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Case Study on Assessment of Radiological Environmental Impact from Potential Exposure

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CASE STUDY ON ASSESSMENT OF RADIOLOGICAL ENVIRONMENTAL IMPACT FROM POTENTIAL EXPOSURE

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IAEA-TECDOC-1914

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FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) started in 2001, on the basis of a resolution of the IAEA General Conference in 2000 (GC(44)/RES/21). INPRO activities have since been continuously endorsed by resolutions of IAEA General Conferences and by the General Assembly of the United Nations.

The objectives of INPRO are to help ensure that nuclear energy is available to contribute, in a sustainable manner, to the goal of meeting the energy needs of the 21st century, and to bring together technology holders and users so that they can consider jointly the international and national actions required for ensuring sustainability of nuclear energy through innovations in technology and/or institutional arrangements.

To fulfil these objectives, INPRO developed a set of basic principles, user requirements and criteria, as well as an assessment method which, taken together, compose the INPRO methodology for the evaluation of the long term sustainability of nuclear energy systems. The most recent full version of the INPRO methodology is documented in IAEA-TECDOC-1575/Rev.1, published in 2008, which consists of an overview volume and eight additional volumes covering economics, infrastructure, waste management, proliferation resistance, physical protection, environment, safety of reactors and safety of nuclear fuel cycle facilities.

The INPRO methodology area of environment provides guidance on the sustainability assessment of criteria relating to the environmental impact of radiological stressors from a nuclear energy system in normal operation and during anticipated operational occurrences. The INPRO methodology areas of safety of reactors and safety of fuel cycle facilities cover sustainability related issues concerning potential exposure in the case of accidents with external release of radiation.

This publication focuses on the INPRO collaborative project on the Environmental Impact of Potential Accidental Releases from Nuclear Energy Systems (ENV-PE), a follow-up to the INPRO collaborative project on Environmental Impact Benchmarking Applicable for Nuclear Energy Systems under Normal Operation. This follow-up project was aimed at providing a set of examples for common understanding in assessing the population health risks from a potential accident scenario in a nuclear power plant. A potential accident scenario was defined as a source term including the associated probability and representative environmental data. Radiation doses and effects were determined by applying environmental dispersion models dedicated to accidental releases and dose–effect functions.

The IAEA officers responsible for this publication were A. Korinny and J. Phillips of the Division of Nuclear Power, and D. Telleria of the Division of Radiation, Transport and Waste Safety.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

The concept of sustainable development was originally introduced in the 1980s. It defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This concept embraces all environmentally sensitive areas of human activities including different types of energy production. In the area of nuclear energy, the focus of sustainable development is on solving key institutional and technological issues including nuclear accident risks, health and environment risks, proliferation risks, economic competitiveness, radioactive waste disposal, sufficiency of institutions and public acceptability. Sustainable development implies demonstration of progress on the key institutional and technological issues. The INPRO methodology is the tool for assessing the sustainability and sustainable development of a nuclear energy system (NES), that was originally created in 2003 under the aegis of the IAEA using broad philosophical outlines of the concept of sustainable development. The latest full version of the INPRO methodology was published in 2008 [1]. The INPRO methodology update project was commenced in 2012 and four updated manuals [2–5] have been published in 2014-2016.

Sustainability issues related to potential exposure in the case of accidents with external release of radiation are discussed in the INPRO methodology area of reactor safety. The INPRO area of reactor safety evaluates enhancements in safety of new nuclear power plant (NPP) designs for the purpose of sustainability assessment but does not evaluate compliance with national or international safety standards. INPRO criteria related to the potential severe accidents, imply reduced frequency of accidents with a major release of radioactivity into the containment due to severe core damage, sufficient natural and engineered processes to control the system, and adequate on-site accident management measures to prevent major radioactive releases into the environment. It is also assumed that in new NPPs the calculated frequency of accidental release of radioactivity into the environment is reduced and the source term of accidental release is so low that calculated consequences would not require public evacuation.

In 2012 the IAEA conceived the project on Environmental Impact of Potential Accidental Releases from Nuclear Energy Systems (ENV-PE) to study different approaches used in the Member States for evaluation of potential accidental releases from nuclear reactors. Eleven institutions from the IAEA Member States took part in the project: the National Atomic Energy Commission, CNEA (Argentina), Republican Scientific-Practical Centre of Hygiene (Belarus), the French Alternative Energies and Atomic Energy Commission, CEA (France), the Karlsruhe Institute of Technology, KIT (Germany), the Indira Gandhi Centre for Atomic Research, IGCAR (India), the National Nuclear Energy Agency, BATAN (Indonesia), the Israel Atomic Energy Commission (Israel), the Russian Institute of Agricultural Radiology and AgroEcology, RIARAE (the Russian Federation), the Centre for Energy, Environment and Technology, CIEMAT (Spain), the Radiation Protection Institute (Ukraine) and Amec Foster Wheeler (the United Kingdom).

This publication is the final report of the ENV-PE summarising results developed under this project by the groups of national experts.

1.2 OBJECTIVE

This publication presents a set of examples of different approaches for estimating potential exposures in different countries based on participants' experience and considering the IAEA Safety Standard [6] on a generic framework for consideration of radiological environmental impact, including potential exposures. It is further intended to provide necessary input for the development of common understanding in assessing the population health risks from potential accident scenarios in a nuclear power plant.

This publication will contribute to further improvement and update of the INPRO methodology for sustainability assessment of nuclear energy systems and can help Member States applying the INPRO methodology to perform a nuclear energy system assessment in the areas of safety and environment.

This publication is intended for use by organizations involved in development and deployment of NESs including planning, design, modification, technical support and operation for nuclear power plants.

1.3 SCOPE

This publication is focused on the estimation of off-site consequences of a severe accident in an NPP resulting in major release of radioactivity to the environment. Assessment of potential exposures was performed by national experts based on their experience, and considering the general framework published in the IAEA Safety Standards [6]. The outcome of independent dose and risk assessments from potential radioactive release to the environment is presented here along with the summary of discussion on the following topics:

- Accident source term definition;
- Exposure scenarios and environmental dispersion models (atmospheric) applicable to accidental releases;
- Representative persons for assessing doses (location, characteristic, habits, age groups);
- Dose assessment (pathways, radionuclides, short term and long-term doses);
- Consideration of levels adopted for protective measures.

A single scenario of release from the postulated accident was evaluated by the participants: release into the atmosphere from a severe accident in an NPP. Potential liquid releases into the sea or rivers are not considered. A potential accident scenario was defined as a postulated source term, the associated probability and representative environmental data. Potential exposures are considered through the estimation of radiation doses and in some cases through the associated risk to human health caused by the radioactive release. In a few cases there were existing national regulations which defined or provided elements for the consideration of potential exposures. Calculation of the need for and effect of response actions as part of emergency preparedness as well as evaluation of economic losses have not been considered in this project.

Protection of the environment includes the protection of living organisms other than humans and also the protection of natural resources, including land, forests, water and raw materials, together with a consideration of non-radiological environmental impacts from the NPP. However, this study is mostly concerned only with the radiological impact on humans as the target group. An example of radiological impact on non-human biota was considered in one national study for completeness. The explicit consideration of effects to non-human biota (currently from normal operation only) is a recent development in the field of radiation protection [7-9] and is being considered and incorporated in the IAEA Safety Standards [6, 10-12] and in some national regulations.

The methods and criteria presented in this report do not represent the national practices required in the regulations and should be considered as a proposal by the experts for possible approaches to estimate potential exposures.

1.4 STRUCTURE

Following this introduction, Section 2 describes general considerations of assessing potential public exposure in nuclear accidents. Information on the input data used, together with the influencing parameters and how they were applied, is given in Section 3. In Section 4, a comparison of models and approaches used in national case studies is provided. Section 5 presents a summary of the results obtained by the national experts. Annexes I to X comprise national studies including:

- Elements for consideration of potential exposures applied in different countries, including dose/risk and protective actions criteria,
- Description of methodologies used by national experts,
- Results of calculations.

2 GENERAL CONSIDERATIONS OF ASSESSING POTENTIAL PUBLIC EXPOSURE IN NUCLEAR ACCIDENTS

2.1 BASIS FOR CONSIDERATION OF POTENTIAL EXPOSURES

Fundamental safety principle 6 of IAEA's Fundamental Safety Principles [10] requires that both the doses and the radiation risks be controlled within specified limits for ensuring the protection of the public and the environment from harmful effects of ionizing radiation. Operation of a radiation source, including operation of an NPP, may create two potential types of radiation exposure to the public. Limited exposures at some level may be expected to occur in normal operation conditions. These exposures are normally characterized as 'expected' and they are not considered further in this report. Unlike 'expected exposure' the 'potential exposure' is not expected to occur with certainty, but could result with certain probability, e.g. from an accident or anticipated operational occurrences (AOOs) [11].

A potential exposure can arise as a consequence of several events other than release of radioactivity to the environment due to a severe accident in a nuclear facility. Examples of the events causing exposure which are not expected at normal operation conditions can be summarized [7, 11] into three groups:

- Events affecting a relatively small number of individuals who are also subject to planned exposures. These exposure situations are relatively simple, e.g. the potential unsafe entry into an irradiation room.
- Events affecting a larger number of people and not only involving health risks but also other detriments, such as contaminated land and the need to control food consumption. Examples are the potential for a major accident in an NPP or the malicious use of radioactive material.
- Events for which the doses can be delivered over long time periods, e.g. accidents in closed waste disposal repositories (after removal of institutional control).

This report is focused only on the estimation of consequences of a severe accident[1] in an NPP resulting in major release of radioactivity to the environment. A severe accident is defined in the IAEA Safety Glossary as an "accident more severe than a design basis accident and involving significant core degradation" [13].

Licensing of a facility or an activity, including licensing of an NPP, is assumed to involve an appropriate prospective assessment made for radiological environmental impacts, commensurate with the radiation risks [6, 11]. This assessment to the extent reasonable and practicable should cover an estimation of the likelihood and magnitude of potential exposures, their likely consequences and the number of persons who may be affected by them. The likelihood and magnitudes of exposures can be restricted by means of measures for preventing accidents and for mitigating the consequences respectively and the corresponding criteria against which the consequences and/or frequencies are assessed should be established based on the results of optimisation[2].

Ref [14] requires that "the possible radiation risks associated with the facility or activity shall be identified and assessed". It explains that "the term 'possible radiation risks' relates to the

[1] A severe accident is a very low probability event.

[2] GSR Part 3 defines the optimisation of protection and safety as the process of determining what level of protection and safety would result in the magnitude of individual doses, the number of individuals (workers and members of the public) subject to exposure and the likelihood of exposure being "as low as reasonably achievable, economic and social factors being taken into account" (ALARA).

maximum possible radiological consequences that could occur when radioactive material is released from the facility or in the activity, with no credit being taken for the safety systems or protective measures in place to prevent this" [14]. It further explains that risks include the level and likelihood of radiation exposure and of the possible release of radioactive material that are associated with AOOs or with accidents.

The structure of evaluation of potential exposures, for the purpose of planning or judging protection measures, may involve the following steps [6, 7, 15-17]:

- construction of scenarios which are intended typically to represent the sequences of events leading to the exposures;
- assessment of probabilities of each of these sequences;
- assessment of the resulting dose;
- evaluation of detriment associated with that dose;
- comparison of the results with some criterion of acceptability;
- optimization of protection which may require several iterations of the previous steps.

Ref [7] further explains:

> "Decisions on the acceptability of potential exposures should take account of both the probability of occurrence of the exposure and its magnitude. In some circumstances, decisions can be made by separate consideration of these two factors. In other circumstances, it is useful to consider the individual probability of radiation-related death, rather than the effective dose".

2.2 BASIC STRUCTURE OF POTENTIAL EXPOSURE ASSESSMENT

2.2.1. General approach

There are a few approaches for the consideration of potential exposure scenarios depending on the type of facility to be assessed, calculation tools to be used and regulatory requirements to be satisfied [6]. The simplest approach is based on selection of a single conservative exposure scenario which is assumed to be a bounding set of characteristics that may be recognized as representative of a worst-case accident scenario. Such an approach is generally applied to simple installations with low inventories of radioactive materials.

A less conservative and more realistic approach involves the identification of a set of characteristic scenarios which can be considered to be a comprehensive representation of the characteristics of a given installation and can be divided into different categories in accordance with their likelihood of occurrence and consequences. Characteristic scenarios do not necessarily include the worst-case scenario which tends to be an over-conservative assumption leading to estimations of unrealistic potential consequences.

More sophisticated and more realistic analysis is usually applied to NPPs and some other complex facilities. It is based on techniques known as probabilistic safety assessment (PSA) which assumes the development of scenarios from a broad range of the initiating events of accidents and environmental conditions, including, among others, the calculation of accident frequencies, source terms, selection of representative environmental characteristics, and estimation of risk characteristics.

For the purpose of the model calculations performed in this project the assessment of potential exposures using estimations of doses to members of the public or a measure of risk has been agreed to be structured, when possible, as presented on Figure 1.

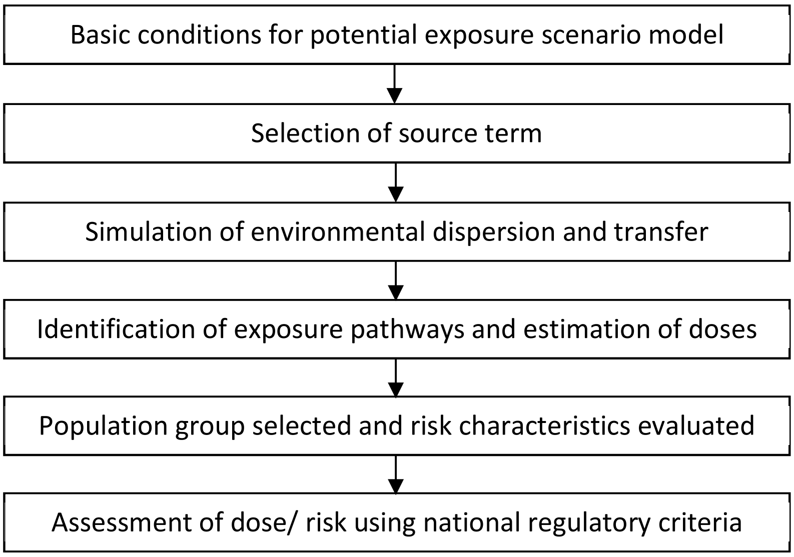

FIG.1. Structure of the assessment of potential exposure (modified from [6])

Definition of the potential exposure scenario model is a universal part provided for this case study, used without modifications in every national assessment within this study and it splits into two steps. To start with, the basic conditions for the potential exposure scenario model have been set up including geographic distribution of population, environmental dispersion scenario assumptions, etc. In the second step the related source term, including quantities of the releases and their physical and chemical characteristics determining behaviour in the environment, are selected to be used as an input to the simulation of environmental dispersion and transport.

To further analyse the sequences of events leading to the exposures, the environmental dispersion and transfer are simulated with the models and tools normally used by the national experts in each country participating in this project. In the next stage the relevant exposure pathways are identified and the doses to the different groups of population are estimated. The most exposed population group is selected, and when possible a measure of the probability or the characteristics of risk of health effects is evaluated. Finally, dose and risk characteristics are compared against criteria used in national regulations.

2.2.2. Source term

A set of parameters characterizing the form, content and the location of the potential release of radioactive material from a given facility is usually called a source term. Isotopic composition, chemical form, temperature, pressure, concentrations and other characteristics of radioactive releases may differ essentially from characteristics of releases emitted during normal operation. In a simplified assessment of a small nuclear installation, the assessor may use conservative assumptions to make the definition of the source term easier, e.g. that the entire inventory of radioactive material is released. This conservative assumption can be acceptable when it allows satisfying the dose and risk criteria used in a given country.

In the case of large nuclear installations, e.g. an NPP, the level of uncertainty introduced by large conservatisms in the definition of the source term needs to be reduced. Definition of the source term for the radioactive release from an NPP normally involves sophisticated methods of safety analysis including simulation of accident processes in the reactor and containment. Carefully determined source terms in this case may include information on the time profile of release [6], having in mind that noble gas radionuclides, volatile radioactive material and aerosol or particulate forms may not be released simultaneously (i.e. have different release profiles).

Calculation of the source term is outside the scope of this report. The source term used within this case study had been defined based on the data publicly available from Ref [18].

2.2.3. Dispersion and transfer in the environment

To calculate dispersion and transfer of radioactive isotopes in the environment the meteorological conditions and hydrological data have to be defined. In the ideal situation the calculation of transport of radioactive material in the environment should be performed for all combinations of meteorological parameters which can occur in the site area. Seasonal and daily variations of meteorological conditions may essentially influence the distribution of the released radioactivity in the environment and concentration of radioisotopes in food. Usually the analysis of transport of radioisotopes involves several different pathways which can make the definition of reasonably conservative meteorological conditions a non-trivial exercise. It is normally expected for an NPP that meteorological and hydrological site-specific data will be used to define the characteristic dispersion conditions for radioactive release [19]. These data are to be collected every hour over a period of one year or longer and used in calculations either directly or with some preliminary statistical processing.

In this project a single set of meteorological data was provided to all participants. The data set includes 8760 records (1 record per hour) for each of 22 meteorological parameters. When needed a preliminary statistical processing of this meteorological array was performed independently based on the national approach.

The dispersion of the released material in the atmosphere, and its consecutive deposition into the soil is the first process to be considered in an accident consequence assessment (ACA). An ACA normally involves a series of calculations to estimate doses to population, to define possible associated mitigation actions and the resulting health effects and economic costs. Calculation of the need for and effect of the emergency preparedness and response actions as well as evaluation of economic losses are outside the scope of this project.

Computer tools and models which are developed to analyse the dispersion and distribution of the radionuclides released from an NPP in an emergency model a major release of radioactivity transported over a very long distance, with variations in meteorological conditions and the time-profile defined for the source term.

For simulation of dispersion and deposition of released materials several models varying in the areas of application and having different advantages and drawbacks can be used. Early ACA tools have been based on the straight-line Gaussian plume dispersion model. More recent ACA programs have used the Gaussian puff model or trajectory models. Models using linear trajectories are applicable for travel distances up to a few tens of kilometres, and they become increasingly inaccurate or unreliable at longer distances. Models which are appropriate for use at longer distances may not be appropriate for use at short distances either because of assumptions they contain or because of their limited spatial resolution [20].

Different models or considerations may apply at different distances from the source of radioactive release. The early effects of radiation are assumed to be deterministic and may only occur when the dose received over a relatively short time period exceeds a certain threshold. Such effects are mostly expected in the areas relatively close to the NPP assuming accidental releases of a significant amount of radioactive material. The late effects (i.e. stochastic effects) of radiation are assumed to appear at any dose and these can occur at any distance. The calculation of late health effects from exposure over extended periods of time is a complex problem involving the time variation of dose (including the time variation of intake and of the concentration in food after deposit for ingestion doses), the variation of risk with the age and life-expectancy of the exposed individuals and the age distribution of the exposed population [20].

Transport and dispersion of substances in the atmosphere are mainly influenced by advection (wind) and processes such as turbulent diffusion. Depletion processes under wet and dry conditions, together with radioactive decay, also alter the content in the plume. The first approaches to solve this problem resulted in analytical solutions of the advection-dispersion process and are known as Gaussian type models.

Gaussian models can be applied in plain terrain and under steady state conditions, i.e. a uniform release with a constant rate, geometry, and altitude, and constant atmospheric conditions. A typical picture of a representation of the plume is shown in Figure 2. The geometry and thus the concentration pattern of the plume is described by Gaussian distributions. These parameters typically are the result of dispersion experiments and are site dependent.

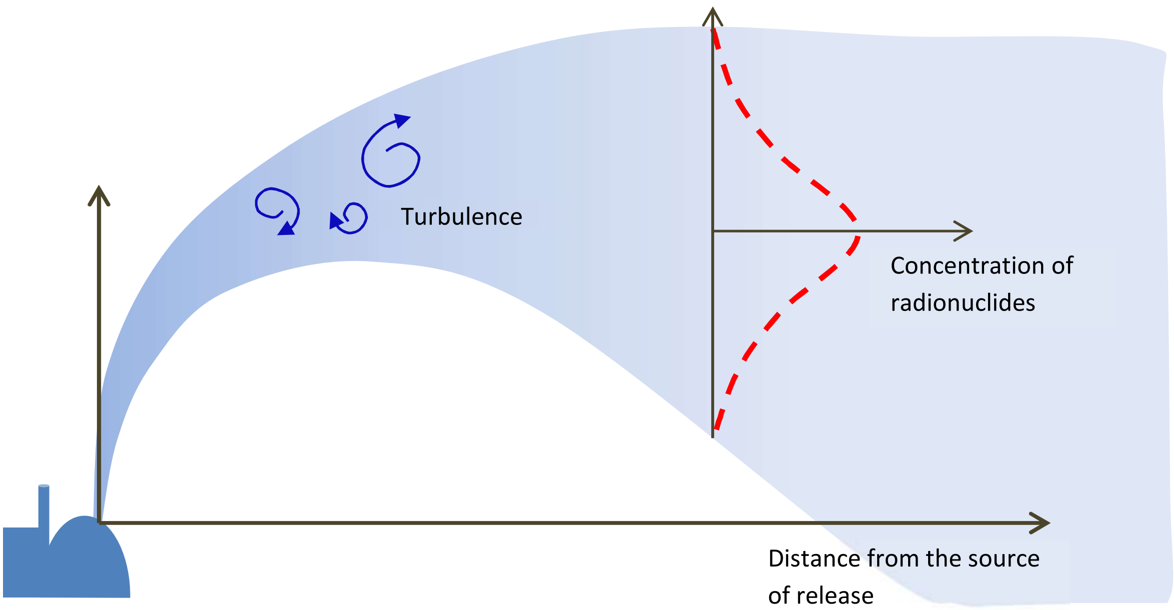

FIG.2. Scheme of a Gaussian plume model

The basic Gaussian plume dispersion model (GPM) equation describes the downwind time integrated concentration χ (x, y, z) in air resulting from a release of material from a point source located at (x=0, y=0, z=H): ·

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \cdot exp\left(-\frac{y^2}{2\sigma_y^2}\right) \cdot \left(exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right) \tag{1}$$

Where Q is the quantity of material released (Bq), u is the mean wind speed (transport speed) in the downwind x direction (m/s) and H is the height of the plume centerline (m). σ_y and σ_z (m) are the diffusion coefficients describing the plume spread in the horizontal and vertical crosswind directions y and z. Generally, the values of σ_y and σ_z depend on the travel time, on the atmospheric stability class[3] [21], on the surface roughness, and on the release height [20]. Pasquill-Gifford atmospheric stability classes depend on the weather characteristics such as

[3]In the new generation Gaussian plume air dispersion model ADMS 5 the atmospheric boundary layer properties are characterised by the boundary layer depth, and the Monin-Obukhov length rather than in terms of the single parameter Pasquill-Gifford class. ADMS is an advanced code combining advantages of Gaussian and Lagrangian models and taking account of topography, buildings etc.

wind speed, day solar insolation and night cloudiness and vary from very unstable (A class) to stable (F class).

The next step to improve the Gaussian type of model to account for the changing atmospheric conditions, was the introduction of the so called "Gaussian puff" model. Here the plume is represented by puffs which can vary depending on the turbulence conditions of the atmosphere and the wind direction. The continuous release is replaced by a consecutive release of many puffs; however, the geometry of the puff is still described by Gaussian functions (see Figure 3). Nevertheless, the puffs can follow trajectories of a 3-D wind field which can be time dependent.

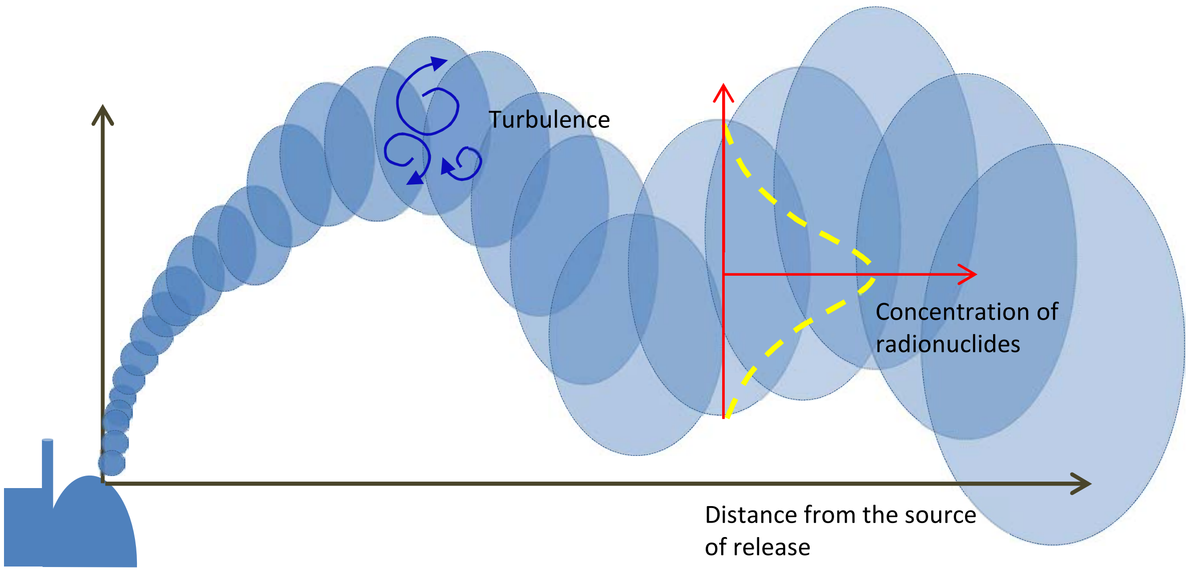

FIG.3. Scheme of a Gaussian puff model

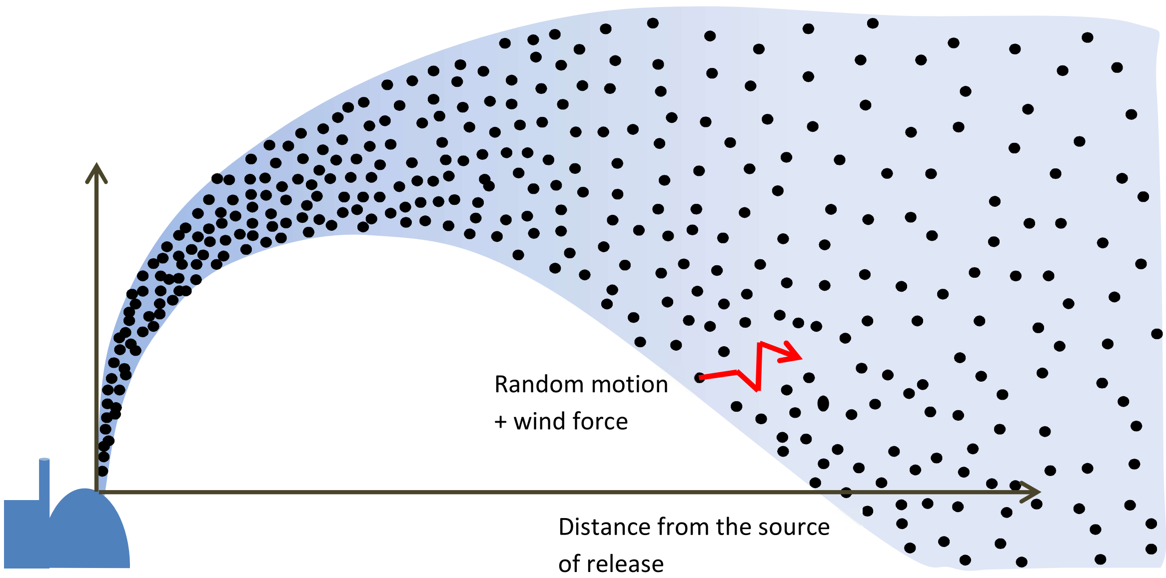

FIG.4. Scheme of a particle model

The next step in advanced dispersion modelling is the so called "Lagrangian" particle models, which represent the plume via a large number of independent particles which move along individual trajectories determined by the wind field and the turbulence of the atmosphere (see

Figure 4). The distribution of the particles in a grid cell gives a stochastic representation of the concentration. The turbulent diffusion is described as an uncorrelated random walk process assuming a mean state and superimposed fluctuations. Velocity fluctuations are computed from eddy diffusivities or defined through parameterizations using the Monin-Obukhov-theory. This independence of individual particles also allows complex meteorological situations to be represented; for example, changes of the wind direction with height resulting in opposite wind directions at ground level and close to the top of the boundary layer.

