plant canopies takes into account the stage of development of the plant's leaves. The deposition velocity is assumed to be proportional to the leaf area index (*LAI*) which is representative of the area of leaves present per unit area of ground:

$$v_{d,i} = v_{d,i,max}\,\frac{LAI_i}{LAI_{i,max}} \qquad 5.2$$

where $v_{d,i,max}$ = maximum deposition velocity for plant type i (m.s^{-1})
$LAI_{i,}$ = leaf area index of plant type i at time of deposition
$LAI_{i,max}$ = leaf area index of plant type i at time of fully developed foliage

The *LAI* is strongly dependent on the time of the year. Dry deposition is therefore strongly dependent on the time of the year: For every type of plant, the *LAI* as a function of time is expressed in the model input parameters by a table. As an example figure 5.1 shows the

development of the *LAI* of some plants for southern German conditions; of course this time dependence can be quite different at other regions of Europe.

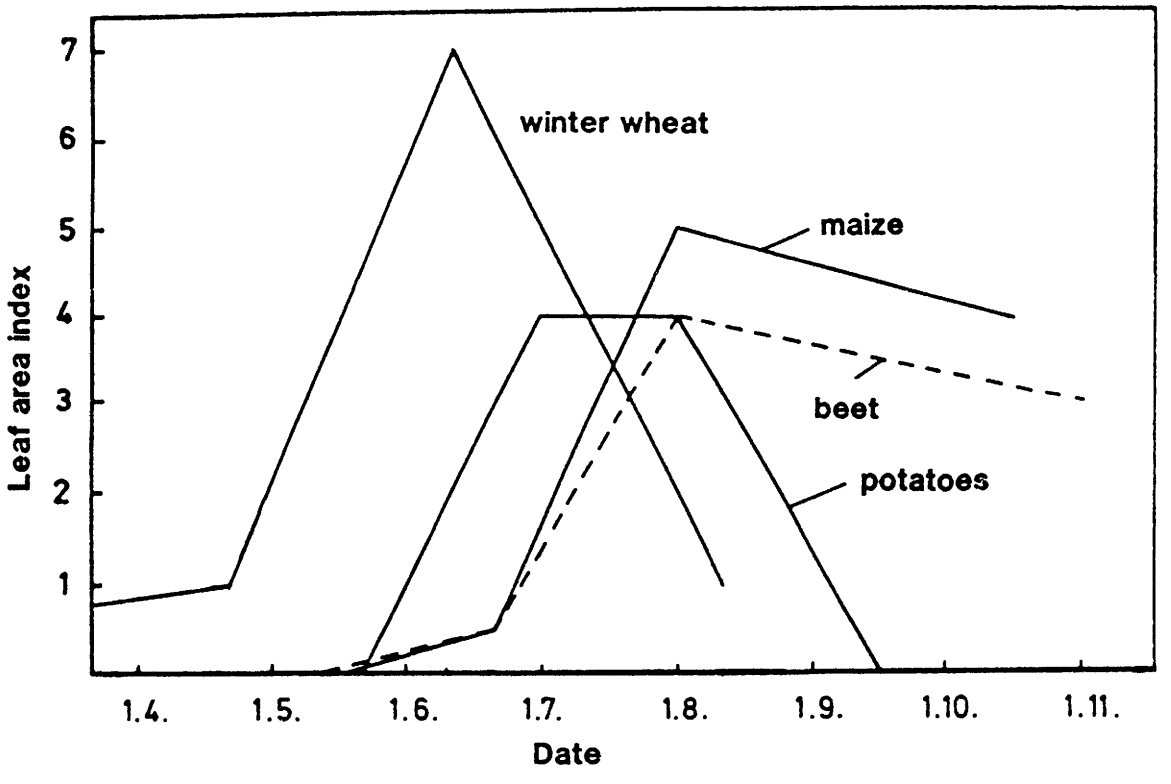

Figure 5.1 Example of the time-dependence of the leaf area index

For grass, the stage of development is expressed by the yield because it is easier to determine. The following function is used to estimate the *LAI* from the yield:

$$LAI_g = LAI_{g,max} (1 - e^{-kY_g}) \qquad 5.3$$

where LAI_g = leaf area index of grass at time of harvest
$LAI_{g,max}$ = maximum leaf area index of grass
k = normalization factor = 1 $m^2.kg^{-1}$
Y_g = yield of grass ($kg.m^{-2}$) at time of harvest

For deposition onto soil, a deposition velocity independent on the time of the year is assumed. Table 5.1 shows the values of the deposition velocity for soil and the maximum values for plants as used as default values in EURALERT. Of course the users are free to apply different values (they can be assumed as dependent on the region considered). The atmospheric dispersion models (see chapter 3) use mean deposition velocities in calculating

surface	deposition velocity (mm/s)		
	aerosol bound radionuclides	elemental iodine	organic bound iodine
soil	0.5	3.	0.05
grass	1.5	15.	0.15
trees	5.	50.	0.5
other plants	2.	20.	0.2

Table 5.1 Default values of EURALERT for the deposition velocities for soil and plants with fully developed foliage.

the plume depletion. These mean deposition velocities can be somewhat different from the values in table 5.1, but this is not a contradiction as the large scale depletion of the plume is represented by a mean deposition over all surface types (including forests, cities etc.), and is influenced only to a minor degree by the agricultural plants considered here.

In the case of wet deposition the total amount of activity deposited with precipitation per square metre of ground is the input of the calculations. A certain fraction of it remains on the leaves of the plants. This interception fraction is dependent on the type of plant, the stage of development of the plant (depending on the time of the year), the properties of the radionuclide considered and the amount of rainfall. In the EURALERT code the interception fraction $f_{w,i}$ for plant type i for one rainfall event is quantitatively expressed (Müller and Pröhl, 1987) by:

$$f_{w,i} = \min\left(1 ; LAI_i \; S_i \frac{1 - e^{-k_i R}}{R}\right) \qquad 5.4$$

where S_i = effective water storage capacity (mm) of plant type i
k_i = $\ln 2/(3 * S_i)$
R = amount of rainfall (mm) of a rainfall event

For longer wet deposition periods, the individual rainfall events have to be considered seperately and the intercepted activity has to be accumulated. The values of the effective water storage capacity S_i applied in the model are given in table 5.2. The three nuclides iodine, caesium and strontium are given in the table as representatives of three groups of nuclides which are considered in the model.

plant species	effective water storage capacity (mm)		
	I	Cs	Sr
grass, cereals, maize	0.1	0.2	0.4
other plants	0.15	0.3	0.6

Table 5.2 Effective water storage capacities S_i for different plants and nuclides

The total deposition onto soil and the leaves of plants is the sum of dry and wet deposition. The total deposition to plants is given by:

$$A_i = A_{d,i} + f_{w,i} A_w \qquad 5.5$$

where A_i = total deposition (Bq.m^{-2}) onto plant type i
$A_{d,i}$ = dry deposition onto plant type i (Bq.m^{-2})
$f_{w,i}$ = interception fraction for plant type i
A_w = total wet deposition (Bq.m^{-2})

The deposition to soil is of importance for the long-term root uptake of the plants. In order to take account of the activity input to soil by organic fertilisation, not only the dry deposition to bare soil but in addition, that on pasture grass is considered. Thus, the total deposition to soil is given by;

$$A_s = A_{d,s} + A_{d,g} + A_w \qquad 5.6$$

where A_s = total deposition to soil (Bq.m^{-2})
A_{ds} = dry deposition to soil (Bq.m^{-2})
A_{dg} = dry deposition to grass (Bq.m^{-2})
A_w = total wet deposition (Bq.m^{-2})

5.3.2 Activity concentration in foodstuffs

Contamination of plants

The contamination of the different plants as a function of time is is given by the sum of the nuclide uptake via the leaves and that via the roots.

$$C_i(t) = C_{l,i}(t) + C_{r,i}(t) \qquad 5.7$$

where $C_i(t)$ = total contamination of plant type i (Bq.kg^{-1})
$C_{l,i}(t)$ = contamination of plant type i due to contamination of leaves (Bq.kg^{-1})
$C_{r,i}(t)$ = contamination of plant type i due to root uptake and resuspension (Bq.kg^{-1})

Contamination of plants after nuclide deposition on the leaves:

It is necessary to distinguish between those plants which are totally consumed by individuals or animals (e.g. leafy vegetables, maize, pasture grass etc.) and those where only a certain part is consumed (e.g. cereals, potatoes etc.).

In the first case, the activity concentration $C_{l,i}(t)$ at time t after the deposition is determined by the concentration immediately after the deposition, the activity loss by weathering effects (rain, wind) and radioactive decay, and the activity dilution due to increasing biomass of the plants. For leafy vegetables, maize and beet leaves, the increase in biomass is considered implicitly as deposition onto the leaves is calculated from the leaf area at the time of deposition;

$$C_{l,i}(t) = \frac{A_i}{Y_i} e^{-(\lambda_w + \lambda_r) t} \qquad 5.8$$

where Y_i = yield (kg.m^{-2}) of plant type i at time of harvest
λ_w = weathering rate (d^{-1})
λ_r = radioactive decay rate (d^{-1})
t = time after deposition (d)

The approach for pasture grass is different because it is harvested continuously. Here the activity decrease by biomass increase is considered explicitly. Moreover for nuclides (e.g. iodine or caesium) which are highly mobile within the plants inner transportation system (phloem), the process of translocation into the root zone and subsequent re-mobilisation at later harvests is considered in the model;

$$C_{l,g}(t) = \frac{A_g}{Y_g} \left[(1 - a) e^{-(\lambda_b + \lambda_w + \lambda_r) t} + a e^{-(\lambda_t + \lambda_r) t} \right] \qquad 5.9$$

where A_g = total activity deposited onto grass (Bq.m^{-2})
Y_g = yield (kg.m^{-2}) of grass at time of deposition
a = fraction of activity translocated to the root zone
λ_b = dilution rate by increase of biomass (d^{-1})
λ_t = rate of activity decrease due to translocation to the root zone (d^{-1})

For plants which are only partly utilized for feeding or human consumption, translocation from the leaves to the edible part of the plant has to be considered. This process is strongly dependent on the chemical properties of the radionuclides under consideration: it is of importance for mobile elements as e.g. iodine and caesium, but it does not occur with immobile elements like strontium; in the latter case only direct deposition onto the edible part of the plants plays a role. Moreover, the amount of translocated activity is highly dependent on the timespan between deposition and harvest. The translocation process is quantitatively expressed in the model by the translocation factor $T_i(t)$ which is given in the model parameters as a tabulated function, dependent on nuclide, plant type, and time between deposition and harvest.

