SAFETY SERIES No. 50-P-12

SAFETY PRACTICES

safety series

Procedures for Conducting Probabilistic Safety Assessments of Nuclear Power Plants (Level 3)

Off-Site Consequences and Estimation of Risks to the Public

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1996

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PROCEDURES FOR CONDUCTING PROBABILISTIC SAFETY ASSESSMENTS OF NUCLEAR POWER PLANTS (LEVEL 3)

Off-site consequences and estimation of risks to the public

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FOREWORD

Probabilistic safety assessment (PSA) is increasingly important in the safe design and operation of nuclear power plants. The activities of the IAEA in this area are focused on facilitating the use of PSA by reviewing the techniques developed in Member States, assisting in the formulation of procedures and helping Member States to apply such procedures to enhance the safety of nuclear power plants.

In this context, a set of publications is being prepared to establish a consistent framework for conducting a PSA and forms of documentation that would facilitate the review and utilization of the results. Since December 1986, several Advisory Group, Technical Committee and consultants meetings have been convened by the IAEA in order to prepare the publications.

The lead publication for this set establishes the role of PSA and probabilistic safety criteria in nuclear power plant safety. Other publications present procedures for the conduct of a PSA in nuclear power plants and recognized practices for specific areas of PSA, such as the analysis of common cause failures, human errors and external hazards, and collection and analysis of reliability data.

The publications are intended to assist technical personnel performing or managing PSAs. They often refer to the existing PSA literature, which should be consulted for more specific information on the modelling details. Therefore, only those technical areas deemed to be less well documented in the literature have been expanded upon. The publications do not prescribe particular methods, but they describe the advantages and limitations of various methods and indicate the ones most widely used to date. However, they are not intended to discourage the use of new or alternative methods; in fact, the advancement of all methods to achieve the objectives of PSA is encouraged.

This report on Level 3 PSAs completes the series on procedures for conducting PSAs of nuclear power plants. Safety Series No. 50-P-4, issued in 1992, covered Level 1 PSAs, while Safety Series No. 50-P-8, issued in 1995, covered Level 2 PSAs.

The IAEA wishes to thank all those who participated in the drafting and review of this publication.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The first comprehensive application of probabilistic safety assessment (PSA) methods and techniques dates back to 1975, to the United States Nuclear Regulatory Commission's Reactor Safety Study (WASH-1400) [1]. Since that landmark study, there has been substantial methodological development, and PSA techniques have become a standard tool in the safety evaluation of nuclear power plants. The main benefit of PSA is to provide insights into the safety aspects of plant design, performance and the potential environmental impacts of postulated accidents, including the identification of dominant risk contributors, and the comparison of options for reducing risk. PSA provides a tool for the systematic and comprehensive assessment of nuclear power plant safety, and thus a coherent and consistent framework for safety related decision making. Moreover, the quantitative estimate of risk provided by PSA facilitates the comparison of changes or alternatives in various design and engineering features of nuclear power plants. PSA also provides a conceptual and mathematical tool for deriving numerical estimates of risk for nuclear power plants and industrial installations in general.

In international practice, three levels of PSA have evolved:

- *Level 1:* The assessment of plant failures leading to core damage and the determination of core damage frequency.
- *Level 2:* The assessment of containment response leading, together with the results of Level 1 analysis, to the determination of release frequencies.
- *Level 3:* The assessment of off-site consequences leading, together with the results of Level 2 analysis, to estimates of risks to the public.

A Level 1 PSA provides insights into design weaknesses and ways of preventing core damage, which in most cases is the event preceding accidents leading to major radioactive releases with potential health and environmental consequences. A Level 2 PSA provides additional insights into the relative importance of accident sequences leading to core damage in terms of the severity of the radioactive releases they might cause, and information on weaknesses in containment, as well as ways of improving the mitigation and management of core damage accidents. A Level 3 PSA provides insights into the relative importance of accident prevention and mitigative measures expressed in terms of the adverse consequences for the health of the public, and the contamination of land, air, water and foodstuffs. Finally, a Level 3 PSA provides insights into the relative effectiveness of emergency response planning aspects of off-site accident management, and into the economic impacts.

A PSA can provide useful insights and inputs for decisions on: (a) plant siting; (b) design and backfitting; (c) plant operations and maintenance; (d) safety analysis and research; (e) plant accident management; (f) countermeasures; and (g) regulatory issues. Furthermore, a PSA can contribute to a systematic application of the concept of keeping exposures as low as reasonably achievable (ALARA) in decision making.

1.2. OBJECTIVE

The main emphasis in this Safety Practices document is on the procedural steps of a PSA, rather than on the details of corresponding methods. This document is primarily intended to assist technical personnel with responsibilities in managing or performing PSAs. A particular aim is to promote a standardized framework, terminology and form of documentation for PSAs so as to facilitate external review of the results of such studies. The report outlines the methodology and indicates the techniques most widely used to date.

In general, this document seeks to provide sufficient detail to define unambiguously the methods to be used, while avoiding prescriptive detail at a level that would inhibit the flexibility of the user in applying available resources, recognizing that the resources available to various studies will vary widely. The publication of this report is therefore not intended to pre-empt the use of new or alternative methods; on the contrary, the advancement of all methods of achieving the objectives of PSA is encouraged.

1.3. SCOPE

This report provides information on conducting a Level 3 PSA. It is concerned with the analysis of the release of radionuclides and their transfer through the environment, and with the assessment of the public health and economic consequences of an accident. This is known variously as consequence modelling, analysis or assessment. Often the words 'probabilistic' or 'accident' are added as a prefix either separately or together, e.g. probabilistic accident consequence assessment.

To date, most of the experience with Level 3 PSAs is related to the assessment of the impact of potential nuclear power plant accidents. For this the methodology is most formalized and several large, sophisticated codes are available. Consequently, this report is limited to the discussion of that type of analysis for which atmospheric release and dispersion of radionuclides have been shown to be dominant. However, the general methodology is also valid for other parts of the nuclear fuel cycle, such as reprocessing plants and spent fuel storage installations, and also for research reactors, although specific aspects of Level 2 and Level 3 analysis may be quite different for such installations and appropriate models would need to be used.

1.4. STRUCTURE

This report has three main sections. Section 2 comprises an overview of consequence analysis, which describes how the health and economic consequences of radioactive releases are calculated. It is intended to aid readers who are unfamiliar with consequence analysis. Section 3 is a step by step set of procedures for performing a Level 3 PSA. The final section deals with the management and organization of a Level 3 PSA.

Annex I discusses some recent and ongoing developments in probabilistic consequence analysis. Annex II gives general guidance on the selection of an appropriate computer code for a Level 3 PSA. A sample structure for a Level 3 PSA report is given in Annex III.

2. PROBABILISTIC CONSEQUENCE ANALYSIS

The discussion in this section is limited to releases to the atmosphere. The main elements of consequence analysis are described; they are shown schematically in Fig. 1. The major sources of input data and the main calculational steps are shown. Invariably, these elements are incorporated into a computer program, referred to as a probabilistic consequence analysis (PCA) code.

2.1. GENERAL ASPECTS OF A LEVEL 3 PSA

2.1.1. Source term

Ideally, the starting points for a consequence assessment are the postulated radionuclide releases to the environment as produced by the Level 2 PSA. In principle, the radionuclide release can be either to the atmosphere or to the aquatic environment. In practice, accidental releases to the aquatic environment make a comparatively small contribution to the overall risk from nuclear power plants [2]. For this reason, historically the assessment of releases to the atmosphere has been the principal concern. The quantity and isotopic composition of released radionuclides, together with their physical and chemical characteristics, the heat content of the plume, the time profile of the release and the release height are known as the source term. Generally, the source term also includes the frequency of the release.

For certain PSA studies it is not possible, or even necessary, to derive specific source terms from a Level 2 PSA. In such cases, for instance in comparative studies or where adequate Level 2 information is unavailable, reference source terms derived from the literature can be used. In order to present credible results, however, it is

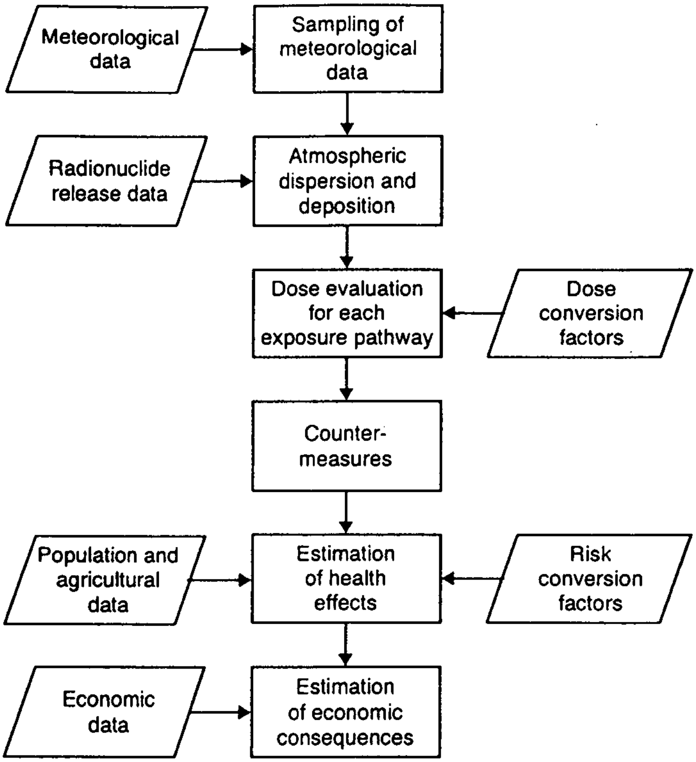

FIG. 1. Basic elements of probabilistic consequence analysis.

essential to provide sufficient information about the method used to determine the source terms.

2.1.2. Scope of modelling

Many Level 3 PSA codes have been developed for a variety of purposes. Codes can contain models for different phenomena, such as atmospheric dispersion, deposition of airborne material, resuspension, migration through food-chains, pathways to humans and the resulting health effects, and economic effects. Additionally, codes may contain a number of different meteorological sampling techniques. The complexity of the models and techniques used in a code depend, among other things, on the end-points to be studied and the nature of the site region. For example, the choice of dispersion model used depends on the maximum distance that one wants to consider from the release point, the topography of the terrain and the meteorology in the considered area. Moreover, the specific characteristics of the environment and human habits, such as extreme weather conditions, terrain complexity and food consumption patterns, may vary quite drastically. Off-site health and economic consequences can be estimated for the near or far range and for the short or long term.

With this in mind, the user should select a code which is suitable for his or her needs. However, in order to obtain credible results from a Level 3 PSA, it is necessary for the user to understand the models and their limitations, such as the underlying assumptions, the range of their validity and the choice of default parameters.

2.1.3. Safety criteria

The results of a Level 3 PSA can be compared with the corresponding probabilistic safety criteria [3] if such criteria have been established. A Level 3 PSA can also be used for impact analysis. In this case, its results are not necessarily checked for compliance with safety criteria, but they can still be used as an input to decision making.

Regulatory bodies are generally responsible for the specification of safety criteria which can be related to PSAs at Level 1, 2 or 3. Examples of these criteria are the frequency of severe core damage for a Level 1 PSA, and the frequencies of large releases of radionuclides for a Level 2 PSA. The most commonly used Level 3 related safety criteria are: the individual risks of early and late fatal health effects; the societal risk of early fatal health effects; collective risks; and the risks of unacceptable land contamination.

2.2. DESCRIPTION OF THE RADIONUCLIDE RELEASE

As noted in the introduction, the starting points for a consequence assessment are the radionuclide releases to the atmosphere, as produced by a Level 2 PSA. This information is provided for each of the representative accidents to be assessed, obtained by grouping accidents with similar release characteristics together, and it is referred to as the 'accident source term spectrum'. This specifies both the time dependent magnitude of the release (i.e. the quantity of each radionuclide released to the atmosphere as a function of time) and, by defining a number of release parameters, the manner of the release. These release parameters include the time of the release after accident initiation, the amount of energy associated with the release, the height of release and the predicted frequency of occurrence of the accident. Often the time available for the initiation of countermeasures before the release of radionuclides to the environment, the warning time, is also given. A more detailed discussion of source terms can be found, for example, in Ref. [4].