Besides the above-mentioned types, another gridded model type is used. The so called "Eulerian" models also solve the general equation for the transport of matter in turbulent fluids, the advection – diffusion differential equation. However, the solution is based on a particular grid. The input is the output of a numerical weather prediction system; thus, Eulerian codes are preferably used for long range dispersion calculations corresponding to the resolution of the numerical weather data.

Reviews of existing transport and dispersion models can be found in Refs [22, 23]. In terms of operability, probabilistic assessment codes so far use Gaussian type of models (e.g. COSYMA and MACCS), however, COSYMA has been further developed by Public Health England (PHE) to integrate the NAME [24] Lagrangian model of the UK Met Office (the PACE code). For non-nuclear applications, Lagrangian models have been used for a long time. For example, the AUSTAL2000 model is the German standard for probabilistic assessments for licensing of industrial installations [25]. Decision support systems for nuclear emergencies such as the RODOS system [26] also comprise Lagrangian models. In its 2014 release, probabilistic assessment capabilities are also included which allow use of advanced dispersion models for weather data covering several years and providing results that can be evaluated statistically outside the system.

2.2.4. Exposure pathways

The routes by which radiation or radionuclides can reach humans and cause exposure, i.e. exposure pathways, depend on the scenario of release, and the pathways of exposure from radioactive release may differ essentially in comparison to normal operation releases. An indicative list of exposure pathways for potential exposure scenarios is provided in Ref [6]:

- External irradiation:
  - from the source;
  - from the plume;
  - from the deposition on skin;
  - from the deposition on the ground or other surfaces;
- Inhalation:
  - from the plume;
  - of resuspended material;
- Intakes of radionuclides:
  - from fresh and processed food and water;
  - due to the inadvertent ingestion of radionuclides deposited on ground or other surfaces.

Contributions to the total dose from different exposure pathways depend on the scenario of release (source term and transport in environment), location and characteristics / habits of individuals, and potential implementation of protective measures.

In this project the distribution of population in the affected area was set up in the beginning of the exercise and used in every national study along with corresponding requirements applicable in a given country. Implementation of protective measures was considered as relevant by the different modellers.

Age is one of the major characteristics of individuals who may be affected by accidental exposure which determines essential differences in the radiological consequences. Infants may be more exposed than adults via intakes of certain radionuclides due to the inadvertent ingestion and inhalation of resuspended contaminated material [27]. Infants may be more vulnerable to the irradiation of the thyroid gland due to the incorporation of radioactive iodine isotopes, which could potentially be released in a nuclear reactor accident [6].

The scope of consideration of individual characteristics of population groups involved in the assessment of potential exposures, and national criteria used in the assessment study to identify the most exposed group of individuals, may vary in different countries. Sometimes specific groups of the most vulnerable individuals need to be selected for dose estimation in advance, while in other cases the distribution of doses or risks among larger affected population groups may involve dose estimations for specific locations (e.g. the nearest village, the biggest town nearby etc.), or calculation of dose distribution for all population groups using the predefined fixed net covering the whole emergency area with the nodes distributed in all directions and in different distances from the release source.

In this project national experts used their national recommendations and requirements on consideration of habits and individual characteristics of population groups and the representative (most exposed) person identification.

2.2.5. Dose calculation and probabilistic assessment

Estimation of the level of radiological impact due to potential exposure normally involves [6, 27]:

- for doses in the range of deterministic effects – calculation of mean absorbed doses to the organ or tissue, weighted by an appropriate relative biological effectiveness (RBE);
- for doses in the range of stochastic effects:
  - calculation of equivalent dose to certain organs (thyroid, fetus);
  - calculation of effective dose resulting from the sum of the committed effective doses from internal exposure pathways and the effective doses from external exposure.

In probabilistic assessments the results of estimation of the health effects are traditionally presented in a set of complementary cumulative distribution functions (CCDF) providing information on the likelihood and magnitude of consequence of the release associated with an AOO or an accident. CCDF can be introduced as

$$P(C) = \int_C^{\infty} p(t)dt \qquad (2)$$

where $P(C)$ is the conditional probability of having consequence equal and higher than C; and $p(t)$ is a function of density of consequences ($\int_0^{\infty} p(t)dt = 1$).

The CCDF are normally displayed as a set of log-log graphs of exceeded probability versus consequences [6, 18]. A point on a CCDF curve gives the conditional probability[4] that a consequence will equal or exceed a given magnitude (Figure 5). The probability of consequence at a specific location will be considered as conditional, as it is assumed that a release had already occurred.

Ref [28] explains that "the conditional probability is the probability that an event will occur, given the occurrence of an earlier defined event. E.g. the probability of dying as the consequence of an exposure to radiation is conditional on the occurrence of the exposure and

[4] Although it is not strictly correct the relative frequencies calculated in the consequence models are generally referred to as probabilities.

on its magnitude. Conditional probabilities must be used with care, since they can be manipulated and combined only if the conditions applying to them remain unchanged".

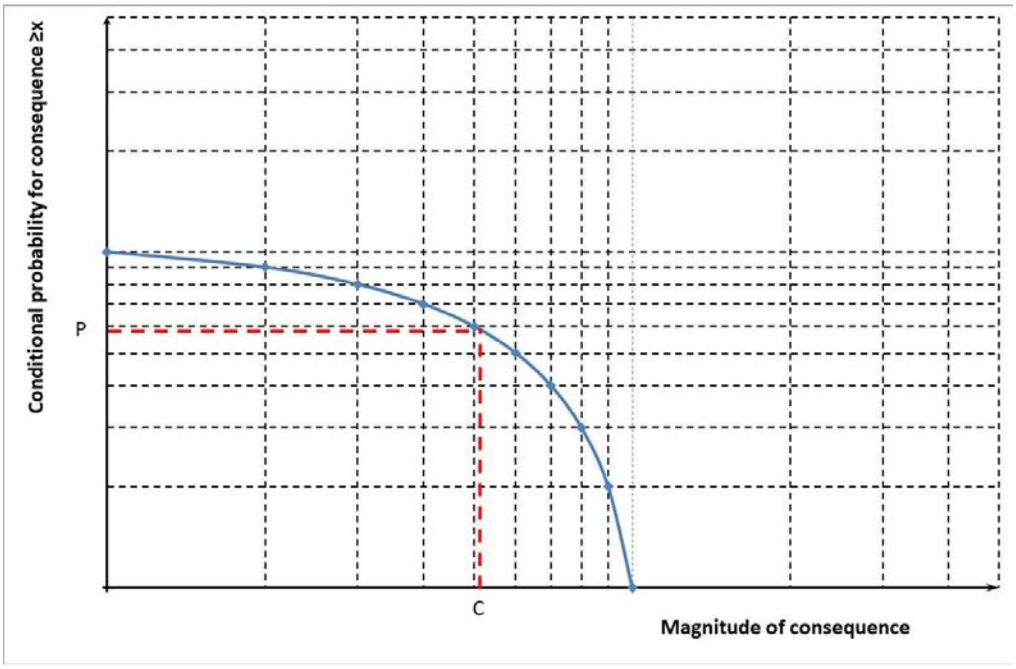

FIG.5. Example of a CCDF

The point marked with red dashed lines on Figure 5 means that the consequence value *C* or a greater value is expected with the probability *P*.

In the results of calculation, the CCDF can be presented as a set of standard percentiles, e.g. 90^{th} percentile, 95^{th} percentile, 99^{th} percentile etc. The values of percentiles can be defined from the CCDF and the n^{th} percentile of consequences is the value of consequence C_n, which can be determined from Eq. (3):

$$P(C_n) = 1 - \frac{n}{100} \tag{3}$$

where $P(C_n)$ is the probability of the occurrence of consequence equal or higher to C_n, and *n* is the number of percentile. E.g. the 97^{th} percentile of the dose from potential exposure is the dose value which will be accrued (or exceeded) by an individual with the probability of 3%.

One assessment typically produces a series of CCDFs for different locations, different types of dose and different groups of individuals.

Different criteria may be set up for different types of facilities in different countries. Ref [11] requires that "the likelihood and magnitude of potential exposures, their likely consequences and the number of individuals who may be affected by them" shall be assessed. In some countries national criteria for assessment of potential exposure may be based on the restrictions of probability of exposure and restriction of doses. In other countries national requirements may be focused on a single aggregated parameter called risk or a combination of both (e.g. in UK). Definition of risk can also vary in different situations.

The ICRP provides recommendations on annual public dose limits for radiation exposure from normal operation that correspond to an annually committed probability of premature death of a few 10^{-5} and implied limit of the probability of death linked to the threshold of the region of unacceptable risk. Based on these recommendations, Ref [28] assumes that the annual individual risk from potential exposure should be of similar magnitudes to the restrictions for normal exposures and that risk from potential exposure, expressed as the annual probability of death attributable to a single installation, should not exceed 10^{-5}. However, it is clarified that “individual risk expressed in terms of potential exposure would only be the determining factor for the safety of nuclear power plants for doses, should they occur, of less than about 10 mSv”. For larger doses the potential exposure will still play a part, but societal consequences, especially of intervention, will increasingly prove to be more limiting. The term societal risk is used to represent the total impact of an accident including the risk to individuals, the number of individuals at risk, the economic impact of such things as the counter-measures needed to protect individuals, including food bans, and the loss of production and the loss of the capital value of the installation.

Ref [28] explores the relationship between individual risk and societal risk and the relevant criteria. It concludes that societal risk is more than the sum of individual risks. For accidents causing serious damage to an NPP or having off-site consequences, individual risk is considered not sufficiently limiting because of the many aspects of societal impact.

In this project every participant has used his national criteria and requirements for the assessment exercise. This report is not intended to criticise national regulations but rather to make a record of the current status and to compare requirements in different Member States. Potential transboundary impacts are not considered in this report.

Other simpler approaches for presenting the results of the potential exposures involve calculating the resulting dose from the accident scenario to a representative person used for assessing doses, including dose reductions due to protective actions if relevant, and estimating the risk using risk factors. Ref [6] discusses definition and use of risk.

3 EXERCISE ON ASSESSMENT OF RADIOLOGICAL ENVIRONMENTAL IMPACT FROM POTENTIAL EXPOSURES

3.1 BASIC CONDITIONS FOR EXPOSURE SCENARIO

In this project a potential accident scenario was defined as a source term, the associated probability and a set of meteorological and geographic data. Radiation doses/effects have been determined by applying environmental dispersion models for the accidental releases to give activities of nuclides released into environmental media and then applying dose/effects functions. In the following, meteorological and geographic components of the scenario preparation are described.

A hypothetical site has been assumed for the exercise by the participating experts to demonstrate the process of assessment of radiological environmental impact from potential exposure. A map of the site is illustrated in Figure 6. There are cities, urban areas, sea, land and a river. The polar coordinate system was superimposed on the site map to facilitate firstly introduction of the site data for performing calculations and secondly to associate the results of modelling with the certain objects on the map. Based on these overlapped schematic maps, the site data were introduced into the modelling as land fraction, population, spatial intervals and wind directions. Information about population, size of areas and distances from the point of release is summarised in Table 1.

TABLE 1. SITE DATA DESCRIPTION

#	Category	Population	Area, km^2	Distance from the point of release, km	Sector, °	Sector, Number
1	City	250 000	25	15	300	14
2	Town	15 000	3	8	220	12
3	Village	50	0.1	2.5	330	15
4	Urbanization	15	1	6.5	40	3, 4
5	Urbanization	20	0.09	3.5	160	8
6	Urbanization	100	2	7	115	6
7	Individual housing, close to the fence	60		1 – 5		5 - 16
8	Megalopolis	2 000 000	100	50	140	7

Meteorological data comprising 8760 weather records from a meteorological station of an operating NPP had been provided for this project by CIEMAT. This set of data describing weather condition during one year with one-hour interval measurements of the wind direction, wind speed, atmospheric stability, and precipitation rate has been available to all participants. In this exercise, use of the real measurement data from a Spanish meteorological tower involved some special processing of these data due to a few gaps in data records, very low wind velocity (less than 0.1 m/s) etc. In total less than 5% of the whole set of meteorological data needed special processing.

The full list of the parameters of the data set includes:

- Month, Day, Hour;
- Wind speed and direction at 80 m and 10 m altitude;
- Temperature at 80 m and 10 m altitude;
- Humidity (relative) and pressure (mmHg);
- Solar irradiation;
- Precipitation (mm);
- Pasquill-Gifford Category.

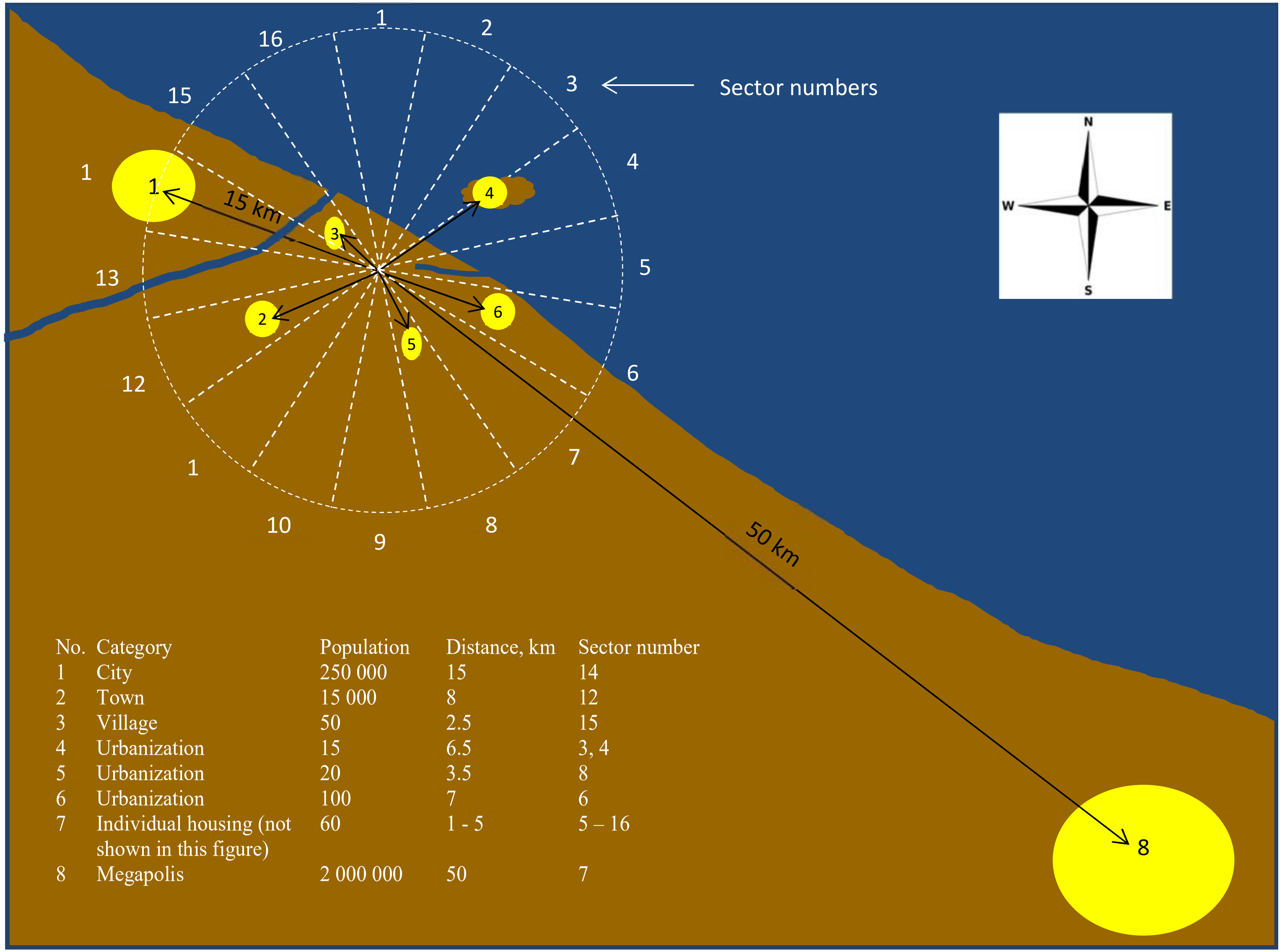

FIG.6. Map of the site

Computer tools and models used by participants in this project could incorporate limited sets of input parameters selected from the available meteorological array. For example, the WinMACCS code used dates, wind direction and velocity at a given height, stability category and precipitation. Processing of data was necessary for categorization of wind direction into sectors according to the polar grid coordinates, the data preparation in adequate units etc.

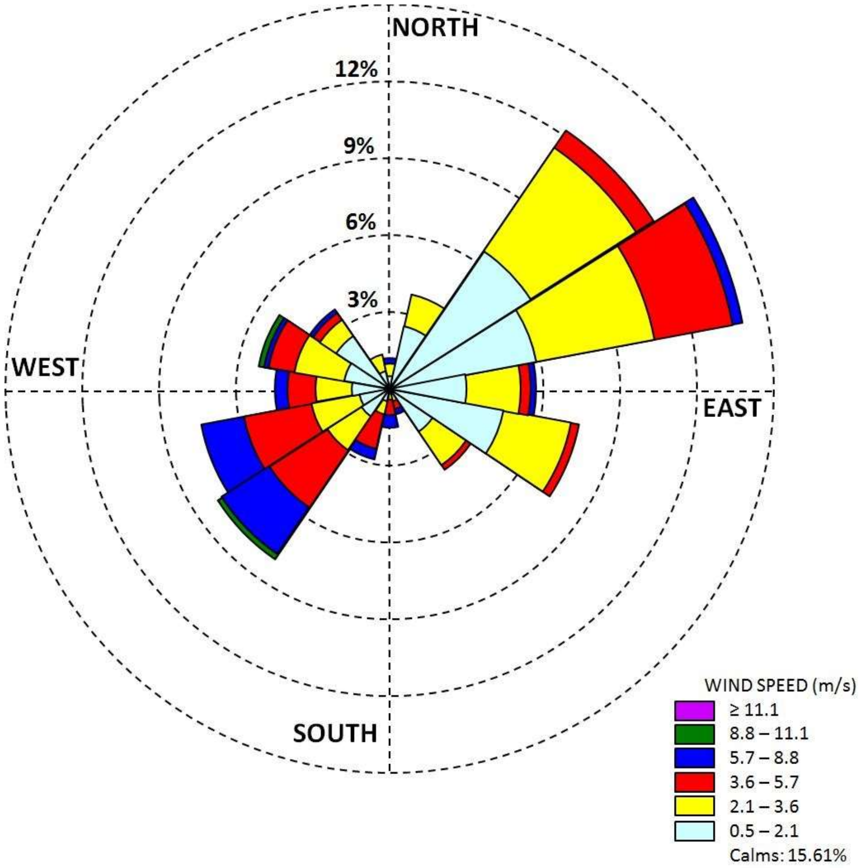

FIG.7. Wind rose at 10 m altitude

The mixing heights (see Table 2) required for the WinMACCS code were specified for each of the four seasons of the year and for 0:00-12:00 hour and 12:00-24:00 hour periods with the range from 500 m for 0:00-12:00 hour intervals during the autumn season till 1900 m for 12:00-24:00 hour intervals of the winter season.

TABLE 2. SEASONAL MIXING HEIGHTS, m

Time periods	0:00-12:00	12:00-24:00
Winter	700	1050
Spring	650	1890
Summer	600	1900
Autumn	500	1400

3.2 SOURCE TERM

The source term used in this exercise was generated using the data published in the State-of-the-Art Reactor Consequence Analysis (SOARCA) project [29]. This project has focused on providing a realistic evaluation of accident progression, source term, and offsite consequences for two NPPs: the Surry Nuclear Power Plant (two 800 MWe PWRs) and the Peach Bottom Nuclear Power Plant (two large BWRs). The SOARCA project had been the most contemporary, comprehensive and sophisticated analysis for which detailed results were publicly available and could be accessed by the participants of ENV-PE exercise.

SOARCA Surry considered five selected accident scenarios. For the ENV-PE exercise, the project participants selected the source term calculated for a short-term station blackout in the SOARCA Surry study [18]. Atmospheric release starts at 25.5 hours and ends at 48 hours after the initiating event. An estimated frequency of this scenario is 1×10^{-6} to 2×10^{-6} a^{-1}.

TABLE 3. RELEASE FRACTIONS FOR PLUME SEGMENTS (ADAPTED FROM [18])

Plume segment	Release fractions								
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La
1	3.9E-03	6.4E-06	1.1E-06	5.5E-05	8.8E-05	1.6E-07	6.9E-07	2.8E-07	1.2E-08
2	8.9E-03	1.4E-05	2.4E-06	1.2E-04	1.9E-04	3.3E-07	1.4E-06	5.9E-07	2.5E-08
3	1.7E-02	2.5E-05	4.4E-06	2.4E-04	3.3E-04	5.7E-07	2.4E-06	1.0E-06	4.5E-08
4	2.3E-02	3.1E-05	5.3E-06	3.0E-04	3.9E-04	6.7E-07	2.8E-06	1.2E-06	5.4E-08
5	2.8E-02	3.7E-05	6.1E-06	3.6E-04	4.4E-04	7.4E-07	3.1E-06	1.3E-06	6.2E-08
6	3.0E-02	3.8E-05	6.2E-06	3.9E-04	4.3E-04	7.1E-07	2.9E-06	1.3E-06	6.2E-08
7	3.1E-02	3.8E-05	6.2E-06	4.1E-04	4.2E-04	6.8E-07	2.7E-06	1.2E-06	6.1E-08
8	3.0E-02	3.5E-05	5.7E-06	3.8E-04	3.8E-04	5.9E-07	2.4E-06	1.1E-06	5.6E-08
9	2.9E-02	3.3E-05	5.4E-06	3.6E-04	3.5E-04	5.3E-07	2.1E-06	9.5E-07	5.2E-08
10	2.9E-02	3.1E-05	5.1E-06	3.5E-04	3.2E-04	4.8E-07	1.8E-06	8.6E-07	4.9E-08
11	2.7E-02	2.9E-05	4.7E-06	3.3E-04	2.8E-04	4.1E-07	1.6E-06	7.4E-07	4.4E-08
12	2.7E-02	2.8E-05	4.6E-06	3.3E-04	2.7E-04	3.8E-07	1.4E-06	6.9E-07	4.2E-08
13	2.7E-02	2.7E-05	4.5E-06	3.3E-04	2.6E-04	3.5E-07	1.3E-06	6.4E-07	4.1E-08
14	2.4E-02	2.5E-05	4.0E-06	3.0E-04	2.2E-04	3.0E-07	1.0E-06	5.4E-07	3.6E-08
15	2.4E-02	2.4E-05	4.0E-06	3.0E-04	2.1E-04	2.7E-07	9.5E-07	5.0E-07	3.5E-08
16	2.4E-02	2.4E-05	3.9E-06	3.0E-04	2.1E-04	2.5E-07	8.6E-07	4.7E-07	3.4E-08
17	2.3E-02	2.3E-05	3.6E-06	2.9E-04	1.9E-04	2.2E-07	7.3E-07	4.1E-07	3.1E-08
18	2.1E-02	2.1E-05	3.3E-06	2.6E-04	1.7E-04	1.9E-07	6.3E-07	3.6E-07	2.9E-08
19	2.1E-02	2.0E-05	3.1E-06	2.6E-04	1.7E-04	1.8E-07	5.8E-07	3.4E-07	2.8E-08
20	2.1E-02	1.8E-05	2.8E-06	2.4E-04	1.6E-04	1.7E-07	5.2E-07	3.1E-07	2.7E-08
21	2.1E-02	1.7E-05	2.6E-06	2.3E-04	1.5E-04	1.5E-07	4.7E-07	2.9E-07	2.7E-08
22	1.9E-02	1.5E-05	2.2E-06	2.0E-04	1.3E-04	1.3E-07	3.9E-07	2.4E-07	2.4E-08
23	8.8E-03	6.8E-06	1.1E-06	8.9E-05	6.2E-05	5.8E-08	1.7E-07	1.1E-07	1.1E-08
24	6.2E-04	4.8E-07	7.6E-08	6.2E-06	4.3E-06	4.0E-09	1.2E-08	7.6E-09	7.8E-10
Total	5.2E-01	5.7E-04	9.3E-05	6.4E-03	5.8E-03	0.9E-05	3.3E-05	1.5E-05	0.1E-05

In the case study published in this report the characteristics of radionuclide release to the atmosphere have been postulated. The accident sequences initiated within the reactor building have not been considered and the release characteristics have been assumed to be similar to those published in [18, 29]. The release was divided in 24 plume segments[5] characterized by the release fractions calculated in [18] using the MELCOR code (see Table 3). Plume characteristics include release height, timing for every segment of release, heat contents, plume mass density and mass flow rate. Release properties defining the source term selected for the current exercise are presented in Table 4 (adapted from [18]).

[5]In the original SOARCA project there were 33 plume segments considered. In this exercise the number of plume segments was limited to 24 because the last nine segments provided a relatively low contribution to the total release.