Figure 5.2 shows an example of the dependence of the translocation factor for caesium, a mobile element, on the time between deposition and harvest for spring and winter wheat. The activity concentration of the plant type i harvested at time t after deposition is given by

$$C_{l,i}(t) = \frac{A_i}{Y_i} T_i(t)\, e^{-\lambda_r t} \qquad 5.10$$

where $T_i(t)$ = translocation factor for plant type i
other symbols are as defined earlier

Contamination of plants by root uptake:

The activity concentration $C_{r,i}$ in plant type i due to root uptake is calculated from the activity concentration in the soil using the transfer factor TF_i which gives the ratio of activity concentration in plants (fresh weight) and soil (dry weight):

$$C_{r,i}(t) = TF_i\, C_s(t) \qquad 5.11$$

where $C_s(t)$ = activity concentration (Bq.kg^{-1}) in the root zone of soil

The activity concentration of the root zone of soil is given by

$$C_s(t) = \frac{A_s}{L\rho_s} e^{-(\lambda_s + \lambda_r + \lambda_f)} \qquad 5.12$$

where A_s = total deposition to soil ($Bq.m^{-2}$)
L = depth of root zone (m)
ρ_s = density of soil ($kg.m^{-3}$)
λ_s = rate of activity decrease due to migration out of the root zone (d^{-1})
λ_f = rate of fixation of radionuclides to soil particles (d^{-1})

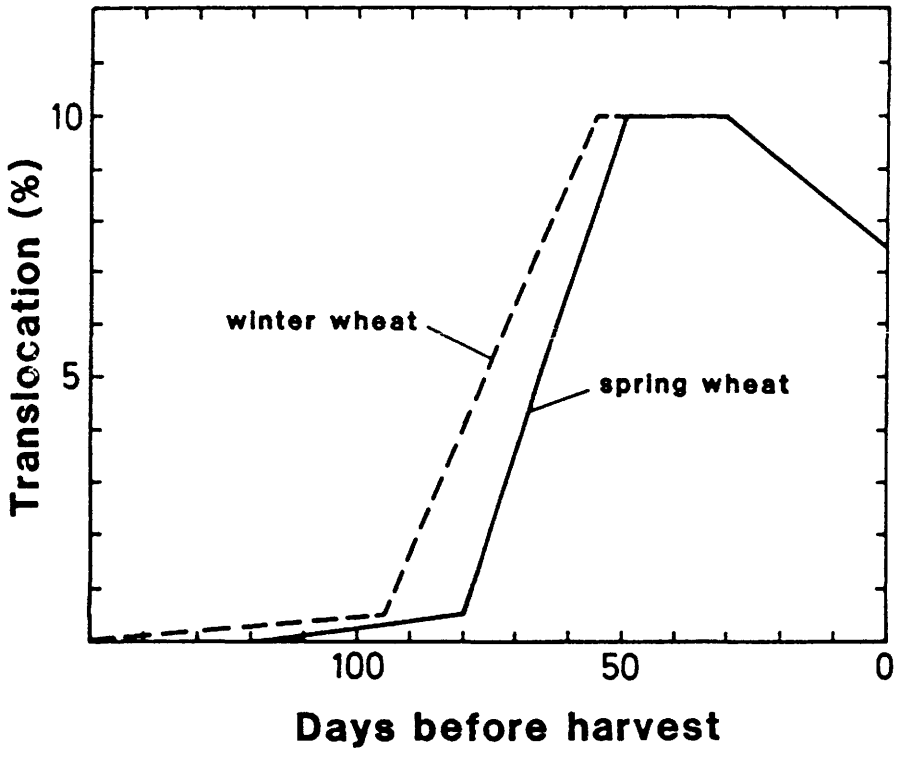

Figure 5.2 Example of the time-dependence of the translocation factor for caesium.

Contamination of animal products

The contamination of animal products (milk, meat, eggs) is dependent upon the activity intake of the animals and the kinetics of the considered radionuclides within the animals metabolism. The amount of activity ingested by the animal is calculated from the activity concentration in the fodder and the feeding rate:

$$A_f(t) = C_f(t)\, I_f \qquad 5.13$$

where $A_f(t)$ = activity intake rate of the animal (Bq.d^{-1})
$C_f(t)$ = activity concentration in the fodder (Bq.kg^{-1})
I_f = feeding rate (kg.d^{-1})

If more than one type of fodder is fed to the animals then 5.13 is summed over all feedstuffs.

The transfer of radionuclides into the animal product l is described by the equilibrium transfer factor TF_l and one or more (up to 4) exponentials representing biological excretion rates (according to respective biological half-lives);

$$C_l(T) = TF_l \sum_{j=1}^{J} \{ a_{l,j} \int_0^T A_f(t)\, \lambda_{b,l,j}\, e^{-(\lambda_{b,l,j} + \lambda_r)(T - t)}\, dt \} \qquad 5.14$$

where $C_l(T)$ = activity concentration (Bq.kg^{-1}) in animal product l at time T
TF_l = transfer factor for animal product l
J = number of biological transfer rates (maximum = 4)
$a_{l,j}$ = fraction of biological transfer rate j
$\lambda_{b,l,j}$ = biological transfer rate j (d^{-1}) for animal product l

Storage and processing of foodstuffs

The contamination of human foodstuffs and of the animal's fodder is calculated taking into account the activity enrichment or dilution during processing, as well as processing and storage times. The activity concentration in feed- or foodstuff l is calculated from the primary product (i.e. the plant or animal product from which it is produced);

$$C_{fs,l} = C_{pp}\, P_l\, e^{-\lambda_r t_p} \qquad 5.15$$

where $C_{fs,l}$ = activity concentration (Bq.kg^{-1}) in foodstuff l
C_{pp} = activity concentration (Bq.kg^{-1}) in the primary product
P_l = processing factor for foodstuff l
t_p = mean storage and processing time (d)

It is also possible to consider feed- or foodstuffs which are produced from more than one primary product (e.g. animal meal is produced from pork and chicken).

5.3.3 Ingestion dose

The activity intake of man is calculated from the time dependent activity concentrations of foodstuffs and the human consumption rates, summing over all foodstuffs considered:

$$A_{ing}(t) = \sum_{l} C_l(t)\, V_l(t) \qquad 5.16$$

where $A_{ing}(t)$ = activity intake rate ($Bq.d^{-1}$)
$C_l(t)$ = activity concentration ($Bq.kg^{-1}$) of foodstuff l
$V_l(t)$ = consumption rate ($kg.d^{-1}$) of foodstuff l

The consumption rates are considered to be age dependent; values for the age groups of 0, 1, 5 10, 15 years and adults are included in the model parameters. It is possible to use as consumption rates either average population values or any user specified dietary habits, thus enabling the consumption habits of critical groups to be considered.

It is possible to apply two kinds of modifying factors to the food consumption rates:

i) For each foodstuff a time independent factor can be applied which can be used to consider, for example, the fraction of the foodstuff imported from uncontaminated regions. The consumption rates of the foodstuff for all age-groups are multiplied by the factor. Default value of this factor is 1.0 for all foodstuffs.

ii) The consumption rates of single foodstuffs can be modified by reduction factors for limited time intervals. Thus, for example, the effect of changes in the population's dietary habits in the time shortly after the deposition event, or the effect of banning certain foodstuffs during limited time spans, can be assessed.

Another possibility for simulating the effect of countermeasures is to introduce limits for the activity concentration in foodstuffs. These limits can be given for every foodstuff independently and for single radionuclides or for groups of nuclides (e.g. the sum of activity of all caesium isotopes). For the calculation of the activity intake of man it is assumed that foodstuffs with a predicted activity exceeding the given limits are not consumed. While activity in the foodstuffs exceeds the limits it can either be assumed that the activity of the concerned foodstuff is equal to the limits, or that it is zero (these are the two extreme cases; reality will be somewhere in between).

The dose $D_{ing}(T)$ due to ingestion of contaminated foodstuffs within the time T after the deposition is given by;

$$D_{ing}(T) = \int_0^T A_{ing}(t)\, g_{ing}(t)\, dt \qquad 5.17$$

where $D_{ing}(T)$ = ingestion dose (Sv)
$g_{ing}(t)$ = dose factor for ingestion ($Sv.Bq^{-1}$)

The dose factors used in the model (Henrichs et al., 1985) are based on the metabolic models of the ICRP 30 publication. They give the 50 year committed dose after activity intake. Age dependent values for the same age groups (except 0 years) as mentioned at the consumption rates are available. If necessary, it is is possible to use different dose factors merely by modifying the respective data files.

5.3.4 Inhalation dose

The dose D_{inh} due to inhalation of radionuclides during the passage of the radioactive cloud is calculated from the time integrated activity concentration in the near ground air (which is input to the model), the inhalation rate, the dose factor for inhalation and a reduction factor which can be used to consider the lower activity in air inside houses:

$$D_{inh} = \chi_{air}\, I_{inh}\, g_{inh}\, R_{inh} \qquad 5.18$$

where D_{inh} = inhalation dose (Sv)
χ_{air} = time-integrated activity concentration in air ($Bq.s.m^{-3}$)
I_{inh} = inhalation rate ($m^3.h^{-1}$)
g_{inh} = dose factor for inhalation ($Sv.Bq^{-1}$)
R_{inh} = reduction factor for staying indoors

The inhalation rate is considered to be age dependent. Values which are representative for persons being partly at rest and partly at light action are used. Any other inhalation rates can be used by exchanging the respective data file.

Like the dose factors for ingestion those for inhalation are based on the metabolic models of the ICRP 30 publication. The values are given for the same age groups. Here too it is is possible to use different dose factors merely by replacing the respective data file.

The reduction factor R_{inh} is derived from the fraction of time during which people are at different locations and integrated air concentration at the locations relative to that outside;

$$R_{inh} = \sum f_i \, c_{a,i} \qquad 5.19$$

where f_i = fraction of time staying at location i
$c_{a,i}$ = concentration of radionuclides in air at location i relative to that in plain air (filtering factor)

The same locations as for the calculation of external doses (see next section) are used.

5.3.5 External exposure from the cloud

In EURALERT, the calculation of the exposure by γ radiation from the cloud assumes that the cloud is semi-infinite and homogeneous. This assumption is only valid for the considered locations at least several kilometres from the point of release. To calculate the exposure from cloud in the vicinity of the release point, the actual 3-dimensional distribution of activity in the cloud has to be considered. This can only be done in the preceding atmospheric dispersion program, since the distribution of activity in the cloud is not transferred to the EURALERT code. Therefore the value of the absorbed cloud γ dose in air is an optional input quantity for EURALERT. If this value is given in the input data file, then it is used to calculate the dose for γ exposure from the cloud instead of the cloud γ dose calculated according to the following scheme.

For a semi-infinite cloud the external exposure is given by

$$D_C = \chi_{air} \, g_C \, R_C \qquad 5.20$$

where D_C = dose due to external radiation from the cloud (Sv)
χ_{air} = time-integrated activity concentration in air (Bq.s.m^{-3})
g_C = dose factor for exposure from the cloud (Sv.m^3.Bq^{-1}.s^{-1})
R_C = reduction factor for staying at different locations

The reduction factor R_C is derived from the fraction of time during which people are at different locations and the shielding from cloud γ radiation provided at these locations.

$$R_C = \sum f_i \, c_{C,i} \qquad 5.21$$

where f_i = fraction of time staying at location i

$c_{C,i}$ = γ dose rate from the cloud at location *i* relative to that in plain air without buildings etc.

Values of $c_{C,i}$ for the different locations utilised in the model are given in table 5.3 in the next section.

5.3.6 External exposure from deposited nuclides

The exposure by γ radiation from nuclides deposited on the ground is calculated assuming a horizontally homogeneous distribution of radionuclides over grassland, this is then corrected for different locations, by taking into account the different patterns of deposition at the various locations, for example on trees or houses.

The dose integrated up to time T after deposition from γ radiation from deposited radionuclides is given by;

$$D_G(T) = \int_0^T A_s \, g_G \, R_G \, e^{-\lambda_r t} \, (a_1 \, e^{-\lambda_1 t} + a_2 \, e^{-\lambda_2 t}) \, dt \qquad 5.22$$

where D_G = dose due to γ radiation from deposited nuclides (Sv)
A_s = total deposition to soil and grass ($Bq.m^{-2}$)
g_G = dose factor for exposure from ground ($Sv.m^2.Bq^{-1}.h^{-1}$)
R_G = reduction factor for staying at different locations
λ_1, λ_2 = migration rates (d^{-1})
a_1, a_2 = coefficients of the migration rates

The reduction factor R_G is derived from the fraction of time during which people are at different locations and the shielding from ground γ radiation provided at these locations;

$$R_G = \sum f_i \, c_{G,i} \qquad 5.23$$

where f_i = fraction of time staying at location *i*
$c_{G,i}$ = γ dose rate from deposited nuclides at location *i* relative to that over grassland

Values of $c_{G,i}$ for the different locations applied in the model are given in table 5.3. These vaues have been derived by Meckbach and Jacob (1988) and are typical for German houses. For application in regions with different conditions, the values should be adapted.