In principle, to fully define the source term, information on the physical and chemical form of the released radionuclides is also required. In practice, very detailed information on the physical and chemical form is seldom available from a Level 2 PSA. The particle size of the released aerosol and the chemical form of its constituents are important, particularly for determining the deposition of particulate material in both the environment and the respiratory tract if inhaled. Given a lack of precise data on the physical and chemical forms of the release, it is generally assumed that the radionuclides are released in a 1 μm activity median aerodynamic diameter (AMAD) aerosol, apart from the noble gases and the fraction of iodine released in an elemental or organic form. For many, though not all, end-points, this results in an overestimation of consequence severity. Most current consequence analysis codes are limited in their treatment of the physical and chemical forms of released radionuclides, so even in those cases where very detailed information is available from the Level 2 study, a simplified approach, based on the above assumption, may still have to be adopted.

2.3. ATMOSPHERIC DISPERSION AND DEPOSITION

Radionuclides released to the atmosphere as a fine aerosol or gas will create a plume which is carried downwind. During this transport process, it expands horizontally and vertically owing to diffusion and turbulent eddies in the atmosphere. Both processes, i.e. transport and diffusion, are often summarized by the word 'dispersion'. The principal question relates to the concentration profiles (crosswind and vertical) and the downwind transport of the dispersing plume. Many simple theoretical formulations of dispersion predict that the concentration profiles will have a Gaussian shape. Additionally, they assume that the downwind transport goes along a straight line. Although the assumptions of the simple theories do not hold for the real atmosphere, the Gaussian shape has been found empirically to be approximately valid in many situations and it forms the basis of the Gaussian plume model which has been, and still is, widely used in consequence assessment.

The above description of plume dispersion is only the starting point for a model of how released plumes behave in the atmosphere. Numerous additional factors have to be taken into account. For example, the release may be into a building wake; dispersion in the vertical direction is usually restricted to a certain height by an inversion 'lid'; the plume may have internal buoyancy, because of the energy or heat of the release, and thus rise bodily as it disperses. Furthermore, although the meteorological conditions at the time of the release can be assumed to persist throughout the plume's dispersion (time invariant meteorology), it is preferable to update the meteorological conditions hourly both during and after the period of the release (time varying meteorology), and this is the usual assumption. These details of atmospheric dispersion analysis cannot be pursued here and interested readers can refer to Refs [5–8] for more details.

Another important feature of the use of the Gaussian plume model in current consequence assessment codes is that the release can be modelled with more than one plume, i.e. as a multiple plume release. Such an approach is required for long duration releases, i.e. those lasting more than a few hours, and for releases which vary with time. For each individual plume it is usual practice to assume that it continues to travel in the direction of the wind prevailing at the time of the release, while at the same time taking into account the temporal changes in other weather characteristics, such as wind speed, stability category and the occurrence of rain.

The above description refers to plume dispersal without a decrease in the total amount of radionuclides it contains. In reality, the radionuclide content diminishes both by radioactive decay and through deposition mechanisms. Deposition mechanisms fall into two categories: 'dry' and 'wet'. Dry deposition is basically a surface effect, whereby material in contact with the ground is removed through a number of processes; for example, particles may impact on surface projections and stick, gases may diffuse to leaf surfaces and be absorbed. Wet deposition is the removal of dispersing material as a result of either the interaction between the dispersing material and rain (snow, etc.) falling through it, or by its incorporation into rain clouds. All these mechanisms for removal from the plume are considered in consequence calculations. Details on how these mechanisms are modelled can be found in Refs [4–6, 8]. These mechanisms, for which the treatment in current consequence codes is generally quite simple, have been the subject of much recent work (see, for example, Refs [9, 10]). An alternative approach to that generally used for modelling dry deposition is described in Ref. [11].

Before ending this section, it is worth commenting on the use of atmospheric dispersion models other than the Gaussian plume. The use of alternative atmospheric dispersion models, such as the Gaussian puff and long range trajectory models, has been widely investigated in recent years, and some current consequence codes contain such models. The main advantage of such models is that they allow changes in wind direction to be taken into account as released material is transported. Although the Gaussian plume model describes only a simple diffusion process and does not account for all the attributes which enter into detailed dispersion characterization, such as topography, it is still widely used in PCAs. The main advantage of the Gaussian plume model is that it produces results which are expected to be close to the average of many observations with minimal computer time requirements [6]. Furthermore, even though the Gaussian plume model has limited accuracy (a factor of 3 for time integrated concentrations over flat terrain [12]) and thus limited applicability, more complex models may do no better, especially if the information required to use these models, such as meteorological data over a wide area, is not readily available, accessible, or usable. Finally, for the particular situations analysed and for the consequences compared in the recent PCA code comparison exercise (see Annex I), the choice of atmospheric dispersion model was found not to be a major contributor to the differences observed between the predictions of the respective codes.

2.4. METEOROLOGICAL DATA AND ITS SAMPLING

Probablistic consequence analysis codes generally require meteorological data recorded on an hourly basis for at least one year. It is normal practice to use meteorological data from the meteorological station nearest to the release point (so-called source meteorology). Data compiled at other meteorological stations may, however, be acceptable if they are representative of the general conditions experienced by the plume. Consequence analysis codes using atmospheric dispersion models other than the Gaussian plume model may require additional meteorological data. Typically, such codes require meteorological data at regular spatial intervals over the region of interest (often referred to as non-source meteorology); this is obtained by interpolation of the available meteorological data. This interpolation process is complex and cannot be pursued here; some of the approaches used are outlined in Ref. [13]. In conclusion, the choice of meteorological data often represents a compromise between the ideal, the available and what is adequate for a particular assessment.

In the case of an hourly meteorological database, each hour's conditions can be regarded as unique and therefore the starting point for a sequence of hourly weather data. Thus, in one year's worth of meteorological data there are 8760 hours and, therefore, 8760 possible sequences. It is neither practicable nor necessary to consider every such sequence. Instead, the one or more year's worth of data is sampled in such a way that a truly representative set of weather sequences is selected. Each sequence has, of course, a probability of occurrence. Initially, random and cyclic sampling techniques (in which sequences are selected with a set time interval between them) were used. The preferred method today is to use stratified sampling so as to minimize the chance of omitting significant but infrequent weather sequences.

In stratified sampling the meteorological sequences are grouped into a number of categories. The objectives of the categorization are: first, to group those meteorological conditions which would lead to comparable radiological consequences in the near range for a given release; and second, to select categories such that adequate resolution is provided over the whole spectrum of consequences that result from the distribution of meteorological conditions. For many sites, weather sequences, including rain, will result in the greatest consequences and, accordingly, rain intensity and the distance from the release at which it starts to rain are the important meteorological conditions to take into consideration. The technique of stratified sampling is discussed in more detail in Ref. [2]. Very little work has been done on the meteorological sampling of non-source meteorological data for intermediate and far range consequences and for long duration releases. Although this subject is mentioned in Ref. [14], detailed guidance on the sampling scheme to be used with atmospheric dispersion models, other than the Gaussian plume model, is not currently available.

2.5. EXPOSURE PATHWAYS AND DOSE ASSESSMENT

There are six principal pathways by which people can accumulate a radiation dose after an accidental release of radioactive material to the atmosphere:

(a) External irradiation from radioactive material in the passing plume or cloud, referred to as 'cloud shine';
(b) External irradiation from radioactive material deposited on the ground, referred to as 'ground shine';
(c) External irradiation from radioactive material deposited on skin and clothing;
(d) Internal irradiation from radioactive material inhaled directly from the passing plume;
(e) Internal irradiation from radioactive material inhaled following resuspension of the ground deposit;
(f) Internal irradiation from radioactive material ingested following the contamination of foodstuffs by radioactive material deposited from the plume.

The principal exposure pathways are shown in Fig. 2. For each pathway a dosimetric model is used to convert the concentration of radionuclides in the atmosphere, on the ground, in foodstuffs, or on skin and clothing to the dose in humans. Only a very brief indication of what is involved in these dosimetric calculations is given below; further details can be found in the references quoted. If other parts of the nuclear fuel cycle are considered, different exposure pathways might be dominant (for instance, migration of radionuclides in soil and groundwater in the cases of waste storage and the storage of spent fuel).

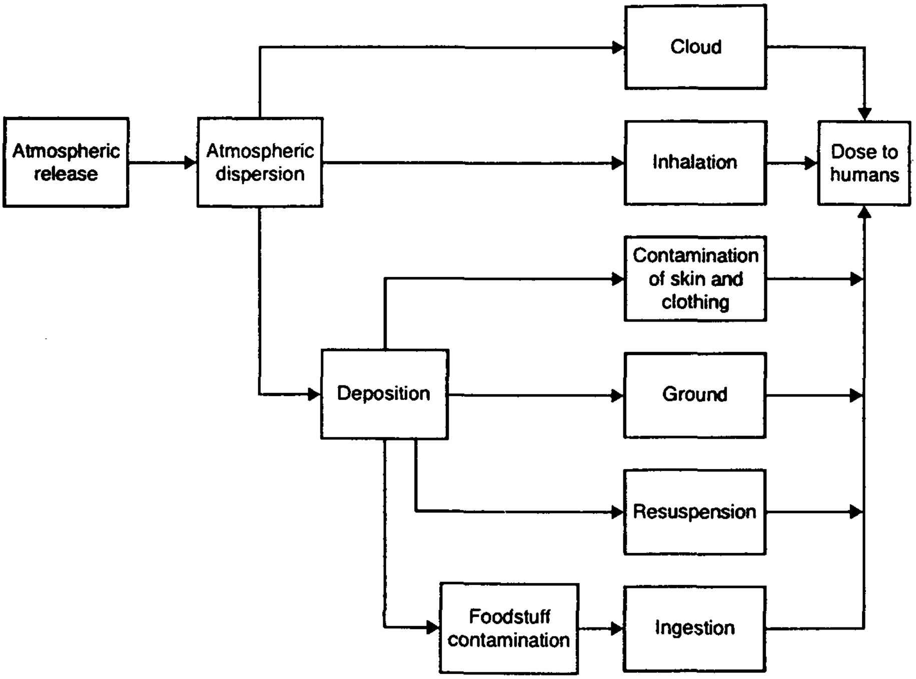

FIG. 2. Principal exposure pathways to humans following an atmospheric release.

2.5.1. External dose from a passing cloud

Both β and γ emitters in the passing cloud contribute to individual external exposures. The evaluation of the β dose is discussed in Ref. [15] but, because of their short range in air (a few metres) and limited penetration (skin irradiation only), the contribution from β particles is often neglected.

Calculation of the γ dose involves, in principle, a three dimensional integration over the whole cloud, making appropriate allowance for the scattering and absorption of γ rays by the air. For low γ ray energies and large cloud dimensions, the tabulated results for a semi-infinite cloud are often considered an adequate approximation of the actual integrals (see Ref. [1]). In general, for a finite cloud these integrals need, however, to be evaluated numerically, a procedure which may involve significant computational time if not solved in an optimal manner. In practice, an approximation is widely used whereby the semi-infinite cloud results are modified by a geometrical correction factor to make them more applicable to a finite cloud (see, for example, Ref. [4]).

For people indoors, the structure of the buildings attenuates the γ rays and so provides shielding. The value of the shielding factor (the ratio of the interior dose to the exterior dose) depends on the type of building. For areas with permanent substantial buildings, representative values range from 0.01 to 0.7 [16]. In evaluating doses it is generally assumed that a certain proportion of the population is indoors and the remainder outdoors at the time of the release. As shown by a recent study [17], it may be necessary to consider persons indoors and outdoors separately in estimating acute health effects rather than averaging the shielding factors in order to avoid underestimation.

2.5.2. External dose from deposited radionuclides

As in the case of airborne radionuclides, the contribution from β particles is generally neglected. The magnitude of the γ dose received by an individual from deposited radionuclides depends not only on the length of time for which the individual is exposed, but also on the behaviour with time of the deposited radionuclides. Radioactive decay will result in a reduction of the dose rate with time. Additionally, however, natural weathering processes may remove the deposit from the exposed surface. For example, migration of radionuclides into soil (dependent on the chemical form of the radionuclide, the properties of the soil, the weather, etc.) or the removal of deposits from urban surfaces by rainfall will reduce dose rates.