TABLE 4. RELEASE PROPERTIES FOR EACH PLUME SEGMENT THAT IS PART OF THE SOURCE TERM [18]

Plume segments	Plume release times, s	Plume heat contents, W	Plume release height[1], m	Plume mass density, kg/m^3	Plume mass flow rate, kg/s	Plume segment durations, s
1	9.19E+04	5.78E+04	35	4.84E-01	1.97E-01	3.72E+03
2	9.56E+04	1.49E+05	35	4.81E-01	5.03E-01	3.48E+03
3	9.91E+04	2.84E+05	35	4.78E-01	9.44E-01	3.72E+03
4	1.03E+05	4.10E+05	35	4.76E-01	1.35E+00	3.48E+03
5	1.06E+05	5.07E+05	35	4.73E-01	1.64E+00	3.60E+03
6	1.10E+05	5.66E+05	35	4.71E-01	1.81E+00	3.60E+03
7	1.14E+05	6.01E+05	35	4.68E-01	1.90E+00	3.72E+03
8	1.17E+05	6.23E+05	35	4.66E-01	1.95E+00	3.60E+03
9	1.21E+05	6.39E+05	35	4.64E-01	1.97E+00	3.60E+03
10	1.24E+05	6.53E+05	35	4.62E-01	2.00E+00	3.60E+03
11	1.28E+05	6.63E+05	35	4.60E-01	2.01E+00	3.48E+03
12	1.32E+05	6.71E+05	35	4.58E-01	2.01E+00	3.60E+03
13	1.35E+05	6.78E+05	35	4.56E-01	2.01E+00	3.72E+03
14	1.39E+05	6.84E+05	35	4.54E-01	2.01E+00	3.48E+03
15	1.42E+05	6.90E+05	35	4.53E-01	2.01E+00	3.60E+03
16	1.46E+05	6.96E+05	35	4.51E-01	2.01E+00	3.72E+03
17	1.50E+05	7.04E+05	35	4.49E-01	2.02E+00	3.60E+03
18	1.53E+05	7.09E+05	35	4.48E-01	2.02E+00	3.48E+03
19	1.57E+05	7.26E+05	35	4.44E-01	2.01E+00	3.60E+03
20	1.60E+05	7.34E+05	35	4.38E-01	1.96E+00	3.60E+03
21	1.64E+05	7.26E+05	35	4.35E-01	1.90E+00	3.72E+03
22	1.68E+05	7.16E+05	35	4.32E-01	1.84E+00	3.48E+03
23	1.71E+05	7.08E+05	35	4.30E-01	1.80E+00	1.68E+03
24	1.73E+05	7.05E+05	35	4.30E-01	1.78E+00	1.20E+02

Note: [1] – ENV-PE exercise participants decided to specify the total release height (including temperature and pressure effects at source) as 35m.

Release fractions for each class of radionuclides specify the fraction of the total core inventory released. Plume release time is the start time of every segment from the beginning of the accident and the duration of segments was introduced through a separate parameter (plume segment duration). These two parameters are not independent. Plume heat content is the rate of heat release and the plume release height is the height of release above ground level (constant parameter in this study). Plume mass density is the density of the plume segment in kg m^{-3}, and mass flow rate is the mass of plume release per second.

Table 5 shows the radionuclides inventory at the scram time of the Surry NPP.

TABLE 5. INVENTORY OF RELEVANT RADIONUCLIDES IN REACTOR CORE AT THE SCRAM TIME (REPRESENTATIVE ELEMENTS IN PARENTHESIS) [18]

No.	Name of chemical group	Isotope	Activity at the time of shutdown, Bq
1	Noble gases (Xe)	Kr-85	2.94E+16
2		Kr-85m	8.07E+17
3		Kr-87	1.60E+18
4		Kr-88	2.14E+18
5		Xe-133	6.07E+18
6		Xe-135	1.80E+18
7		Xe-135m	1.29E+18
8	Alkali metals (Cs)	Cs-134	4.32E+17
9		Cs-136	1.57E+17
10		Cs-137	3.05E+17
11		Rb-86	5.36E+15
12		Rb-88	2.16E+18
13	Alkaline earth (Ba)	Ba-139	5.54E+18
14		Ba-140	5.37E+18
15		Sr-89	2.98E+18
16		Sr-90	2.27E+17
17		Sr-91	3.75E+18
18		Sr-92	4.00E+18
19		Ba-137m	2.92E+17
20	Halogens (I)	I-131	2.78E+18
21		I-132	4.08E+18
22		I-133	5.76E+18
23		I-134	6.48E+18
24		I-135	5.49E+18
25	Chalcogens (Te)	Te-127	2.60E+17
26		Te-127m	4.22E+16
27		Te-129	7.79E+17
28		Te-129m	1.49E+17
29		Te-131m	5.71E+17
30		Te-132	4.29E+18
31		Te-131	2.55E+18
32	Platinoids (Ru)	Rh-105	2.90E+18
33		Ru-103	4.61E+18
34		Ru-105	3.14E+18
35		Ru-106	1.40E+18
36		Rh-103m	4.61E+18
37		Rh-106	1.56E+18
38	Early transition element (Mo)	Nb-95	5.18E+18
39		Co-58	4.79E+13
40		Co-60	2.65E+14
41		Mo-99	5.68E+18
42		Tc-99m	5.03E+18
43		Nb-97	5.24E+18
44		Nb-97m	4.95E+18

TABLE 5. INVENTORY OF RELEVANT RADIONUCLIDES IN REACTOR CORE AT THE SCRAM TIME (REPRESENTATIVE ELEMENTS IN PARENTHESIS) [18] (cont.)

No.	Name of chemical group	Isotope	Activity at the time of shutdown, Bq
45	Tetravalent (Ce)	Ce-141	4.87E+18
46		Ce-143	4.55E+18
47		Ce-144	3.42E+18
48		Np-239	5.67E+19
49		Pu-238	8.31E+15
50		Pu-239	9.56E+14
51		Pu-240	1.17E+15
52		Pu-241	3.39E+17
53		Zr-95	4.96E+18
54		Zr-97	5.00E+18
55	Trivalents (La)	Am-241	3.43E+14
56		Cm-242	1.14E+17
57		Cm-244	1.13E+16
58		La-140	5.67E+18
59		La-141	5.10E+18
60		La-142	4.92E+18
61		Nd-147	2.04E+18
62		Pr-143	4.65E+18
63		Y-90	2.39E+17
64		Y-91	3.93E+18
65		Y-92	4.11E+18
66		Y-93	4.62E+18
67		Y-91m	2.20E+18
68		Pr-144	3.63E+18
69		Pr-144m	5.06E+16

The integral release fractions distributed by chemical groups are provided in Table 6 [18].

TABLE 6. INTEGRAL RELEASE FRACTIONS BY CHEMICAL GROUPS [18]

Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La
0.518	0.001	0.000	0.006	0.006	0.000	0.000	0.000	0.000

Aerosol particles distribution for the selected scenario is presented in Figure 8. For noble gases (Xe group) a uniform distribution of aerosol particles was used (10% in every bin). Table 7 presents the mass median diameter (MMD) and the deposition velocity associated with bins of aerosol groups distribution. The majority of the released contamination is associated with the bins 4, 5 and 6, which correspondent to the size of mass median aerosol diameter around 1, 2 and 3 µm and particle size of the bins are log-normally distributed, except normally distributed alkali metals (Cs) group.

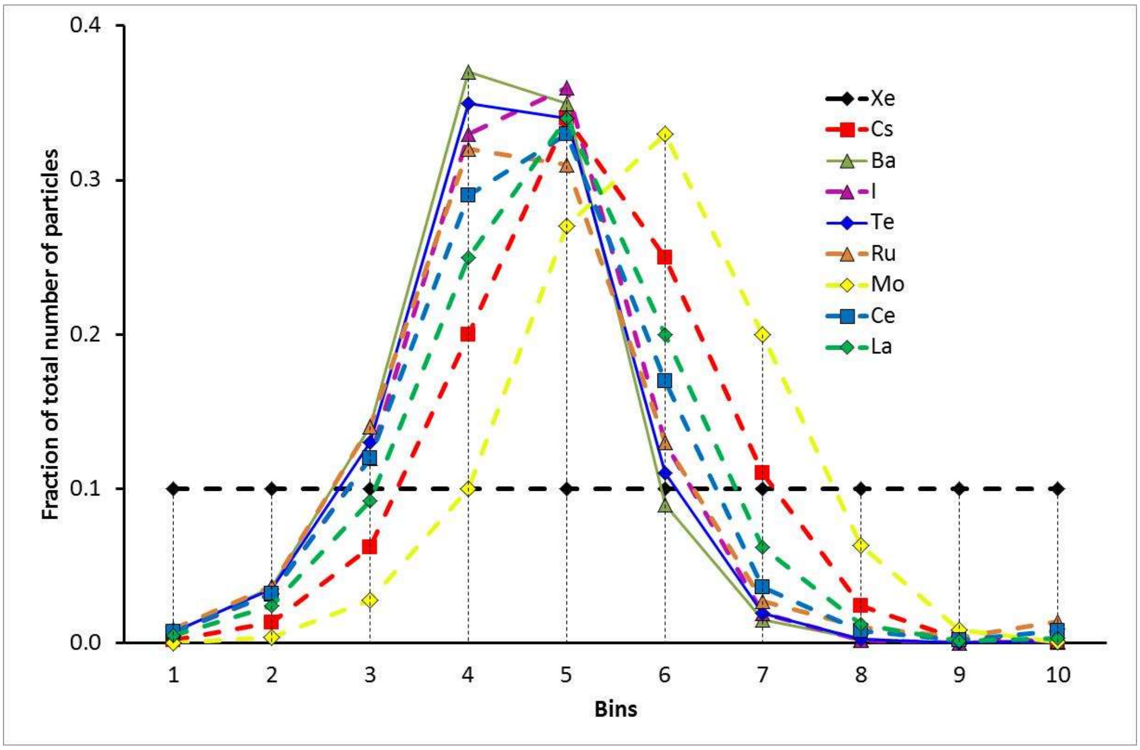

FIG.8. Distribution of aerosol particles by chemical groups and by size

TABLE 7. MASS MEDIAN DIAMETER AND DEPOSITION VELOCITY FOR ALL AEROSOL GROUPS DISTRIBUTIONS [18, 29]

Bins	1	2	3	4	5	6	7	8	9	10
MMD class, µm	0.15	0.29	0.53	0.99	1.8	3.4	6.4	11.9	22.1	41.2
Deposition velocity, V_{dep} mm/s	0.54	0.49	0.64	1.08	2.12	4.34	8.37	13.7	17.0	17.0

The size of the building, where the release occurred was assumed as $40 \cdot 40 \cdot 40$ m. In the WinMACCS code the size of the building is not explicitly required, and it was introduced indirectly through the sigma coefficients. Equations (4) and (5) display the initial values of the crosswind and the vertical sigma as functions of width and height of the building.

$$\sigma_y(x = 0) = \frac{W_b}{4.3} = 0.23W_b \quad (4)$$

$$\sigma_z(x = 0) = \frac{H_b}{2.15} = 0.47H_b \quad (5)$$

where: σ_y - Gaussian Crosswind Dispersion Parameter; σ_z - Gaussian Vertical Dispersion Parameter; W_b- Width of the building from which release occurred (m); H_b - Height of the building from which release occurred (m).

4 COMPARISON OF MODELS AND APPROACHES USED IN NATIONAL CASE STUDIES

4.1 GENERAL CONSIDERATIONS

Each participant considered the following topics related to the unplanned releases to the environment:

- Accident source term definition;
- Exposure scenarios and environmental dispersion models (atmospheric) applicable to accidental releases;
- Representative persons for assessing doses (location, characteristic, habits, age groups);
- Dose assessment (pathways, radionuclides, short-term and long-term doses);
- Use of dose/health effects relations and risk factors;
- Selection and use of reference doses and risk constraints;
- Consideration of protective actions.

These topics correspond to the steps in an assessment of potential exposures from unplanned releases as shown in Figure 1 above (taken with modifications from Ref [6]). The following sections describe approaches taken by each of the participants and the results obtained; each of the above topics is considered in turn below.

The methodologies and parameter values used are those reported by the participants in this exercise. For the purposes of this exercise, each participant generally followed the regulatory requirements and guidelines of the regulator in their respective Member State (as far as the constraints of the exercise allowed); however, this does not imply any endorsement by the respective regulatory bodies of the Member States. For convenience in reporting, each approach may be referred to by the Member State of the participant; this does not imply that this is necessarily the only approach that could be adopted in that Member State. For example, in some Member States such as the UK, the regulatory regime is goal-setting rather than prescriptive and it is up to the applicant to propose and justify the methodology they use to demonstrate that the safety goals are met; no particular methodology is prescribed although some guidance is issued. In other Member States a methodology is prescribed.

As mentioned in Section 2.2.2, there are a number of different approaches of varying complexity that can be applied; the basic types of approach are briefly discussed below. Which approach to use will depend on type of facility to be assessed, the stage in the assessment and the regulatory requirements to be satisfied. This is the graded approach discussed in IAEA GSR Part 3 [11]. The basic approaches are to assess:

- A single conservative release scenario usually representative of a worst-case accident scenario.
- A set of scenarios selected to represent the range of scenarios that could occur at a given facility usually with some cut-off frequency (either explicit or implicit) so that extremely unlikely events are not considered.
- A full-scope PSA with the intention to consider all initiating events (e.g. plant faults, internal hazards, external hazards), all plant states (e.g. full-power, shutdown, fuel handling for an NPP) and all facilities on site (e.g. multiple units, fuel stores, radioactive waste management facilities). Again, extremely unlikely initiating events or scenarios are not considered; this is to keep the analysis manageable and for the same reason, binning (or grouping) of scenarios that are considered to have similar consequences into release categories is carried out. Nevertheless, the number of scenarios for which environmental consequences are assessed may be up to 100 or more.

Each release scenario would then be assessed for either a single set of meteorological conditions (usually worst-case) or a set of meteorological conditions or sequences (representing changing conditions over the duration of the release) usually sampled from – or derived from – measured meteorological data. The number of meteorological sequences that might typically be assessed for each release scenario could be 100 or more.

As only one scenario was required to be analysed for this exercise, it may not be apparent from each participant's contribution whether this would have been sufficient in their regulatory regime, or whether a full PSA would have been required; this is discussed in the concluding section below.

4.2 DISCUSSION ON METEOROLOGY, POTENTIAL EXPOSURE SCENARIOS AND SPECIFICATION OF THE SOURCE TERM

4.2.1. Meteorological conditions used in national case studies

In this exercise a single set of meteorological data was provided to participants. The data set included 8760 records (1 record per hour) for each of 22 meteorological parameters.

Several approaches to using this data were adopted which are summarized as follows:

- In some assessments, the hourly data were sampled (to keep the analysis manageable) and atmospheric and dose calculations were performed for each meteorological sequence (the set of hourly conditions for each segment of the plume); this amounts typically to some hundred dispersion calculations for each scenario considered (different types of sampling were performed – namely cyclic and stratified – see discussion in Annex X).
- In some assessments, the data were analysed to determine typical (average) or worst-case meteorological scenarios (e.g. Russian Federation and Ukraine) and dispersion and dose calculations performed for these cases (typically one or two runs).
- In some assessments, the data were not used at all and what is considered typical or worst-case meteorological conditions for the country in question were used instead.
- In some assessments, the calculations were performed for all six stability categories (A-F)

Although only one year of data was provided for this exercise, most participants who used the data would typically have used more years of data in their own national assessments; this is to avoid the possibility that one year's data may not be typical and to get a better representation of what the weather at the moment of potential accident at the site in question might be.

The meteorological dataset included the following parameters:

- Month, Day, Hour;
- Wind speed and direction at 80 m and 10 m altitude;
- Temperature at 80 m and 10 m altitude;
- Humidity (relative) and pressure (mm Hg);
- Solar irradiation;
- Precipitation (mm);
- Pasquill-Gifford Category.

Most of the participants who used the meteorological data, used the Pasquill-Gifford Category directly; however, the participant from France used the temperature gradient and solar irradiation to derive a stability category using the Doury model.

None of the participants used the wind speed and direction and temperature at 80 m (other than the participant from France using the temperature gradient as mentioned above). Only the participant from Israel used the temperature at 10 m to determine the effective height of the release allowing for plume rise due to the heat content associated with the release.

Among the participants who carried out probabilistic meteorological assessments for dose versus downwind distance, the participants from Argentina and Ukraine actually used the wind direction information; the other participants (from Germany, Spain, and the UK) performed analyses for each downwind distance regardless of direction. The UK participant did consider the wind direction distribution – along with the population distribution – when calculating the societal risk.

None of the participants used the relative humidity, pressure, or solar irradiation data. Some experimental studies have suggested that the deposition velocity depends on relative humidity [30] (see discussion below), and therefore humidity could have some impact on the results and it would, in principle, be possible to use deposition velocities that are dependent on the relative humidity.

4.2.2. Source terms and exposure scenarios used in national case studies

The source term was determined in the form of quantities of radionuclides released and their physical and chemical characteristics that define their behaviour in the environment. As described in Section 3.2 above, the source term used in the comparison exercise was selected from data published in the SOARCA project [29] considering the Surry NPP (two 800 MWe Westinghouse PWRs). Just one scenario was selected for this exercise to facilitate the comparison even though it is recognized that the regulatory requirements in some Member States would require a full range of scenarios to be assessed.

The SOARCA report [29] states that the project focused on providing a realistic evaluation of the accident progression and a 'best-estimate' for a source term. However, some national requirement may require a pessimistic estimate for the source term.

The main elements of the source term description are summarized below:

- core inventory (the activities of 69 nuclides),
- release fraction for 9 radionuclide groups broken down into 24 plume segments each of roughly one-hour duration,
- plume heat content for each plume segment,
- plume release height for each plume segment (all 35 m),
- plume mass density,
- plume mass flow rates,
- particle size distribution for each radionuclide group.

Some of the participants did not use some the elements of the source term provided. Each element of the source term is discussed in turn below.

For the comparison exercise a reduced inventory of only the most radiologically significant radionuclides was produced including 14 or 15 of the original 69 nuclides. All the participants used such a reduced inventory.

The deterministic assessments considered a single release under constant meteorological conditions (wind speed and direction, Stability Category, etc.) and assumed a release duration. The Gaussian plume model allows small changes in the wind direction over the duration of the release – often called 'wind meander' or 'wind veer' – to be accounted for with a release duration parameter. Essentially longer wind duration will broaden the plume in the cross-wind direction reducing the plume centreline concentrations; so longer release durations give lower peak concentrations and hence lower doses.

This is discussed in more detail in the first report by the UK Working Group on Atmospheric Dispersion [31]. The report states that the dispersion of the plume in the horizontal plane is a result of turbulence processes together with fluctuations in wind direction with these two components combining to give the overall horizontal dispersion according to the following Eg. (6):

$$\sigma_y^2 = \sigma_{y_t}^2 + \sigma_{y_w}^2 \tag{6}$$

where σ_y is the standard deviation for the horizontal crosswind dispersion, σ_{y_t} is the turbulent diffusion or three-minute term, σ_{y_w} is the component due to fluctuations in wind direction.

The report adds that the values of σ_y given originally by Pasquill were essentially for very short releases (~3 minutes) and this component should be used for releases much less than 30 minutes, but for longer duration releases, some account should be taken of fluctuations in wind direction; the report provides an expression for σ_{y_w} as follows:

$$\sigma_{y_w} = 0.065\sqrt{\frac{7T}{u_{10}}}x \tag{7}$$

where T is the release duration in hours, u_{10} is the wind speed in m/s at a height of 10 m, and x is the downwind distance in m.

It adds that these expressions should be used for any duration of release longer than about 30 minutes for which the stability category and wind direction remain unchanged.

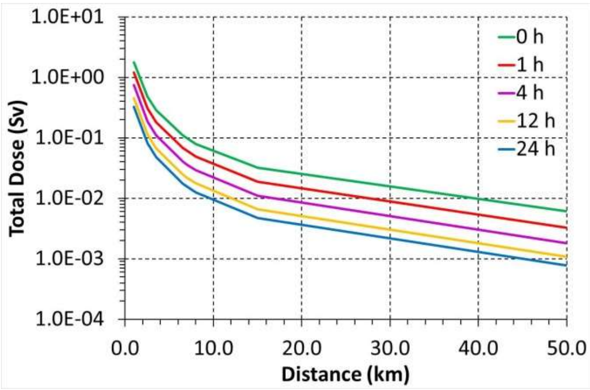

FIG.9: Effect of release duration, adult, D5 weather (1-day integration time for deposited dose)

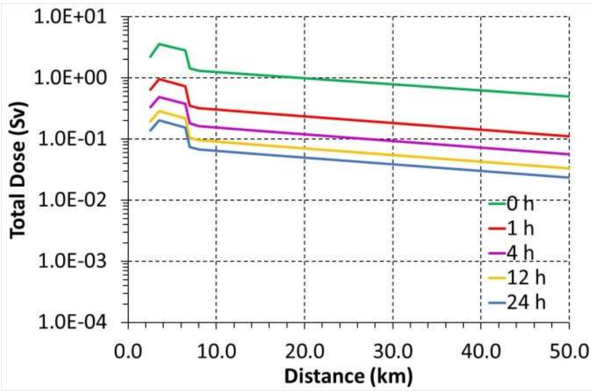

FIG.10: Effect of release duration, adult, F2 weather (1-day integration time for deposited dose)

FIG.9 and FIG.10 illustrate the effect for the results from the exercise (total adult dose for 1-day integration of the deposited dose) for D5 (Pasquill-Gifford atmospheric stability class D and wind speed 5 m/s) and F2 (stability class F and wind speed 2 m/s) weather. For D5 weather, the peak concentration for a one-hour release duration is about ~70% of that for an instantaneous release (<3 minutes) and for longer release durations this falls further to ~20% for 24 hours. For F2 weather the corresponding fractions are lower; this is because the σ_{yt} term is smaller for more stable conditions and therefore the σ_{yw} term is a bigger contributor to the overall σ_y term and makes more difference to the overall horizontal cross-wind dispersion.

The probabilistic assessments considered the release in segments performing a dispersion calculation for each segment under the meteorological conditions from the meteorological data file at the time of the release of each segment. So, for example, if the release were split into 6 segments (or phases) of 1 hour, six consecutive sets of hourly data from the data file would be used in the dispersion calculations. If the phases were longer than an hour, the release for each segment is still considered to be an hour but the meteorological conditions for the subsequent segments will depend on the start times for each segment; for example for three segments each of 4 hours, the meteorological data for hour X, X+4, and X+8 would be used to model the release in the respective segments.

The source term was split into 24 segments of one hour. However, because some the codes have a maximum number of segments that can be input (e.g. nine for main-frame COSYMA and six for PC-COSYMA) the source terms in some segments were aggregated. The meteorological conditions over the 24-hour period of the release will still be considered by taking every 4th hour of data for six segments as discussed above.

Heat content in the plume will cause the plume to rise leading to an effective release height higher than the actual release height. For a release associated with a building the plume also needs to have sufficient energy to break clear from the building wake. Since increasing the release height increases dispersion and reduces ground level concentrations, not including plume rise is deemed to be generally conservative. All the participants assumed an effective release height of 35 m as specified in the exercise[6].

None of the participants used the data on plume mass density and mass flow rate.

If different particle sizes were to be considered, different deposition velocities would have to be used for each size range and also different inhalation dose coefficients. The ICRP Database [32] provides inhalation dose coefficients for ten aerosol activity median aerodynamic diameter (AMAD) values, namely; 0.001(0.0006)[7], 0.003(0.0016), 0.01(0.0051), 0.03(0.016), 0.1(0.056), 0.3(0.19), 1, 3, 5 and 10 µm. ICRP Publication 71 [33] recommends 1 µm AMAD for exposures to members of the public as the default and ICRP Publication 68 [34] recommends 5 µm AMAD as the default for aerosols in the workplace.

The participant from Ukraine performed analysis of the particle size distribution data considering the distribution of particle size for the different radionuclide groups, the variation in dose coefficient for different particle sizes, and the change in the particle size distribution during transit of the plume due to the differential deposition velocities of the different particle sizes (larger particles have a higher deposition velocity and deposit more quickly from the plume leading to the mean particle size decreasing with distance). The Ukrainian assessment concluded that it could be reasonable to use one particle size of 1 µm to represent all particulates. Considering the particle size distribution would be possible but would complicate the analysis considerably; therefore, using one representative size is a pragmatic option. This was the approach adopted by all the other participants.

4.3 MODELLING OF DIRECT IRRADIATION, DISPERSION, AND ENVIRONMENTAL TRANSFER

The various types of models are described in Section 2.2.3. The types of models and specific codes used by each participant are summarized in the Table 8. The comparison shows that for atmospheric dispersion most participants used simple Gaussian or Gaussian puff models although a few use Lagrangian models. Lagrangian models are clearly more accurate if the accompanying meteorological and terrain data are available, and for modelling of real events would be used in preference to a Gaussian model. However, for licensing purposes, for which the scenarios are hypothetical and may be based on conservative assumptions, the merits of the

[6]The participant from Israel considered plume rise from 8.4 to 35 m (effective release height) due to heat content and temperature at 10 m.

[7] The ICRP Database states that since it may be more useful to refer to the Activity Median Thermodynamic Diameter (AMTD) for the smaller sizes, AMTDs are given in parentheses for AMADs of 0.5 µm and less.

Lagrangian approach are less clear, and their practicality for a full-scope PSA – where many hundreds if not thousands or even tens of thousands of simulations (e.g. ~100 dispersion calculations for each of ~100 release scenarios) may be required – is less clear still.

TABLE 8. MODELS AND CODES USED BY ENV-PE EXERCISE PARTICIPANTS

Participant	Deterministic		Probabilistic	
	Type of model	Code	Type of model	Code
Argentina			Gaussian	WinMACCs
Belarus			Gaussian + Gaussian puff/ Lagrangian	InterRAS
France	Gaussian multi-puff	MITHRA® software of the CERES® platform		
Germany			Gaussian/ Gaussian puff	Mainframe COSYMA v90/1
India	Simple Gaussian[1]	In-house		
Israel	Simple Gaussian	HOTSPOT		
Russia	Simple Gaussian	Express/RECASS		
Spain	Lagrangian puff / particle model	JRODOS	Gaussian	WinMACCs
Ukraine	Simple Gaussian	In-house	Gaussian puff	SOARS
UK	Simple Gaussian[1, 2]	In-house	Gaussian puff	PC-COSYMA v2.03

[1] modified to account for plume depletion by wet and dry deposition
[2] modified to account for wet and dry deposition and building wake effects [31, 35-37]

PHE (Public Health England) has compared the UK Met Office (the UK's national weather service) NAME Lagrangian model with a Gaussian model [38] and concluded the Gaussian model to be more conservative; this is discussed further in Section 5.4.

The chemical forms of the radionuclides released can be important because they can affect the behaviour of the radionuclides in the environment in terms of deposition velocities (dry and wet), and because different chemical forms can have different inhalation dose coefficients (the chemical form can determine how quickly a radionuclide is transferred from the lungs to other organs in the body).

The radionuclides in the source term for this exercise – and in most reactor accidents – can be considered in three groups as follows:

- noble gases – krypton and xenon nuclides
    - being chemically inert they do not undergo dry or wet deposition and are not assumed to be absorbed into the body when inhaled, and therefore give rise to only a cloud-shine dose
- iodine nuclides
    - iodine is usually considered to have three chemical forms – elemental or molecular iodine (I_2), particulate (e.g. CsI), or organic iodide (e.g. methyl iodide)
- particulates – most other nuclides
    - for volatile chemical forms of radionuclides (e.g. oxides, hydroxides, and others) that are released as fine solid particles or as an aerosol in the plume; their behaviour in the environment – dispersion and deposition – is determined by the particle size (see above) rather than the chemical form
    - the inhalation dose coefficients can still depend on the exact chemical form.