Location	Location factor for exposure from the cloud $c_{C,i}$	ground $c_{G,i}$
Outside houses:		
suburban	1.0	1.0
urban	0.6	0.3
Single family houses:		
above ground	0.3	0.1
basement with windows	0.05	0.01
basement, no windows	0.01	0.001
Large buildings:		
above ground	0.05	0.01
basement	0.001	0.0005

Table 5.3 Correction factors for external exposure at different locations

5.4 Structure of the program system

Only a brief overview on the single components of the program system is given here; a more detailed description is to be found in Chapters 2 and 3 of the User's Guide.

Due to the requirements to give very detailed informations on the one hand and a high spatial resolution on the other hand within short calculation times, the program system EURALERT is split into two branches as shown in figure 5.3. The system starts with the activity in air and precipitation at many locations and the program DEPOS calculates the deposition of activity onto the leaves of the plants and onto soil at all these locations. Further, those radiation exposures which are caused only during the passage of the radioactive cloud, i.e. the external γ exposure from the cloud and the inhalation of radionuclides, are calculated in this program and stored in data files. After that the user can either continue with the program ALL to calculate a limited amount of information at all locations, or with the program SINGLE to get a very detailed radiological assessment at one selected location. Of course, the SINGLE program can be run several times to make the detailed assessment for more than one location.

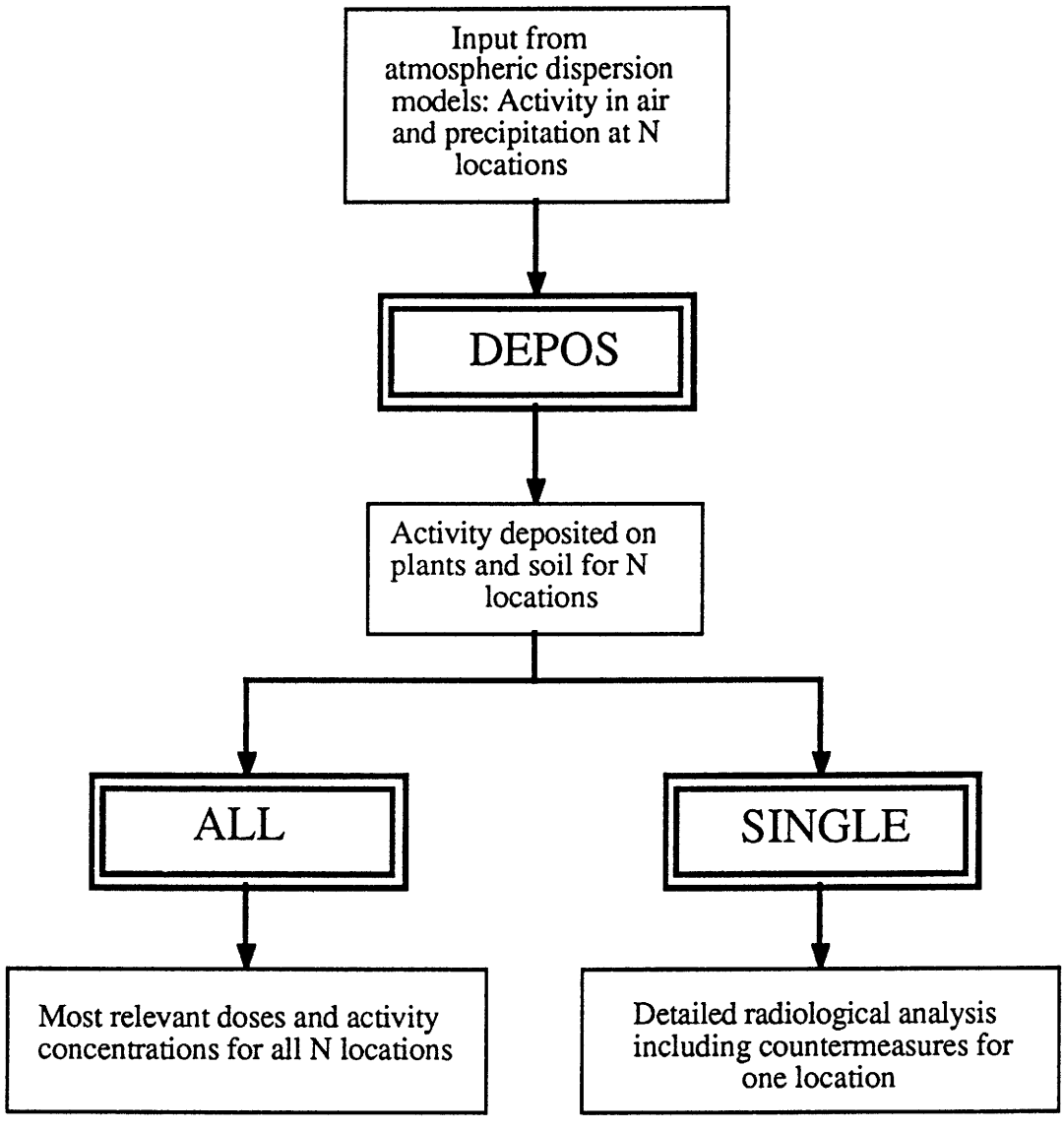

Figure 5.3 Basic flow scheme of program system EURALERT. The double rectangles represent programs or procedures.

The procedure ALL consists of several calculation steps:

i) For the locations with the highest deposition of radionuclides, detailed dose calculations (i.e. considering all foodstuffs) are performed.

ii) From the results, those pairs of nuclides and foodstuffs (e.g. I-131/milk; Cs-137/wheat etc.) which contribute most to the ingestion dose are determined.

iii) For all locations the dose calculations are performed with limited information, i.e. for the ingestion dose calculation only those nuclide-foodstuff combinations are considered which have been chosen in step 2.

The procedure SINGLE performs the following calculations:

i) One of the locations is selected by the user.

ii) The activity concentration in all foodstuffs is calculated with high time resolution.

iii) The doses via all pathways are calculated with high time resolution.

Since the generated results are so numerous that they can not be displayed in tables or diagrams completely it is necessary to chose those which are of interest for the user. For this purpose the program system contains programs which allow the selection of the desired output in a dialogue.

Moreover there are different programs for further calculations for the chosen single location:

i) The activities in animal products can be calculated using different feeding practices, e.g. it is possible to replace one type of fodder by another one for certain time periods.

ii) Activity limits in foodstuffs can be introduced; the time spans during which these limits are exceeded and the resulting doses are calculated for this case.

iii) The doses can be calculated using different dietary habits; also changes of the consumption rates for limited time periods can be considered.

iv) The doses can be calculated using different times of outdoor activities.

For all these cases it is possible to calculate not only the absolute doses but also the doses relative to the 'standard' case.

5.5 Model output

For every location for which the activity in air and precipitation is given in the input file, EURALERT calculates the respective doses to an individual living at this location. The ingestion doses are estimated assuming all foodstuffs are produced either locally (i.e. having activities derived from the input data for that location) or partly from uncontaminated areas. Thus, the resulting doses have to be considered as potential doses.

If a location is representative of a certain area (i.e. if the activities in air and precipitation are mean values for this area) the resulting dose is to be regarded as a mean dose for this area; multiplying by the number of inhabitants of the area will yield an estimate of their collective dose. Variations in individual dose within the area which are due to variations in the dietary habits of the inhabitants, agricultural practices etc. can be estimated by re-running the programs with different values for the relevant parameters.

The following data are written to files, and can subsequently be represented graphically (using the users' graphical software), or they can be printed out as tables.

Program DEPOS gives the following quantities for every location and nuclide considered:

i) Total deposition onto each type of plant and onto soil (resulting from dry deposition and interception of wet deposited activity).

ii) Inhalation dose for two age groups.

iii) Dose from external radiation from the cloud for two age groups.

All these data can be mapped using either grey scales or isopleths (depending on the representativeness of the locations for which the input data have been provided). As an example, the inhalation dose to infants within the countries of the EC following a simulated accident similar to that at Chernobyl is illustrated in figure 5.4. The nuclide concentrations and deposition of ^{134}Cs, ^{137}Cs, and ^{131}I are taken from UNSCEAR (1988) for the countries or parts of countries considered.

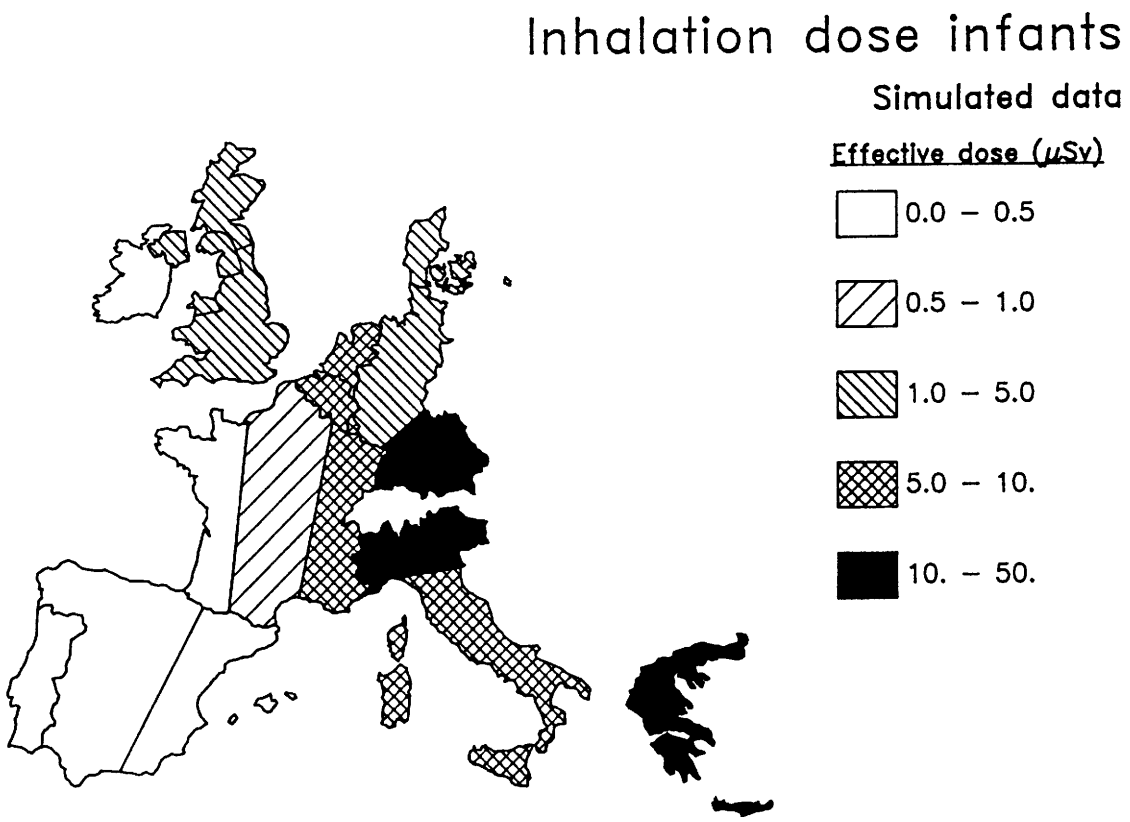

Figure 5.4 Example of EURALERT results showing the spatial distribution of doses to be expected.