This pathway is often evaluated by multiplying the deposit by a dose per unit deposit conversion factor, integrated to appropriate time periods. These conversion factors are precalculated using simple formulas to account for long term removal mechanisms. These precalculated factors are stored in a database. Usually they are derived for deposition on an undisturbed soil surface (see Refs [18, 19] for details). More complex models have been developed in recent years to predict radiation exposure following deposition on different surfaces in the environment (see, for example, Ref. [20]). However, the need to use different ground shine dose conversion factors in consequence analyses for the various types of surface found in the environment has not been demonstrated by studies to date [19].

The doses from deposited γ emitters, calculated as outlined above, are appropriate for people who are outdoors. For people indoors, shielding by buildings will reduce the dose. For urban areas with permanent substantial buildings, representative shielding factors range from 0.01 to 0.5 [19]. Finally, it is common to assume that people spend a certain proportion of their time indoors.

2.5.3. External dose from radioactive material deposited on the skin and clothing

Both β and γ emitters contribute to individual external exposure following the deposition of radioactive material onto the skin and clothing. The dose received is generally evaluated by multiplying the amount of radioactive material deposited on the skin and clothing by a precalculated dose per unit activity of particular radionuclides. The amount of radionuclides deposited on the skin and clothing is often calculated as a fraction of that deposited on the ground (see, for example, Ref. [21]). Precalculated factors of β and γ dose per unit activity of radionuclides deposited can be derived from the dose rate information of Henrichs et al. [22]. With the exception of the head, which is assumed to be uncovered and treated separately, it is standard practice to use a shielding factor to account for the shielding effects of clothing on the β dose to the skin.

2.5.4. Inhalation dose from a passing cloud

The direct inhalation dose is obtained as the product of the breathing rate, the time integrated air concentration and a precalculated dose per unit activity inhaled. The breathing rate depends on the age of the person and on the level of physical activity; a typical value for adults is 2.66×10^{-4} m^3/s. The precalculated inhalation dose conversion factors are held in a database. These factors, which are also age dependent, are obtained from metabolic models. A number of such models, which both track the radioactive material as it moves through the body after inhalation and calculate individual organ doses, are available (see, for example, Refs [23–25]).

For short term releases, air concentrations inside and outside buildings may be different, and most current consequence codes include a ‘filtering factor’ for this situation which can be used to modify the inhaled dose. This factor, which will be less than 1, can be applied to the proportion of the population that is indoors; further information can be found in Ref. [26].

2.5.5. Inhalation dose from resuspended radionuclides

In the resuspension process, radionuclides initially deposited on the ground become airborne, and hence available for inhalation owing to some physical disturbance, such as the action of the wind or human activities (e.g. driving vehicles or ploughing). This can occur over long periods of time after the initial depositing event. In current consequence analysis codes, the relationship between the air concentration and the amount of material deposited is generally described by a time dependent resuspension factor. This factor is defined as the ratio of the air concentration due to resuspension and the initial surface concentration, and is generally determined from measurements made in the environment (see, for example, Ref. [27]). The organ doses arising from inhalation of resuspended radionuclides are calculated using the methods described in the previous section.

2.5.6. Ingestion dose

Humans consume a wide range of foodstuffs and, in principle, each foodstuff represents a separate pathway or food-chain for the intake of radionuclides. Generally, ingestion doses are calculated from the amount of radionuclides deposited on foodstuffs, the activity concentration of particular radionuclides in foods per unit deposition, the consumption rate of the food products and the dose per unit activity ingested. Both the consumption rate and the dose per unit activity ingested are age dependent.

Radionuclide concentrations in food are time dependent, and they are usually evaluated using a dynamic food-chain transport model normalized to unit deposit. Since dynamic food-chain transport models themselves are normally rather complex and require significant computing time, they are not usually included in consequence analysis codes, but are used to create a database containing the information needed. The information takes the form of specific activity concentrations in foodstuffs and their time integrals normalized to unit deposition for a series of times after an accident. This provides, for example, an account of food restrictions. This information is normally available for the more important foodstuffs and for accidents occurring at different times of the year (so that seasonal effects, which can be very significant, can be taken into account). Dynamic food-chain transport models are described in more detail in, for example, Refs [28, 29].

Consumption is generally treated in one of two ways: either local production and consumption of the foodstuff is assumed, or the assumption is made that all produce in the contaminated area is consumed somewhere, but not necessarily locally. In the first approach, individual consumption rates and the number of individuals in the local area (obtained from the population data grid — see Section 2.6) are used to estimate individual and collective doses. This method has the advantage of being relatively easy to apply as population data are generally available and data on agricultural production are not required, but has the disadvantage of overpredicting individual doses. In the second approach, the spatial distributions of foodstuff production (obtained from agricultural production data grids — see Section 2.6) are used directly to estimate the collective ingestion dose (with the assumption that all food produced is consumed and contributes to the collective intake). This method will give a more accurate estimate of the collective dose than the first method. It has the disadvantage that no information is obtained on the ranges of individual doses which make up the collective dose. As food is not, in general, consumed in the immediate area in which it is produced, more realistic estimates of individual ingestion doses require data on the distribution of food between the point of production and the point of consumption. Food distribution is discussed in more detail in Ref. [30] and is included in at least one current consequence analysis code [31]. Finally, both food processing and culinary techniques can reduce the concentrations of radioactive materials in foodstuffs; the influence of such factors is described in Refs [32, 33].

Doses per unit activity ingested (known usually as ingestion dose conversion factors) are obtained from the same metabolic models used to evaluate inhalation doses (see, for example, Refs [24, 25]). Again, these precalculated ingestion dose conversion factors are stored in a database.

As noted at the beginning of this section, humans consume a wide range of foodstuffs and each represents, in principle, a separate pathway or food-chain for the intake of radionuclides. Many of the world's major foodstuffs have been extensively investigated. Considerable information has also been gathered about food-chains, such as those that include freshwater fish and game, which are generally of minor significance but which may be important in some areas. Although this information is available, most current PCA codes are limited to modelling the major central European and North American food-chains, either by design or because the appropriate data are not included in the relevant databases. Finally, some codes also estimate the dose from aquatic pathways directly contaminated as a result of the passage of the plume over water bodies, or indirectly by drainage from contaminated land.

2.6. POPULATION, AGRICULTURAL AND ECONOMIC DATA

The spatial distribution of the population, agricultural production and economic data are important elements of consequence analysis codes. These data are necessary, firstly, in evaluating the health effects within the population arising from the external dose and the internal exposure due to inhalation and ingestion pathways and, secondly, in the calculation of the economic impact of implementing countermeasures, such as relocation and food bans.

Consequence analysis codes invariably require that population data be assigned to annuli, centred on the release site and segmented by radial lines (i.e. a (r, θ) grid). However, population data are usually not available in this format, so they have to be created. Generally, this is done with a conversion code which maps the available data onto the (r, θ) grid being used. Many codes also require agricultural production data in the same format. When compiling such data, it is important to take into account the growth cycle of crops (so that seasonal effects, which can be very significant, are properly taken into account). In general, the spatial resolution of the data in the (r, θ) grid needs to be finer near to the site than in the far range.

Population data are widely available (from the national census in each country), but agricultural production and economic data are more difficult to obtain. For member countries of the European Union (EU), both population and agricultural production data have been compiled. This work is described, for instance, in Ref. [34]. Programs to transform this data to a (r, θ) grid for any release location in the EU are also available (see, for example, Ref. [35]). As the spatial resolution of the data is, by necessity, limited, it is generally necessary to supplement it by local data in the immediate vicinity of the release. When agricultural production data are not available, they can be approximated by using information on the land area used for farming within each (r, θ) grid element in conjunction with information on the proportion of the farmland devoted to each agricultural product (in the region or the country).

Information on economic activity (gross domestic product (GDP) by economic sectors, land and housing values, etc.) is usually available on a regional basis. Thus, it is necessary to map the regions for which economic data are available to the (r, θ) grid being used by the consequence modelling code. Similarly, if food distribution is taken into account it is necessary to specify regions of food production and consumption and to map these regions to the (r, θ) grid being used. Finally, some consequence modelling codes also require the spatial distribution of land surface types (e.g. urban and rural) and the positions of land and sea.

2.7. COUNTERMEASURES

A variety of possible countermeasures or protective actions may be taken following an accidental release to reduce the impact of the accident on the environment and the public. A realistic estimate of the exposure of the population must therefore take appropriate account of these countermeasures. Current consequence analysis codes allow the user considerable freedom in specifying a wide range of emergency actions and criteria at which these actions will be assumed to be imposed and withdrawn. Thus, the different recommendations and criteria adopted in different countries can generally be simulated.

The various protective actions available fall broadly into two categories depending upon the time at which they are implemented and the effects which they are designed to mitigate. Short term protective actions, sometimes termed ‘emergency response’ actions, include those measures which might be implemented either before or shortly after a release to the environment. The primary objective of such measures is to limit the exposure of the population to both internal and external irradiation with the intention of preventing deterministic effects and minimizing risks of stochastic effects. Long term countermeasures are designed to reduce chronic exposure to radiation, both externally from deposited material and internally from ingestion of contaminated food, with the intention of reducing the incidence of late health effects. The principal short and long term countermeasures are described briefly below; further information can be found, for example, in Ref. [36].

2.7.1. Short term countermeasures

Short term countermeasures include sheltering, evacuation, the issuing of stable iodine tablets, and the decontamination of people. Sheltering refers to staying inside, with doors and windows closed and ventilation systems turned off. It is intended to reduce cloud shine, ground shine and inhalation exposures, as well as clothing and skin contamination while the plume is passing. The protection provided by sheltering depends on the structural building materials used and the ventilation rates, and will be offset by any deposition of radionuclides indoors.

Evacuation can usually be either unconditional (within a fixed area) or based on some level of estimated dose in the absence of countermeasures. This dose is also known as the *projected dose*. It could also be based on the *avertable dose*, which is the dose that can be saved in the time period during which the countermeasure is in force.

The emergency plans in some countries provide for the distribution of tablets containing stable iodine. The administration of stable iodine tablets, known variously as iodine prophylaxis or thyroid blocking, is intended to saturate the thyroid gland with the non-active isotope, thus preventing radioactive isotopes from being absorbed.

Finally, decontamination of people consists of changing their clothes and requiring them to shower or bathe to remove contamination from their skin.

2.7.2. Long term countermeasures

Long term countermeasures usually incorporated into PCA codes include relocation, land decontamination and food bans. There are other long term countermeasures which are generally not modelled in current PCA codes. These include changes to agricultural practices, deep ploughing, alternative feed, caesium binders, alternative crops and alternative production (e.g. cheese instead of milk).

Relocation refers to the moving away of people from the area affected by an accident for substantial periods of time (months or years). It may be carried out as an extension to evacuation, or it could be implemented at a later stage in order to reduce long term doses and allow time for decontamination of land and buildings or other remedial measures. Often the land from which people are relocated is said to be 'interdicted'.

Decontamination means the cleaning of land, buildings, equipment, etc., by the removal or redistribution of radioactive material. There is a great deal of data available on the cost and effectiveness of specific decontamination techniques on particular surfaces (see, for example, Ref. [37]), but comparatively little on decontaminating large areas with a combination of techniques. In current consequence codes the decontamination process is simply modelled with a decontamination factor (DF), defined generally as the ratio of the contaminant existing before to that remaining after decontamination. The DFs used in consequence analyses are typically in the range of 2 to 10, with higher DF values being associated with higher decontamination costs [38].

It is usual practice in consequence analysis codes to include intervention levels for imposing or withdrawing food bans. Generally, these intervention levels are based either on activity levels in food and drinking water or on maximum individual doses, which should be incurred although in some codes they are based on the level of ground contamination.

2.8. HEALTH EFFECTS

The exposure of individuals to ionizing radiation can lead to health effects which are generally classified as either 'deterministic' or 'stochastic'. Deterministic effects result from exposure of the whole or part of the body to high doses of radiation. Their severity is observed to increase with dose and there is usually a threshold dose below which the effects are not induced. Stochastic effects of radiation include increased incidence of cancer among the exposed population and of hereditary disease in their descendants. For stochastic effects the probability of occurrence, but not the severity, depends on the radiation dose. Effects observed in exposed individuals, i.e. deterministic effects and cancers, are termed 'somatic' effects, while those observed in their descendants are known as 'hereditary' effects. Deterministic effects and stochastic effects are often referred to as 'early' effects and 'late' effects, respectively.

The methods currently used in consequence analysis for evaluating the various health effects identified above are now briefly summarized.