Other nuclides that were not considered in this exercise but that could occur in an accidental release from a reactor, and for which different chemical forms might need to be considered, include tritium and carbon-14.

Of the three groups listed above the behaviour of noble gases and particulates is fairly straightforward and only iodine may require special consideration. In early assessments, iodine release was usually considered to be all elemental iodine; this is probably the most pessimistic assumption to make as elemental iodine is the most reactive of the three forms giving it the highest deposition velocities leading to higher ground-shine doses at short distances, and it has the highest inhalation dose coefficient of the three forms. However, analysis following the Three Mile Island accident in 1979 [39] showed that 95% of the iodine in the containment atmosphere was in particulate form with the rest as elemental iodine, and a small amount of organic iodide. Assuming the entire iodine release to be elemental iodine might therefore be overly pessimistic.

A realistic severe accident analysis should therefore include modelling of iodine behaviour and chemistry in the containment. Some national requirements specify the iodine chemical form to consider, e.g. some requirements specify that the entire iodine release should be assumed to be elemental iodine.

For the purposes of this comparison exercise all the iodine was assumed to be elemental iodine. In fact, for the source term in this exercise, the iodine chemical form assumed would be a key assumption; the participants' assessments that give a breakdown by radionuclide and pathway show that the doses are dominated by inhalation of iodine isotopes and each iodine chemical form has a different dose coefficient.

Figure 11 and Figure 12 show the effect on the total calculated dose by assuming different iodine chemical forms for adult and infant dose respectively. Particulate iodine (e.g. CsI) produces about half the dose of elemental iodine and organic iodide produces about 80% of the dose of elemental iodine. For longer integration periods where ground-shine becomes more important, the different deposition velocities would also have an effect in that greater quantities of elemental iodine would be deposited.

The deposition velocity will determine how much of a nuclide is deposited on the ground and therefore determines the ground-shine dose. Two deposition velocities are usually defined – 'dry' and 'wet'. Dry deposition occurs when the plume impacts with ground and wet deposition occurs when rain falls through the plume. Wet deposition increases with increasing rainfall rate. The dry deposition velocity of a given radionuclide will depend *inter alia* on its particle size, its chemical form, the atmospheric conditions (e.g. humidity, temperature, wind speed, stability), and the nature of the surface onto which it is depositing.

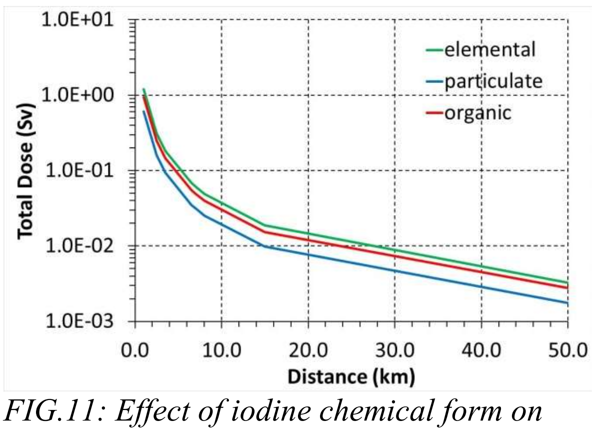

FIG.11: Effect of iodine chemical form on total dose (adult, 1-day integration time for deposited dose)

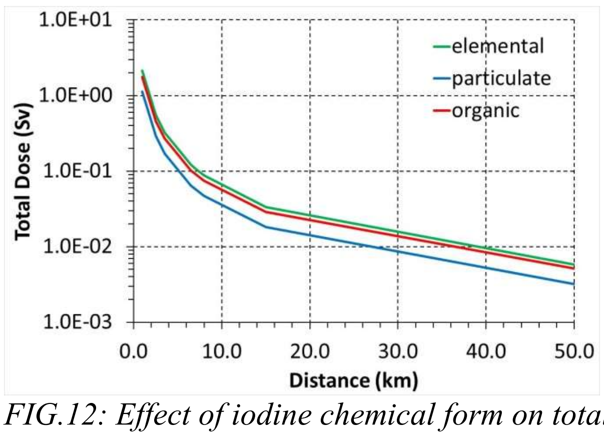

FIG.12: Effect of iodine chemical form on total dose (infant, 1-day integration time for deposited dose)

There have been several reviews of modelling and experimental studies on deposition velocities. IAEA-TECDOC-760 [40] considered wet and dry deposition processes in a review of the scientific understanding at that time and discussed the available empirical data to support this understanding. Also, the results of the partial model validation exercise carried out under the auspices of the project are discussed. The report concluded that Caesium-137 deposition with 1 μm aerosols on grass in urban areas appeared to be well described by deposition velocities in the range of $2 \cdot 10^{-4} - 1 \cdot 10^{-3}$ m/s, depending on the grass biomass per unit area. Caesium-137 deposition on roads was found to be consistent with deposition velocities in the order of $1 \cdot 10^{-4}$ m/s.

The UK National Radiological Protection Board (now Public Health England) reviewed deposition velocities [30] and suggested 'best judgement' and 'conservative values'. For particulate of 1 μm aerodynamic diameter depositing on meadow grass and low crops (the most appropriate value to use when calculating ingestion dose) 'best judgement' and 'conservative values' are given as $6.61 \cdot 10^{-4}$ ms^{-1} and $3.35 \cdot 10^{-3}$ ms^{-1} respectively and for deposition in the urban environment (lawns, paved areas, etc.) $6.4 \cdot 10^{-4}$ ms^{-1} and $2.9 \cdot 10^{-3}$ ms^{-1} respectively.

For deposition of elemental iodine on vegetation, it has been concluded that the situation is complex, and deposition depends on many factors. Curves are given for the deposition velocity as a function of wind speed for different relative humidities. For deposition in the urban environment, values are given for different surfaces and for example 'best judgement' and 'conservative values' are given for lawns as $2.6 \cdot 10^{-3}$ ms^{-1} and $1 \cdot 10^{-2}$ ms^{-1} respectively, and for paved areas as $4.6 \cdot 10^{-4}$ ms^{-1} and $2.3 \cdot 10^{-3}$ ms^{-1} respectively. For methyl iodide, the study concluded that there are little data available but gives 'best judgement' and 'conservative values' as $1 \cdot 10^{-5}$ ms^{-1} and $1 \cdot 10^{-4}$ ms^{-1} respectively [30].

Since in this exercise, inhalation seems to be the dominant pathway, the different values here are unlikely to affect significantly the overall results. The values of dry deposition velocity in Table 9 are those used by the participants. The difference in the values used may reflect the use of conservative and best-estimate approaches.

Rain increases deposition of particulates and iodine depending on the rainfall rate. However, consideration of rainfall is not likely to have much of an effect on the results in this exercise. For the meteorological data used in this exercise, 54% of the hourly lines of data had no rain at all and a further 14% had a rainfall less than 0.01 mm/hour. None of the deterministic assessments considered rainfall. The probabilistic assessments considered rainfall in sampling meteorological sequences from the hourly data provided.

TABLE 9. DRY DEPOSITION VELOCITY USED BY THE PARTICIPANTS

Participant	Dry deposition velocity (ms^{-1})		
	Particulates (1 μm)	Elemental iodine (I_2)	Organic iodide (methyl iodide)
Argentina	$1 \cdot 10^{-3}$	-	-
Belarus	$3 \cdot 10^{-3}$	-	-
France	$5 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-4}$
Germany	$1 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$5 \cdot 10^{-4}$
India	-	-	-
Israel	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	-
Russia	$8 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-4}$
Spain	$1 \cdot 10^{-3}$	-	-
Ukraine	$2 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-4}$
UK	$1 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$1 \cdot 10^{-5}$

The parameter that has the biggest effect on the atmospheric dispersion results is the Stability Category. The participants usually used a stable category such as F as a conservative approach because this results in less dispersion and therefore higher doses; however, for elevated releases, this will not be conservative for short distances downwind since the plume may not disperse enough in the vertical direction to reach the ground. Instead unstable conditions (Category A or B) would be the conservative assumption since the increased vertical dispersion will cause the plume to reach the ground at shorter distances downwind. This is shown in Fig.13 for the 35 m release height considered in the exercise; the two curves cross at about 1.5 km in this case.

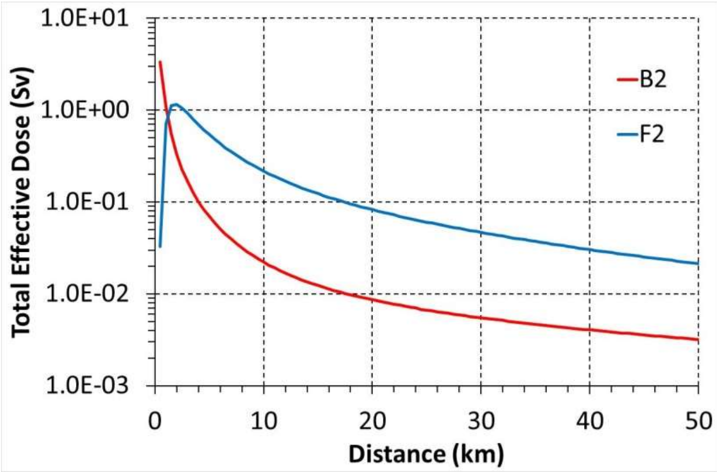

FIG.13. Comparison of B2 and F2 weather (adult, 7-day integration time for deposited dose)

Best-estimate approaches use typical conditions which usually correspond to neutral conditions (Category D). Windspeeds are correlated with the Stability Category and typical combinations would be D5 (Category D with a windspeed of 5 m/s), F2, B2, and A1.

The probabilistic assessments sampled the meteorological data file using the Stability Categories that occurred for the location and year of the data. The level of conservatism here comes in the choice of the percentile to use – e.g. 90th or 99th.

The height of the boundary layer assumed for each Stability Category can also have an effect on the calculated dose. For long distances downwind from the release, the plume becomes fully mixed in the vertical direction from the ground up to the bottom of the boundary layer; therefore, the higher the value for boundary layer selected, the lower the radionuclide concentration and hence the lower the dose will be.

Some example values for boundary layer heights used in the UK assessment [31] are shown in Table 10, which can be compared with the values used in WinMACCS – as used by the participants from Argentina and Spain – presented in Table 2.

TABLE 10. BOUNDARY LAYER HEIGHTS USED IN THE UK ASSESSMENT

Boundary layer heights for each Stability Category (m)					
A	B	C	D	E	F
1300	900	850	800	400	100

No details of the terrain type were provided for this exercise. Gaussian models can be modified to take account of different terrain types by use of a roughness length although this has only a minor effect.

4.4 IDENTIFICATION OF EXPOSURE PATHWAYS

The exposure pathways are discussed in Section 2.2.4 above. All the participants considered the major exposure pathways of inhalation, ground-shine, and cloud-shine; ingestion was considered by most participants but since the dose from ingestion depends on the choice of many parameters such as consumption rates for each food type – which may vary from Member State to Member State – ingestion dose was not included in the comparison in Section 5. Some participants did not consider beta-dose from deposition on skin and the inhalation of resuspended activities but these are usually very minor contributors to the total dose. The participants who did consider these pathways included those from Argentina and Spain, who used the MACCS code, and those from Germany and the UK who used the COSYMA and PC-COSYMA codes respectively. The participant from the Russian Federation noted that the skin pathway could be included if required. The participants from France and Ukraine noted that absorption of tritium through the skin is considered if the source term includes tritium.

Whether credit can be taken for implementation of protective actions such as food bans also varied among the participants.

The duration of the exposure is another important parameter. For the comparison exercise, pre-determined values were used to facilitate comparison; however, the regulatory requirements in different Member States may specify different time periods. The durations correspond to the time before protective actions, such as evacuation or food bans, can be implemented.

The regulatory requirements in some Member States – for example, the UK deterministic assessment (Target 8 of the ONR's Safety Assessment Principles [41]) – specify that unmitigated doses should be calculated (i.e. no evacuation or food bans); the rationale for this is that the unmitigated doses can be used as a surrogate for the economic costs of the accident in terms of the protective actions that need to be implemented (see Para. 752 f of Ref [41]) and the targets are set accordingly.

Thyroid dose is calculated mainly for determining whether the countermeasure of providing stable iodine tablets is necessary; it is not normally part of any risk or dose assessment against targets.

4.5 IDENTIFICATION OF REPRESENTATIVE PERSON FOR ASSESSING DOSES FROM POTENTIAL EXPOSURE SCENARIOS

The population distribution was defined for the purposes of this exercise. The population data comprises only numbers and locations. No information was provided on habit data such as food consumption rates for different types of food, breathing rates, fraction of time spent indoors or outdoors etc. Also. no details were provided about the age distribution of the population. Where data were not provided, the participants used whatever values they would normally use in their national assessments.

For the ingestion pathway, some participants considered different food stuffs; this is to be expected as agricultural practices and habit data (food consumption) differ between Member States. Consideration of all food types would not be practical so only the most important need to be considered. For other habit data there was little variation.

As far as the age groups are concerned, there are ICRP dose coefficient data available for the following age groups: 3 months, 1 year, 5 years, 10 years, 15 years and adult [33]. Data are also available for the fetus [42]. The age groups that participants used in their national case studies varied and are summarized in Table 11.

TABLE 11. AGE GROUPS USED IN NATIONAL CASE STUDIES

Participants of ENV-PE study	Age groups considered
Argentina	mean
Belarus	adult, infant
France	adult, child, infant
Germany	adult, infant
India	adult
Israel	infant
Russia	adult, infant
Spain	adult
Ukraine	six age groups
UK	adult, child, infant

For the comparison exercise, dose/risk values were requested for three age groups: infants (1-year old); children (10 years old); and adults.

In the UK for example, for deterministic assessments, three age groups would usually be assessed: adults, 10-year old children, and infants (1-year old children) and whichever receives the highest dose is used in the assessment. The total dose will depend on the combination of dose coefficients – which increase with decreasing age for inhalation and ingestion – and habit data such as breathing rates and food consumptions rates which usually decrease with decreasing age. It might also be assumed that children or infants spend more time indoors than adults and therefore shielding and location factors reduce the dose. In other words, no age group is an obvious choice as a conservative assumption. The assessment from Germany showed that the most exposed age group depended on distance from the release.

The identification of the representative person for assessing doses varied amongst participants. In some cases, it was a person at a specified location (a distance or at the site boundary) and in others at the location of highest dose or risk for a given age group.

Some participants did not use the population distribution provided. The population data specifies only where people live, not where they might go. There may be a requirement to calculate the dose at the site boundary or some pre-determined distance because people might be there at the time of the release even if there is no habitation there specified by the population data. In deterministic assessments some participants assumed the most exposed person was at a particular distance from the release and therefore didn't use the population distribution data. Other participants used the provided population distribution data to determine the closest habitation and calculated the dose at that point. In calculating longer term exposures, it may be more appropriate to use population data that specifies where people live.

In a probabilistic assessment, the dose at all the locations where people live may be calculated for each meteorological sequence used. This determines the risk or dose to all individuals in the assessment area and the most exposed individual is identified. The highest risk is not necessarily at the closest point to the release as it will depend on the meteorological conditions (for elevated releases the highest ground level concentration and therefore dose can occur some distance downwind of the release especially in stable conditions (Category E and F)), the frequency the wind blows in a particular direction, and other conditions (rainfall etc.).

For calculating the dose versus downwind distance, only the participant from Ukraine used the actual population distribution (settlement locations). The other participants calculated the doses at each distance regardless of whether there was any habitation or not. The UK participant did use the population distribution data to calculate the societal risk.

4.6 ASSESSMENT OF DOSE/RISK TO THE REPRESENTATIVE PERSON FROM POTENTIAL EXPOSURES

All the participants used dose coefficients from ICRP [32-34] either directly or through national regulations. For assessments of calculated risks, risk coefficients are also required; these can include risk of short-term fatalities, risks of long-term effects such as latent fatalities, incidence of cancer, and hereditary effects.

The risks of stochastic (long-term) health effects are assumed to be based on a linear dose response relationship with no threshold (LNT). For example, mainframe COSYMA and PC-COSYMA [43] – as used by the participants from Germany and the UK respectively – calculate the risks of fatal and non-fatal cancers in 10 organs as well as the risk of leukaemia and the risk of hereditary effects. The codes also consider deterministic (short-term) health effects. The various models used have been described in Ref. [43].

The participants from Argentina, Israel, Russian Federation, and Spain used coefficients published by the U.S. Environmental Protection Agency [44], applicable to the U.S. population, either directly or through use of the MACCS code.

The participants from Belarus used specific national data for risk coefficients. The UK participant used the PC-COSYMA code v2.03 which was updated to include the option of using UK-specific cancer risk coefficients published by the NRPB [45] or ICRP risk coefficients [46]; for this exercise the NRPB values were used. Both NRPB (at that time HPA and now Public Health England) [47] and ICRP [7] have since updated their risk coefficients as a result of more recent epidemiological studies; in its report, HPA makes the following statement about these risk estimates:

> "The UK-specific risk estimates for radiation-induced cancer given in this document are not intended to replace the more general values that ICRP has developed for setting standards in radiological protection for a world population. In that case it is necessary to have values that different countries can use consistently. The UK-specific values are intended for use in calculating late health effects within the UK population where more precise information is required – for example, in accident consequence assessments or in determining probability or causation following significant radiation exposures."

The participant from Israel used the ICRP risk coefficient [46] to weight all increases in risk including cases of sufferers from a disease (with or without latent deaths). This means that the suffering caused from exposure to 1 Sv is equivalent to 7% rise in the risk of cancer.

Table 12 reproduces the risk coefficients from ICRP Publication 103 [7] which also gives the previous values from ICRP Publication 60 [46]. From this it can be seen that the recommended risk coefficients have been reduced in the ICRP publication.

TABLE 12. DETRIMENT-ADJUSTED NOMINAL RISK COEFFICIENTS (10^{-2} Sv^{-1}) FOR STOCHASTIC EFFECTS AFTER EXPOSURE TO RADIATION AT LOW DOSE RATE

Exposed population	Cancer		Heritable effects		Total	
	ICRP-103	ICRP-60	ICRP-103	ICRP-60	ICRP-103	ICRP-60
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

For comparison, the UK-specific value used in PC-COSYMA (version 2.03) is $5.9 \cdot 10^{-2}$ Sv^{-1} [45] and US-specific value used in MACCS is $5.75 \cdot 10^{-2}$ Sv^{-1} [44] for radiation-induced fatal cancer for all ages and both sexes for low doses or dose rates.

The differences in the various risk coefficients used are small – certainly compared with other differences in approach – and are unlikely to have a significant effect on the results used in this comparison.

5 SUMMARY OF RESULTS AND DISCUSSION

5.1 DOSE CALCULATION RESULTS

The same source term and the probability of release scenario were postulated for all national studies presented in this report. These data are the result of probabilistic safety assessments of level 1 and 2 which are publicly available in the open domain [18, 29]. A one-year set of meteorological data was taken from the data base comprising the results of real measurements at the site of an operating NPP. These meteorological data were used as an input for most (see the 3rd bullet of Section 4.2.1) of the national studies in this report. However, in some cases this information was subject to preliminary processing prior to the main part of the calculation. Other environmental data (landscape, population distribution etc.) used for the assessment are not related to any existing site. This set of input has been developed by the participants of this exercise assuming locations of the reactor site and populated areas which could provide sufficient information for further comparison of different assessment tools and methods.

Several participants of the exercise used commercially available computer tools for their calculations; other participants applied methodologies and tools developed in their institutions or relied on the generic estimation methods. Simplified methods could not provide as many details in the results as could be obtained by sophisticated computer tools; they normally produce conservative estimates of doses which can be interpreted relatively easy due to the transparency of the algorithms used. Authors have found these approaches to be applicable for providing a generalized prospective assessment of radiological impacts from the potential accidents identified through safety analysis.

Detailed results of calculations provided by national experts are presented in Annexes I to X to this publication. This section summarises the results of dose estimations. Figures 14 to 31 below show comparisons of the results of each participant's assessment for those using a deterministic method and Figures 32 to 87 for those using a probabilistic method. From the comparison of the deterministic methodologies, the following conclusions can be drawn:

- The differences and similarities can be most clearly seen in the comparison for cloud-shine dose (Figure 28) since the results depend only on the time-integrated activity concentration in air, the time spent indoors and outdoors, the shielding effect of buildings and the dose coefficients for cloud-shine. In comparison to the dose from deposited activity and inhalation, cloud-shine dose depends on fewer parameters and so there is less scope for participants to choose different values. The dose from deposited activity, in addition to depending on all the parameters values and models used for dispersion, also depends on the choice of values for deposition velocities. Similarly, inhalation dose also depends on the value used for breathing rate and the choice of lung clearance type for the inhalation dose coefficient.
- There are two broad groups of results:
    - The two groups differ from each other at most distances by about an order of magnitude.
    - Within each group there is reasonably close agreement.
    - The difference between the two groups is probably due to the choice of stability category which reflects whether a conservative (stable conditions – for example Category F) or best-estimate (neutral conditions – for example Category D) approach was adopted.
    - Some participants (India and Russia) performed calculations for six stability categories; results for Category D and F are shown in the plots below.

- The participant from the UK performed the analysis on a best-estimate basis for comparison with the UK's severe accident targets.
- The comparison of inhalation dose (Figures 26 and 27 for adult and infant respectively) also shows a clear grouping into two groups indicating that similar assumptions have been made by participants on the parameters listed in the first bullet above.
- The comparison of deposition dose (or ground-shine) (Figures 29 to 31 for integration periods of 1, 2, and 7 days respectively) reflects both the assumptions made for dispersion and the deposition velocities assumed for particulate and elemental iodine as well as the atmospheric dispersion assumptions discussed above.
    - The upper group is broadly consistent, although the results from the participant from India seem somewhat anomalous at long distances.
    - The low values for the UK assessment compared with the assessment from Russia (both Stability Category D) – about a factor of 5 lower at short distances falling to about a factor 9 lower at 50 km – probably reflects different assumptions on deposition velocity (the UK participant used lower values consistent with its selection of a best-estimate approach), and possibly also reflects modelling of the plume depletion from deposition which will have a larger effect at longer distances.
- The results for thyroid dose show a similar pattern.
- Some results show a peak dose at 2.5 km (the exact location may lie between 1.0 and 3.5 km as these were the distances selected); this probably reflects:
    - The assumptions made about the effective release height; i.e. whether any plume rise effects were accounted for due to the heat associated with the release increasing the effective height of the release or whether any building wake effects were accounted for reducing the effective height.
    - The stability category selected – for a given effective release height, the peak ground-level concentration will occur further downwind for more stable conditions.
- Other differences in the results may be due to different assumptions on release duration, boundary layer heights, and terrain (as discussed above).

With regard to comparison of the probabilistic methodologies, it is more difficult to draw conclusions because there are fewer assessments and less overlap between the assessments of the different participants; however, the following conclusions are drawn:

- There is generally greater consistency between the assessments when comparing the same percentiles (apart from the assessment from Argentina which is discussed below) than for the deterministic assessments.
    - This is because the main reason for the large variation in the deterministic results is due to the level of conservatism used (e.g. D5 weather for a best-estimate approach and F2 weather for a conservative approach).
    - For the probabilistic assessments, on the other hand, the level of conservatism is reflected in the percentile – although choices of parameter values such as deposition velocities may also affect the results – and comparing assessments for the same percentiles is comparing assessments with the same level of conservatism.
    - Differences in approach may then be reflected in which percentile is used for the national assessment.
- The results from the participants from Germany and the UK are very close as might be expected as they used the same computer code (COSYMA) albeit different versions.
    - The small differences between these two assessments that are observed probably result from the different sampling regimes used, namely cyclic or stratified (as discussed in Annex X).
- The results from the Argentinian participant are approximately an order of magnitude higher than those of the other participants other than those for the maximum dose.

- This is probably a consequence of different approaches for processing the results from the different meteorological sequences. For example, COSYMA – as used by the German and UK participants – calculates results for each radius and for each sector (direction) defined (in the UK case 72) for each of the 144 meteorological sequences sampled; it then determines the percentiles for each radius from the 144·72 results. This gives the same results whichever way the wind is blowing and so no account is taken of the actual windrose. The Argentinian assessment, on the other hand, selects the direction with the maximum result for each radius and calculates the percentiles from the one per sample results.
    - When the maximum value is required rather than a percentile, COSYMA finds the maximum value from the 144·72 results for each radius which then essentially becomes the same as the Argentinian approach – both approaches are finding the maximum for each radius; this explains why there is much better agreement among the participants for the maximum than there is for the other percentiles.
    - The maximum value from the sampling is not really a statistically meaningful quantity as the values will depend on the sample taken and the size of the sample. The maximum will generally increase with increasing size of the sample whereas the other percentiles should converge on a value.
- A different approach was used by the participant from Ukraine:
    - In this approach, the doses were calculated at actual locations for the areas of habitation (the distance and the bearing).
    - Using this approach requires a much larger sample; this is because for many meteorological sequences, the wind direction will be away from the habitation and lead to no dose at all – in fact, the Ukrainian assessment used every sequence, i.e. 8760 samples as opposed to the 144 used by the German and UK participants.
    - When using the actual locations, the percentiles of dose for some locations further away might give higher doses than locations closer in if the wind blows in that direction more often and with more stable weather.
    - The assessment from Ukraine (Annex IX) shows the windrose (inverted to show the direction to which the wind blows) overlaid on the location of the population centres; this shows that the frequency with which the wind blows towards the populations at 2.5 km and 3.5 km is much lower than that for the other populations.
    - This approach does use the windrose and the population distribution.
    - This is why the results from the Ukrainian participant show a variable pattern with distance when compared with the monotonically decreasing pattern shown in the results from the other participants for percentiles other than the maximum (Figure 36 to Figure 39, Figure 44 to Figure 55, Figure 60 to Figure 63).
    - Comparing the results from Ukraine with those from the UK, for example, for total dose and 2-day integration time (Figure 36 to Figure 39) shows that sampling and not considering wind direction is giving a reasonably good representation of the full dataset (with a more uniform population distribution and windrose the comparison would have been even better).
- Another difference between the assessments may be how – or whether – the release is split into different phases to reproduce the release profile.

Figures 88 and 89 show a comparison of deterministic and probabilistic results using the UK results as an example; the following conclusions are drawn:

- The best-estimate or typical weather condition (D5) approach roughly corresponds to the 99th percentile – in other words, making the deterministic assumption that the exposed person is directly downwind of the release is roughly equivalent to using the 99th percentile in a probabilistic assessment.

- o This case study considers 72 sectors giving a 1/72 chance of wind blowing in a given direction. The weather most likely will be typical. From the meteorological data file used in this exercise ~37% of the hourly data lines were category D.
  - o Fractions of weather records attributed to other categories are the following: ~9% attributed to category B, ~19% to category C, ~15% and ~18% to categories E and F. These categories are less likely and would correspond to a higher percentile.
- The conservative weather condition (F2) approach roughly corresponds to the maximum values from the probabilistic assessment; this is again as might be expected although it also shows that F2 does not give the maximum dose at distances close to the release point for elevated releases as is the case here.
  - o For short distances, the probabilistic maximum dose is much higher than for a deterministic assessment using F2 weather conditions; this is because, as discussed above, it may take some distance for the plume to ground in stable conditions (Category E and F) and unstable weather (Category A or B) may give higher air concentrations close to the release.
  - o For the probabilistic assessments, the meteorological sequence that gives the maximum value at each distance may be different; the meteorological sequence that gives the maximum dose may be different at different distances and the maximum dose possible may be higher at distances further downwind in some cases.