Program ALL calculates the following values for the locations with the highest deposition:

i) Ingestion dose for all foodstuffs and nuclides.

ii) External dose from all nuclides deposited on the ground.

iii) Nuclide-foodstuff-combinations which contribute most to the ingestion dose and their relative contribution to the total ingestion dose.

ALL also gives the following output for all locations, which can be represented as maps:

i) Maximum activity concentration in the selected foodstuffs.

ii) Ingestion dose from the selected nuclide-foodstuff-combinations.

iii) External dose from all nuclides deposited on the ground.

Additionally, ALL can give:

i) Cumulative distributions of numbers of people versus their doses, as illustrated in figure 5.5.

ii) A rough estimate of collective dose.

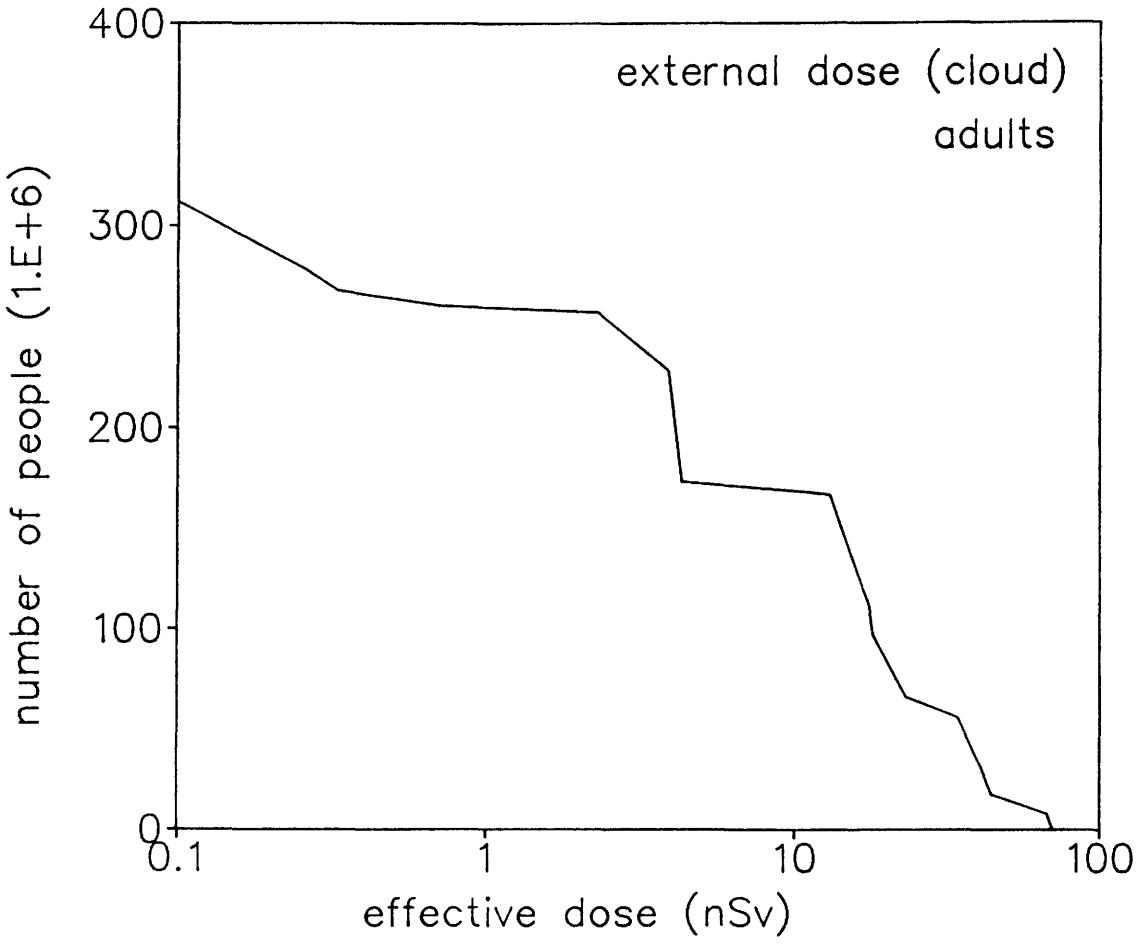

Figure 5.5 Cumulative distribution of numbers of people versus their expected cloud γ dose, for the same case as figure 5.4.

The program SINGLE gives the following results for one of the locations which is selected by the user:

i) Time dependent activity concentration in all feed and foodstuffs for all nuclides, illustrated in figure 5.6.

ii) Time dependent ingestion dose for all foodstuffs and nuclides, illustrated in fiugure 5.7.

iii) Doses from inhalation, external radiation and the sum over all pathways, illustrated in figure 5.8.

iv) Activity concentrations in foodstuffs for different feeding habits.

v) Times of exceeding activity limits in foodstuffs.

vi) Ingestion dose with application of activity limits.

vii) Ingestion dose with different consumption rates.

viii) External doses at different locations (inside and outside houses, in the cellar).

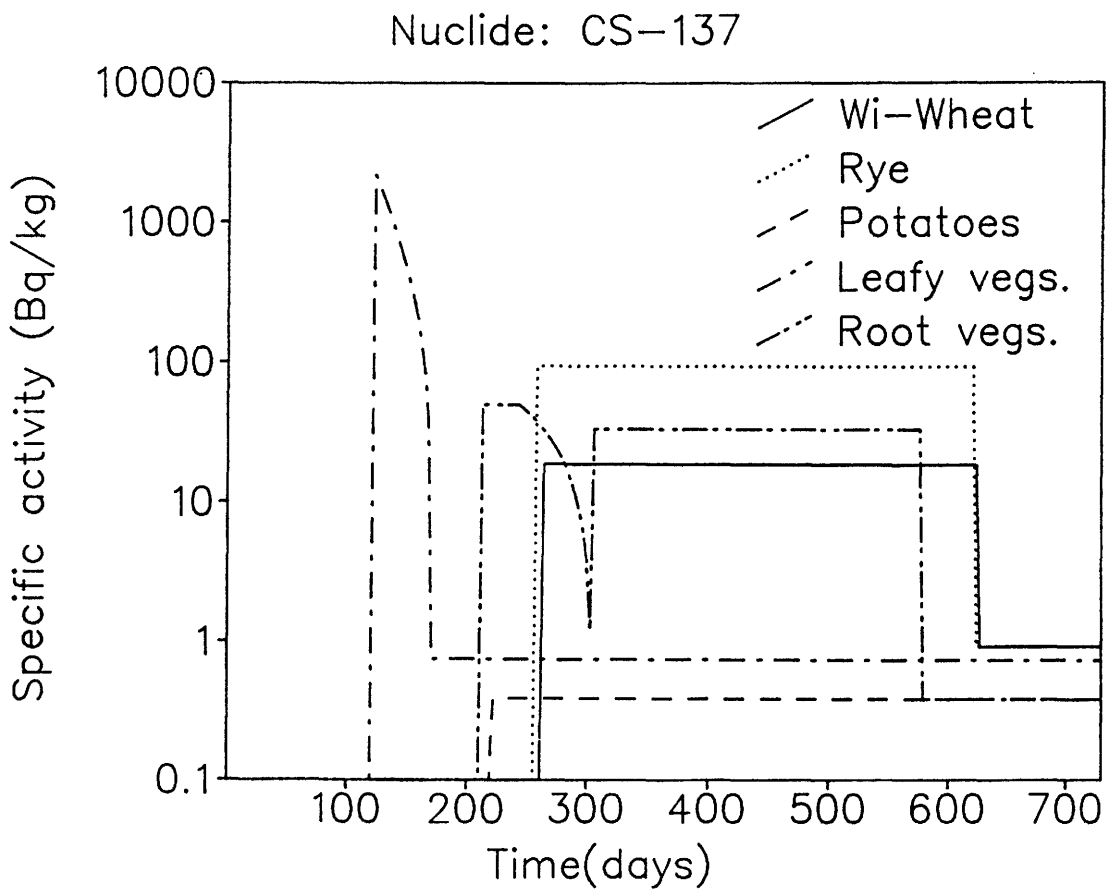

Figure 5.6 Time dependent activity concentration in different crops at one location following caesium deposition on 1st May.

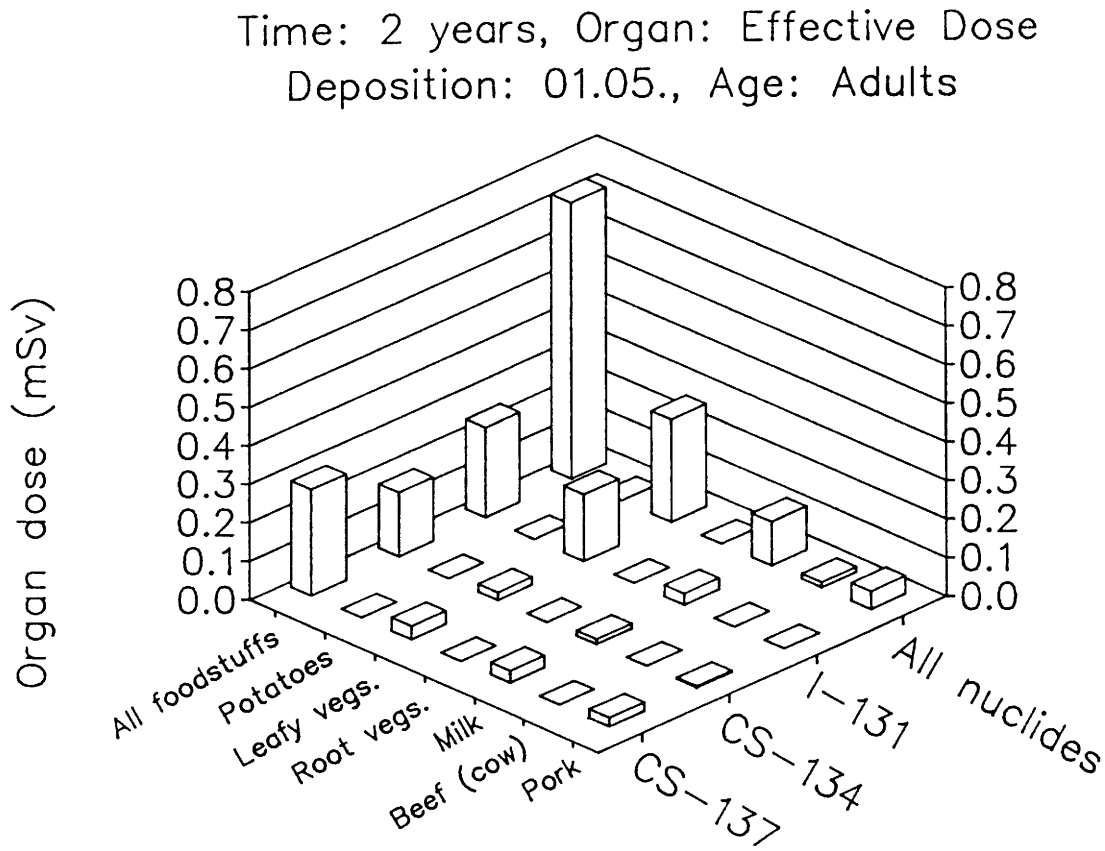

Figure 5.7 Ingestion dose within the first two years for one location following caesium deposition on 1st May.