2.8.1. Deterministic effects

Following Scott and Hahn [39], who developed a model of deterministic effects for the NRC, it is now common practice to evaluate deterministic effects using a 'hazard function'. In this approach, the probability or risk of an individual being affected, r, is given by:

$$r = 1 - \exp(-H) \tag{1}$$

Generally, H, the cumulative hazard, is given by a two parameter Weibull function of the form:

$$H = \ln 2 \left(\frac{D}{D_{50}}\right)^{S} \qquad \text{for } D > T \qquad (2)$$

where

D is the (average absorbed) dose to the relevant organ;

D_{50} is the dose which causes the effect in 50% of the exposed population;

S is the shape parameter, which characterizes the slope of the dose–risk function;

T is the threshold dose.

Doses which are protracted over a period of time are less harmful than those delivered over a very short period. This is included in the model by summing over doses delivered in different time periods, with each normalized by an appropriate D_{50}. The equation above is then replaced by:

$$H = \ln 2 \left(\sum_{i} \frac{D_i}{D_{i,50}}\right)^{S} \qquad \text{for } D_i > T_i \qquad (3)$$

where

D_i is the dose delivered in the time period i;

$D_{i,50}$ is the dose which causes the effect in 50% of the exposed population if delivered in time period i;

T_i is the threshold dose for time period i.

In a recent revision to the NRC health effects model [40], dose rate dependent models are proposed for fatal deterministic effects. These account for the fact that the dose received at a low dose rate is less harmful than the dose received at a high rate. This dependency is expressed by a medium lethal dose LD_{50} as a function of dose rate. This development is now being implemented in most current consequence analysis codes.

The deterministic fatal effects usually calculated with the above model comprise those following irradiation of the bone marrow (haematopoietic syndrome), the lung (pulmonary syndrome), the GI tract (gastrointestinal syndrome) and skin (skin burns). In addition, the mortality of pre- and neonates after exposure in utero is normally quantified. The above model also enables a wide variety of radiation induced injuries to be estimated (e.g. hypothyroidism, temporary sterility, microcephaly and cataracts.)

2.8.2. Stochastic somatic effects

The principal stochastic somatic effects are the increased incidence of cancers, both fatal and non-fatal, in the irradiated population. Their appearance is likely to be spread over several decades following an accidental release. Generally, for each cancer type the risk of cancer incidence r is given by a linear–quadratic dose response function of the form:

$$r = aD + bD^2 \qquad (4)$$

where

D	is the absorbed dose to the organ of interest;
a and b	are effect specific model parameters that quantify the risk per unit dose and are usually referred to as 'risk coefficients'.

In current consequence analysis codes it is usual to assume $b = 0$, so that a linear dose response function is used. The application of such a no-threshold linear dose response function is in accordance with recent recommendations of the International Commission on Radiological Protection (ICRP) [41] and may lead to an overestimation of the stochastic somatic effects at low doses. For low doses and dose rates below some dose rate threshold, some codes modify the parameter a by a low dose and dose rate effectiveness factor (DDREF).

Two types of model are available for estimating the risk coefficients a and b, the relative and absolute risk models. The absolute (additive) risk model is based on the assumption that the probability of incurring radiation induced cancer depends only on the dose received and is independent of the cancer incidence due to natural and other causes. Alternatively, the relative (multiplicative) risk model assumes that the incidence of radiation induced cancer is related directly to the spontaneous rate and that radiation acts multiplicatively to yield total risk. Which model is used depends on the type of cancer [40, 42, 43].

In the calculation of the number of stochastic somatic effects in the population as a result of an accident, the following aspects have to be considered:

(a) The life expectancy and age distribution of the exposed population;
(b) As stochastic effects may not appear for some tens of years after a single exposure, some of the risks may not be expressed in the population, as people may die naturally before the possible radiation induced effect occurs;
(c) Most of the routes of irradiation lead to doses protracted over a period of years or decades, with changing contributions of the various radionuclides released.

The calculation of the risk of stochastic somatic effects allowing for the time variation of dose and the age and lifetime distribution of the population requires, in principle, the evaluation of complex multiple integrals. Some codes, however, use a much simpler approximation.

2.8.3. Stochastic hereditary effects

Hereditary effects may occur by changes arising in the base sequence in the DNA of a single gene,'gene mutation', or by rearrangement of collections of genes within and between chromosomes, 'chromosomal aberrations'. Radiation damage to the male and female germ cells may increase the incidence of these effects; they range from being very obvious to being virtually undetectable. The procedure used for evaluating hereditary effects in current consequence codes follows that outlined above for evaluating stochastic somatic effects; Refs [40, 43] can be consulted for further details.

2.9. ECONOMIC CONSEQUENCES

A common framework into which many of the consequences of an accidental release of radionuclides may be translated is their economic cost. This provides a measure of the impact of the accident and enables the different effects of the accident to be expressed in the same terms, and combined as appropriate. Several models for predicting the economic impact of accidents have been developed and incorporated into consequence analysis codes (see Ref. [44]). In general, these models include the cost of countermeasures, namely evacuation, relocation, sheltering, food restrictions and decontamination, and also the cost of health effects in the exposed population. However, the methods used by these models differ. This is particularly true of the methods used to assess economic consequences in areas affected by countermeasures. Here a basic restriction for the modelling is the limited availability of national economic statistics to be used for deriving the economic input data.

Some accident costs are generally not included in today's PCA codes. These include some of the directly measurable impacts, such as the cost of on-site consequences, the replacement of the damaged plant and the provision of alternative power. Also excluded are all impacts that are not directly measurable, such as ecological damage, anxiety and political impact. Economic modelling is still a developing area of consequence analysis and it is likely to be some time before a generally accepted approach to evaluating economic costs emerges.

2.10. PRESENTATION OF RESULTS

The consequences of a given accident release at a given location vary with the meteorological conditions and the wind direction. Generally, in present PCA codes, the consequences are evaluated on a (r, θ) grid around the release location (see Section 2.6) for each wind direction and meteorological sequence in turn. The wind directions and meteorological sequences used, and their probabilities of occurrence, are determined by the meteorological sampling model included in the code (see Section 2.4). At each (r, θ) grid element around the release location, the following quantities can in principle be evaluated:

(a) Concentrations of important radionuclides;
(b) Radiation doses, individual and collective;
(c) Health effects, individual and collective;
(d) Areas, persons and amounts of agricultural produce affected by countermeasures as a function of time;
(e) Economic costs.

The following discussion focuses on the results for health effects, but the other results can be treated in essentially the same manner.

The dispersion, deposition, exposure and health effects models in combination make it possible to calculate the risk of various health effects for each (r, θ) grid element. In a Level 3 PSA, these risks are calculated for a large number of different weather conditions. This produces a distribution of individual risk for each health effect at each grid element. For each of these distributions a mean value of individual risk can be obtained. Rather than presenting these mean values of the individual risk for each grid element, it has become standard practice to further average them over all directions of the wind-rose. In this way the mean individual risk is presented as a function of distance from the release point. It is generally felt that this approach is sufficiently accurate, since the frequency with which the wind blows in the various directions does not normally vary very much. The evaluation of individual risk is more complex in some consequence analysis codes because of the way the movement of people (e.g. those evacuated) is modelled, but the principle of the calculation as outlined above remains the same.

Calculation of the collective health effects is performed in a somewhat different manner. For a particular weather condition, the individual risks for each health effect at each grid element are multiplied by the population of that grid element and summed over all grid elements affected. This gives the predicted number of each type of health effect for a particular weather condition. When this type of calculation is performed for a large number of different weather conditions, the distribution of collective health effects is obtained. This distribution is usually built up by successively placing the numbers of each type of health effect calculated for different weather conditions in classes or bins. These classes cover the full range of consequence values, and usually the class widths are logarithmically equidistant. Once all the results for all weather conditions have been binned, a class frequency distribution has been produced. (In fact, given that the probabilities of the different weather conditions sum to 1, we have a relative frequency distribution.) In consequence models it is traditional to present results as complementary cumulative distribution functions (CCDFs), also known as complementary cumulative frequency distributions (CCFDs). A point on a CCDF

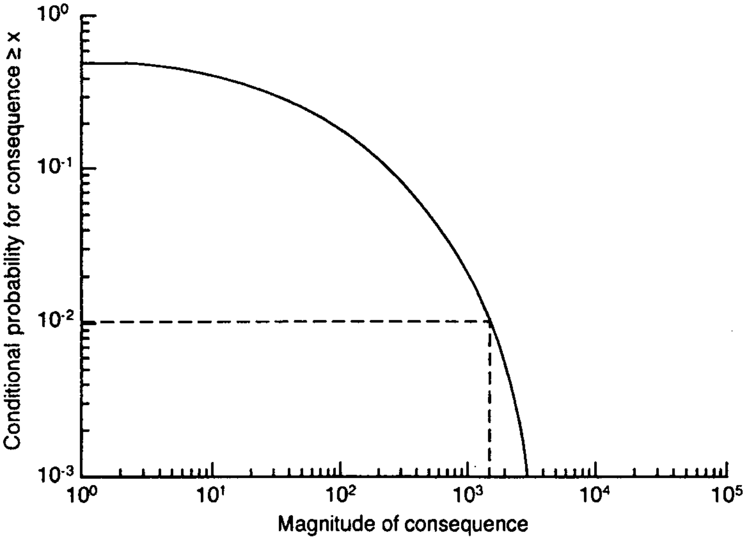

FIG. 3. An example of a CCDF.

curve gives the probability that the corresponding consequence value or a greater value is expected. For each health effect the CCDF is derived from the (class) frequency distribution. Although it is not strictly correct, the relative frequencies mentioned above are generally referred to as probabilities. An example of a CCDF is shown in Fig. 3.

Along with producing CCDFs, it is also standard practice to produce the expectation and various percentile values for each CCDF. The expectation value or arithmetic mean is usually obtained by summing the products of the consequence value and the probability of the weather conditions; it can also be obtained approximately from the class frequency distribution. The values of various percentiles can easily be derived from the CCDF. The pth percentile is that value of consequence, C_p, for which the following relation holds:

$$\text{Probability } (C_p) = 1 - p/100 \tag{5}$$

The 50th percentile is also called the median value. In addition to the above values, it is standard practice to produce the probability of zero effects for each consequence. It is not usual to tabulate maximum values, although they can be readily obtained from the CCDFs, as past experience has shown that public discussions concentrate on these values without consideration of their low probability and their large uncertainties.

The derivation of the class frequency distributions and the CCDFs above assumes that at a specific location a release has actually occurred. In recognition of this, the above results are prefixed by the word 'conditional' and we talk about conditional probabilities of consequences given that a release has occurred. While these results are useful in themselves, a result of more significance is the frequency of particular consequences occurring or being exceeded. Results in this format can be obtained directly from the CCDFs by multiplying the conditional probabilities of exceeding a given number of consequences by the frequency of occurrence of the assumed release. These release frequencies are provided by the Level 2 PSA. Given that in producing the release frequencies of the representative accidents analysed in the Level 3 PSA all possible accidents have been considered, the frequency distributions for each representative release can be summed together to give, for the nuclear installation under consideration, the overall frequency of particular numbers of consequences. Such distributions provide a useful measure of the public risk presented by an installation; they are the usual end points of a Level 3 PSA.

Although in any published report on a Level 3 PSA attention is focused on the CCDFs giving the overall frequency with which particular consequence values are equalled or exceeded, a number of other results are also useful. These results, which can be used to explain the final CCDFs, include:

(a) Conditional CCDF results for particular accidents;
(b) Contribution of the different radionuclides, exposure pathways and organs to the health effects;
(c) Distribution of collective dose in individual dose bands.

Most current consequence analysis codes can produce such information. In addition, some consequence analysis codes can also produce information on the time dependence of the health effects, although such information is generally not available on a routine basis.

A fuller description of the calculation of CCDFs and related quantities is given in Appendix 1 of Ref. [2].

2.11. SENSITIVITY AND UNCERTAINTY ANALYSIS

Current consequence analysis codes endeavour to produce 'best' estimates of the various consequence end points, i.e. without undue conservatism. Ideally, in order to assist in the interpretation of these results, they should be associated with an estimate of the uncertainties. During the last decade considerable importance has been attached to the development and application of methods to quantify the uncertainties in consequence analysis codes. In particular, a number of investigations have been made of the uncertainty in the prediction of particular parts (e.g. atmospheric dispersion) of consequence analysis codes (see, for example, Refs [45, 46]). Nevertheless, although considerable progress has been achieved in this area, much remains to be done before well founded estimates of uncertainty can be produced on a regular basis. Further, while most current consequence modelling codes are capable of performing uncertainty analysis, such capabilities are generally not utilized for routine assessments.