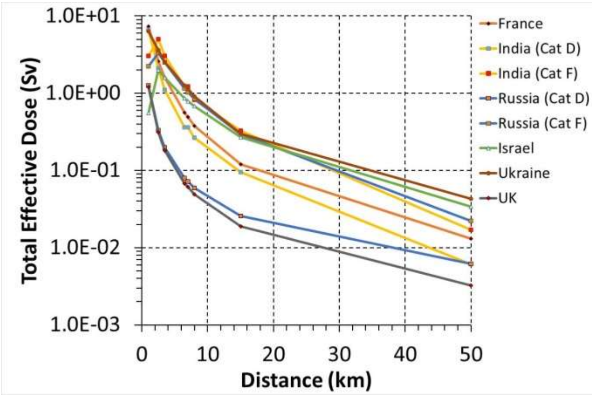

FIG.14. Total Effective Dose (adult, 1-day integration for deposited dose)

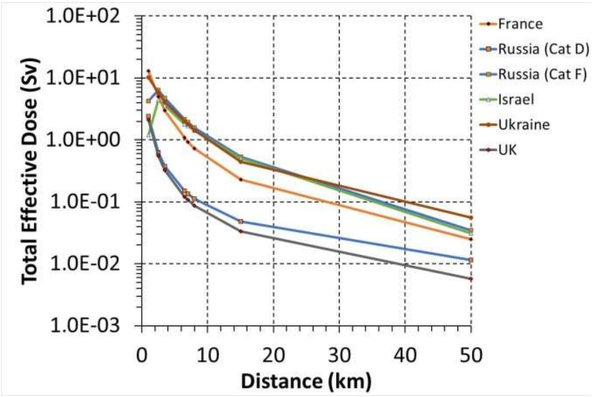

FIG.15. Total Effective Dose (infant, 1-day integration for deposited dose)

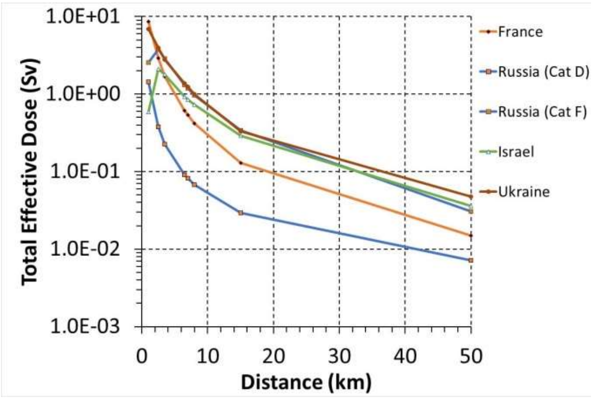

FIG.16. Total Effective Dose (adult, 2-day integration for deposited dose)

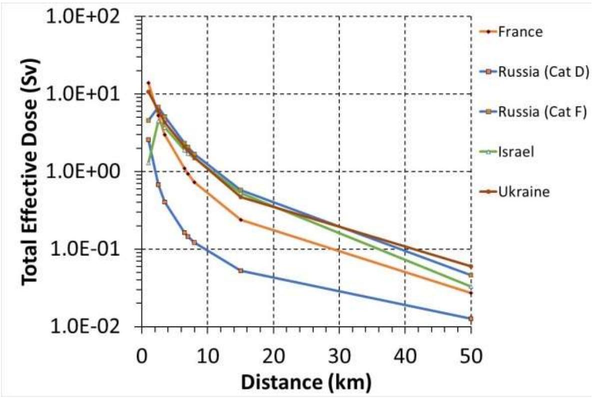

FIG.17. Total Effective Dose (infant, 2-day integration for deposited dose)

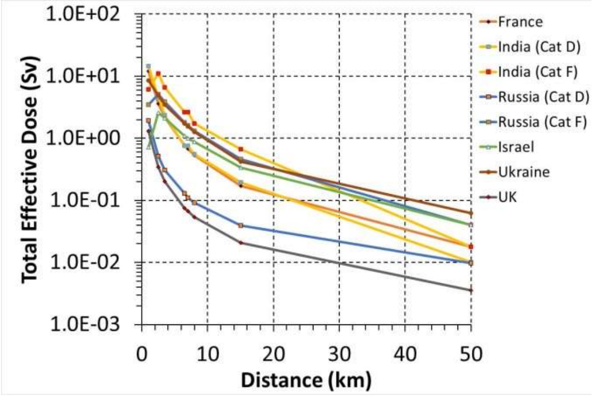

FIG.18. Total Effective Dose (adult, 7-day integration for deposited dose)

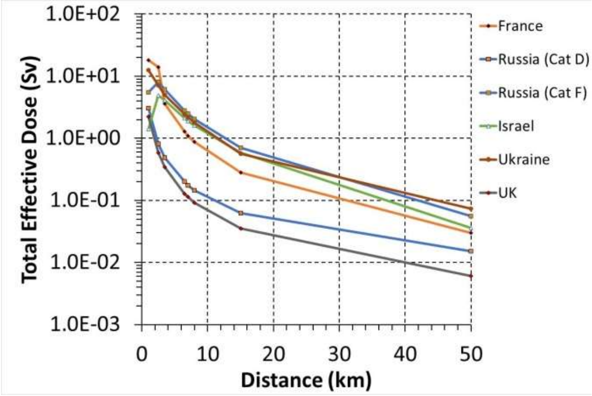

FIG.19. Total Effective Dose (infant, 7-day integration for deposited dose)

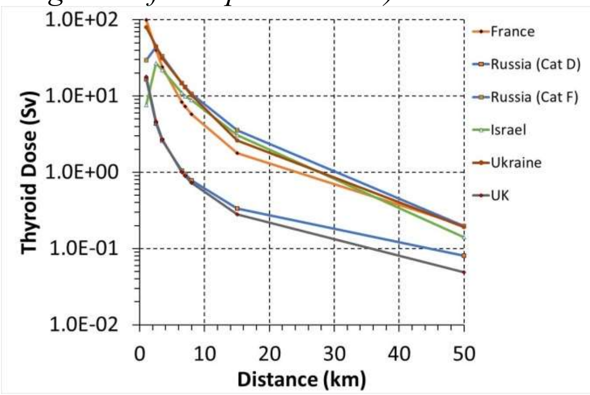

FIG.20. Thyroid Dose (adult, 1-day integration for deposited dose)

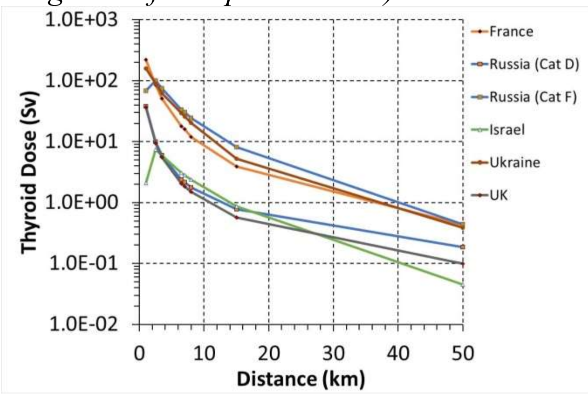

FIG.21. Thyroid Dose (infant, 1-day integration for deposited dose)

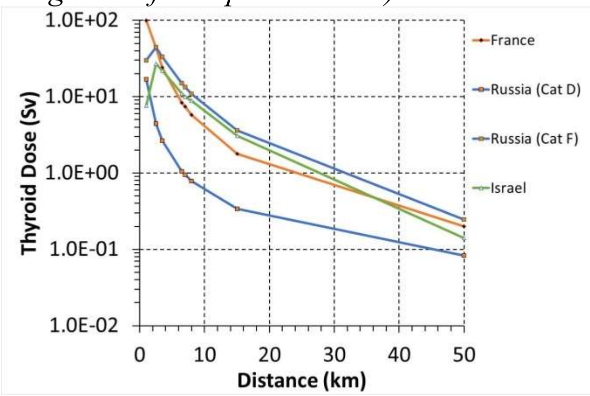

FIG.22. Thyroid Dose (adult, 2-day integration for deposited dose)

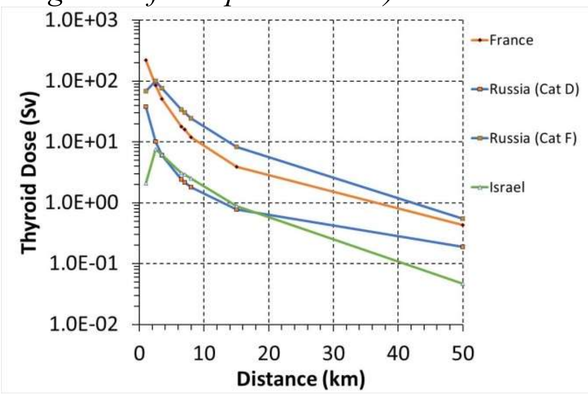

FIG.23. Thyroid Dose (infant, 2-day integration for deposited dose)

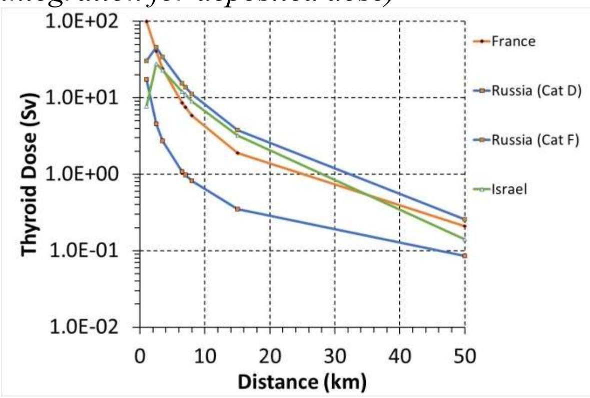

FIG.24. Thyroid Dose (adult, 7-day integration for deposited dose)

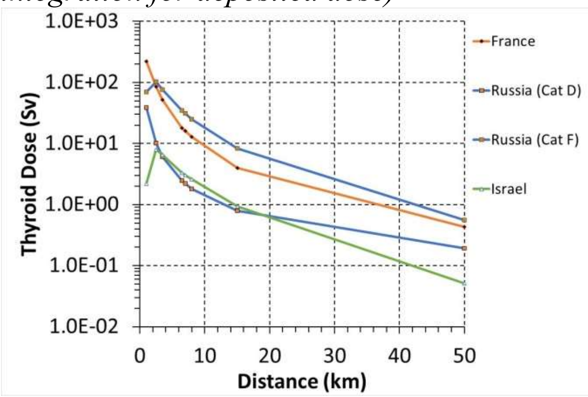

FIG.25. Thyroid Dose (infant, 7-day integration for deposited dose)

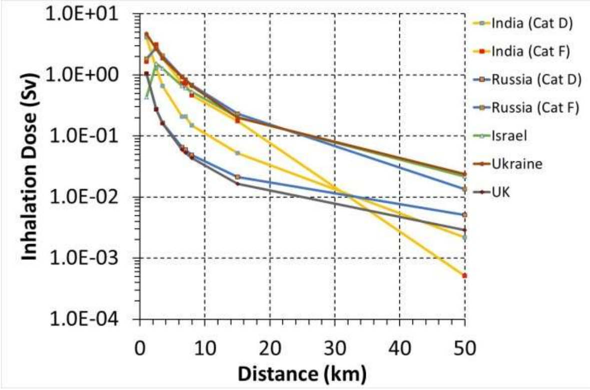

FIG.26. Inhalation Dose (adult)

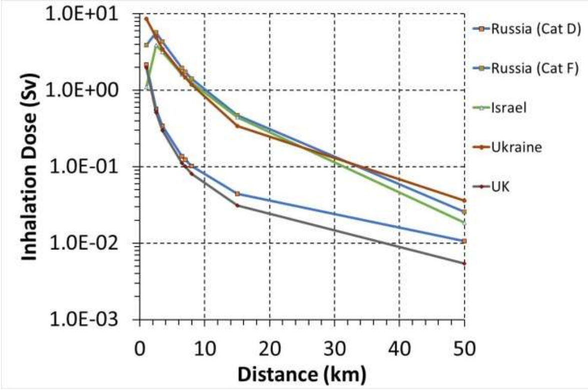

FIG.27. Inhalation Dose (infant)

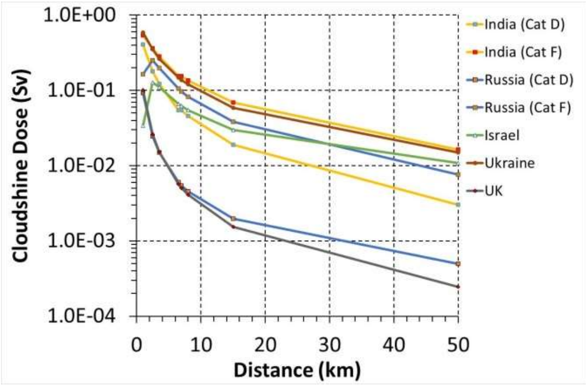

FIG.28. Cloud shine dose

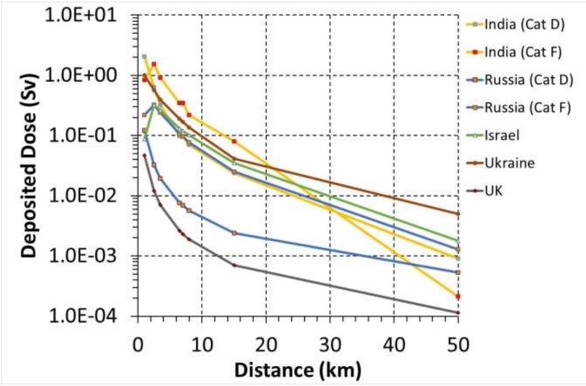

FIG.29. Deposited Dose (1-day integration)

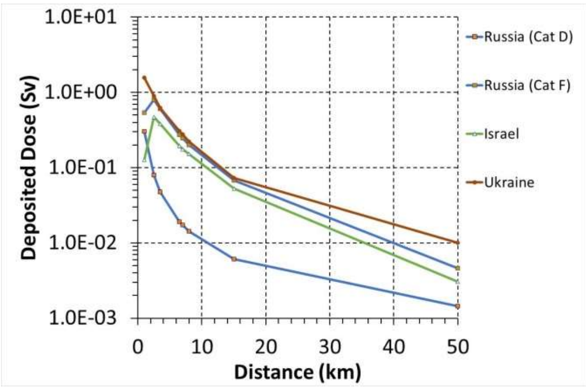

FIG.30. Deposited Dose (2-day integration)

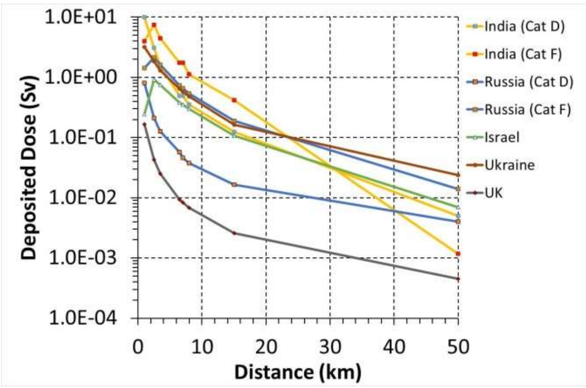

FIG.31. Deposited Dose (7-day integration)

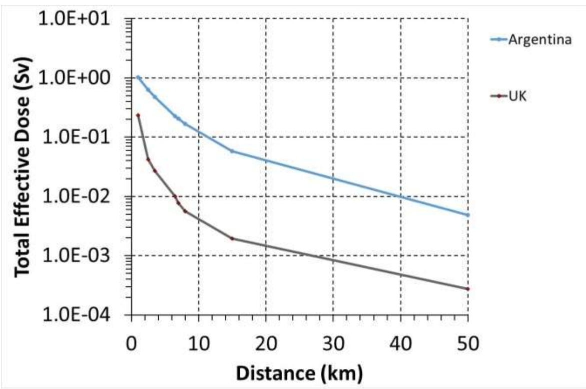

FIG.32. Total Effective Dose, 90th percentile (adult, 1-day integration for deposited dose)

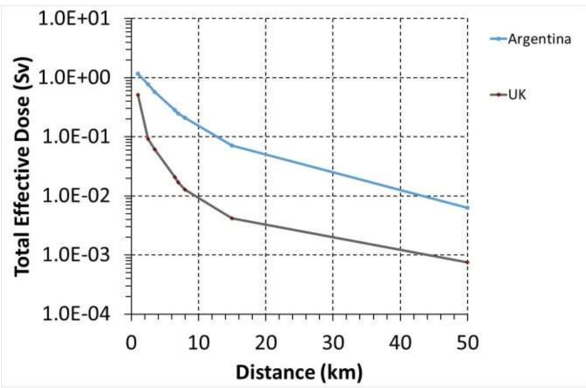

FIG.33. Total Effective Dose, 95th percentile (adult, 1-day integration for deposited dose)

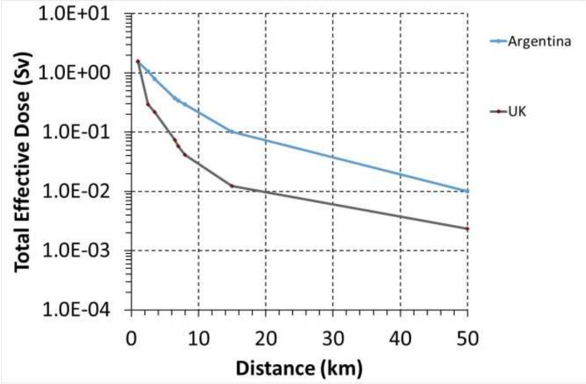

FIG.34. Total Effective Dose, 99th percentile (adult, 1-day integration for deposited dose)

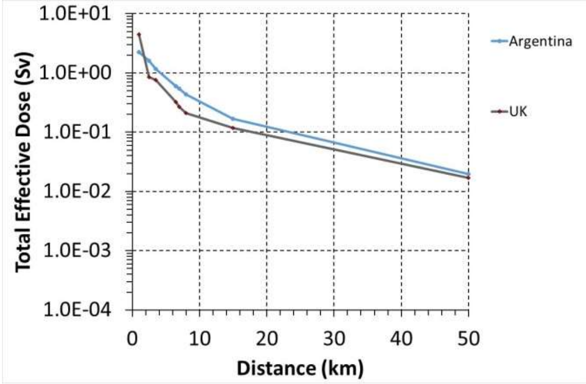

FIG.35. Total Effective Dose, maximum (adult, 1-day integration for deposited dose)

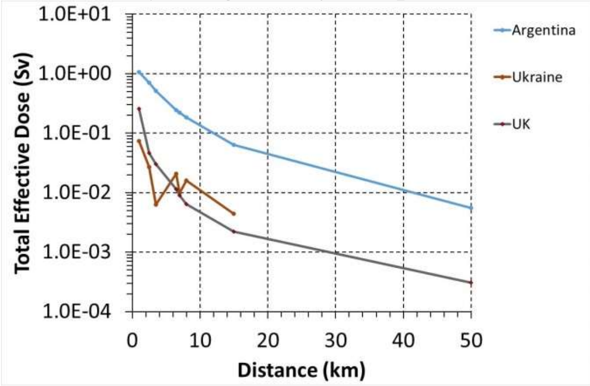

FIG.36. Total Effective Dose, 90th percentile (adult, 2-day integration for deposited dose)

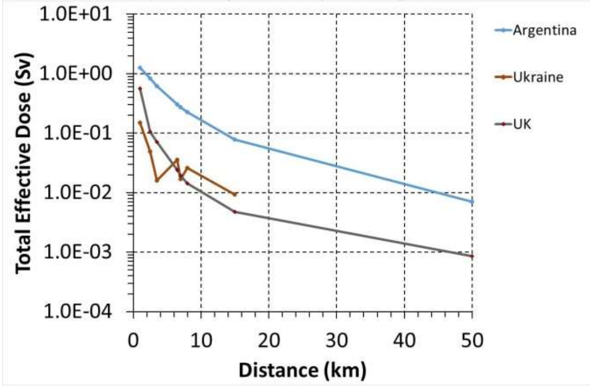

FIG.37. Total Effective Dose, 95th percentile (adult, 2-day integration for deposited dose)

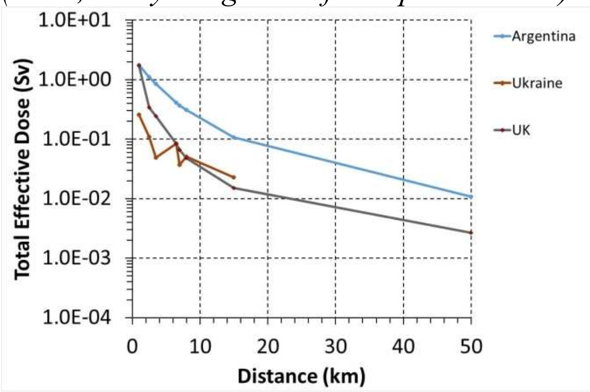

FIG.38. Total Effective Dose, 99th percentile (adult, 2-day integration for deposited dose)

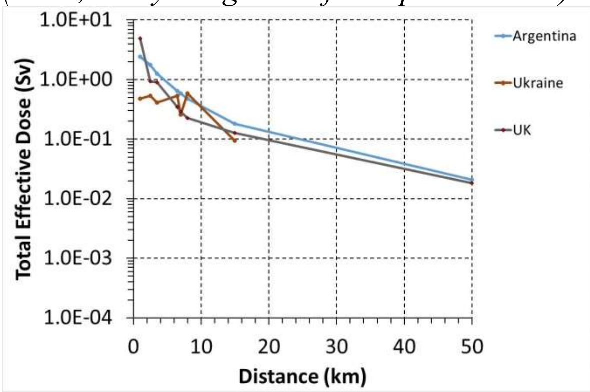

FIG.39. Total Effective Dose, maximum (adult, 2-day integration for deposited dose)

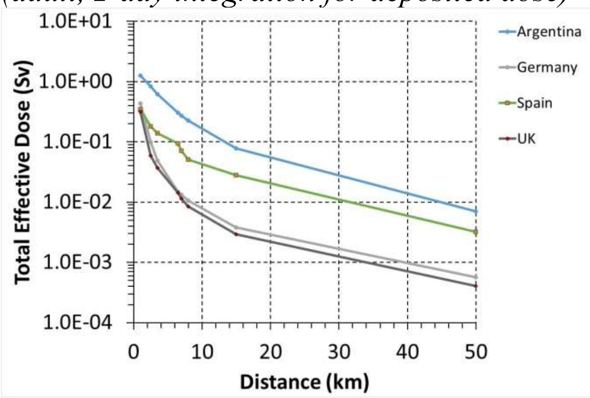

FIG.40. Total Effective Dose, 90th percentile (adult, 7-day integration for deposited dose)

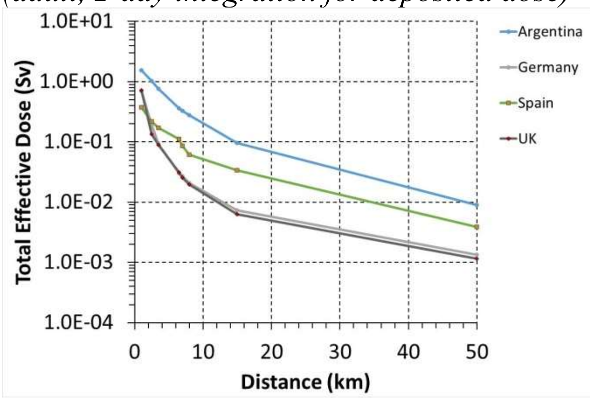

FIG.41. Total Effective Dose, 95th percentile (adult, 7-day integration for deposited dose)

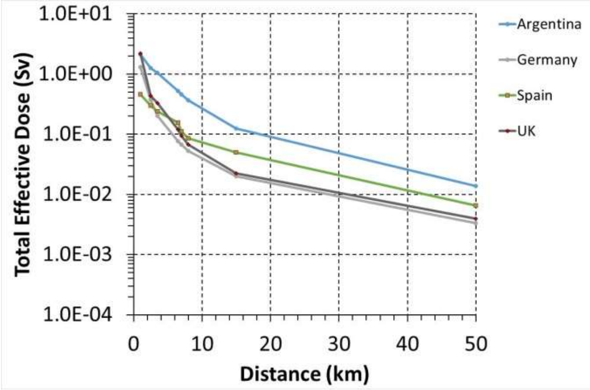

FIG.42. Total Effective Dose, 99th percentile (adult, 7-day integration for deposited dose)

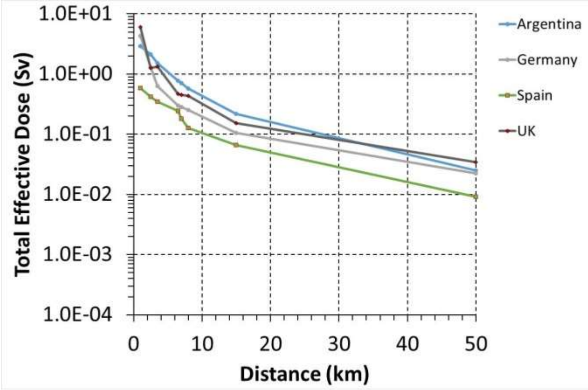

FIG.43. Total Effective Dose, maximum (adult, 7-day integration for deposited dose)

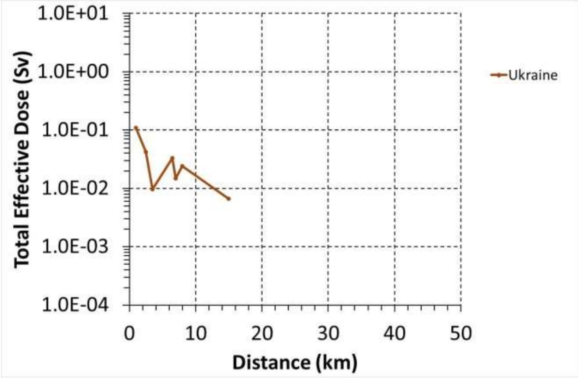

FIG.44. Total Effective Dose, 90th percentile (infant, 2-day integration for deposited dose)

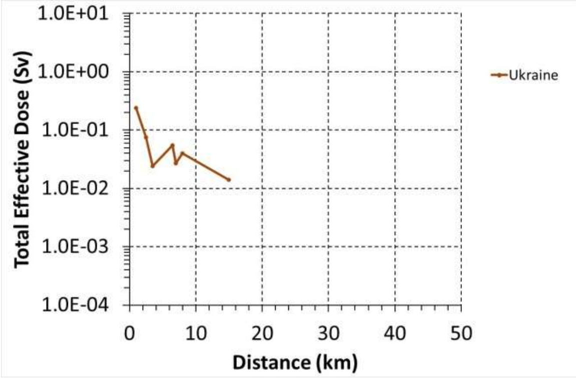

FIG.45. Total Effective Dose, 95th percentile (infant, 2-day integration for deposited dose)