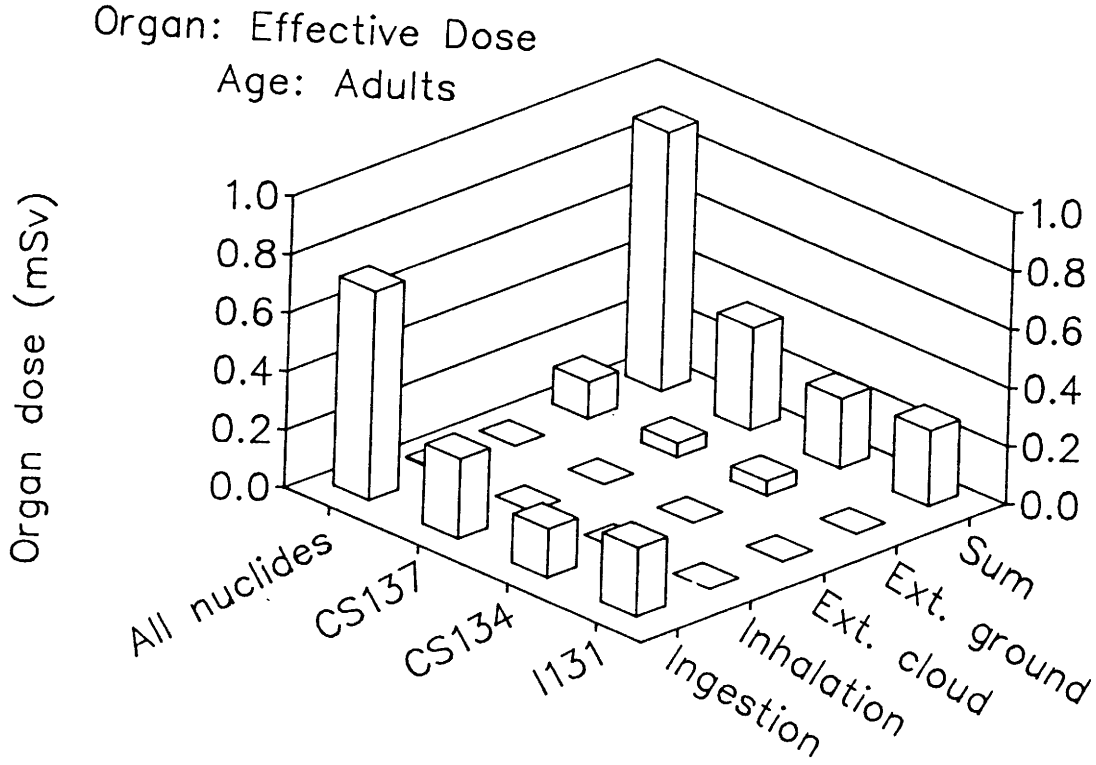

Figure 5.8 Doses from all exposure pathways within the first two calendar years at one location, following ^{134}Cs, ^{137}Cs and ^{131}I deposition on 1st May.

6. CONCLUSIONS

As part of the post-Chernobyl programme, the need was recognised for improved capabilities for the real-time assessment of accident consequences and emergency response procedures. Whereas such emergency response capabilities had hitherto concentrated on smaller accidental releases characteristic of design basis accidents, it was recognised as important to cater for a wider spectrum of accident scenarios, including those with potential consequences on a European scale. In particular, those responsible for decision making and the introduction of countermeasures would require computer-based support systems. This project (post-Chernobyl activity 4a) has therefore worked towards the provision of key components of real-time computerised support systems, embodied in software packages to be made generally available for use in European Community countries.

The software packages incorporate numerical models to simulate atmospheric dispersion locally, near the source (SPADE), over mesoscale distances, out to a few hundred kilometres (MC31) and on a continental scale (3-DRAW). The models reflect the particular requirements and complexities over these different distances, within the context of a nuclear accident emergency.

In addition, attention has been given to combined interpretation of radiological measurements and model estimates, particularly in those situations where there are large uncertainties in the source term and the relative quantities of different nuclides released. The modules STEP and STAR provide alternative approaches to using available measurements and model estimates to make deductions about the source term; STAR also optimises model parameter values and the agreement between the observed and estimated data.

The introduction of countermeasures and their effectiveness will depend on both the levels of the exposures and the reductions in doses that the countermeasures can achieve. A flexible module for dose assessment (EURALERT) has therefore been provided. This estimates doses from different exposure pathways based on levels of contamination in near-ground air and deposited on the ground in precipitation, which may be supplied either by the dispersion models or directly from measurements.

These packages have been developed in the overall context of an computerized real-time emergency response system, and attention has been given to making them compatible with each other. However, each package may also be used individually as appropriate; for example, the short-range model could be applied alone at a local emergency centre at the

accident site. All the codes have been written in FORTRAN 77 and implemented on the same system (VAX). Detailed technical descriptions of the models, the concepts on which they are based and the computational techniques used are given in the combined project report, together with an indication of the data and computational resources required. User manuals are already available for some of the packages, although additional work would be required to make them more user friendly, a highly desirable attribute of any computer-based support system, especially those designed to provide assistance in emergencies.

The main limitations and uncertainties have been discussed at joint meetings during the project and have led to the identification of areas where useful improvements can be made. In addition the need for more work on model validation and testing has been recognised.

The accuracy and uncertainties in the various types of model estimates produced depend only partly on the models themselves. They are largely limited by the representativeness of the data available, which is likely to vary greatly according to the particular accident situation. How these uncertainties can be effectively communicated to the decision makers in an emergency is also a difficult problem.

Certain contributory factors can be identified where more detailed consideration and evaluation are desirable. These include, for example, topographical effects, demographic and geographical aspects and agricultural practices; also complex meteorological situations such as frontal systems, or stagnant anticyclones where wind directions are highly variable. The probable significance of such factors will vary throughout Europe. There are also several processes which are not yet allowed for, such as deposition in mist and fog, or gravitational settling and the complicating effects of buildings on the dispersion of the release close to the source.

Further attention is also required to how model components may be integrated into overall emergency response and assessment procedures. Although the interfaces between the software packages developed under this project have been defined in relation to the data transferred between them, there are further considerations. For example, there may be a step between supplying an average wet deposition value based on rainfall averaged over a grid cell in a dispersion model mesh, and the identification of potential 'hot spots' within that area which may be critical for dose impact and countermeasures assessment. Similar problems apply to the interfaces between dispersion model output and measured data.

More work is also required on the combined interpretation of radiological measurements and modelling results and the feed-back between the two, for example the updating and revision of modelling estimates of dispersion and contamination, as measurements become available. There are also major tasks involved in the provision of high quality graphics and the clear presentation of assessments according to user needs. Bearing in mind the rapid advance in computer technology it is also worthwhile considering the potential for improvements to the models that these advances will permit. Thus, parallel processing techniques could introduce significant improvements in the costs and operating speed of the Monte Carlo dispersion models.

In conclusion, in developing and expanding these software packages, it is important to lay sound foundations for the development of emergency response procedures, not just for the present but also for future decades.

REFERENCES

ApSimon, H.M., Kitson, K., Fawcett, M. & Goddard, A.J.H., 1984, Development of a prototype mesoscale model incorporating treatment of topography. Report SAF 067, Nuclear Power Section, Mech. Eng. Dep't, Imperial College.

ApSimon, H.M., Goddard, A.H.G. & Wrigley, J., 1985, Long-range atmospheric dispersion of radioisotopes. I. The MESOS model. *Atmos. Environ.* **19**, 99 - 111.

ApSimon, H.M., Wilson, J.J.N. & Simms, K.L., 1989, Analysis of the dispersal and deposition of radionuclides from Chernobyl across Europe. *Proc. R. Soc. Lond.* A **425**, 365 - 405.

Briggs, G.A., 1969, Plume rise. Critical Review Series (TID-25075). Atomic Energy Commission, Division of Technical Information , Oak Ridge, TN.

Briggs, G.A., 1973, Diffusion Estimation for Small Emission. ATDL Cont. File 79, ATDL, Oak Ridge, TN.

Briggs, G.A., 1975, Plume rise predictions. Lectures on Air Pollution and Environmental Impact Analysis. American Meteorological Society Workshop, Boston, MA.

Bussac, J. and Reuss, P., 1979, Traité de neutronique, Hermann, Paris.

Cagnetti, P., Desiato, F., Gaglione, P. and Pellegrini, A., An atmospheric diffusion study on a local scale at a coastal site, *Atm. Env.* 1988, **22**, 1051-1056.

Cagnetti, P. and V. Ferrara, 1981, Metodo per la valutazione della stabilita' atmosferica applicato al sito della Casaccia, Rapp. ENEA RT PROT (81) 23.

Cagnetti, P., V. Ferrara and A. Pellegrini, 1984, A local scale atmospheric diffusion at a coastal site in the presence of breeze effect. Contract ENEA-CEC n. SR-027/1,6C.

Carson, D.J. 1973 The development of a dry inversion-capped convectively unstable boundary layer. *Quart. J. R. Met. Soc.* **99**, 450.

Desiato, F., 1985, SPADE: a real time lagrangian puff model for atmospheric diffusion evaluation, Workshop on Real time computing of the environmental consequences of an accidental release to atmosphere from a nuclear installation, 1985, CEC, Luxembourg.

Draxler, R.R., 1976, Determination of atmospheric diffusion parameters, *Atm. Env.* **10**,99.

Egan, B.R. and Mahoney, J.R., 1972, Numerical modelling of advection and diffusion of urban area source pollutants, *J. Appl. Met.*, **11**, 312-322.

Garnier, A. & Sauve, A. 1981 Étude de la répartition géographique de la population Européene en vue de l'evaluation des consequences radiologiques des rejets d'effluents radioactifs. Fontenay-aux-Roses, EUR/CEA departement de protection.

Gaspar, P., 1980, Modèle mathématique de dispersion des polluants autour d'obstacles dans la couche limite planétaire, Mémoire de l'Université Catholique de Louvain, Faculté des Sciences Appliquées.

Gassmann, F. et al., 1986, Experimental Investigation of atmospheric dispersion over complex terrain in a Prealpine region (Experiment SIESTA), EIR-Bericht Nr. 604.

Guikhman, L. and Skorokhod, A., 1972, Stochastic differential equations, Springer-Verlag, Berlin.

Guikhman, L. and Skorokhod, A., 1980, Introduction à la théorie des processus aléatoires, Edition MIR, Moscow.

Heffter, J.L. and Ferber, G.J., 1975, A regional continental scale transport diffusion and deposition model. NOAAdministration, techn. memo. ERL - ARL - 50.

Henrichs, K., Elsasser, U., Schotola ,C. and Kaul, A., 1985, Dosisfaktoren fuer Inhalation oder Ingestion von Radionuklidverbindungen (Altersklasse 10 Jahre) Bundesgesundheitsamt, Neuherberg (Germany), ISH-Heft 80, and other ISH-reports (for other age groups)

IAEA, 1982, Safety Series No 57, Generic models and parameters for assessing the environmental transfer of radionuclides from routine releases.

Irwin, J.S., 1982, Estimating plume dispersion - A comparison of several sigma schemes, *J. Clim. Appl. Met.* **22**,92.

Jones, J.A., 1980: ESCLOUD, A Computer Program to Calculate the Air Concentration, Deposition Rate and External Dose Rate from a Continous Discharge of Radioactive Material to Atmosphere, National Radiological Protection Board, NRPB-R101.

Lange, R., 1973, A three dimensional computer code for the study of pollutant dispersal and deposition under complex conditions, Lawrence Livermore Laboratory, UCRL - 51462.

Lange, R., 1978, ADPIC - A three-dimensional particle in cell model for the dispersal of atmospheric pollutants and its comparison to regional tracer studies, *J.Appl.Met.* **17**,320.