There are three major categories of uncertainty: incompleteness, modelling and the input parameter. The first category includes uncertainties caused by a lack of completeness in accident scenarios. This type of uncertainty is difficult to analyse and quantify. The uncertainties caused by modelling are a subject of the uncertainty and sensitivity analysis in PSA, but it is often difficult to quantify them owing to a lack of data. Input parameter uncertainties are the most readily quantifiable. Parameter uncertainty takes two forms, there are parameters which are random because of their nature and can be defined only on a statistical basis, and parameters which are not exactly known because of a lack of information. Both these types of uncertainty are usually quantified in the same manner, i.e. by Monte Carlo simulation. However, this method requires detailed knowledge and understanding of the parameters input to the Level 3 PSA.

In addition to the more recent uncertainty studies, a large number of relatively simple sensitivity studies have also been carried out over the years (for example, those summarized in Ref. [4]). Generally, in such studies a single modelling assumption or a single parameter value is changed and the CCDFs are recalculated in order to see how they vary. For example, they are used to identify key analysis assumptions and parameter values which need to be included in any meaningful uncertainty analysis.

Judgements in these areas are complex and require a detailed understanding of the interfaces and dependences between the many diverse analysis disciplines which include atmospheric dispersion, emergency planning, radiobiology and economics.

3. PERFORMING A LEVEL 3 PSA

This section explains how a Level 3 PSA is generally performed, focusing on a Level 3 PSA for nuclear power plants. It is recognized that this document may also be used as guidance for a Level 3 PSA for other nuclear facilities. It is also recognized that Level 3 PSA tools will be used in a context other than risk assessment, e.g. emergency response studies. For these applications not every task in this chapter is of equal importance. The main tasks that have to be carried out in a Level 3 PSA are identified in Fig. 4; they are discussed in turn below. The experience of the consequence analysis team will, of course, determine which tasks need to be done. A new team would start with Task 1. An experienced team which already has a working code would start with Task 2 and omit Task 4.

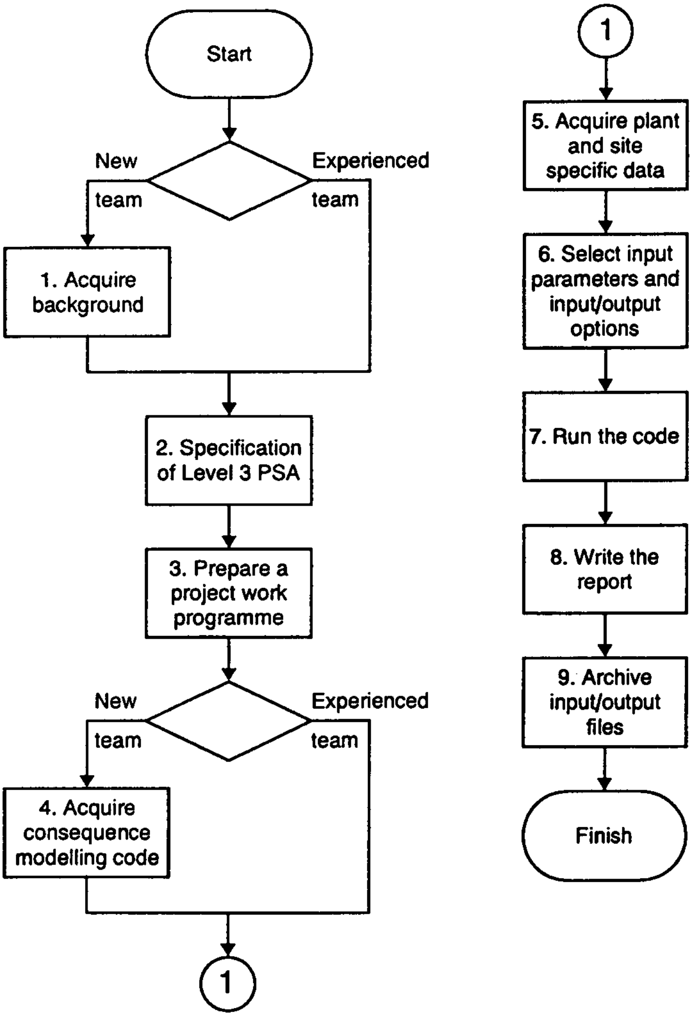

FIG. 4. Tasks involved in performing a Level 3 PSA.

In this section, it is assumed that one of the existing Level 3 PSA codes is used to carry out the assessment. Depending on the kind of assessment, there is not always a code available that is tailored to the job. Sometimes it may be necessary to use intermediate results from a Level 3 PSA code and process these results with another program.

As explained in the previous section, a Level 3 PSA is performed with an accident consequence assessment code. The new users of such a code should realize that they require not only a considerable amount of input data, but also careful thought when it comes to running them. These matters are considered later in this section, although it is not possible for their treatment to be comprehensive, since different codes have different data requirements, etc. Hence, new users will need to carefully study the user guide of the code they plan to use. Apart from having a working knowledge of the code, new users must also have a good background knowledge of the overall subject to enable them to prepare appropriate input and to choose appropriate analysis options.

3.1. TASK 1: ACQUIRING BACKGROUND

As an introduction to the subject, the overview in Section 2 of this report outlines all of the essential elements. This overview drew extensively on the most up to date source of published information at the time of writing, namely the proceedings of a seminar on 'Methods and Codes for Assessing the Off-site Consequences of Nuclear Accidents', which was held in Athens in May 1990. The papers in these proceedings, some of which are cited in the reference section of this report, together with the other references given in the overview, should be consulted for additional information. There are a number of other overviews in the literature which in their time have served as a valuable introduction to the subject, for example Refs [2, 4, 47]. Additionally, the recent International Code Comparison Exercise compared approaches and methods for a PCA from many organizations and countries throughout the world [48]. This exercise provided a number of insights into the strengths and limitations of the participating PCA codes.

Some of the many Level 3 PSAs that have been performed (see, for example, Refs [49–51]) should also be studied by the complete beginner. They are a valuable source of additional information and while they do not, as a rule, describe the methodology used in detail, they do indicate how such PSAs are performed and also how the results are presented and discussed.

3.2. TASK 2: SPECIFICATION FOR A LEVEL 3 PSA

To ensure that there is a proper definition of work it is essential to produce a project specification at the start of any Level 3 PSA. This is the point at which the experienced PSA consequence analyst, who already has a consequence analysis code available for use, begins a Level 3 PSA (see Fig. 4).

A project specification for a Level 3 PSA needs to address as a minimum the following:

(a) The objectives of the work to be carried out, specifying the facilities to be assessed, the object of the assessment and, if appropriate, the risk criteria upon which the study will be judged;
(b) The basis upon which the consequence analysis code and any supporting programs will be chosen;

(c) The basis for acquiring all necessary site and meteorological data;
(d) The interface with the Level 2 PSA, particularly with regard to the source terms, including their release frequencies;
(e) The countermeasures strategy that is to be modelled;
(f) The basis upon which any special analysis assumptions are to be determined to cover the choice of models and key parameter values;
(g) The results required;
(h) The format of the final report;
(i) The quality assurance (QA) requirements to be met and the QA procedures to be followed;
(j) The required milestones and the completion date.

3.3. TASK 3: PREPARING A PROJECT WORK PROGRAMME

The work programme for a Level 3 PSA is an implementation plan for completing the project according to the project specification. The essential purpose of the work programme is to clearly identify the tasks that have to be done, the dates by which they have to be started and completed, the staff effort required to carry them out and, ideally, the staff who will accomplish them. When drawing up the work programme the following minimum points should be addressed:

(a) Identification of the staff who will work on the project;
(b) Estimation of the number of runs of the consequence analysis code required;
(c) Estimation of the staff time (i.e. number of person-days) required;
(d) Estimation of the financial resources required (including the purchase of data and the cost of any subcontracts);
(e) Possible use of subcontractors;

Invariably, the work programme will be prepared by the Level 3 PSA project manager (see Section 4). Once prepared, it should be made available to senior managers so that they are aware of the resources being used and the time-scales over which their resources are required.

3.4. TASK 4: ACQUIRING AND INSTALLING A CONSEQUENCE ANALYSIS CODE

Consequence analysis codes are large (typically many tens of thousands of lines of coding), require many tens of megabytes of storage and may have long run times depending upon the particular computer system used. In fact, the word code is, in most cases, a misnomer as often the consequence analysis code is not a single program, but a whole package of programs and databases, with some of the programs being used to create the databases required. The complete development of a new consequence analysis code is now beyond the resources of all but the largest of organizations. Indeed, most consequence analysis codes developed recently have been collaborative ventures involving several organizations. Given this, it is likely that a team new to the topic will use an existing, proven consequence analysis code.

There are a number of codes in existence worldwide that contain all the necessary elements of a consequence model and perform the probabilistic manipulations necessary for the calculation of CCDFs. Many of these codes, for example the US code CRAC2 which was widely used in the past, are neither up to date nor supported by the organizations which initially developed them, as they have been superseded by newer systems. Ideally, the inexperienced team should attempt to acquire an up to date code that employs models and calculational approaches that are generally accepted. It is also important that the prospective user compare the objectives of his or her study with the capabilities and options in the available codes prior to making a selection. For example, some of the important considerations which influence code selection are:

(a) The purpose and objectives of the study — e.g. site selection, comparison of reactor types/design features and regulatory permits/licensing (see Section 3.2 for a discussion on the development of PSA specifications).
(b) Topography of the proposed site(s) — rugged or mountainous (complex) terrain may make use of the simple atmospheric dispersion models available in most Level 3 PSA codes questionable and dictate the consideration of alternate approaches.
(c) Computer hardware/software compatibility — the code selected should run on or be easily adapted to the computer system available.
(d) QA requirements — ideally a code should have continuous support from the originating organization, including a complete QA validation and error correction program. This is essential in PSAs that involve regulatory/licensing application.

The topic of code selection is considered further in Annex II.

Of all the consequence analysis codes available, no one code is manifestly the best as they all have their strengths and weaknesses. Ultimately, the choice of code will be determined not only by the above considerations, but also by the availability of the code and any arrangements that can be made for continuing support.

Once the user team has acquired a code it has to be installed on their computer. Installation of such codes should not be a major task, given that the computer being used has the capability to run the code. Part of the installation is to test the code; this is normally done with the standard test problems supplied with the code package. Apart from testing that the code has been installed correctly, the user will also gain essential experience from this exercise. It is strongly recommended that further experience in using the code be gained to build up competence before a major programme of work is embarked upon. Such experience could be gained by running some of the international benchmark problems in this area; either those done in the early 1980s (see Ref. [52]), or preferably those done more recently (see Annex I). Alternatively, previous studies with earlier generation codes could be repeated. In both cases the published results can be used as a guide to the answers that should be produced. Another way of quickly building up competence is to arrange a temporary exchange of experienced staff between the organization supplying the code and the user organization.

3.5. TASK 5: ACQUISITION OF PLANT AND SITE SPECIFIC DATA

Consequence analysis codes require large amounts of site and plant specific input data. The main types of data required are:

- Source term,
- Meteorological,
- Population,
- Countermeasures,
- Agricultural production,
- Land,
- Food distribution,
- Economic.

Not all the types of data mentioned may be required, since their need depends on the particular consequence analysis code being used and the desired results. In some cases the user may be willing to consider changes in code default data which are not site or plant specific, e.g. radiological data. Generally, the collection of these data is a time consuming process and should be started as soon as possible. Furthermore, to minimize the overall data collection time the various types of data should be acquired in parallel.

3.5.1. Task 5.1: Source term data

Traditionally, source term data are provided by the Level 2 PSA for a small number of representative release categories. These release categories, each with an assigned frequency of occurrence, represent the spectrum of potential releases from the nuclear power plant being analysed. For each release category the Level 2 PSA generally provides, at a minimum, the following information:

(a) Magnitude of the release of radioactive material to the atmosphere;
(b) Release timing;
(c) Rate of energy release;
(d) Release height and building dimensions;
(e) Frequency of occurrence of the release category.