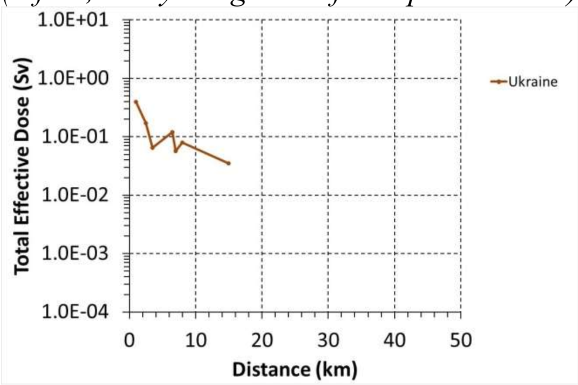

FIG.46. Total Effective Dose, 99th percentile (infant, 2-day integration for deposited dose)

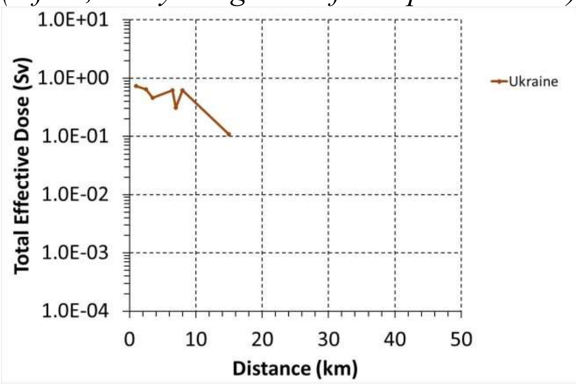

FIG.47. Total Effective Dose, maximum (infant, 2-day integration for deposited dose)

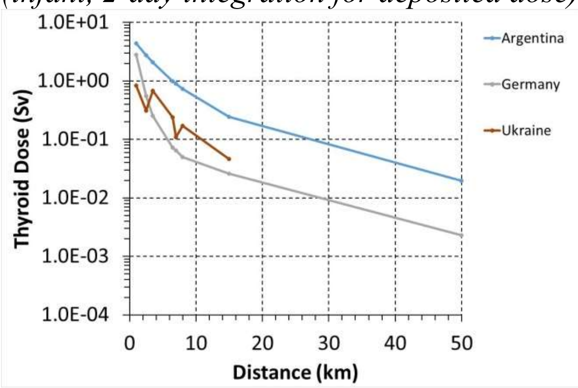

FIG.48. Thyroid Dose, 90th percentile (adult, 1-day integration for deposited dose, Ukraine results for 2 days added to aid comparison)

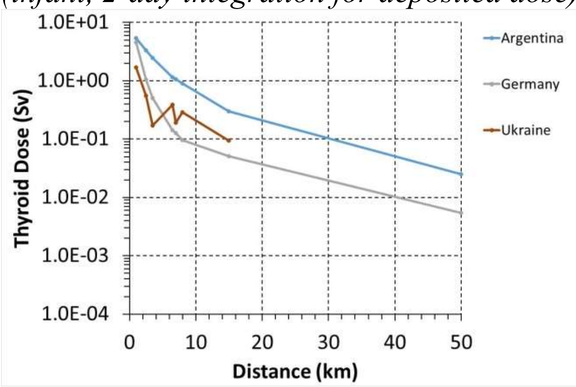

FIG.49. Thyroid Dose, 95th percentile (adult, 1-day integration for deposited dose, Ukraine results for 2 days added to aid comparison)

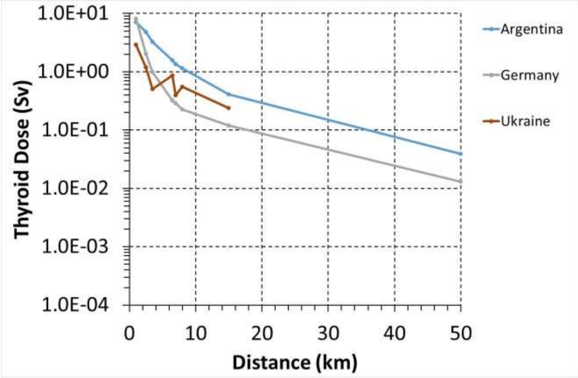

FIG.50. Thyroid Dose, 99th percentile (adult, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

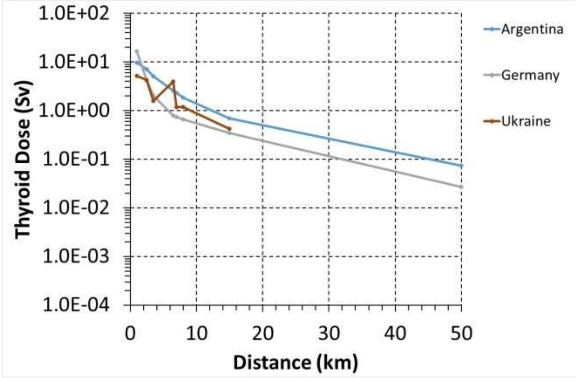

FIG.51. Thyroid Dose, maximum (adult, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

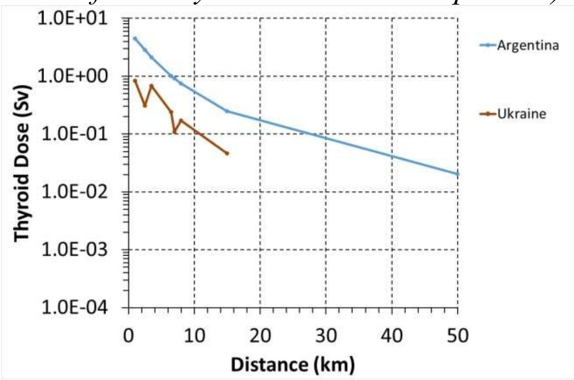

FIG.52. Thyroid Dose, 90th percentile (adult, 2-day integration for deposited dose)

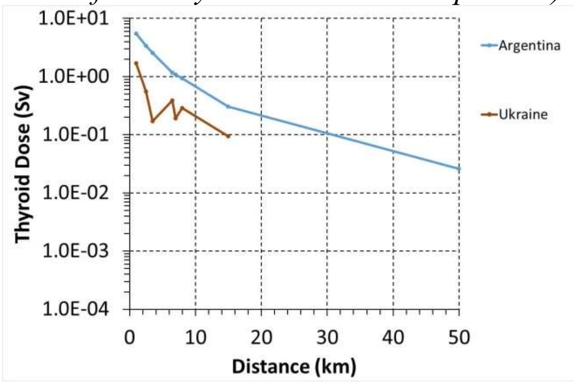

FIG.53. Thyroid Dose, 95 th percentile (adult, 2-day integration for deposited dose)

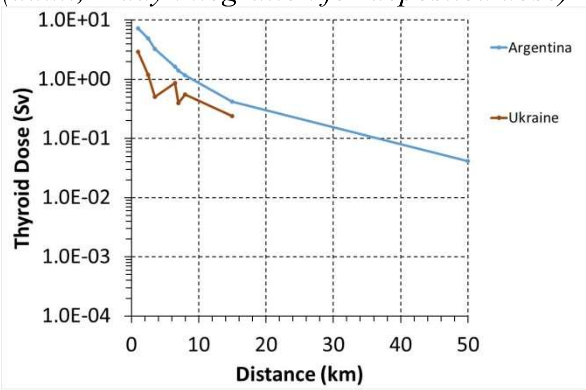

FIG.54. Thyroid Dose, 99th percentile (adult, 2-day integration for deposited dose)

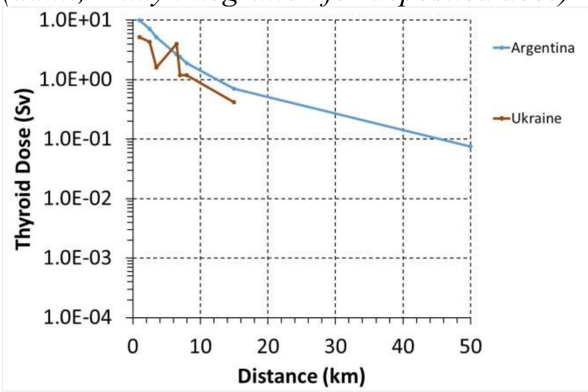

FIG.55. Thyroid Dose, maximum (adult, 2-day integration for deposited dose)

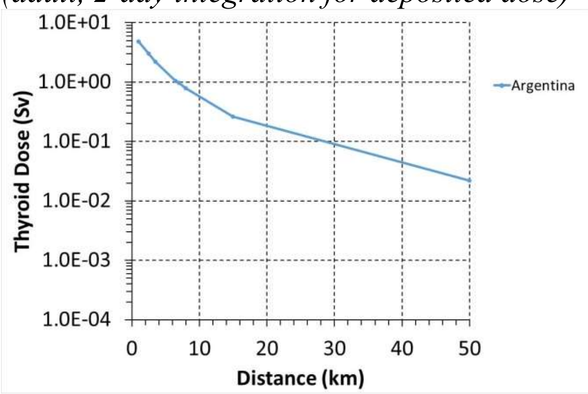

FIG.56. Thyroid Dose, 90th percentile (adult, 7-day integration for deposited dose)

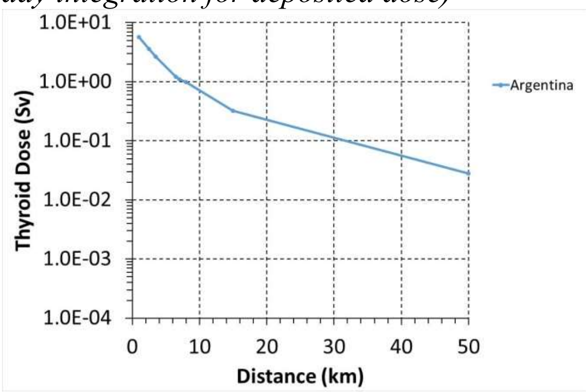

FIG.57. Thyroid Dose, 95th percentile (adult, 7-day integration for deposited dose)

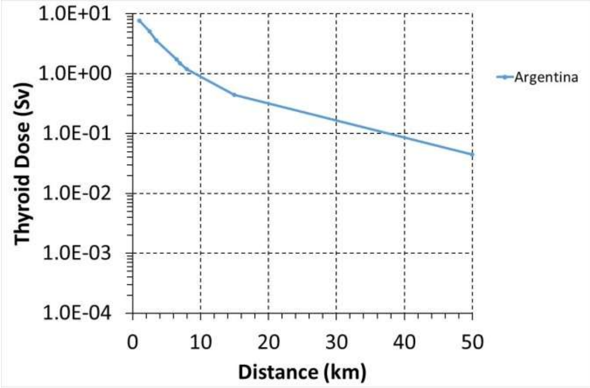

FIG.58. Thyroid Dose, 99th percentile (adult, 7-day integration for deposited dose)

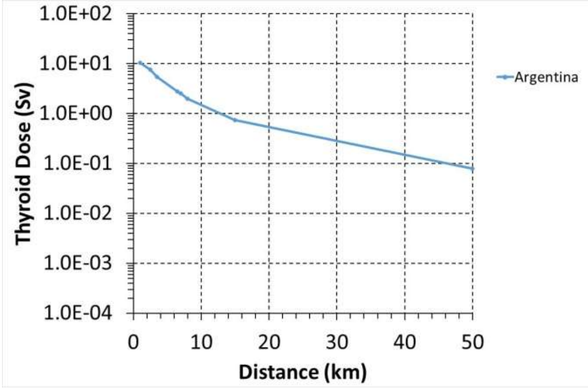

FIG.59. Thyroid Dose, maximum (adult, 7-day integration for deposited dose)

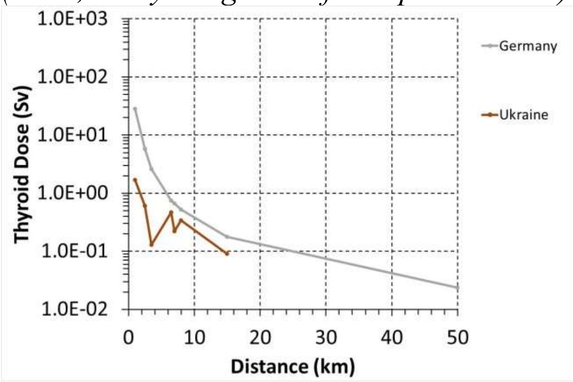

FIG.60. Thyroid Dose, 90th percentile (infant, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

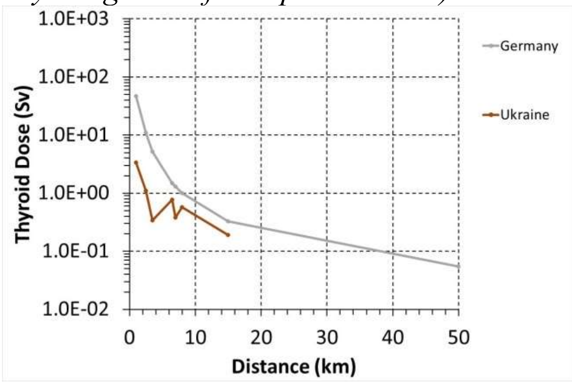

FIG.61. Thyroid Dose, 95th percentile (infant, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

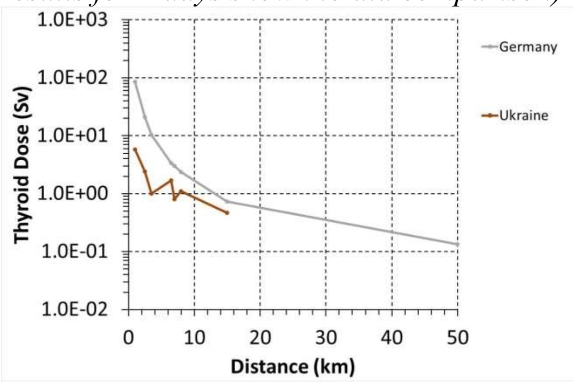

FIG.62. Thyroid Dose, 99th percentile (infant, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

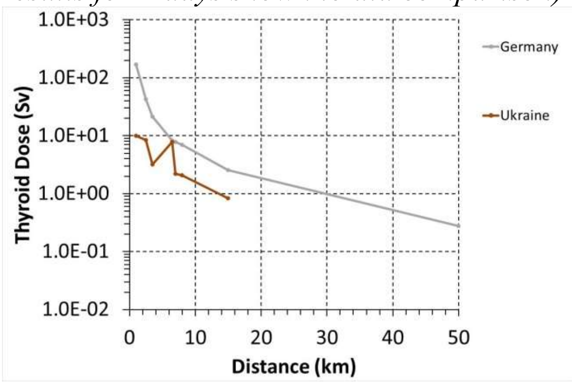

FIG.63. Thyroid Dose, maximum (infant, 1-day integration for deposited dose, Ukraine results for 2 days shown to aid comparison)

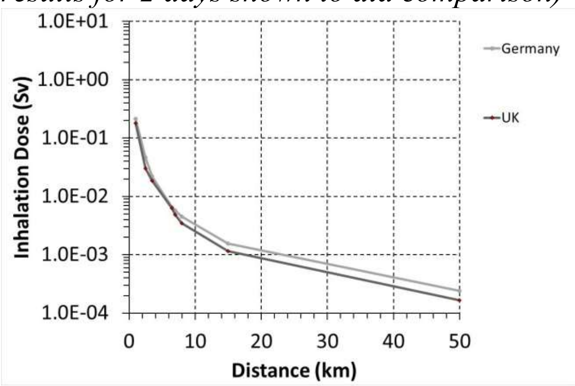

FIG.64. Inhalation Dose, 90th percentile (adult)

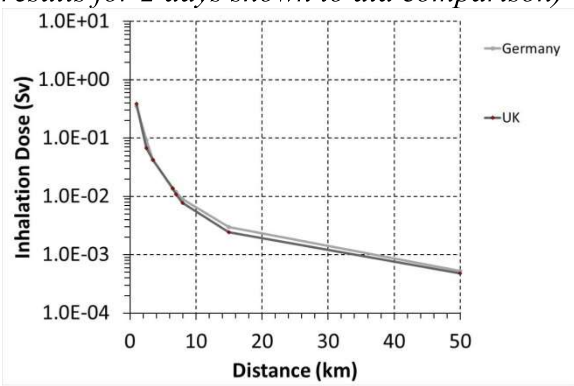

FIG.65. Inhalation Dose, 95th percentile (adult)

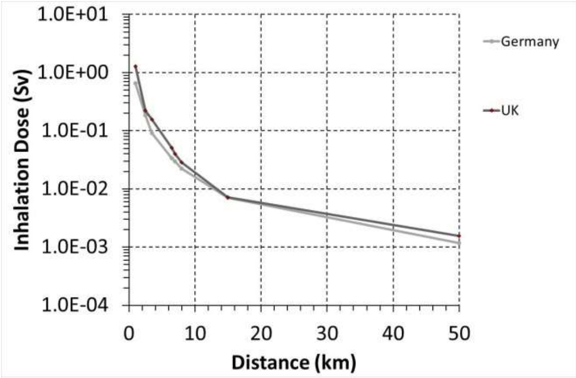

FIG.66. Inhalation Dose, 99th percentile (adult)

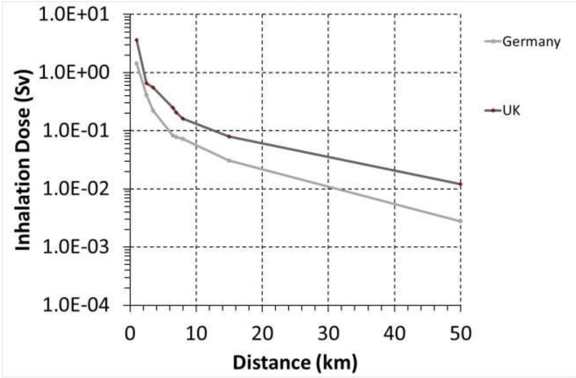

FIG.67. Inhalation Dose, maximum (adult)

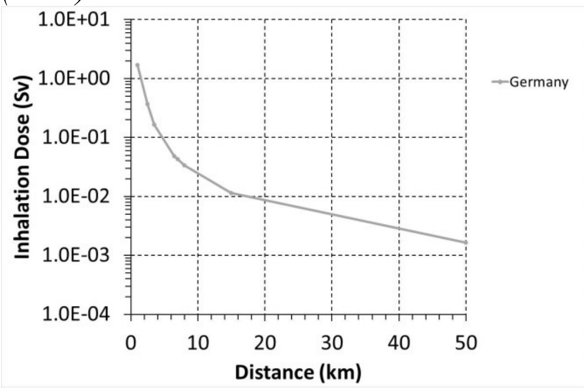

FIG.68. Inhalation Dose, 90th percentile (infant)

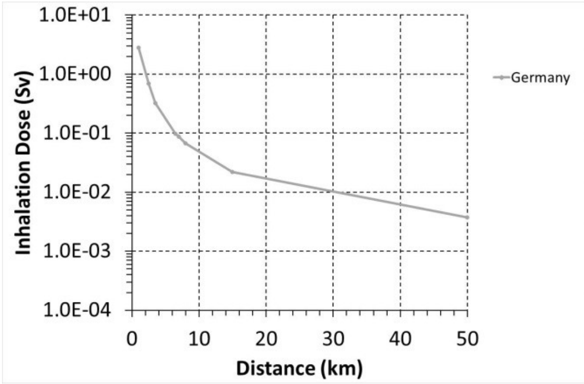

FIG.69. Inhalation Dose, 95th percentile (infant)

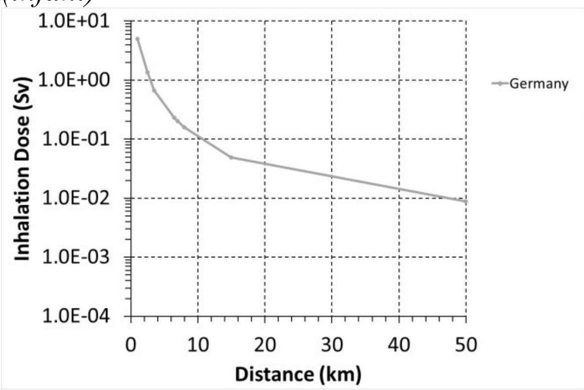

FIG.70. Inhalation Dose, 99 th percentile (infant)

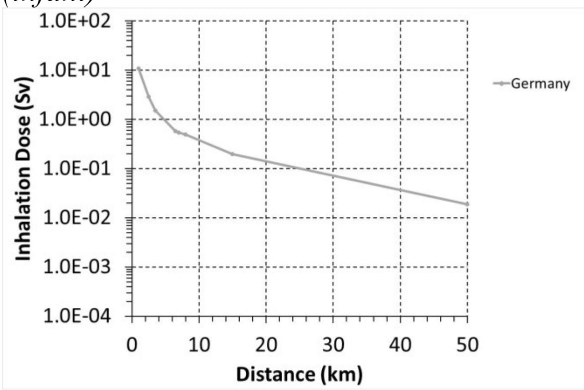

FIG.71. Inhalation Dose, maximum (infant)

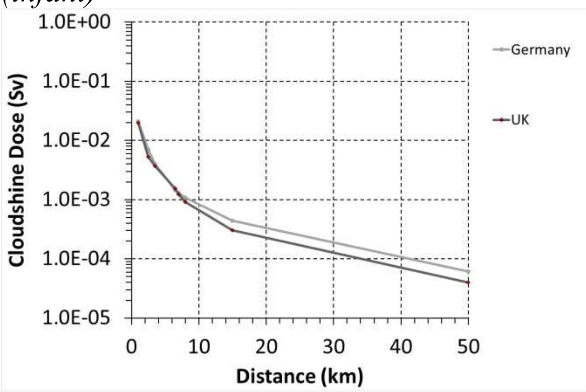

FIG.72. Cloud-shine Dose, 90 th percentile

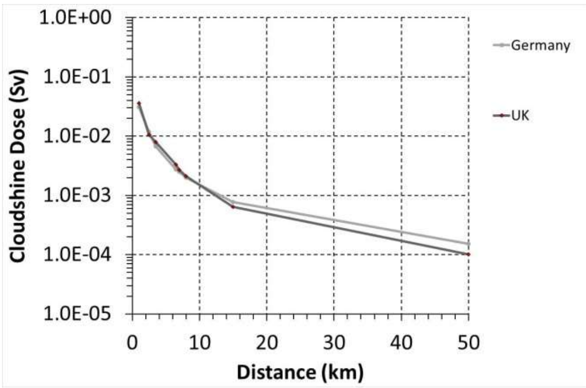

FIG.73. Cloud-shine Dose, 95 th percentile

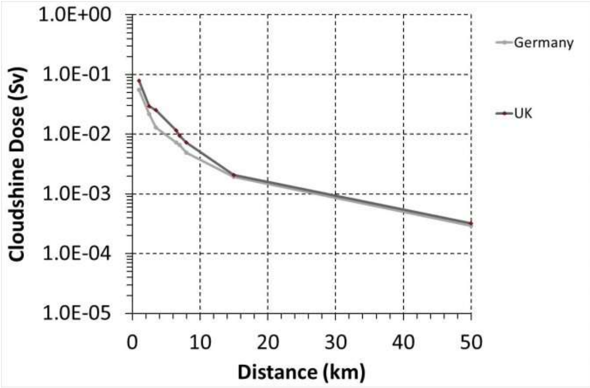

FIG.74. Cloud-shine Dose, 99 th percentile

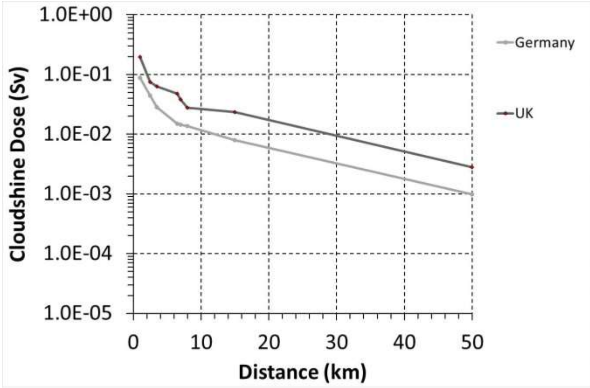

FIG.75. Cloud-shine Dose, maximum

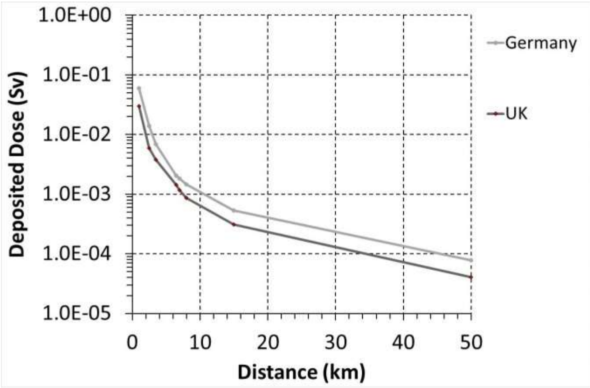

FIG.76. Deposited Dose, 90 th percentile (1-day integration)

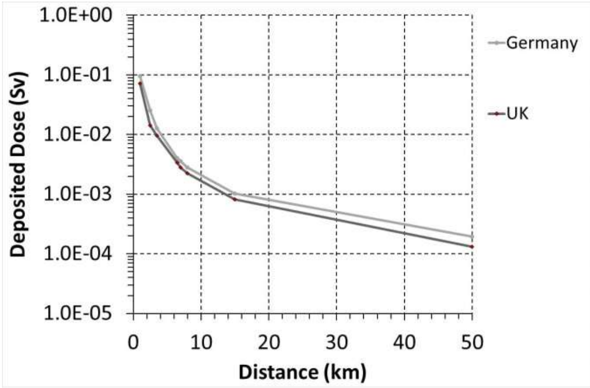

FIG.77. Deposited Dose, 95 th percentile (1-day integration)

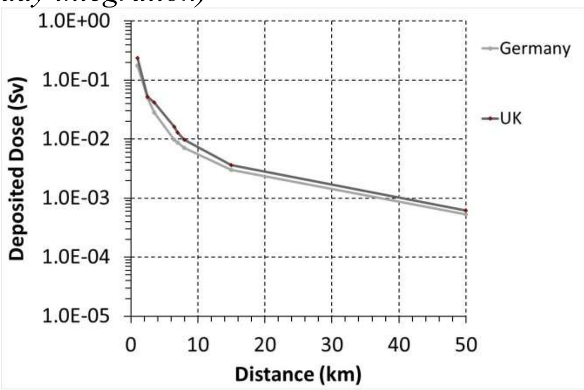

FIG.78. Deposited Dose, 99 th percentile (1-day integration)

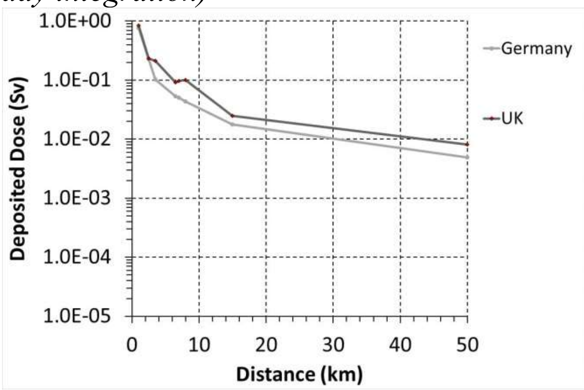

FIG.79. Deposited Dose, maximum (1-day integration)