Levy, P., 1948, Processus stochastiques et mouvement brownien, Gauthier-Villars, Paris.

Ludwig, F.L., L.S. Gasiorek and R.E. Ruff, 1977, Simplification of a gaussian puff model for real-time minicomputer use, *Atm. Env.* **11**, 431.

Meckbach, R. and Jacob, P., 1988, Gamma exposures due to radionuclides deposited in urban environments. Part II: Location factors for different deposition patterns, *Radn. Prot. Dosimetry*, **25**, 181 - 190.

Müller, H., Friedland, W., Pröhl, G. and Paretzke, H.G., 1990, EURALERT-89 User's Guide, GSF-Report.

Müller, H. and Pröhl, G., 1987, Cesium Transport in Food Chains - Comparison of Model Predictions and Observations. Workshop 'Methods for Assessing the Reliability of Environmental Transfer Models Predictions', Athens, Oct. 5-9, 1987

Pasquill, F., 1976, Atmospheric dispersion parameters in gaussian plume modeling, Part 2, US Environmental Protection Agency report EPA-600/4-76-030b.

Pröhl, G., 1990, Modellierung der Radionuklidausbreitung in Nahrungsketten nach Deposition von Strontium-90, Caesium-137 und Jod-131 auf landwirtschaftlich genutzte Flächen, GSF-Report.

Pröhl, G., Müller, H., Jacob, P. and Paretzke, H.G., 1988, The dynamic radioecological model ECOSYS - a tool for the management of nuclear accidents' consequences. 4th International Symposium on Radioecology, Cadarache (France), March 14-18, 1988.

Rodriguez, D. J. and Rosen, L.C., 1984, An evaluation of a series of SF_6 tracer releases using the MATHEW/ADPIC model, Lawrence Livermore National Laboratory, UCRL-91854.

Saaty, T.L., 1981, Modern nonlinear equations, Dover Publications, New York.

Saffman, P.G. 1962 The effect of windshear on horizontal spread from an instantaneous ground source. *Ann. J. R. Met. Soc.* **88**, 323 - 393.

Sheih, C.M. 1978, A Puff-on-cell model for computing pollutant transport and diffusion *J. appl. Met.*, **17**, 140-147.

Smith, M.E., 1968, recommended Guide for the prediction of the dispersion of airborne effluents, 1st ed., Am. Soc. of Mech. Engineers, N.Y.

Start, G.E. and L.L. Wendell, 1974, Regional effluent dispersion calculations considering spatial and temporal meteorological variations. NOAA techn. memo. ERL-ARL-44, Air Resources Laboratories.

Turner, D.B., 1964, A diffusion model for an urban area, *J. Appl. Met.*, **3**, 83.

Turner, D.B., 1969, Workbook of atmospheric diffusion estimates, US Environmental Protection Agency Report EPA- 999-ap-26.

Underwood B.Y, P.J. Cooper, N.J. Halloway, G.D. Kaiser, W. Nixon, 1984, Review of specific effects in atmospheric dispersion calculations, CEC Rep. Contract SR011-80 UK.

Underwood, B.Y., The modelling of gravitational settling in assessment of the consequences of accidental releases of radioactivity. Contract report from SRD (contract 1225-83-9L/V with the EEC) published as a report of the EEC.)

UNSCEAR, 1988, United Nations scientific committee on the effects of atomic radiation: Sources, effects and risks of ionizing radiation, 1988 report to the U.N. general assembly, New York, ISBN 92-1-142143-8.

Van Ulden, A.P and A.A.M. Holstlag, 1985, Estimation of atmospheric boundary layer parameters for diffusion applications, *J. Clim. Appl. Meteor.*, **24**, 1196.

Venstel, H., 1973, Theories of probability. Edition MIR, Moscow.

Vogt, K.J., 1977, Empirical investigations of the diffusion of waste air plumes over terrain of major surface roughness, *Nucl. Techn.* **34**,43.

APPENDIX A: THE ROLE AND DESIGN OF EMERGENCY RESPONSE SYSTEMS

A.1 Introduction

Some of the information in this appendix is derived from the recommendations of IAEA safety Guide No.86.

The purpose of a system for real-time management of emergencies (hereafter referred to as an emergency response system), is to provide information about an accident and it's consequences, that is useful in determining effective measures to protect the health and safety of the public and the environment. In designing an emergency response system, the functional objectives of the system can be defined according to the need of the users. Users can be usefully characterized as either decision makers or technical assessors, and each will have different requirements of the system .

Decision makers will be found at the nuclear facility operating organization and the relevant public authorities. When an emergency is in progress, decisions will be required about:

i) Appropriate measures to be taken to protect people and the environment.

ii) Measures needed to manage resources in support of the protective measures which are implemented, and to obtain further information upon which later decisions on protective measures (continuation, extension or withdrawal) can be based.

The people who take these decisions require different types of information. As a rule, the degree of detail which the decision maker requires is inversely proportional to their position in the decision making hierarchy. The number of information sources utilised by the decision maker is similarly inversely proportional to the level of the decision maker. The decision makers, will require the most accurate information available, as soon as possible and, after they have made their initial judgements, they need reassessments as the situation progresses.

Typically, a decision maker will require the answers to questions such as, where is the radioactive plume in relation to population centres? how many people may be affected? what is the geographical extent of the plume? The technical content of this information may be complex, but it can generally be summarized in a simple and broad presentation, by single numbers or on a map of the areas affected.

The role of the technical assessor is to carry out the calculational assessment during the accident, along with the assessment team, and provide results that meet the needs of the decision maker. The needs of the technical assessor thus vary considerably from those of the decision maker, although there are some similarities and overlap between them. The needs of the the technical assessor are thus;

i) An understanding of and responsiveness to the needs of the decision maker;

ii) Tools (methodology, hardware, software, etc.) for carrying out the actual assessment;

iii) Data for use with the tools;

iv) An overall assessment system.

In the light of the above, groups of functional objectives for an emergency response system, listed in table A.1, can be identified. Table A.1 is not an exaustive list of functional objectives, and in any case it will not be possible, due to inevitable logistic and economic constraints, to design a system that will be capable of meeting all these objectives. However, the collection of environmental data, estimation of the concentration field and of the doses by modelling in real-time, estimation of the source term, and generation of results capable of taking into account proposed countermeasures, should be considered fundamental objectives.

Furthermore, the relative importance of the objectives will vary with time. During the early phase, the prime objectives are; the identification of the time, location and scale of the accident, an initial assessment of the exposure from the cloud and the ground and the inhalation dose pathways and the necessity for immediate countermeasures. Subsequently, the identification of potentially contaminated areas, and assessment of other dose pathways for example the contamination of foodstuffs like vegetables, milk, meat, etc., become more important.

As far as the operational requirements of a computerized emergency response system are concerned, the principal factors which determine the scale of the consequences of an accident are:

i) The source characteristics

ii) The time and location of the release, including the geography of the area exposed by the release.

iii) The meteorological and other environmental conditions during the release;

iv) The population distribution.

Accident and source overview:	- Identify time, location and scale of the accident; - Relate accident to design basis or reference accident; - Estimate source term,characteristics and duration;
Data handling:	- Collect appropriate data; - Check for errors and missing data; - Store data; - Supply default data; - Select appropriate and delete extraneous information; - Provide easy access to all current information/data; - Provide current demographic data; - Provide geographical and territorial data
Calculation methodologies:	- Calculate air concentrations; - Calculate wet and dry deposition; - Calculate time of arrival of release; - Identify potential contaminated areas; - Calculate doses: * effective dose; * most important organ doses; * external dose from cloud; * inhalation; * external dose from deposited nuclides; * ingestion; * specific nuclides; * cumulative; * integrated; - Calculate source term; - Calculate uncertainties in calculated results: * warn of data errors; * warn of significant extrapolations; * effects of uncertainties in technical parameters; - Calculate consequences corresponding to weather forecast;
Presentation of results:	- Select appropriate results and delete extraneous information; - Provide editing of results; - Provide tabular presentation of results; - Provide clear, well marked graphical displays;
Countermeasures:	- Recommend protective measures; - Provide sheltering suggestions; - Identify available evacuation routes and modes.

Table A.1 Functional objectives for an emergency response system.

v) The effectiveness of provisional and in-action countermeasures.

In order to provide an effective and accurate assessment of the off-site consequences, an emergency response system needs to be able take into account the above factors, satisfying the following operational requirements:

i) The system should be able to handle the real-time acquisition and pre-processing of data and information concerning the accident and the source term, and environmental data like radiological and meteorological data.

ii) The system should be able to handle static environmental and geographical data (topography, demography, land use etc.).

iii) The system should be able to model the dispersion of radioactive material through the relevant environmental medium and over the relevant distance range for the scale of the accident, in real-time, or in predictive mode.

iv) The system should be capable of the assessment of the off-site radiological consequences of the accident, including the effects of countermeasureas.

v) The system should include software to manage the component codes and their input and output, and in particular the presentation of results in an easily assimilable 'user-friendly' form.

vi) The system should be able to transmit results and information to remote users.

A.2 Components of an emergency response system

The following are 'general' components of a computerised emergency response system able to satisfy the operational requirements detailed in the previous section:

i) A module for data acquisition, handling and management.

ii) A module to model the dispersion and transport of the release.

iii) A feedback module.

iv) A module for the identification of the consequences of an accidental release.

v) An output module.

With the exception of the output module, the stucture and operation of which will be strongly machine dependent, the operation of these modules, together with relevant software and hardware considerations are discussed in the following sections.

A.2.1 Data acquisition, handling and database management

Operational considerations

The data management module in an emergency response system will manage the acquisition and processing of the real-time data relating to the accident, the static databases and also the intermediate output files generated by the dispersion models. There are three possible sources of real-time data, namely; radiological data from the site, by which the source term may be characterised, radiological data from off-site, and meteorological data.

Ideally, sufficient radiological data would be available from the site characterise the source term, including, the total quantity of the radioactive material released, the relative mixture of radionuclides and any temporal variations, and their phsical form, however this is very unlikely to be the case. The data management module should therefore devote considerable effort to processing rapidly field radiological data into a format comparable with initial dispersion model results, in order to provide estimates of the source term by regression techniques. The module thus needs to be able to manage the real-time acquisition and storage of radiological data recorded by both fixed and mobile off-site instrumentation, bearing in mind that the data are likely to be received at irregular time intervals and are likely to be irregulaly spaced down wind of the release.

The module also needs to be capable of acquiring and processing the relevant meteorological data for the initial, short range dispersion model, on the same time scale as the field radiological data. Depending on the particular model requirements, this may involve on-line access to surface and upper air data collected by the relevant national meteorological service as well as any on-site instrumentation (meteorological tower or masts, ground stations, remote-sensing instruments stations etc.). Over a slightly longer time scale the module should be capable of acquiring and pre-prcessing as necessary, the forecast windfields and synoptic data, or other data as relevant, that are required as input for any mesoscale and long range dispersion models, that are part of the system and may be required. Again this data may be supplied by the relevant national meteorological service, if available, or from the European Centre for Medium range Weather Forecasting.

Software considerations

The main functions that the software of a data acquisition handling and management package will have to perform are as follows:

i) To allow the user to specify his hardware configuration for carrying out the subsequent data acquisition and handling.

ii) To receive and record all the initial information from the site regarding the accident (time, location, any source term data etc.);

iii) To receive, pre-process as necessary, record, and represent as approporiate, all off-site real-time radiological data.

iv) To receive, pre-process as necessary, record, and represent as approporiate, all meteorological data both from the site, as available and from the relevant meteorological services.

v) To allow the user to select the 'best' available input data for the relevant dispersion model according to what source, radiological and meteorological data has been received to date.

vi) To maintain the relevant static databases, (demographic, land use, topographic etc.)

vii) To manage the intermediate output from the dispersion models and permit the display of the output as appropriate.