3.5.1.1. Magnitude of release

Usually the release is given as a fraction of the core inventory at shutdown. A number of inventory codes are available and these can be used to produce radionuclide inventories appropriate for the reactor type and reactor power level under consideration. Typically, such codes consider hundreds of radionuclides. However, many of these can be and are disregarded as they do not significantly affect the results of the radiation dose calculations (see Ref. [4] for details). Most current consequence analysis codes have data libraries which contain half-life information for a wide range of radiologically significant radionuclides. Some also have data libraries which contain decay chain information. It is expected that any radionuclide which has the potential to contribute significantly to radiation doses following a nuclear power plant accident will have been included in these libraries.

To simplify the calculations for the source term analysis, the radioactive species are usually grouped according to volatility. Traditionally, the magnitude of the release of each group of radionuclides is specified by defining the fraction of the reactor inventory of each group which is released to the atmosphere. These release fractions can be a function of time. It is generally not necessary to account for radioactive growth and decay during transport inside the plant, as most consequence analysis codes already evaluate these effects from reactor shutdown.

Except for nuclides present as noble gases and gaseous forms of iodine (I_2, CH_3I), all nuclides during transport in the containment or after release to the atmosphere are expected to condense and form aerosol particles (though the particle may, of course, scavenge the gaseous species, in which case the behaviour, particularly of the scavenged species, may be changed). Thus, the calculation of radionuclide behaviour inside the containment and after release from the containment to the environment is usually reduced to the following three classes:

(a) Noble gases (insoluble, non-reactive);
(b) Gaseous forms of iodine (water soluble and/or reactive gases);
(c) Aerosol particles.

Clearly, the behaviour of aerosol particles, both within the reactor containment and in the environment, is dependent on particle size, shape factors, particle density and particle concentration. Usually, however, the chemical composition is of minor importance. Thus, in principle, to fully define the source term, information on the physical characteristics of the released aerosol upon release to the atmosphere is required. In practice, such information is seldom available from the Level 2 PSA. As discussed in Section 2.1 of this report, it has often been assumed that the non-gaseous radionuclides are released in a 1 μm AMAD aerosol. For many, though not all, purposes this results in an overestimation of the consequence. In practice, many current consequence analysis codes are limited in their treatment of the physical and chemical form of released radionuclides, so it would be unlikely that they could utilize detailed information on the size of the released particles.

3.5.1.2. Release timing

The time history of the radionuclide releases obtained from a Level 2 PSA is an important input to consequence calculations. This includes the time of release, the duration of release and the warning time.

From the point of view of a Level 3 PSA for nuclear power plants, the time of release is the time between reactor shutdown and the beginning of the release to the atmosphere, during which radioactive decay is accounted for. The current generation of consequence analysis codes can in fact handle phased releases, where the total quantity of radionuclides released in any release category is divided between a number of separate releases, each typically specified by their own set of release fractions. Therefore, the time between reactor shutdown and the start of the release and the release duration of each of these distinct releases is required from the Level 2 PSA. Meteorological information has frequently been recorded on an hourly basis and for this reason hourly increments have often been used for phased releases. The interval actually chosen should facilitate matching of the Level 2 and 3 PSAs and, in particular, should reflect any discontinuities, such as the onset of secondary containment venting. Warning time is essentially the period of time available for the initiation of countermeasures before the release to the atmosphere begins.

3.5.1.3. Rate of energy release

Plume rise can be important in reducing the predicted value of consequences near the site, particularly the early health effects. The minimum information required is the rate of heat release that accompanies the escaping radionuclides, and this should emerge from the analysis of physical processes. However, the analyst must remember that the occurrence of aerosol particles in the larger size ranges may affect this reduction.

3.5.1.4. Release height and building dimensions

Current consequence analysis codes can readily model a point source release from a known elevation. If the Level 2 PSA predicts a release of this nature, then the height of release should be provided. Alternatively, if the release does not emerge from a well defined source, or if that source is on the side or roof of a reactor building, then it is generally assumed that mixing will occur throughout the reactor building wake. For model mixing in the building wake, the reactor building dimensions are generally required.

3.5.1.5. Frequency of release

The frequencies of the various release categories being considered are a direct output of the Level 2 PSA.

3.5.2. Task 5.2: Meteorological data

Current consequence analysis codes usually require, at a minimum, a data file containing hourly values of wind direction, wind speed, stability category, rainfall and mixing layer depth. These hourly values are required for at least a year; ideally, ten years of data should be used so that the probability of rare weather conditions is better estimated. Usually, the wind speed and direction are required at a height of 10 m. As discussed in Section 2.4, consequence analysis codes using atmospheric dispersion models other than the Gaussian plume model may require additional meteorological data, e.g. detailed windfield information (see below). The user guide for the code selected should fully define any additional meteorological data required and should be consulted for further details.

Generally, site meteorological data, if they exist, neither include all the different sorts of data required nor have been measured over a long enough period of time. Hence, as discussed in Section 2.4, an alternative source of data may need to be found. Additionally, neither the stability category nor the mixing layer depth are measured routinely. They have to be derived from other measured data. Thus, some processing of the measured data may be required. Further, it is not unusual for there to be sequences of hours or even days when data are incomplete or inconsistent and expert judgement is required to fill in the gaps. Generally, suitable meteorological data either for a new site or for a site without a local meteorological station have to be obtained from, say, a national weather service and the advice of their expert meteorologists is required to obtain all the different sorts of data needed. Some codes may require input of off-site meteorological data to better estimate the wind trajectories. In such cases, again, skilled interpolation of the available data may be required.

In simpler probabilistic accident consequence analyses, especially when considering short duration releases, a simplified meteorological database, e.g. a joint frequency matrix of various weather categories, may be sufficient.

3.5.3. Task 5.3: Population data

Consequence analysis codes invariably require that population data be assigned to annuli, centred on the release site and segmented by radial lines (i.e. a (r, θ) grid). The directions of the sectors should be consistent with the wind sectors. The available population data have to be mapped onto this (r, θ) grid. Population information can generally be obtained from the government census data in each country, although it will probably have to be supplemented by local data in the immediate vicinity of the release location. For member countries of the EU, population data have been compiled on a grid consisting of a series of elements of equal area defined by their latitude and longitude (see Section 2.6). In these countries, these data can generally be used at distances beyond a few tens of kilometres of the release location. Although census data will, to some extent, be out of date by the time they are used, they are generally sufficient for the purposes of consequence assessment, unless there have been major population changes in the area around the plant since the census was taken.

In many areas the population varies considerably with the time of year. Holiday resorts are an obvious example. There can also be large daily and weekly variations in population as people go to and return from work, school, etc. Generally, such effects are ignored as they are not thought to be major contributors to the uncertainty in CCDF results (see Ref. [4]). However, the issue needs to be addressed and, if considered significant, should be accounted for in the population distribution used as code input. Population variations experienced at holiday resorts and schools also have to be considered when countermeasures strategies and emergency actions are developed.

3.5.4. Task 5.4: Countermeasures data

Consequence analysis codes require values for a number of shielding and filtering factors which are applicable to the various exposure pathways (see Section 2.6). The data required by the code selected must be prepared in the appropriate format specific to the code. As buildings provide different degrees of protection, shielding factors are often calculated as sums of shielding factors for individual types of buildings weighted by the fraction of the population in each type. Some codes require the user to perform these summations. In any event, the user must identify the common types of buildings and their numbers in the region around the reactor location and the fractions of time spent in each type. The user must take note that use of average shielding factors may underestimate acute effects. Additionally, if any default shielding and filtering factors provided with a code are used, the user should carefully check whether they are applicable to their situation. With regard to evacuation, the code may require timing and route data as input. Finally, codes may also require countermeasures data for the late phase of the calculations (e.g. interdiction of foodstuffs).

Experience has shown that the results of a consequence assessment can be particularly sensitive for the choice of shielding factors and the timing of countermeasures in relation to the timing of the release [17].

3.5.5. Task 5.5: Agricultural production data

For the assessment of the collective dose due to ingestion, most consequence analysis codes also require agricultural production data on the same (r, θ) grid that is used for the population data. The precise agricultural data required depend on the consequence analysis code, and the user guide of the code used should be consulted for details. Nevertheless, the following is a typical list of agricultural products used to indicate the range of data required:

(a) Cow's milk (consumed as milk),
(b) Cow's milk products,
(c) Green vegetables,
(d) Root vegetables,
(e) Cow's meat,
(f) Cow's liver,
(g) Sheep meat,
(h) Sheep liver,
(i) Grain.

This list is based mainly on food production practices in countries where the codes most used currently originated. For countries with other food production practices and consumption patterns, data for a different range of agricultural products may be required. Typically, for each product the following data are required: production, season of growth, time of harvest and time from harvest up to consumption. Some codes may require the following additional agricultural data for their economic models:

(j) Number of livestock,
(k) Area of land on which crops are grown.

Agricultural data are generally more difficult to obtain than population data. National information on agricultural production should, however, be available from appropriate government ministries or national agencies. Again, the available data have to be mapped onto the (r, θ) grid being used. A problem often encountered is that the areas for which the agricultural production data are known are large. This, however, will generally not be a major limitation as agricultural production data are not required with the same level of spatial detail as the population data. Again, for member countries of the EU agricultural production data have been compiled on a grid consisting of a series of elements of equal area defined by their latitude and longitude (see Section 2.6). If ingestion doses from contaminated water are required, detailed data on surface water and water consumption would also be needed.

3.5.6. Task 5.6: Land data

Most current consequence analysis codes require information on which areas are land and which are sea or lakes. Generally, such information is provided by defining the fraction of each spatial element of the (r, θ) grid that is land (as opposed to lakes, seas, etc.). For any particular site these data can usually be estimated fairly quickly from both small and large scale maps. Additionally, for the land fraction a further subdivision into urban and rural areas may be required. It is possible to generate such information using the land fraction data, the population information and a critical population density (e.g. 100 persons per km^2) above which a spatial element is classified as urban and below which it is classified as rural.

3.5.7. Task 5.7: Food distribution data

If a code has an option to account for food distribution, then the area over which the consequences are being evaluated has to be divided into regions. For each region and each agricultural product, the quantity of food which is consumed locally within the region and that which is distributed to the other regions is required. While there are considerable data available on the movement of food between some countries, there are less data on broad distribution patterns within countries. Some suggested sources of these data are given in Ref. [30], but in general the collection of food distribution data is likely to be a difficult and time consuming process. Nevertheless, the data need only be collected once for a given country or group of countries. In addition to the food distribution information, each spatial element of the (r, θ) grid needs to be allocated to a food distribution region. This can readily be done using a map with the grid elements and the regions marked on it.

3.5.8. Task 5.8: Economic data

Economic data are required when economic results are desired. Generally, an approach similar to that described above for food distribution data is used. Again, the area over which the consequences are being evaluated is divided into regions, in this case regions of economic activity. For each of these regions various economic data, e.g. the value of the land and its assets, have to be specified. The precise data requirements depend on the consequence analysis code, and the user guide of the code being used should be consulted for details. In general, obtaining all the required economic data can be a difficult and time consuming process even where the published economic statistics are plentiful. Nevertheless, the data need only be collected once for a given country or group of countries. In addition to the above mentioned economic data for each region, data defining the economic region that each spatial element of the (r, θ) grid belongs to are required. Such data can be readily estimated from a map with the grid elements and the regions marked on it.

3.6. TASK 6: OTHER INPUT PARAMETERS AND INPUT/OUTPUT OPTIONS

Current consequence analysis codes generally have a great deal of flexibility when it comes to running them as most of their parameters can be changed by the user. Although defaults are usually provided, the user still has to decide how to set the various available code options when creating the basic input data file(s). These code options specify, for example, a particular model or set of parameter values to be used. The main areas in which the user will have to select the code options are discussed below.

3.6.1. Task 6.1: Atmospheric dispersion and deposition parameters

Invariably, any consequence analysis code has extensive defaults set up in this area and the user generally has little to do apart from selecting, where necessary, the atmospheric dispersion model to use. There are, however, great uncertainties in the choice of sigma parameters, dry deposition velocities, washout coefficients and resuspension coefficients which most current consequence analysis codes use. These parameters can have a significant influence on the consequences evaluated. Hence, the user should check that any default values they use for these parameters are not inappropriate for the source term(s) and location(s) they are studying.