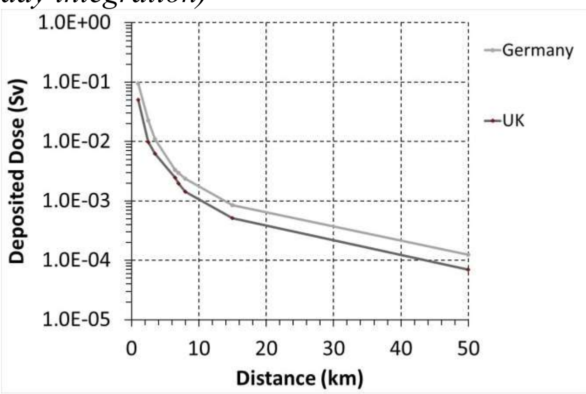

FIG.80. Deposited Dose, 90 th percentile (2-day integration)

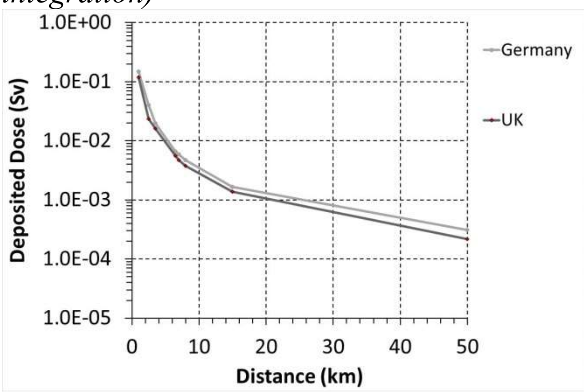

FIG.81. Deposited Dose, 95 th percentile (2-day integration)

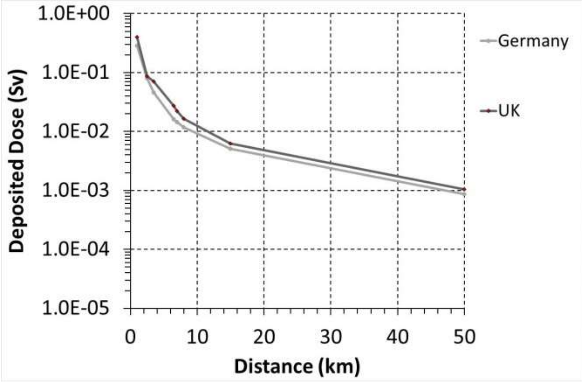

FIG.82. Deposited Dose, 99 th percentile (2-day integration)

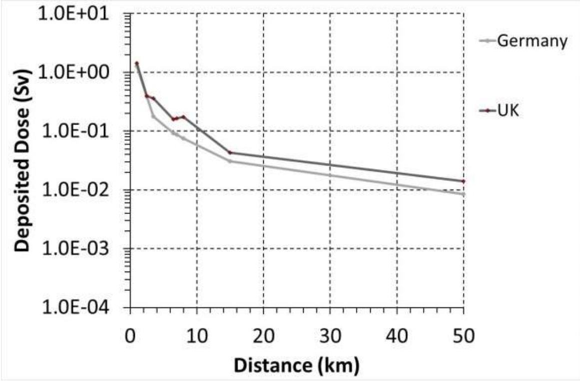

FIG.83. Deposited Dose, maximum (2-day integration)

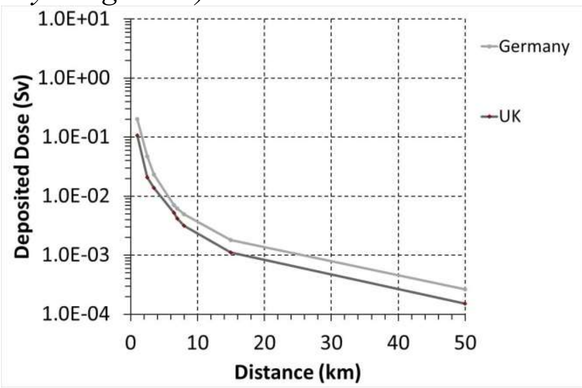

FIG.84. Deposited Dose, 90th percentile (7-day integration)

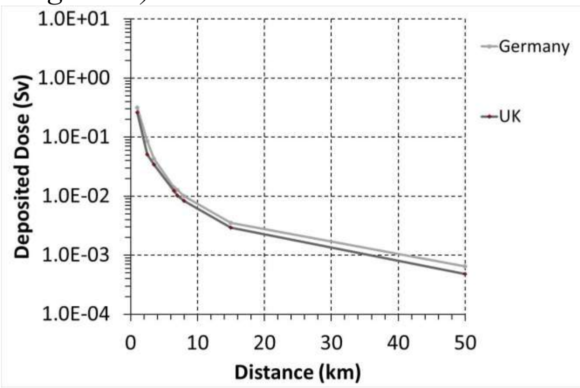

FIG.85. Deposited Dose, 95th percentile (7-day integration)

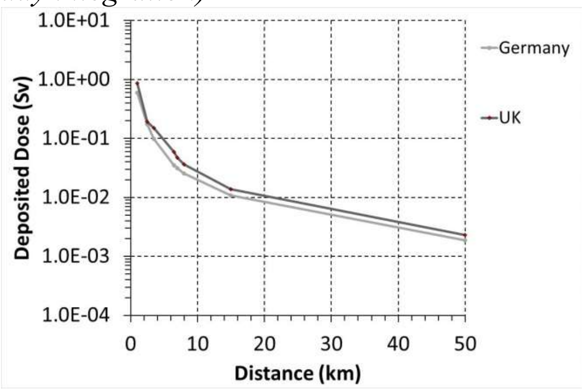

FIG.86. Deposited Dose, 99th percentile (7-day integration)

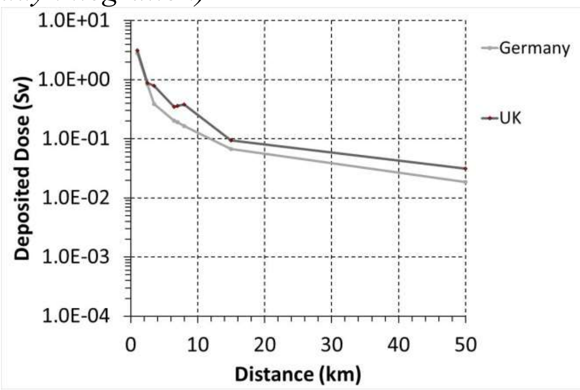

FIG.87. Deposited Dose, maximum (7-day integration)

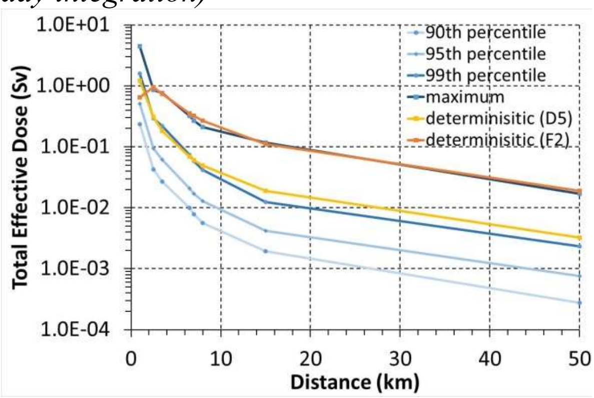

FIG.88. Comparison of probabilistic and deterministic assessments for total effective dose (adult, 1-day integration)

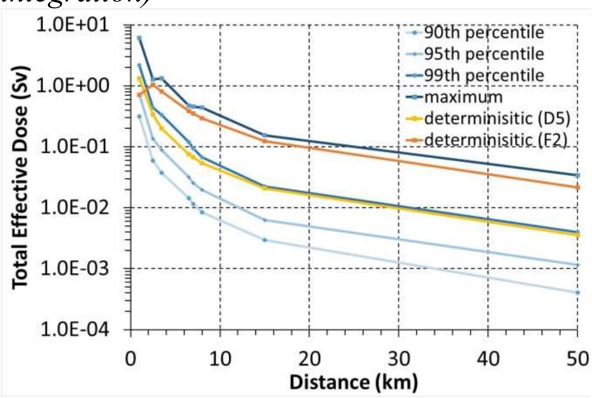

FIG.89. Comparison of probabilistic and deterministic assessments for total effective dose (adult, 7-day integration)

5.2 COMPARISON OF APPLICATION OF PROTECTIVE ACTIONS

Table 13 summarizes levels adopted for various protective actions in each Member State. The IAEA Generic Criteria from Ref [17] are presented for information.

The levels – known as Council Food Intervention Levels (CFILs) – are set to restrict the dose from ingestion of contaminated food to less than 1 mSv per year on the assumption that 10 % of food consumed annually is contaminated. However, different assumptions apply to infants under 1 year leading to corresponding lower levels for infant food.

There are limits for iodine isotopes, strontium isotopes, alpha emitting nuclides and other nuclides (notably Cs-137 and Cs-134).

The Russian Federation, Ukraine, and the UK have upper and lower levels for protective actions. The rationale for the upper and lower levels in the UK is discussed in Annex X. In the European Union, Council Regulation (Euratom) 2016/52 [48] specifies the maximum permitted levels of radioactive contamination in food and animal feed which may be placed on the market following a release of radioactivity into the environment.

TABLE 13. INFORMATION ON LEVELS ADOPTED FOR PROTECTIVE ACTIONS IN MEMBER STATES USED BY THE PARTICIPANTS

Participant	Criteria for protective actions					
	Stable iodine (thyroid dose, mSv)	Sheltering (total effective dose, mSv)		Evacuation (total effective dose, mSv)		Food restrictions
		Whole body	Thyroid, lungs and skin	Whole body	Thyroid, lungs and skin	
Argentina						
Belarus (in first 7 days)	50	100				
France (in first 2 days)	50	10		50		CFILs (see discussion below)
Germany	250 for adults, 50 for children	10		100		CFILs
India						
Israel	50	10		50		
Russia (in first 10 days)	250-2500 for adults, 100-1000 for children	5-50	50-500	50-500	500-5000	
Spain	100	10 (in first 2 days)		50 (in first 7 days)		CFILs
Ukraine (in first 2 weeks)	200-500 for adults, 50-200 for children	5-50	50-300 for thyroid, 100-500 for skin	50-500	300-1000 for thyroid, 500-3000 for skin	
UK	30-300	3-30	30-300	30-300	300-3000	CFILs
IAEA GSR Part 7 (in first 7 days)	50	100		100		100 mSv

IAEA TECDOC-1788 [49] considers the various international standards and criteria for radionuclide activity concentrations for food and drinking water in different circumstances for purposes of control at a national level.

5.3 COMPARISON OF PARTICIPANT'S RESULTS AGAINST NATIONAL CRITERIA

Several national participants of the ENV-PE exercise provided their interpretation of the calculation results in terms of potentially meeting the current or potential national criteria. Some of the project participants considered the criterion requiring that significant off-site protective actions such as evacuation should not be necessary; this implies a dose of ~50-100 mSv. These considerations were intended for evaluation of the links among the requirements, methods of calculation and associated assumptions, and the source term, and shouldn't be considered in any relation to the authorisation process. Consideration of severe accidents by means of a full PSA (Levels 1 to 3) involves summing the risks – the combination of the consequence and the event frequency – from many scenarios, and the results from one individual scenario can hardly be used to draw a conclusion on the plant acceptability. Population distribution assumed in this ENV-PE case study intentionally does not account for a protection zone which is normally established around an NPP and can have a radius from a few kilometres up to a few tens of kilometres depending on the national requirements. Moreover, the regulatory requirements normally evolve, and may need to be carefully applied/ interpreted by the authorised personnel as it was explained, e.g. by the UK regulator (ONR) in the Technical Assessment Guide on ALARP [50][8]:

> "4.3 It is ONR policy that a new facility or activity should at least meet the BSLs (note that in a few cases the BSLs are legal limits derived from IRRs - these are designated as BSL(LL) in SAPs). All the other Targets are policy guidance for inspectors and are not mandatory. Older facilities may have been designed and constructed to different safety standards and deterioration over time now means that BSLs are exceeded. In these cases, provided the BSL is not a legal limit, it may be reasonable for operation to continue if:
>
> i) it has been shown that no reasonably practicable options are available to reduce risks further in the short term; and
> ii) a clear longer-term plan to manage and reduce risks within as short a period as reasonably practicable is in place."

The regulatory requirements and criteria used by Member States involved in this exercise are described in Annexes I to X below. Some Member States have individual dose criteria for reference accidents without explicit consideration of the frequency of the event, although this may be implicit in the selection of the accident. Other Member States have frequency-dose/risk criteria which may be linear on a log-log plot or may be more complex (Argentina for example). The Ukraine and the UK adopt a similar approach in having a lower and an upper level. Simply, any result exceeding the upper level would be clearly unacceptable in most cases and any result below the lower level would be broadly acceptable. For any result between the upper level and the lower level, a justification must be made that the risks have been reduced to a level as low as reasonably practicable. Only the UK has a target for societal risk. The SAPs [41] state:

> "For accidents causing serious damage to an NPP or having off-site consequences, individual risk is considered not sufficiently limiting because of the many aspects of societal impact."

The UK approach is explained further in Annex X.

Some Member States also use PSA metrics (e.g. frequencies of releases) as criteria. In the future, metrics involving core damage may be not fully appropriate for some innovative reactors, e.g. the molten salt reactor.

[8] In this document BSL stands for 'Basic Safety Level', IRR stands for 'Ionizing Radiation Regulations 1999', SAP stands for 'Safety Assessment Principles'.

5.4 CONCLUSION

ENV-PE exercise participants have demonstrated a large variety of approaches used in different Member States. The estimates of potential exposures to people for accident scenarios vary widely among the approaches. These variations are caused by specific regulatory requirements in Member States for assessing potential exposures, the underlying models for atmospheric dispersion, radioecology, and dosimetry and the approaches to take into account weather statistics. The different approaches can be broadly categorized as follows:

- deterministic,
- probabilistic (for an NPP this requires a full-scope level 3 PSA),
- combinations of all the above.

There are also several ways to combine the scenario selection and consequence assessment which are summarized as follows:

- deterministic – deterministic,
  - one (or a few) scenarios are defined with a corresponding source term (usually conservative) and the consequences assessed for a single set of meteorological conditions (usually to give worst case or conservative results),
  - the assessments from France and India are examples,
- deterministic – probabilistic,
  - the source term is defined as above, but the consequences are calculated for many meteorological sequences statistically sampled from hourly meteorological data,
  - the assessment from Germany is an example of this,
- probabilistic – deterministic,
  - a range of scenarios with corresponding source terms is developed from a PSA analysis for example (Level 1 and 2) and accident modelling and the consequences calculated for a single meteorological sequence which could be typical or worst case,
  - the deterministic assessment from the UK is an example of this although for this exercise performed for a single scenario,
- probabilistic – probabilistic,
  - a full probabilistic assessment requires assessment of a range of accident sequences (with different frequencies) for each meteorological sequence – in other words a Level 3 PSA,
  - the probabilistic assessments from Argentina and the UK are examples of this.

The probabilistic assessment performed by Israel seems to be a simplified version in which only the probability of the wind blowing to a particular sector with habitation is considered; other meteorological parameters such as the exact wind direction (not just the sector), wind speed, the Stability Category, etc, are not taken into account. This has the advantage of simplicity compared with a full probabilistic assessment as it doesn’t require dispersion calculations to be performed for every hourly meteorological sequence sampled; however, the risk results may be quite conservative as conservative assumptions are made for the meteorological conditions (Stability Category F and 2 m/s wind speed for example). In other words, the implicit assumption is that the weather is always F2.

Another difference in the approaches adopted by participants is whether the assessment is performed on a conservative or best-estimate basis. Deterministic assessments for design basis accident analyses should be performed on a conservative basis whereas the severe accident assessment and PSA should be performed on a best-estimate basis. In Member States where a PSA would be performed, a deterministic assessment for the design basis accident analysis would also be performed; this would be the case in the UK for example [41, 51].

Where frequency-consequence curves are used there is a difference between whether individual events are compared against a target or whether frequencies of events in dose-bands are summed and the resultant total frequency compared against targets. An example of the latter is the UK Target 8 (see Annex X), for which the rationale is that summing frequencies in dose bands avoids any tendency for 'salami-slicing' (i.e. separating – or not binning – similar events together so that instead of one event with frequency *f* and consequence *C* which exceeds a criterion, there are, for example, 10 events with frequency *f/10* and consequence *C* each of which individually meets the criterion).

Simple Gaussian dispersion models are still widely used by nearly all participants although in some cases also supplemented by Gaussian puff models (COSYMA – Germany and UK) and Lagrangian modelling. For licensing purposes where the source terms and meteorological conditions are hypothetical – as opposed to modelling the dispersion following a real event – this seems reasonable. Studies have shown that Gaussian models are generally conservative when compared with Lagrangian models. For example, the UK Health Protection Agency (HPA) – formerly NRPB (National Radiological Protection Board) and now PHE (Public Health England) – performed an inter-comparison exercise of the modified 'R-91' Gaussian model with the Lagrangian model NAME III from the UK Met Office. The inter-comparison report [38] concluded that:

- There is a disparity (of up to a factor of ~3) between the plume centre-line time-integrated activity in air concentrations (TIAC) of each model most notably in the near field.
- R-91 was conservative in that it estimated higher TIACs.
- There are significantly larger differences in TIACs between the two models for Pasquill stability Category A and G conditions (low wind speeds) than there are for Category D.
- There are larger differences in TIACs for higher release heights (80 and 200 m) than for a 10 m release height.

For licensing where many source terms in combination with many meteorological sequences may need to be considered (perhaps >10,000 simulations in total), Gaussian models may still be the best option as they are simple, well-understood, need little computer power, and need few meteorological data; Lagrangian models, on the other hand, although more accurate in representing the dispersion – and able to account for factors such as the variation of meteorological conditions with height, distance, and time, and complex terrain for example – require more computing power and meteorological data as input and may still not be a practical option for a full probabilistic assessment.

Supplementing a probabilistic assessment by examination of individual meteorological sequences in more detail with a Lagrangian model is also an option. This was done in the Spanish assessment that used MACCS for the probabilistic assessment and then JRODOS, which has a Lagrangian model, to examine the sequences giving the peak doses.

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ANNEX I. ARGENTINA

I–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

The Argentine Nuclear Regulatory Authority (ARN) has defined an Acceptability Criterion Curve (a function) against which the nuclear safety level of a nuclear power plant can be assessed [I–1, I–2]. The criterion is based on the individual radiological risk limitation quantified in terms of probability and it is related to the dose limitation system recommended by the International Commission on Radiological Protection for protection against exposures to ionizing radiation resulting from normal operation [I–3].

The objective of the Acceptability Criterion is to limit the individual risk to members of the public associated with potential exposures that could originate from living in the proximity of a nuclear facility to values not greater than the individual risk associated with exposures from normal operations.

The ICRP has suggested a risk coefficient for stochastic effects of $5 \cdot 10^{-2}$ Sv^{-1} [I–3]. The ARN applies a dose constraint for exposure from a single source such as an NPP of 0.3 mSv per year and derives an annual limit value of the individual risk R, associated with exposures due to normal operation originating in a single practice or source of $1.5 \cdot 10^{-5}$.

For potential exposures the individual risk will be the sum of the risks associated with exposures from all possible accident sequences (a sequence is the series of events leading up to the radioactive release followed by a particular set of meteorological conditions or other exposure pathways that lead to exposure of an individual). ARN recognizes that there are many uncertainties involved in probabilistic methods such as PSA, and to account for this a lower value (a factor of 15 lower) for the risk limit of 10^{-6} is selected, i.e. the individual risk of death from accidents at a nuclear facility for the most exposed individual must be lower than 10^{-6}.

The regulation [I–1] is mainly focused on the plant design in order to evaluate its strength and weaknesses to mitigate internal and external events; that is, fulfillment of the regulation must be verified by an analysis prior to the reactor construction and operation. In brief, Argentina's regulation [I–1] requires that:

- In order to calculate the radiological risk due to an NPP, accident sequences with radiological implications for the members of the public must be identified. The associated source terms and their annual probabilities of occurrence should be evaluated by means of PSA Level 1 and Level 2. Then with the source term frequency and the meteorological conditions and their probability of occurrence, the probability of exposure (P_e) is calculated at each point around the NPP. Moreover, the effective dose is also evaluated at each point of the domain by means of atmospheric dispersion and dose calculation models.
- 24 hours exposure time is assumed for the effective dose calculation and the application of protective actions shall not be considered.
- The treatment of numerous source terms can be simplified by grouping them in different Release Categories (RCs). In this case a representative accident sequence can be selected, and it shall be the one that causes the worst radiological consequence. The annual probability of occurrence for a given RC is the sum of the annual probabilities of occurrence of the accident sequences that are members of this RC.
- Accidents with radiological consequences for the public shall have an annual probability of occurrence that, when represented graphically according to the effective dose, results in a point located in the acceptable area of the criterion curve (see Fig. I–1).

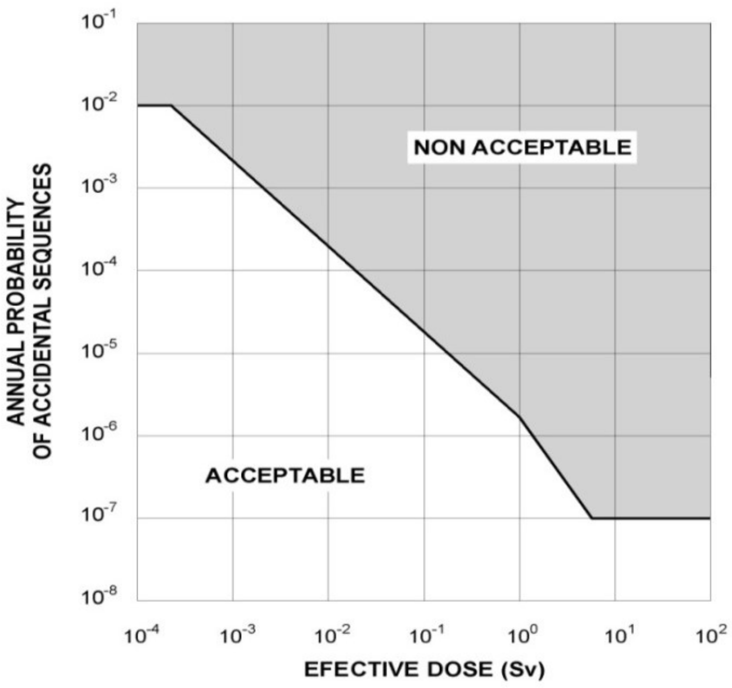

FIG. I–1. Argentine acceptability criterion curve for consideration of potential exposure of the public [I–1].

Figure I–1, taken from the ARN regulation [I–1], is a plot of the annual probability of accidental sequences against the effective dose resulting from all accidents with that annual probability showing the criterion curve. The criterion curve is an iso-risk curve of 10^{-7} (risk limit) for doses higher than 0.2 mSv whereas the points of the upper horizontal section have an associated risk lower than 10^{-7}, which is conservative in favour of nuclear safety. Different sections can be distinguished in the curve:

- For doses lower than 1 Sv that corresponds to the stochastic dose effects region;
- For doses greater than 6 Sv that corresponds to the deterministic dose effects region;
- For doses between 1 and 6 Sv that corresponds to a linear interpolation, in a log-log plot, between the two previous sections;
- Upper horizontal section which results from truncating the value $P_e = 10^{-2}$, indicates that the ARN does not accept a RC with a high probability of radiological accidents, independent from the doses involved.

In the criterion curve, on the probability-dose plane two zones can be identified, one as acceptable and the other as non-acceptable. The acceptable zone points have associated risk values lower than 10^{-7}, whereas the non-acceptable zone points have higher associated risk values. It is requested that a point characterizing each release category has to be plotted on the criterion curve graph. The x-coordinate of each point is the Risk Equivalent Dose and the y-coordinate is the annual probability of the RC. If all the points are below the risk limit the nuclear power plant could be potentially licensable.

The radiological risk, R, as defined by the ARN, see Eq. (I–1), is expressed in terms of probability and is equal to the probability of exposure (P_e) in members of the public (which depends on the type of exposure, plant characteristics, meteorological conditions, topography, etc) multiplied by the probability $P(F/e)$ of fatality F due to the exposure e:

$$R = P_e \cdot P(F/e) \qquad \text{(I–1)}$$

The conditional probability $P(F/e)$, is a function of the effective dose, D, incurred by the exposed individual, that is:

$$P(F/e) = f(D) \tag{I–2}$$

In accordance with Ref [I–3] ("dose-response" curve), this probability increases linearly up to 1 Sv (stochastic dose effects region, with an approximate slope $\alpha \cong 5 \times 10^{-2}$ Sv^{-1}) and then varies as a sigmoid curve (deterministic dose effects region), until reaching values nearby the unit for doses of approximately 6 Sv or greater. However, to be conservative in terms of risk, ARN decided to approximate the sigmoid section of the dose-response curve through a straight line in the log-log graph, hence the function $f(D)$ results:

$$f(D) = \begin{cases} 10^{-5} & for\ D \leq 0.2\ mSv \\ 0.05 \cdot D & for\ 0.2\ mSv \leq D \leq 1\ Sv \\ 0.05 \cdot D^{1.67} & for\ 1\ Sv \leq D \leq 6\ Sv \\ 1 & for\ D \geq 6\ Sv \end{cases} \tag{I–3}$$

From Eqs (I-1) and (I-2), the individual radiological risk can be expressed as follows:

$$R = P_e \cdot f(D) \tag{I–4}$$

In order to calculate the Individual Radiological Risk, an individual effective dose must be assessed for each accidental sequence that represents the RC. The dose that an individual located at a specific point (j) around the NPP will receive depends on the weather conditions at the time of the release, hence the radiological risk for each location can be calculated as Eq. (I–5):

$$R_{ji}^{n} = P(RC^{n}) \cdot P(E_j) \cdot P(D_{ji}/E_j) \cdot f(D_{ji}) \tag{I–5}$$

where: $P(E_j)$ – probability of exposure in j position (number of meteorological conditions that give a dose divided by the total number of meteorological conditions considered); $P(D_{ji}/E_j)$ – probability of D_{ji} given an exposure E_j (number of meteorological conditions that give a dose D_{ji} divided by the total number of meteorological conditions that give a dose); D_{ji} – effective dose for the weather condition i at the position j; $f(D_{ji})$ – dose response value calculated according to ARN specification.

The total radiological risk of an individual, associated with the n RC at the position j, $R_{j\,TOT}^{n}$ is

$$R_{j\,TOT}^{n} = \sum_i R_{ji}^{n} = P(RC^{n}) \cdot P(E_j) \cdot \sum_i P(D_{ji}/E_j) \cdot f(D_{ji}) \tag{I–6}$$

This can be repeated for each individual located around the NPP. Then the highest of these risks $R_{MAX}^{n} = \max_j (R_{j\,TOT}^{n}) = R^{n}$, should be identified, and the person that is located in this position is the critical group (a posteriori definition).