The pre-processing referred to in the above functions, is the calculation of model input parameters such as mixing layer height or atmospheric stability, which are not measured directly. The pre-processing should be as flexible as possible, allowing the calculation of the desired model parameters from a variety of measured data.

The static databases comprise geographical and territorial data like topography, geographical and administrative boundaries, communication paths, demography, land use etc. These data are of particlular importance in determining the potential consequences of an accident, while the topographic data may also be used by one or more of the dispersion models. Thus, static data should be stored in an adequate data base, which gives easy rapid access, with the data regularly updated.

Hardware considerations

The relevant hardware components for the acquisition handling and management of data in a computer based emergency response system are as follows:

i) modems and telephone lines for data communication.

ii) radio receivers.

iii) network management hardware.

iv) processing unit(s).

v) data storage and mangement peripherals.

The telephone lines need not be dedicated, but, together with the modems, must have sufficent capacity for the receipt of all data feom external sources. In addition, back up capacity should be included, which may be further telephone lines, radio receivers or both.

Where the emergency system is based on a network, network management hardware will be required in addition to central processing capacity for the data acquistion and management. Data storage capacity should be predominantly on hard disk, with magnetic tapes as a backup or for the storage of large volumes of data that are not required immediately, while video-terminals, graphical terminals, printers, plotters, etc.will be reqired for data management.

A.2.2 Modelling the dispersion and transport of an accidental release in real-time

Objectives and general considerations

In the aftermath of an accident, off-site radiological data can at best, only give an 'historical' picture of the radioactive release and it's consequences. The emergency response system must be therefore be capable of modelling the atmospheric dispersion of the release in real-time, and possibly in predictive mode, in order to make assessments of the resulting consequences, and identify any relevant countermeasures. This applies equally over short time and distance scales, where evacuation may be a priority, to longer distances and timescales where other countermeasures such as sheltering and food bans may be neccessary.

In considering atmospheric dispersion models, three distance bands can be characterised; the short range, out to a few tens of kilometres, over which models using meteorological input parameters, measured at or derived from measurements made from the source are applicable, the mesoscale, out to a few hundred kilometres, over which models need to be able to take

into account spatial variations in the topography, windfield, and synoptic conditions, and the long range, where spatial variation in windfield and synoptic conditions are still important, but variations in topography less so. Depending upon the severity of the accident, immediate countermeasures, primarily evacuation and sheltering will generally only be required in the short and mesoscale ranges, while food bans and other preventitive measures to reduce ingestion of contaminated food may be applicable over all three distance ranges.

Thus, the emergency response system should include dispersion codes able to model transport and diffusion of radionuclide releases over all three distance scales. Furthermore, the models should be able to at least operate in real-time, taking into account time needed for pre-processing the relevant input data, and any necessary post-processing of output.

Besides providing updated instantaneous and integrated air concentrations and deposition for dose and consequence assessment, the dispersion models can be used for the following tasks:

i) Determining source terms.

ii) Providing guidance for deploying measurements teams.

iii) Evaluating the consequences of assumed release mechanisms and rates.

iv) Providing a consistency check on measurements.

A wide range of atmospheric dispersion models are available, and applicable over different distance scales and the possible choices are discussed in chapter 3.1. However, in choosing a dispersion model for an emergency response system, the following factors need to be taken into consideration:

i) Radionuclide releases are generally from point sources.

ii) Dispersion models developed for conventional air pollutants tend to give short term air concentrations (averages of hours to days), whereas the important quantity in the case of radionuclide releases is the time-integrated air concentration. Models are however required for calculating concentrations from short releases such as might occur in accident conditions.

3) Quantification of deposition onto vegetation and other surfaces is necessary for some radionuclides, since the deposited radionuclides are the input to several pathways to man, for example via food consumption and external irradiation from contaminated surfaces.

In addition, the following are important factors affecting the dispersion of a radioactive cloud, that may need to be considered by the dispersion models:

i) The complexity of the underlying terrain, e.g. mountain valleys.

ii) The relationships between land masses and large bodies of water.

iii) The thermal structure of the atmosphere.

iv) The roughness of the underlying terrain, e.g. afforested areas versus grassland.

v) The thermal stability of the atmosphere, e.g. a stable atmosphere at night versus an unstable atmosphere during the day, when the sun is heating the ground.

vi) The effects of buildings on air flow near the release point that can trap the effluent in the building wake or can cause extra dispersion of the radioactive cloud before it is transported by the mean winds.

vii) Plume rise due to momentum and/or thermal energy of the emitted activity.

viii) Radioactive decay of the activity released.

ix) The chemical and physical properties of the released material, such as solubility and particle size distribution.

x) Dry deposition of particulates onto the ground due to effects of the surface roughness at the interface.

xi) Deposition of particulates in precipitation due to washout or rainout.

When choosing which particular dispersion models to implement in an emergency response system, the following general guidelines should be followed;

i) Plume transport and dispersion behaviour for the area corresponding to the outer boundary of the emergency planning zone should be adequately represented by the models.

ii) The first model results should be available to users within 15 minutes of initiation.

iii) The chosen models should have a known field evaluation history appropriate to the site, and known standards of accuracy or desired conservatism.

iv) The chosen models should be capable of considering short-term releases (instantaneous to 2 hours) and intermediate duration releases (2 - 24 hours).

v) The chosen models should include plume depletion mechanisms, such as wet and dry deposition.

vi) The chosen models should be able to accept input meteorological data from a variety of sources.

In general, it is difficult to satisfy the criteria listed above with one model, even once the scale of the accident is defined. The requirement of a rapid initial real-time response limits the complexity that can be included in the first response calculations, indeed it may be necessary to sacrifice accuracy in the interests of speed. For this reason, simple Gaussian

plume or puff models are common choices for short range models in emergency response systems. Over the mesoscale and long ranges, the need to be able to simulate spatial variation in the windfield and synoptic conditions, means that appropriate models are likely to use 3-dimensional windfields generated elsewhere, for example from the relevant national meteorological service.

Software and hardware considerations

As stated above, the need for speed of assessment in the short range, precludes much model complexity. Short range model codes will not therefore have significant processing requirements, while storage requirements are also relatively limited, as the models use a single set of input meteorological data. Suitable short range models like Gaussian puff and plume models can normally be run on personal and micro-computers. The mesoscale and long range models, on the other hand utilise a far larger input dataset, particularly if the are fully 3-dimensional, and the processing and storage requirements of such codes are consequently far greater than for the short range models. Furthermore, if the codes generate a large amount of data, effort should be devoted to providing easily understandable results, for example 2-dimensional or possibly 3-D representation of the results on plotters or graphics terminals. Thus, hardware requirements for the mesocale and long range models are far greater than for the short range models. The memory requirements of the models wil generally mean that a system with virtual memory is required, while the particular model requirements will determine whether it can run at the required speed on mini or main frame computers.

A.2.3 Feedback mechanisms between data and models

Operational considerations

In the early phase of an accident reliable information will be very scarce and the initial assessment may have to be made in the absence of any corroborative data. Subsequently, as off-site radiological data is received by the system, it is necessary revise the modelling assessment in the light of the known radiological observations. Ideally this should be a continuous process of adjustment of the modelling assessment to achieve the 'best fit' with the observations, however, the complexities of the situation, where in reality, an imperfect model is being compared with observations of unknown quality, mean that this is the least

straightforward component of any emergency response system. The design of feedback mechanisms within an emergency response system is thus very much still a 'grey area' at present, and the subject of considerable current research.

The potential scope of feedback mechanisms in emergency response systems is considered further in chapter 4. Briefly, there are two possible approaches to the problem; which can be characterised as a 'pragmatic' approach and a 'theoretical' approach. In the former, model adjustments are restricted to those parameters, for example the wind direction at the source in the case of a short range model, which are the known from experience to be the most likely causes of differences between modelling results and observations, and other less critical parameters are ignored. In the latter, all parameters would be analysed. As with the choice of dispersion models, there is an inevitable trade-off between speed and complexity of the analysis. Over the mesoscale and longer distance ranges, the complexity of the models precludes a thorough analysis of all parameters, and feedback between the model and observations may be best achieved by the construction of a 'best estimate' of the position and composition of the pollutant cloud from the observations, which is then adopted by the model in place of it's simulated position and composition.

Software and hardware considerations

An important software and hardware component for feedback between model results and observations is a mapping facility, so that the two datasets can be displayed on a terminal or plotted and any differences easily identified. The rapid display of the relevant model output and observations provides valuable information as to which types of feedback mechanism to invoke, particularly where it is intended to analyse a subset of the model parameters by for example regression techniques.

Models for the estimating the source term on the basis of coupling of field observations with model output concentrations can be considered a specific category of feed-back models, due to the importance of having a source term estimate in the early stage of the accident, when there may be no reliable data from on-site.

A.2.4 Evaluation of the consequences of an accidental release

Operational considerations

In order to determine the most effective countermeasures to minimize the consequences of an accident the system must be able to evaluate as accurately as possible the contamination of the different environmental compartments (air, water, soil, vegetables, animals, etc.) and the resulting radiological doses to the population.

The assessment of the contamination should be based on the 'best estimate' of the pattern of the dispersion of the release and deposition of activity from within it, which will generally be synthsised from both the off-site radiological observations and the model output.

The four important dose calculations are:

i) External exposure from the radioactive airborne plume.

ii) Inhalation of the plume.

iii) External exposure from deposited activity.

iv) Ingestion of contaminated food and water.

The external exposure from the cloud and the inhalation exposure pathways are the most critical for the early phase of an accident, because total exposure is directly coupled with passage of the cloud or plume. Once the cloud has passed overhead they become negligible, the only further contributions to dose from thse pathways coming from any resuspension of deposited activity.

Ground deposition is the next most critical exposure pathway, followed by the food and water ingestion pathways. Both pathways are relevant in the intermediate and late (recovery) phases, as well as the early phase of an accident, due to the contributions from medium and long lived nuclides.

Doses from all pathways and for all nuclides released should be evaluated to determine whether additional protective measures should be undertaken to provide another level of protection to the public, and the effects on doses of the implementing the various possible countermeasures should also be evaluated.

Software and hardware considerations

The software components of the consequence evaluation module must be able to carry out the calculation of doses and consequences, with and without the imposition of countermeasures in real time. The evaluation of consequences will require demographic data for the areas exposed by the realease, as well as land use data, which will be used in determining ingestion doses. The management of these static data is referred to in section A.2.2. Dose factors and radionuclide transfers through the foodchain can be pre-calculated for unit integrated air concentrations or deposition, in order to save on execution time and this data will also be part of the static database.

Thus, while individual modules of the system may have comparitively small processing and data requirements, an integrated system, comprising data acquisition modules, atmospheric dispersion models for the short mesoscale and long ranges, model-observation feedback modules, and a consequence evaluation module, is likely to need at least the processing power of a high performance mini-computer in order to produce the required results over the desired timescale.

A.3 General system characteristics

In constructing an emergency response system, consideration should be given to the following general characteristics.

Reliability

There is little point in having a emergency response system if it is unable to function in an emergency. Thus, critical components whose failure leads directly to system failure should be identified, and either eliminated or protected. Use of redundant components should be considered as well as alternative backups. Battery or other backup power in the event of power loss is another consideration. Modular design using common, easily obtained components will allow quick replacements if necessary, while software that is easily transported to other available systems may also enhance reliability. It may also be worthwhile maintaining manual assessment facilities as a cover for catastrophic failure.