3.6.2. Task 6.2: Meteorological sampling scheme

The user of any consequence analysis code is required to provide a meteorological sampling scheme, and generally the users have a considerable amount of choice in tailoring the scheme to their own requirements. As noted in Section 2.4, stratified sampling is the current preferred method when hourly source meteorology is used. Such sampling schemes have been investigated extensively (e.g. Refs [14, 17]). Almost certainly, a default meteorological sampling scheme applicable to large reactor source terms will be available with the code being used. It may need, however, some minor adjustments to ensure, for example, that the various distance bands used in the meteorological selection criteria are appropriate for the population distribution around the release location. Furthermore, any such default scheme will almost certainly be applicable only to the Gaussian plume model of atmospheric dispersion. The user is unlikely to find either a default meteorological sampling scheme or even detailed guidance on how to create one for other models of atmospheric dispersion. In some cases, the choice of an appropriate sampling scheme may be influenced by the type of results to be calculated [17].

3.6.3. Task 6.3: Countermeasures options

Most current consequence analysis codes allow a wide range of emergency actions to be considered and the user has considerable flexibility in setting the criteria for these countermeasures, both in terms of the dose levels at which the actions are assumed to be undertaken and their timing. As many of the consequences evaluated are extremely sensitive to these parameters, this is one area where the parameter values must be chosen with care. It is not possible to give detailed guidance here as this tends to be code specific. Nevertheless, a general indication of the options for which the user will have to provide input data is given below. Again, this task will be considerably simplified if the Level 3 PSA specification (see Section 3.3) has clearly defined the countermeasures strategies that are to be modelled. In most codes, different countermeasures can be combined to produce a compound emergency response: for example, an evacuation zone can be defined, with sheltering first followed by evacuation and, outside of the evacuation zone, sheltering followed by relocation. Generally, the user has to specify the particular combination of countermeasures parameters needed.

Additionally, as noted above, the user has to specify the parameters which define the criteria, e.g. dose levels, used to implement these countermeasures and the times at which they are initiated. Further, some codes allow the population to be split into different groups within the area(s) to be evacuated. The people in these groups can behave differently; for example, they can shelter initially in different locations. Furthermore, the doses received by people while they are being evacuated generally allow for the time required to travel out of the affected area. In the same way, for long term countermeasures, e.g. relocation, decontamination and food bans, related parameters must be provided.

3.6.4. Task 6.4: Dose assessment parameters

As a rule, the user has little to do in this area as generally all the data required to evaluate the doses from the various exposure pathways are contained in databases which accompany the code. Sometimes, however, there is a choice of databases available where the data have been calculated with different models of the exposure pathway, so the user will have to decide which of these is the most appropriate for assessment. Generally, the recalculation of any of the dosimetric databases is a major exercise. Thus, unless the user feels strongly that the available databases are really not appropriate for the assessment, the data provided should be used. One database which may be a problem in this respect is that used to give the activity concentrations in foods for unit deposition. Some of the assumptions used in creating this database are likely to be country and even region specific and these should be carefully checked.

3.6.5. Task 6.5: Health effects parameters

Again, this is another area where the user should have little to do as all the dose risk relationships required (or activity risk relationships which at least one consequence analysis code uses) will be defined, with default data possibly contained in a database. The user, however, generally has the option of changing the default data values. If some specific critical groups (e.g. children) are considered the user should ensure that the appropriate data values are used.

3.6.6. Task 6.6: Economic consequence parameters

The collection of the economic data required to estimate the economic consequences is described in Section 3.5.8. Sometimes such data are placed directly into the basic input data file(s), although in some codes they are incorporated into a database. Either way, apart from possibly having to decide on particular analysis approaches for evaluating the economic costs where there is a choice of model, the user should have little to do except follow the instructions in the user guide.

3.6.7. Task 6.7: Result options

Current consequence analysis codes can generate a large number of consequence end points in a variety of formats (see Section 2.10). Given that the Level 3 PSA specification (see Section 3.2) has clearly defined the results required, it should be straightforward to ensure that the appropriate result options (which will be specified in the user guide of the code being used) are set to produce them.

3.7. TASK 7: RUNNING THE CODE AND CHECKING THE RESULTS

In principle, this should be the least complex part of a Level 3 PSA; all that is required is the requisite number of code runs to produce the CCDFs, sensitivity analysis, or other results required and a check of these results. In practice it is generally the most time consuming and frustrating of tasks, often requiring a number of attempts before, for example, the input data have been set up correctly for the code. For any assessment requiring more than a few runs, it is often useful to do a representative selection of runs first as a preliminary study and check before embarking on the full assessment. These different phases are discussed in turn.

3.7.1. Task 7.1: Preliminary study

A preliminary study should be performed with a representative selection of runs, and for each run both the input and the output should be fully checked. On the input side, it is necessary to verify that the correct input data for the source term, site, etc., are being used and that they have been set up correctly. Similarly, it is necessary to confirm that all the code options required have been correctly implemented. Additionally, it is necessary to check as far as possible those default data assumptions and code options that are unchanged, to ensure that they are not incompatible with any changes made by the user. This can be achieved by having some type of peer review process. On the output side, as for any other code that is run, the results should be checked as thoroughly as possible. They can be checked in a number of ways; a first rough check is to ensure that they are in line with the results to be expected for the source term being used. More thorough checking can involve comparison with the results of similar previous studies (e.g. those performed at a different site), or, if no suitable results are available, comparison with the results of similar studies in the literature. It should be borne in mind, however, that the results will probably be different from those of previous studies if, for example, there have been plant improvements. Another useful check to make is to ensure that the various results produced by the code, both in one run and between runs, are consistent with each other. An additional benefit of a preliminary study and check is that it allows possible problems to be identified at an early stage. Finally, it is often useful to discuss the results of a preliminary study with the person or organization commissioning the work.

3.7.2. Task 7.2: Full assessment

The runs carried out for the full assessment require no less checking than that done for the preliminary study. It is equally important to check the input to ensure that the correct data for the source term, site, etc., have been used and to ensure that the results are consistent with earlier results and are in line with expectations. However, the elimination of many of the more obvious errors in the preliminary study will, in practice, greatly minimize the time required to check the input and the results of the full assessment. Although it depends on the exact number of runs required and the computer system being used, it still generally takes a considerable amount of time to carry out all the runs for a full study. It should also be noted that it is common practice for consequence analysis codes to produce results for only one source term at a time. Thus, it is generally necessary to sum the frequency distributions for each of the representative source terms used, multiplied by their frequencies of occurrence (see Section 2.10). This is done either with a separate program provided or by using a standard software package. This gives the overall frequency of particular numbers of consequences, which are the usual end points of a Level 3 PSA. In some cases, a full study might include sensitivity and/or uncertainty analyses, at least for key parameters. This issue is discussed in Section 2.11.

3.8. TASK 8: WRITING THE REPORT

A suggested outline for a final report on a Level 3 PSA is given in Annex III. The main sections proposed are methodology, input data and results, and an indication is given of what each of these should contain. The first two sections can be written before all the code runs are performed; indeed, parts of them could well be taken from earlier reports. Before writing the results section it is worthwhile spending some time analysing the final results produced and deciding how best to present and explain them (and in particular what supporting results are required to do this). The actual presentation of results in a Level 3 PSA has already been described in Section 2.10 and the reader should consult that section for information on this aspect of the final report.

3.9. TASK 9: ARCHIVING OF INPUT AND OUTPUT FILES

An essential task at the end of any project, which is often overlooked, is to properly archive all the information produced. Such information includes not only the project files and the final report, but also the input and output files used and produced (on appropriate magnetic media). This information should be suitably labelled, so that it can readily be retrieved. This not only allows the information to be used in future studies, but also enables results to be rechecked and, if necessary, recalculated. This task is required as part of any good QA programme.

4. MANAGING A LEVEL 3 PSA

This section deals with the management and organization of the consequence assessment part of a PSA, i.e. those tasks discussed in this report which are additional to those performed for a Level 2 PSA. It is aimed at those who are given the responsibility of project managing the consequence assessment. A major assessment can take anywhere from 6 to 24 person-months of work and involve several members of staff. An additional 3 to 6 person-months of effort is likely to be needed by the complete beginner, who has to acquire the background and a consequence analysis code and then get the code up and running satisfactorily.

Apart from the usual day-to-day project management activities, project managers should at least aim to do the following:

(a) Prepare a project specification (Task 2);
(b) Prepare a work programme (Task 3);
(c) Ensure the selection of a suitable code (Task 4) if necessary;
(d) Ensure that all input data prepared under Task 5 are checked and approved;
(e) Ensure that the most appropriate code options are chosen, or approve those that are chosen under Task 6;
(f) Involve themselves in any preliminary study and check (Task 7.1);
(g) Ensure the checking of the results of the full study (Task 7.2) and approve them;
(h) Take the lead in analysing the results and in writing the results section of the final report, which is Task 8 (project managers of course have responsibility for the whole report);
(i) Ensure that the project is properly closed (Task 9).

Depending on the size of the consequence assessment and the number of staff involved, the project manager may also contribute significantly to tasks other than those identified above.

In general, it is not possible to accurately state the amount of effort required to perform each task in a major Level 3 PSA. Clearly, the effort is dependent upon the project specifications. As a rough guide, practice has shown that the effort is typically distributed as follows:

— Task 2.	Specification of a Level 3 PSA:	1–2%
— Task 3.	Preparation of a work programme:	2–4%
— Task 4.	Acquisition of a consequence code (if a code is not already available):	10–15%
— Task 5.	Acquisition of data:	20–40%
— Task 6.	Selection of other input parameters and code options:	4–8%
— Task 7.	Running of the code and checking the results:	40–60%
— Task 8.	Writing the report:	10–15%
— Task 9.	Archiving the input/output files:	1%.

Although the organization of the consequence assessment part of a Level 3 PSA has already been considered in Section 3.3, there are two more general points which should be made here. Firstly, the Level 3 assessment can and should be started early in the whole PSA; there is no need to wait until the Level 2 PSA is completed before commencing work. In particular, this maximizes the amount of time available for the collection of input data, Task 5, which should be commenced as soon as possible (this of course requires Tasks 2–4 to be completed first). Indeed, even the preliminary study and check, Task 7.1, can be completed with 'provisional' source terms before the final source terms of the Level 2 PSA become available. If this approach is adopted, however, it does entail some additional runs of the consequence analysis code. Nevertheless, in a well organized PSA it is possible to begin with Task 7.2 once the final results of the Level 2 PSA are available.

The second point concerns the personnel involved in the project. Ideally, some if not all of them should have some experience in consequence assessments and in running the particular code being used. For organizations embarking on a Level 3 PSA for the first time, or even those using a new consequence analysis code, there may be few if any personnel with the necessary experience. In such cases, having a knowledgeable person attached from another organization may be beneficial. Alternatively, the assignment of staff to other organizations to gain experience prior to commencing the Level 3 PSA could be considered. Further advice on the management and organization of a Level 3 PSA is given in Ref. [53].

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Annex I

CURRENT DEVELOPMENTS IN PROBABILISTIC CONSEQUENCE ANALYSIS

Two major international activities in this area are worthy of note. Firstly, the Nuclear Energy Agency of the OECD and the European Commission recently co-sponsored an intercomparison exercise on probabilistic accident consequence analysis codes. Secondly, the European Commission and the United States Nuclear Regulatory Commission (NRC) are currently co-sponsoring a joint project to first develop a state of the art methodology for uncertainty estimation and then to apply it to estimate the uncertainties associated with the predictions of current probabilistic accident consequence assessment codes.

The intercomparison exercise on probabilistic consequence analysis (PCA) codes took place during the period 1991–1993. Seven codes from various countries were evaluated in the exercise: ARANO (Finland), CONDOR (United Kingdom), COSYMA (European Commission), LENA (Sweden), MACCS (USA), MECA2 (Spain) and OSCAAR (Japan); the main features of these codes are summarized in Annex II. A wide range of consequences were calculated in the exercise, for example, collective doses, early and late health effects, economic costs and the effects of countermeasures on people and agriculture. In each case, the probability distributions predicted by the codes were compared, with the main focus on the mean and 99th percentile values of these distributions. As expected, in view of known modelling and other differences between these codes, there were differences between the predicted consequences. The magnitude of the spread depended on the particular consequence end point being considered. However, with few exceptions the spreads were within a narrow range. This spread of variation between code predictions is small in comparison with the overall uncertainty associated with the estimation of risk from postulated accidents at nuclear installations (i.e. including the estimation of the probability of a release, the characteristics of the released material and the resulting consequences); the results of the comparison were therefore considered to show acceptable agreement. The overview and technical reports on this exercise [I-1, I-2] should be consulted for further information, since they provide a key reference point for future activities in this field.