Accuracy and precision

The technical assessor is an important link in the entire assessment system and effort should be made to ensure that his work is accurate. One way of increasing accuracy is to give considerable attention to the design of the inputs and outputs of the system as well as the calculational flow. In general, the technical assessor should have obvious choices, easy input (minimal keystrokes) and relevant output. Consideration should be given to using standardised input formats, reducing the potential for error when running the different modules.

Full day operation

The system should be on-line 24 hours a day, as it is continuously recieving data, even when not in use. It must also be able to be put into operation at any time. This will require the rostering of potential operating personnel outside working hours, and it may be necessary to have remote links to key personnel in order to meet operating deadlines.

Centralized operation

A centralized system configuration offers the following advantages:

i) It avoids duplication of resources and provides a 'state-of-the-art' proven response capability.

ii) It provides experienced staff devoted to emergency preparedness, response and assessment.

iii) It provides a standard (or criterion) for emergency response assessment while maintaining flexibility to meet site-specific and agency requirements.

iv) It focuses research and development on timely improvement and evaluation of emergency response resources.

v) It applies integrated research and development resources to specialized emergency response requirements in real-time.

vi) It is cost-effective when applied to a large number of nuclear facilities and integrated into national emergency preparedness programs.

In general such a system can be utilized both in case of nuclear and conventional accidents, provided the necessary modifications are performed, in which case the system would

become more cost-effective.

User friendliness

The system should be designed in a way to avoid any problem of understanding. A user friendly system will not provoke additional stress or strain at an already difficult time. The most important way to make a system user friendly is to listen to, and to act on, user complaints and suggestions. Additionally, a system should be 'human engineered' in advance during the design stage by human factors speciatists.

European Communities – Commission

EUR 12552/1 – Radiological aspects of nuclear accident scenarios
Volume 1 – Real-time emergency response systems
Post-Chernobyl action

Edited by: *J. Sinnaeve*

Luxembourg: Office for Official Publications of the European Communities

1991 – XXVIII, 133 pp., num. tab., fig. – 21.0 × 29.7 cm

Radiation protection series

ISBN 92-826-2938-4

Catalogue number: CD-NA-12552-EN-C

Price (excluding VAT) in Luxembourg: ECU 12.50

In the event of a nuclear accident, there is a need for a rapid assessment of the resulting levels of environmental contamination in order to facilitate decisions on possible countermeasures. Volume 1 of this report covers the development of numerical models, in the form of software packages, to simulate atmospheric transport and deposition over various distances, and techniques for estimation of the resulting doses. Volume 2 describes the RADE-AID project to develop a computer system which can be used to support the formulation of decisions on countermeasures following an accidental release of radionuclides. The system is intended as an aid following an actual accident and a tool for assistance in planning and training.

Venta y suscripciones • Salg og abonnement • Verkauf und Abonnement • Πωλήσεις και συνδρομές
Sales and subscriptions • Vente et abonnements • Vendita e abbonamenti
Verkoop en abonnementen • Venda e assinaturas

BELGIQUE / BELGIË

Moniteur belge / Belgisch Staatsblad
Rue de Louvain 42 / Leuvenseweg 42
1000 Bruxelles / 1000 Brussel
Tél. (02) 512 00 26
Fax 511 01 84
CCP / Postrekening 000-2005502-27

Autres distributeurs /
Overige verkooppunten

Librairie européenne/ Europese Boekhandel
Avenue Albert Jonnart 50 /
Albert Jonnartlaan 50
1200 Bruxelles / 1200 Brussel
Tél. (02) 734 02 81
Fax 735 08 60

Jean De Lannoy
Avenue du Roi 202 /Koningslaan 202
1060 Bruxelles / 1060 Brussel
Tél. (02) 538 51 69
Télex 63220 UNBOOK B
Fax (02) 538 08 41

CREDOC
Rue de la Montagne 34 / Bergstraat 34
Bte 11 / Bus 11
1000 Bruxelles / 1000 Brussel

DANMARK

J. H. Schultz Information A/S
EF-Publikationer
Ottiliavej 18
2500 Valby
Tlf. 36 44 22 66
Fax 36 44 01 41
Girokonto 6 00 08 86

BR DEUTSCHLAND

Bundesanzeiger Verlag
Breite Straße
Postfach 10 80 06
5000 Köln 1
Tel. (02 21) 20 29-0
Telex ANZEIGER BONN 8 882 595
Fax 20 29 278

GREECE

G.C. Eleftheroudakis SA
International Bookstore
Nikis Street 4
10563 Athens
Tel. (01) 322 63 23
Telex 219410 ELEF
Fax 323 98 21

ESPAÑA

Boletín Oficial del Estado
Trafalgar, 27
28010 Madrid
Tel. (91) 44 82 135

Mundi-Prensa Libros, S.A.
Castelló, 37
28001 Madrid
Tel. (91) 431 33 99 (Libros)
431 32 22 (Suscripciones)
435 36 37 (Dirección)
Télex 49370-MPLI-E
Fax (91) 575 39 98

Sucursal:
Librería Internacional AEDOS
Consejo de Ciento, 391
08009 Barcelona
Tel. (93) 301 86 15
Fax (93) 317 01 41

Librería de la Generalitat de Catalunya
Rambla dels Estudis, 118 (Palau Moja)
08002 Barcelona
Tel. (93) 302 68 35
302 64 62
Fax (93) 302 12 99

FRANCE

Journal officiel
Service des publications des Communautés européennes
26, rue Desaix
75727 Paris Cedex 15
Tél. (1) 40 58 75 00
Fax (1) 40 58 75 74

IRELAND

Government Publications Sales Office
Sun Alliance House
Molesworth Street
Dublin 2
Tel. (1) 71 03 09

or by post

Government Stationery Office
EEC Section
6th floor
Bishop Street
Dublin 8
Tel. (1) 78 16 66
Fax (1) 78 06 45

ITALIA

Licosa Spa
Via Benedetto Fortini, 120/10
Casella postale 552
50125 Firenze
Tel. (055) 64 54 15
Fax 64 12 57
Telex 570466 LICOSA I
CCP 343 509

Subagenti:

Libreria scientifica Lucio de Biasio - AEIOU
Via Meravigli, 16
20123 Milano
Tel. (02) 80 76 79

Herder Editrice e Libreria
Piazza Montecitorio, 117-120
00186 Roma
Tel. (06) 679 46 28/679 53 04

Libreria giuridica
Via XII Ottobre, 172/R
16121 Genova
Tel. (010) 59 56 93

GRAND-DUCHÉ DE LUXEMBOURG

Messageries Paul Kraus
11, rue Christophe Plantin
2339 Luxembourg
Tél. 499 88 88
Télex 2515
Fax 499 88 84 44
CCP 49242-63

NEDERLAND

SDU Overheidsinformatie
Externe Fondsen
Postbus 20014
2500 EA 's-Gravenhage
Tel. (070) 37 89 911
Fax (070) 34 75 778

PORTUGAL

Imprensa Nacional
Casa da Moeda, EP
Rua D. Francisco Manuel de Melo, 5
1092 Lisboa Codex
Tel. (01) 69 34 14

Distribuidora de Livros Bertrand, Ld.ª
Grupo Bertrand, SA
Rua das Terras dos Vales, 4-A
Apartado 37
2700 Amadora Codex
Tel. (01) 49 59 050
Telex 15798 BERDIS
Fax 49 60 255

UNITED KINGDOM

HMSO Books (PC 16)
HMSO Publications Centre
51 Nine Elms Lane
London SW8 5DR
Tel. (071) 873 2000
Fax GP3 873 8463
Telex 29 71 138

ÖSTERREICH

Manz'sche Verlags- und Universitätsbuchhandlung
Kohlmarkt 16
1014 Wien
Tel. (0222) 531 61-0
Telex 11 25 00 BOX A
Fax (0222) 531 61-81

SUOMI

Akateeminen Kirjakauppa
Keskuskatu 1
PO Box 128
00101 Helsinki
Tel (0) 121 41
Fax (0) 121 44 41

NORGE

Narvesen Information center
Bertrand Narvesens vei 2
PO Box 6125 Etterstad
0602 Oslo 6
Tel. (2) 57 33 00
Telex 79668 NIC N
Fax (2) 68 19 01

SVERIGE

BTJ
Box 200
22100 Lund
Tel. (046) 18 00 00
Fax (046) 18 01 25

SCHWEIZ / SUISSE / SVIZZERA

OSEC
Stampfenbachstraße 85
8035 Zürich
Tel. (01) 365 54 49
Fax (01) 365 54 11

CESKOSLOVENSKO

NIS
Havelkova 22
13000 Praha 3
Tel. (02) 235 84 46
Fax 42-2-264775

MAGYARORSZÁG

Agroinform
Budapest I. Kir.
Attila út 93
1012 Budapest
Tel. (1) 56 82 11
Telex (22) 4717 AGINF H-61

POLAND

Business Foundation
ul. Krucza 38/42
00-512 Warszawa
Tel. (22) 21 99 93, 628-28-82
International Fax&Phone
(0-39) 12-00-77

YUGOSLAVIA

Privredni Vjesnik
Bulevar Lenjina 171/XIV
11070 Beograd
Tel. (11) 123 23 40

CYPRUS

Cyprus Chamber of Commerce and Industry
Chamber Building
38 Grivas Dhigenis Ave
3 Deligiorgis Street
PO Box 1455
Nicosia
Tel. (2) 449500/462312
Fax (2) 458630

TURKIYE

Pres Gazete Kitap Dergi Pazarlama Dağitim Ticaret ve sanayi AŞ
Narlibahçe Sokak N. 15
Istanbul-Cağaloğlu
Tel. (1) 520 92 96 - 528 55 66
Fax 520 64 57
Telex 23822 DSVO-TR

AUTRES PAYS
OTHER COUNTRIES
ANDERE LÄNDER

Office des publications officielles des Communautés européennes
2, rue Mercier
2985 Luxembourg
Tél. 49 92 81
Télex PUBOF LU 1324 b
Fax 48 85 73
CC bancaire BIL 8-109/6003/700

CANADA

Renouf Publishing Co. Ltd
Mail orders — Head Office:
1294 Algoma Road
Ottawa, Ontario K1B 3W8
Tel. (613) 741 43 33
Fax (613) 741 54 39
Telex 0534783

Ottawa Store:
61 Sparks Street
Tel. (613) 238 89 85

Toronto Store:
211 Yonge Street
Tel. (416) 363 31 71

UNITED STATES OF AMERICA

UNIPUB
4611-F Assembly Drive
Lanham, MD 20706-4391
Tel. Toll Free (800) 274 4888
Fax (301) 459 0056

AUSTRALIA

Hunter Publications
58A Gipps Street
Collingwood
Victoria 3066

JAPAN

Kinokuniya Company Ltd
17-7 Shinjuku 3-Chome
Shinjuku-ku
Tokyo 160-91
Tel. (03) 3439-0121

Journal Department
PO Box 55 Chitose
Tokyo 156
Tel. (03) 3439-0124

CD-NA-12552-EN-C

NOTICE TO THE READER

All scientific and technical reports published by the Commission of the European Communities are announced in the monthly periodical **'euro abstracts'**. For subscription (1 year: ECU 92) please write to the address below.

Price (excluding VAT) in Luxembourg: Volume 1: ECU 12.50
Volumes 1 + 2: ECU 26

ISBN 92-826-2938-4

OFFICE FOR OFFICIAL PUBLICATIONS
OF THE EUROPEAN COMMUNITIES

L-2985 Luxembourg