Two of the codes in the intercomparison exercise, COSYMA and MACCS, are used by several institutes and, in parallel exercises, comparisons were also made between the predictions of users of the same code [I-3, I-4]. Differences in the predictions were also observed in these parallel exercises. The sources of these differences were studied in more detail and explanations were found. The results of the users' intercomparison gave valuable extra information and supported the conclusions of the main code intercomparison exercise.

Another important area of recent activity concerns incorporation into current PCA codes of the considerable body of information gathered on the environmental behaviour of radionuclides (particularly caesium) following the Chernobyl accident. Much is still left to be done in this area.

The current trend seems to be to:

(a) Develop more user friendly PCA codes,
(b) Implement PCA codes on personal computers,
(c) Incorporate more sophisticated models (particularly for atmospheric dispersion) as faster computers become available.

Finally, the importance of having available a whole range of computer programs of varying complexity for different types of applications is also becoming widely recognized.

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Annex II

SELECTION OF A CONSEQUENCE ANALYSIS CODE

The material in this annex is intended to give potential users some general guidance in the selection of an appropriate computer code for a Level 3 PSA. The selection depends very much on the requirements of the user. The following is a list of points which a potential user should consider:

- **Computer compatibility.** Users should check that the machine on which they intend to run the code has the required capability.
- **Ease of use.** Most recently developed codes have a modular basis and are said to be user friendly. It would be worthwhile, however, to look at demonstrations of the code to see if there will be any problems.
- **Availability and support.** Many codes which were widely used in the past have now been superseded and are no longer supported by their developers. Ideally, up to date codes should be acquired, together with a commitment for continued support in terms of future revisions and notification of errors.
- **Transfer of data from Level 2.** The chances for errors will be reduced if the form of input for the Level 3 code matches the output from the Level 2 assessments being used. For example, a Level 2 assessment might give output in terms of becquerels of various isotopes, whereas the Level 3 code requires input in terms of the fraction of core inventory.
- **Atmospheric dispersion model.** If the site to be assessed includes complicated terrain (i.e. not gently rolling countryside), then a simple Gaussian dispersion model may not be sufficient. Conversely, complex dispersion models generally require extensive meteorological data, and if these are not available such models may not be suitable.
- **Methodology.** The user should check the methodology used in the codes to verify that it fits the particular situation. While most of the analysis is based on physical models which are valid worldwide, there are aspects which are peculiar to local environments. Examples may be the criteria on which countermeasures decisions are based, or local food intake patterns which may not be taken into account in a particular code.

— **Quality assurance.** The user should check that the code has been developed using formal procedures for QA. This may be particularly important if the results are to be used either in the public arena or in a regulatory or licensing process.

— **Code verification.** True verification in terms of a comparison of predictions against measurements is not practicable for PCA codes. However, a degree of confidence in the results can be obtained if a code has been part of a code comparison exercise.

As mentioned in Annex I, the most recent code comparison exercise has been organized by the Nuclear Energy Agency of the OECD (OECD/NEA) and the European Commission. The following PCA codes were part of the code intercomparison: ARANO [II-1], CONDOR [II-2], COSYMA [II-3], LENA [II-4], MACCS[1] [II-5] and OSCAAR [II-6]. These codes can be regarded as examples of the current generation of PCA tools. In Table II-1, the major features of these codes are listed. More detailed information on the models used in these codes, and the differences between them, can be found in Ref. [II-7].

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[1] Additionally, MECA2 [II-8], a Spanish code coupled to MACCS and containing an alternative model for assessing off-site economic risks, was part of the comparison of economic consequences.

REFERENCES TO ANNEX II

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TABLE II-1. MAJOR FEATURES OF THE PCA CODES INVOLVED IN THE OECD/NEA–EUROPEAN COMMISSION CODE COMPARISON EXERCISE

Country	PCA code	Atmospheric dispersion			Deposition		Meteorological sampling		Exposure pathways					
		Gaussian plume	Trajectory	Time variant	Dry	Wet	Stratified	Other	Cloud shine	Ground shine	Skin	Inhalation	Resuspension	Ingestion
Finland	ARANO	X	—	—	X	X	—	X	X	X	—	X	—	X
United Kingdom	CONDOR	X	—	X	X	X	X	X	X	X	X	X	X	X
Germany	COSYMA	X	X	X	X	X	X	X	X	X	X	X	X	X
Sweden	LENA	X	—	X	X	X	X	—	X	X	—	X	—	X
USA	MACCS	X	—	X	X	X	X	X	X	X	X	X	X	X
Japan	OSCAAR	—	X	X	X	X	X	X	X	X	—	X	X	X

TABLE II-1. (cont.)

Country	PCA code	Countermeasures					Health effects		Economic consequences
		Sheltering	Thyroid blocking	Evacuation	Relocation	Food bans	Early	Late	
Finland	ARANO	X	X	X	X	X	X	X	X
United Kingdom	CONDOR	X	X	X	X	X	X	X	X
Germany	COSYMA	X	X	X	X	X	X	X	X
Sweden	LENA	X	—	X	X	X	—	X	—
USA	MACCS	X	—	X	X	X	X	X	X
Japan	OSCAAR	X	—	X	X	X	X	X	—

Annex III

SAMPLE STRUCTURE FOR A LEVEL 3 PSA REPORT

This annex presents a suggested outline for a final report on a Level 3 PSA or a chapter in a report summarizing a complete PSA. It is important to ensure that the text is compatible with other reports or chapters describing the complete PSA.

III-1. EXECUTIVE SUMMARY

The executive summary should be two or three pages; it is particularly important for major Level 3 PSAs which may have wide circulation.

III-2. INTRODUCTION

The introduction should clearly state the objectives set for the Level 3 PSA; it should also highlight any limitations or constraints applicable to the study.

III-3. METHODOLOGY

The description of the methodology can be split into two parts. The first part should describe the consequence analysis code that was chosen. A brief description with appropriate references is all that is required. The version number of the code should also be given. The second part should summarize the models and parameter values adopted for this particular study. Frequently, it is convenient to summarize the models and default values of the major parameters used in the consequence analysis code and its databases in a table or in an appendix. Any changes made to the usual default values should be highlighted in this section and the reasons for adopting the new values should be given. Similarly, the major code options used should be identified and discussed.

III-4. INPUT DATA

This section describes the input data used (see Section 3.5 of the main text). Generally, as a minimum it should consider the source term, meteorological and site data in separate subsections. With the exception of the source term, these data are invariably extensive and no attempt should be made to tabulate them in the report or chapter. What is required is a clear statement of the source of the data, properly referenced (e.g. the national census from which the population data were derived), together with information on how the data were processed and, if relevant, a note on what was done to overcome any problems associated with data of poor quality.

III-5. RESULTS

This section will vary considerably from study to study, so only a few general guidelines can be given here. The key requirement is to lay out and explain the final results in some logical order. Some analysis of the results should be presented; generally, it is not sufficient just to present the results. Given the vast quantity of results that can be produced, it is also essential to be selective. Only those final results required and those that are really necessary to make the points in the explanation of the final results should be included.

III-6. SUMMARY AND CONCLUSIONS

This section should briefly summarize the assessment performed and clearly state the conclusion(s) of the study. It should be followed by the usual acknowledgement and reference sections, the tables and figures, and finally any appendices.

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Consultants Meetings

Vienna, Austria: 25–29 November 1991;
9–13 November 1992;
18–22 October 1993

Technical Committee Meeting

Vienna, Austria: 9–13 November 1992

LIST OF NUSS PROGRAMME TITLES

It should be noted that some books in the
series may be revised in the near future.
Those that have already been revised are indicated by the
addition of '(Rev. 1)' to the number.

1. GOVERNMENTAL ORGANIZATION

50-C-G (Rev. 1)	Code on the safety of nuclear power plants: Governmental organization	1988
	Safety Guides	
50-SG-G1	Qualifications and training of staff of the regulatory body for nuclear power plants	1979
50-SG-G2	Information to be submitted in support of licensing applications for nuclear power plants	1979
50-SG-G3	Conduct of regulatory review and assessment during the licensing process for nuclear power plants	1980
50-SG-G4 (Rev. 1)	Inspection and enforcement by the regulatory body for nuclear power plants	1996
50-SG-G6	Preparedness of public authorities for emergencies at nuclear power plants	1982
50-SG-G8	Licences for nuclear power plants: Content, format and legal considerations	1982
50-SG-G9	Regulations and guides for nuclear power plants	1984

2. SITING

50-C-S (Rev. 1)	Code on the safety of nuclear power plants: Siting	1988
	Safety Guides	
50-SG-S1 (Rev. 1)	Earthquakes and associated topics in relation to nuclear power plant siting	1991
50-SG-S3	Atmospheric dispersion in nuclear power plant siting	1980
50-SG-S4	Site selection and evaluation for nuclear power plants with respect to population distribution	1980
50-SG-S5	External man-induced events in relation to nuclear power plant siting	1981

50-SG-S6	Hydrological dispersion of radioactive material in relation to nuclear power plant siting	1985
50-SG-S7	Nuclear power plant siting: Hydrogeological aspects	1984
50-SG-S8	Safety aspects of the foundations of nuclear power plants	1986
50-SG-S9	Site survey for nuclear power plants	1984
50-SG-S10A	Design basis flood for nuclear power plants on river sites	1983
50-SG-S10B	Design basis flood for nuclear power plants on coastal sites	1983
50-SG-S11A	Extreme meteorological events in nuclear power plant siting, excluding tropical cyclones	1981
50-SG-S11B	Design basis tropical cyclone for nuclear power plants	1984

3. DESIGN

50-C-D (Rev. 1)	Code on the safety of nuclear power plants: Design	1988
	Safety Guides	
50-SG-D1	Safety functions and component classification for BWR, PWR and PTR	1979
50-SG-D2 (Rev. 1)	Fire protection in nuclear power plants	1992
50-SG-D3	Protection system and related features in nuclear power plants	1980
50-SG-D4	Protection against internally generated missiles and their secondary effects in nuclear power plants	1980
50-SG-D5 (Rev. 1)	External man-induced events in relation to nuclear power plant design	1996
50-SG-D6	Ultimate heat sink and directly associated heat transport systems for nuclear power plants	1981
50-SG-D7 (Rev. 1)	Emergency power systems at nuclear power plants	1991
50-SG-D8	Safety-related instrumentation and control systems for nuclear power plants	1984
50-SG-D9	Design aspects of radiation protection for nuclear power plants	1985
50-SG-D10	Fuel handling and storage systems in nuclear power plants	1984
50-SG-D11	General design safety principles for nuclear power plants	1986
50-SG-D12	Design of the reactor containment systems in nuclear power plants	1985

50-SG-D13	Reactor coolant and associated systems in nuclear power plants	1986
50-SG-D14	Design for reactor core safety in nuclear power plants	1986
50-SG-D15	Seismic design and qualification for nuclear power plants	1992

4. OPERATION

50-C-O (Rev. 1)	Code on the safety of nuclear power plants: Operation	1988
	Safety Guides	
50-SG-O1 (Rev. 1)	Staffing of nuclear power plants and the recruitment, training and authorization of operating personnel	1991
50-SG-O2	In-service inspection for nuclear power plants	1980
50-SG-O3	Operational limits and conditions for nuclear power plants	1979
50-SG-O4	Commissioning procedures for nuclear power plants	1980
50-SG-O5	Radiation protection during operation of nuclear power plants	1983
50-SG-O6	Preparedness of the operating organization (licensee) for emergencies at nuclear power plants	1982
50-SG-O7 (Rev. 1)	Maintenance of nuclear power plants	1990
50-SG-O8 (Rev. 1)	Surveillance of items important to safety in nuclear power plants	1990
50-SG-O9	Management of nuclear power plants for safe operation	1984
50-SG-O10	Core management and fuel handling for nuclear power plants	1985
50-SG-O11	Operational management of radioactive effluents and wastes arising in nuclear power plants	1986
50-SG-O12	Periodic safety review of operational nuclear power plants	1994

5. QUALITY ASSURANCE

	Code	
50-C/SG-Q	Quality assurance for safety in nuclear power plants and other nuclear installations	1996

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