Then we can use this value R^{n} to obtain the Risk Equivalent Dose D_{EQR}, defined as the dose such that:

$$f(D_{EQR}) = \frac{R^{n}}{P(RC^{n}) \cdot P(E_j)} = \sum_i P(D_{ji}/E_j) \cdot f(D_{ji}) \tag{I–7}$$

For the ARN acceptability criterion, an accidental sequence is a series of events that could include technological system malfunction as well as human errors, which has the potential of causing radiological exposures to the public. The exposure takes place when the accidental sequence entails a radionuclide release to the environment Ref [I–4].

The limit for the individual radiological risk due to potential exposure is derived from the radiological risk due to normal exposure, considering the annual limit for the dose in the public for routine exposures (0.3 mSv) and also considering that the probability of exposure is 1 (routine or planed exposure). So, from Eqs (I–3) and (I–4), it is understood that in order to fulfil this purpose, the following requirement on the risk limit must be imposed:

$$R_{PE\ lim} \leq R_{NE\ lim} = P_e \cdot f(D) = 1 \cdot 0.05 \cdot 0.0003 = 15 \cdot 10^{-6} \quad \text{(I–8)}$$

where $R_{PE\ lim}$ is the limit of the risk for potential exposures and $R_{NE\ lim}$ is the limit of the risk for routine exposures.

The criterion needs to account for the uncertainties typical of probabilistic methodologies used to assess nuclear safety in NPPs and other relevant facilities. Based on these uncertainties, an additional restriction to $R_{PE\ lim}$ was imposed. To consider this, the regulatory body has limited the annual individual radiological risk for the members of the public to a value of $R_{PE\ lim} = 10^{-6}$. This is an annual value for a single nuclear facility (hereinafter “per reactor-year”), and the value is for every associated critical group. In summary, it is adopted:

$$R_{PE\ lim} = 10^{-6} < 15 \cdot 10^{-6} = R_{NE\ lim} \quad \text{(I–9)}$$

In this case and in reference to a single nuclear facility, there can be n RCs, each one with an associated individual radiological risk R^n. Thus, every risk R^n (the individual radiological risk associated with RC^n) contributes to the total individual radiological risk, R_T, associated to the facility (R_T equals the sum of all R^n). It is requested that:

$$R_T \leq R_{PE\ lim} = 10^{-6} \quad \text{(I–10)}$$

Moreover, considering that ten or fewer RCs represent the NPP, it is required that each one has a radiological risk lower than of 10^{-7}, i.e. $R^n \leq 10^{-7}$. If N is greater than 10 the individual risk limit must be $R^n \leq \frac{10^{-6}}{N}$.

The exposure time defined by the regulatory body for all postulated accidents with radiological implications for the members of the public is 24 hours, and no protective actions shall be considered. Due to this the exposure pathways considered are:

- External exposure due to immersion in the radioactive cloud (cloud-shine).
- External exposure due to radionuclide deposits in the environment (ground-shine).
- Internal contamination due to inhalation of contaminated air.

The beginning of the exposure period is calculated considering two different zones:

- Zone 1 - distance to the NPP is less than 10 km; public is assumed to remain in this zone 24 hours after emergency notification;
- Zone 2 - beyond 10 km; public is assumed to remain 24 hours after the plume arrival.

Thus, the dose calculation corresponding to both pathways of external exposure is carried out taking into account the intersection of the exposure time defined above and the following times:

- Radioactive cloud passage period for cloud-shine.
- The period following cloud arrival, corresponding to the beginning of deposition, for ground-shine.

In relation with the third exposure pathway, internal contamination by inhalation, the dose to be calculated is the corresponding committed dose for the exposure period beginning with cloud arrival. The total effective dose for the concerned site is the sum of the doses for these three exposure pathways.

The doses incurred by members of the public, as a consequence of exposures to ionizing radiations due to an accidental situation of a nuclear facility, may have a wide range of values due to multiple causes; these causes are intrinsically heterogeneous so they are very hard or even impossible to evaluate accurately. Some examples of these causes are:

- Variation of atmospheric conditions.
- Distribution of the population around the nuclear facility and identification of the critical group.
- Technological characteristics of the concerned nuclear facility.
- Metabolic and anatomical characteristics and differences between individuals.
- Features of specific residential housing areas, e.g. type of construction.
- Domestic habits and behaviour.
- Influence of age differences.
- Use of uniform, empirical dose conversion factors that may not be representative of the phenomena at a specific site.

All the parameters in this list, except the first two, may be addressed by using the concept of a mean value. Then, this methodology is focused on accounting for the different weather conditions and where the individual is located.

I–2. DESCRIPTION OF MODELS AND METHODOLOGIES APPLIED

The source term and the meteorological data used for the ENV-PE example have been described in the previous sections of this report. The effective doses were calculated with the WinMACCS Ref [I–5] code for PSA L3 calculations and the input deck was developed making the following assumptions:

- Release path to the atmosphere: one path 8m height.
- Dispersion parameters: the same that were used in Surry NPP site.
- Inner and outer ring: according to the Regulatory body regulation:
  - Inner Ring: 1-10 km;
  - Outer Ring: 10-20 km.
- Domain discretization: 35 rings from 250 m to 25 km, 16 angular sectors.
- Population distribution: The regulatory body allows the use of real or uniform population distribution around the NPP. In this case uniform population distribution was used for the inner and outer ring.
- Dose factors from Federal Guide Regulation 13: The dose factors used for the calculations were the included in the WinMACCS code (see Ref [I–6]).
- Population shielding: This information was extracted from Ref [I–7] for normal conditions. This was because the data in the example case are for the Surry location.
  - CSFACT = 0.68, cloud-shine (0 total shielding);
  - PROTIN = 0.46, intake (0 total shielding);
  - SKPFAC = 0.46, skin deposition (0 total shielding);
  - GSHFAC = 0.26, ground-shine (0 total shielding).
- Alarm Time definition: 2 hours, this is the time of battery depletion.

I–3. RESULTS OF ASSESSMENT

Total effective dose (90^{th}, 95^{th} and 99^{th} percentiles, and maximum) calculated at different distances from the source of release and integrated over 1 day, 2 days and 7 days after release are presented in Tables I–1 to I–3.

TABLE I–1. TOTAL EFFECTIVE DOSE, Sv. ONE DAY AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	1.020	1.160	1.550	2.250
2.5	0.635	0.781	1.060	1.620
3.5	0.474	0.577	0.793	1.170
6.5	0.226	0.281	0.378	0.601
7	0.206	0.250	0.343	0.544
8	0.169	0.212	0.295	0.439
15	0.058	0.072	0.101	0.168
50	0.005	0.006	0.010	0.020

TABLE I–2. TOTAL EFFECTIVE DOSE, Sv. TWO DAYS AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	1.070	1.250	1.770	2.430
2.5	0.701	0.840	1.100	1.750
3.5	0.517	0.622	0.855	1.260
6.5	0.245	0.307	0.411	0.648
7	0.222	0.273	0.367	0.587
8	0.186	0.227	0.312	0.474
15	0.063	0.078	0.108	0.181
50	0.005	0.007	0.011	0.021

TABLE I–3. TOTAL EFFECTIVE DOSE, Sv. SEVEN DAYS AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	1.260	1.540	2.110	2.930
2.5	0.832	1.020	1.270	2.110
3.5	0.624	0.765	1.040	1.520
6.5	0.306	0.364	0.525	0.783
7	0.274	0.330	0.462	0.709
8	0.225	0.279	0.370	0.572
15	0.078	0.097	0.124	0.218
50	0.007	0.009	0.014	0.025

Dose to thyroid (90th, 95th and 99th percentiles, and maximum) calculated at different distances from the source of release and integrated over 1 day, 2 days and 7 days after release are presented in Tables I–4 to I–6.

TABLE I–4. DOSE TO THYROID, Sv. ONE DAY AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	4.400	5.400	7.210	9.850
2.5	2.780	3.350	4.790	7.070
3.5	2.070	2.490	3.270	5.090
6.5	0.998	1.140	1.570	2.630
7	0.896	1.070	1.370	2.350
8	0.736	0.905	1.150	1.850
15	0.244	0.302	0.413	0.699
50	0.020	0.025	0.039	0.074

TABLE I–5. DOSE TO THYROID, Sv. TWO DAYS AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	4.500	5.490	7.270	10.000
2.5	2.860	3.420	4.940	7.200
3.5	2.110	2.540	3.290	5.190
6.5	1.010	1.170	1.630	2.680
7	0.914	1.080	1.410	2.400
8	0.749	0.927	1.160	1.890
15	0.249	0.307	0.419	0.712
50	0.021	0.026	0.042	0.076

TABLE I–6. DOSE TO THYROID, Sv. SEVEN DAYS AFTER RELEASE.

Distance, km	Percentiles			Peak consequence
	90th	95th	99th	
1	4.800	5.750	7.640	10.500
2.5	3.030	3.590	5.140	7.560
3.5	2.200	2.660	3.570	5.450
6.5	1.050	1.220	1.740	2.810
7	0.963	1.110	1.490	2.520
8	0.787	0.984	1.190	1.990
15	0.264	0.321	0.446	0.749
50	0.022	0.028	0.044	0.080

Table I–7 shows the risk equivalent dose and the maximum radiological risk, obtained using the guidelines described above. It can be observed that the radiological risk is less than 10^{-7}.

TABLE I–7. CALCULATED ANNUAL PROBABILITY, RISK EQUIVALENT DOSE (D_{EQR}), FATALITY PROBABILITY AND MAXIMUM RADIOLOGICAL RISK

Annual probability of RC	Risk	Risk Equiv. Dose, D_{EQR} (Sv)	Probability of fatality for D_{EQR}
1.5×10^{-6}	8.8×10^{-10}	0.023	1.2×10^{-3}

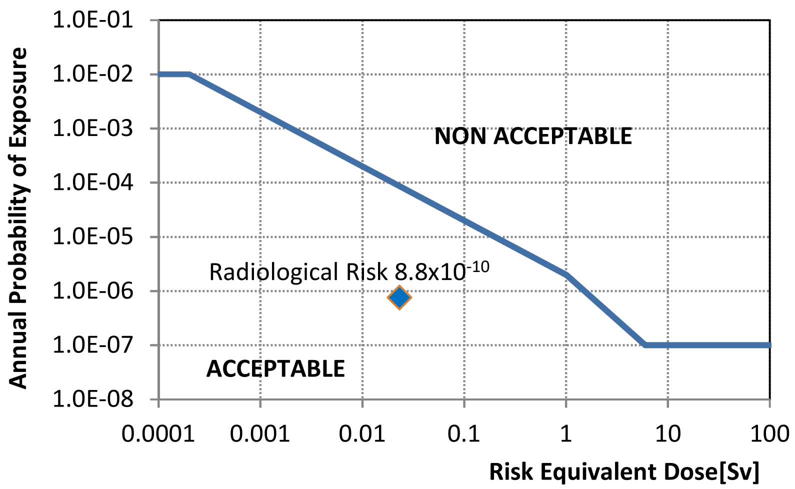

FIG. I–2. Criterion curve for the public and maximum radiological risk.

Figure I–2 shows the criterion curve for the public and the points representing the maximum radiological risk. It is in the acceptable zone of the plot (below the boundary of 10^{-7} for radiological risk). As additional information, Figure I–3 shows the relationship between the effective doses calculated for all meteorological conditions at the location of the maximum risk. It is easy to see that the risk equivalent dose is between the doses calculated.

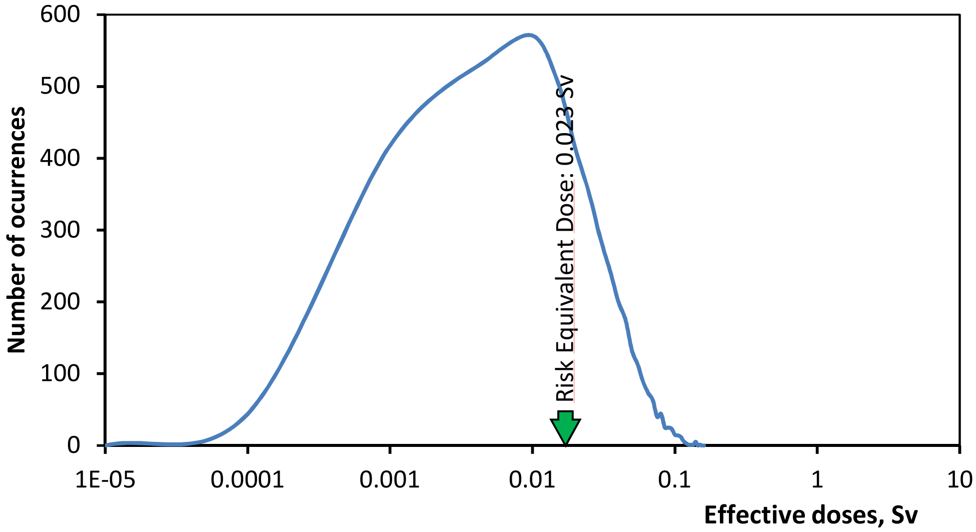

FIG. I–3. Relationship between the effective dose distribution at the maximum risk location and the risk equivalent dose

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ANNEX II. BELARUS

II–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

The regulations of Belarus relevant to the potential exposure comprise:

- Safety requirements to ensure that the activities relating to the construction, operation and decommissioning of facilities are conducted to achieve the highest standards of safety that can be reasonably achieved;
- Risk criteria which address the risk of mortality and of cancer from nuclear installations;
- Dose and risk constraints for planned exposure situations and reference levels for emergency and existing exposure situations;
- Emergency preparedness and response planning to mitigate the consequences of nuclear accidents.

For the NPP-2006 design which is being constructed in Belarus the acceptance criteria for design basis accidents are defined in accordance with the Russian Federation requirements [II–1]:

- Less than 1 mSv/event for the accidents with probability higher than 10^{-4} events/a;
- Less than 5 mSv/event for the accidents with probability lower than 10^{-4} events/a.

The calculated probability of a beyond design basis accident for the Belarusian NPP is lower than 10^{-6} a^{-1}.

TABLE II–1. NOMINAL RISK COEFFICIENTS TAKING INTO ACCOUNT CANCER RISK AND RISK OF HERITABLE EFFECTS [II–2]

Exposed population	Cancer$\cdot 10^{-2}$ Sv^{-1}	Heritable effects$\cdot 10^{-2}$ Sv^{-1}	Total$\cdot 10^{-2}$ Sv^{-1}
Whole	5.5	0.2	5.7
Adults (Workers)	4.1	0.1	4.2

TABLE II–2. GENERIC CRITERIA FOR ACTIONS IN EMERGENCY EXPOSURE SITUATIONS TO REDUCE THE RISK OF STOCHASTIC EFFECTS [II–2]

	Generic criteria		Examples of protective actions and other response actions
Criteria for urgent protective actions	$H_{thyroid}$	50 mSv in the first 7 days	Iodine thyroid blocking
	E	100 mSv in the first 7 days	Sheltering; evacuation; decontamination; restriction of consumption of food, milk and water; contamination test; public information
	H_{fetus}	100 mSv in the first 7 days	
Criteria for protective actions in early phase of accident	E	100 mSv per annum	Temporary relocation; decontamination; replacement of food, milk and water; public information
	H_{fetus}	100 mSv for the full period of in utero development	
Criteria for long-term medical actions for diagnostics and treatment of diseases	E	100 mSv in a month	Screening based on equivalent doses to specific radiosensitive organs (as a basis for medical follow-up), consulting
	H_{fetus}	100 mSv for the full period of in utero development	Counselling to allow informed decisions to be made in individual circumstances

Note: E – effective dose, H – equivalent dose

Ref [II–3] states that the risk of death for the public living in the vicinity of an NPP caused by a reactor accident should not exceed 0.1 % of the sum of all risks of death caused by other accidents. Belarus regulation Ref [II–2] defines the nominal risk coefficients as sex-averaged and age-at-exposure-averaged lifetime risk estimates for a representative population. These coefficients are presented in Table II–1. Ref [II–2] further introduces:

- Generic criteria for protective actions and other response actions in the emergency exposure situations to reduce the risk of stochastic health effects (Table II–2);
- Generic criteria for acute doses for which protective actions and other response actions are to be undertaken under any circumstances, to avoid or to minimize severe deterministic health effects (Table II–3);
- Guidance values for limiting exposure of emergency workers;
- Limited dose rates for protective actions in radiation emergency exposure situation.

TABLE II–3. GENERIC CRITERIA FOR ACUTE DOSES FOR WHICH ACTIONS ARE TO BE TAKEN TO AVOID OR MINIMIZE SEVERE DETERMINISTIC EFFECTS [II–2]

	External acute exposure (less than 10 hours)	Internal exposure in 30 days
$AD_{\text{Red marrow}}$	1 Gy	0.2 Gy for radionuclides with atomic number $Z \geq 90$; 2 Gy for radionuclides with atomic number $Z \leq 89$
AD_{Fetus}	0.1 Gy	0.1 Gy
AD_{Tissue}	25 Gy at 0.5 cm depth	-
AD_{Skin}	10 Gy to 100 cm^2	-
AD_{Thyroid}	-	2 Gy
AD_{Lung}	-	30 Gy
AD_{Colon}	-	20 Gy

Ref [II–4] defines emergency zones (radius sizes) for the Belarusian NPP and operational intervention levels for food, milk and drinking water.

II–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

The International Radiological Assessment System (InterRAS) was used for dose assessment. InterRAS is a computer-based tool that was developed for the IAEA to assist with the technical assessment of nuclear reactor accidents for the purpose of determining protective actions for the public and emergency workers. It is based on the RASCAL code Ref [II–5] and consistent with the generic assessment procedures presented in Ref [II–6].

InterRAS is a set of three computer-based tools: Decay Calculator, Field Measurement to Dose and Source Term to Dose Ref [II–7]. The source term to dose model (ST-DOSE) is considered as the primary tool of InterRAS. It is designed to provide a rapid assessment of potential consequences from a set of information about the plant conditions or source term and meteorology at the accident site. The model generates estimates of integrated dose.

There are six ways of setting the source term. Three assume some sort of measurement of the radionuclide mix. The remaining three source term methods are specifically for use with reactor accidents. They generate a radionuclide mix based on the information provided about plant conditions, containment monitor reading, or irradiated nuclear fuel condition.

The 5 entries on the event time screen describe the sequence of the release events and also define when the cumulative dose should be calculated: Shutdown, Release to containment, Release to environment, End of release, End of calculation.

Meteorological conditions are required to be defined for the time of the radioactive release to the environment. ST-DOSE requires a minimum of one set of meteorological data to operate. There is a default set (wind is 3 m/s from the west, D stability, 500 m mixing height, no precipitation) which is used if the user makes no changes. Up to 4 sets of meteorological data may be entered. Effective release height as well as the release location must be defined by the modeller.

After defining the problem, the ST-DOSE model automatically generates a source term, models the transport and diffusion of the material in the environment, and estimates integrated doses. The process of calculation is briefly described in the following paragraphs.

The first step in the calculation process is the generation of a source term if the user has not explicitly defined the isotopic mix. This mix of radionuclides starts with the core inventory and the severity of core damage. As needed, the mix is decayed, and reduction factors are applied to account for the removal processes (e.g. filters, sprays, and holdup). A final computed source term is created to be released at the specified leak rate over the specified release interval.

Depending on the distance from the point of release two transport and diffusion models are used. Close to the release point (inside 5 km) a straight-line Gaussian plume model is used. It computes doses at receptors arrayed on a polar grid, spaced every 10 degrees around at distances of 1, 2 and 5 km each. This grid provides better resolution close to the release point. Beyond 5 km a Lagrangian trajectory Gaussian puff model is assumed. This model computes doses at receptors arrayed in a square, 31x31 Cartesian grid with a 50 km radius. This gives a 3.33 km spacing between the receptor points.

Doses are calculated at the end of exposure which is to be set by the user. Inhalation doses are computed from the time-integrated air concentrations using dose factors and the breathing rates. Ground shine dose is computed from the cumulative surface concentration assuming a surface correction factor of 0.7. Cloud-shine is computed using a finite puff approximation near the source; switching to a semi-infinite cloud model when the horizontal diffusion coefficient (sigma-y) exceeds 400 m. Cs-137 deposition can also be computed.

II–3. REPRESENTATIVE PERSON/CRITICAL GROUP FOR THE EXERCISE

To define the representative person for assessing doses in case of an emergency the data about population distribution around the nuclear installation is used together with the data about highest doses (TEDE and, in some cases, Thyroid doses).

For the purpose of dose assessment one age group is normally used (adults), but in some cases one more age group could be considered (1-year old children). For an assessment of the impact of accidental releases, the following doses are usually considered for atmospheric discharges:

- Cloudshine dose from the plume;
- Groundshine dose from deposited radionuclides;
- Inhalation dose from the plume;
- Ingestion dose;
- Total effective dose;
- Thyroid dose.

Habit data for dose assessment must be chosen according to the survey data of the region of interest or, if not available, national statistical data can be used. In principle, preliminary dose assessment may be based on conservative assumptions (like consumption of local food only, no sheltering, etc.), whilst further assessment may include more realistic and site-specific information.

The actual location of the population is also taken into account. According to Belarusian legislation a Sanitary Protective Zone (SPZ) which is an area where dwellings, or any kind of recreational or economic activities, are strictly prohibited is established around each nuclear installation. The size of such an SPZ depends on the type of installation and on estimated levels of public exposure during normal operation of the NPP. The representative person for assessing doses is normally assumed to be the person most affected by the discharges, located in the areas around the NPP. Thus, in Belarus, a representative person for assessing doses in case of potential emergency will be the person beyond the SPZ and receiving the maximum individual effective dose.

In the current exercise the maximum calculated dose was observed in the area 7, but as it is located at the distance 1 km from the NPP (and 1-km radius will be within the SPZ), the representative person for assessing doses is the person located in the area 2[9].

II–4. RESULTS OF ASSESSMENT

Dose assessment was made with the help of InterRAS tool [II–7]. As described previously in this report, in the InterRAS up to 4 sets of meteorological data can be entered, so all the meteorological data were averaged over a year and 4 meteorological scenarios were produced (Table II–4). The total effective dose calculated at different locations for different meteorological scenarios is presented in Table II–5. The total effective dose is assumed to be a combination of the effective dose from inhalation and the dose from cloud-shine and 7-day ground-shine exposure.

TABLE II–4. METEOROLOGICAL CONDITIONS

Scenario	1	2 a	2 b	3
Release height, m	8.4	8.4	8.4	35
Wind speed, m/s	2	5	5	4
Wind direction at 10m	60	60	60	60
Mixing layer, m	150	500	500	500
Stability class	F	D	D	D
Air temperature, °C	10	10	10	10
Precipitation	None	None	Light rain	None

TABLE II–5. TOTAL EFFECTIVE DOSE, Sv

Scenario/ Receptor	Bearing, degrees	Distance, km	Meteorological Scenario			
			1	2a	2b	3
1	300	15	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	220	8	1.26E-02	2.02E-03	1.06E-02	2.59E-03
3	330	2.5	2.86E-02	6.08E-03	6.95E-03	5.55E-03
4	40	6.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	160	3.5	1.18E-07	3.69E-08	4.68E-08	2.69E-09
6	115	7.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	200	1.0	3.05E-01	6.42E-02	7.45E-02	8.58E-02
8	140	50	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	345	0.3	4.89E-01	1.04E-01	1.5E-01	9.50E-02

The maximum doses (see Table II–6) were observed in case of meteorological scenario 1.

[9]At the same time, there could be exceptional cases when people from the category “public” could be located inside the SPZ (e.g. visitors, builders, etc.).

TABLE II–6. MAXIMUM DOSES FOR ADULTS (FIRST 7 DAYS), Sv

Distance, km	0.3	1	2.5	3.5	5	6.5	7	8	10
Total Effective dose	1.1E+01	2.6E+00	1.2E+00	8.7E-01	6.5E-01	5.2E-01	4.9E-01	4.1E-01	3.3E-01
Thyroid CDE	7.4E+02	2.4E+01	1.1E+01	8.0E+00	6.2E+00	5.1E+00	5.0E+00	4.4E+00	3.5E+00
Inhalation Eff	3.0E+01	9.9E-01	4.4E-01	3.4E-01	2.6E-01	2.1E-01	2.1E-01	1.8E-01	1.5E-01
Cloud-shine	5.3E+00	6.9E-01	3.1E-01	2.3E-01	1.6E-01	1.2E-01	9.4E-02	7.1E-02	5.9E-02
7-day Ground-shine	2.8E+01	9.1E-01	4.0E-01	3.1E-01	2.3E-01	1.9E-01	1.9E-01	1.6E-01	1.3E-01
ET per Annum EP	4.8E+01	1.6E+00	6.8E-01	5.2E-01	4.0E-01	3.3E-01	3.3E-01	2.8E-01	2.3E-01

TABLE II–6. MAXIMUM DOSES FOR ADULTS (FIRST 7 DAYS), Sv (cont.)

Distance, km	15	20	25	30	35	40	45	50
Total Effective dose	1.8E-01	1.3E-01	8.9E-02	6.4E-02	4.7E-02	4.0E-02	3.0E-02	2.3E-02
Thyroid CDE	1.7E+00	1.3E+00	9.6E-01	7.3E-01	5.5E-01	4.8E-01	3.6E-01	3.0E-01
Inhalation Eff	7.2E-02	5.4E-02	4.0E-02	3.0E-02	2.2E-02	2.0E-02	1.5E-02	1.2E-02
Cloud-shine	5.6E-02	3.8E-02	2.6E-02	1.7E-02	1.2E-02	1.0E-02	6.7E-03	5.5E-03
7-day Ground-shine	5.0E-02	3.5E-02	2.4E-02	1.7E-02	1.2E-02	1.0E-02	7.1E-03	5.6E-03
ET per Annum EP	8.7E-02	6.1E-02	4.3E-03	3.0E-02	2.2E-02	1.8E-02	1.3E-02	1.0E-02

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ANNEX III. FRANCE

III–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

According to the French regulation Ref [III–1], the assessment of nuclear safety is performed using a deterministic and cautious approach which also includes probabilistic analyses of accidents and their consequences. The assessment has to deal with *multiple* plausible events which could trigger accidents. At present there is no national framework to account for the environment when performing an impact assessment: it is considered that the environment is protected if the human being is protected. But according to the new French and European regulations, a methodology has to be developed so that the safety assessment includes the protection of both people and the environment.

Stress tests and investigation of cliff-edge effects for the accidents with multiple causes (complementary safety assessment) have been performed in French nuclear facilities. The cliff-edge effect is associated with total effective dose to the reference group higher than 10 mSv. If a cliff-edge effect is obtained during the stress test analysis, the facility has to implement corrective measures. The results are expressed in terms of total effective dose and the dose to the thyroid. The short-term exposure (i.e. integrated over 48 hours only by external irradiation and inhalation) must be compared to the intervention levels for the public presented in Table III–1. Activity added to the food products has to be compared to the limits for the commercialization of foodstuff presented in Table III–2.

TABLE III–1. INTERVENTION LEVELS FOR PUBLIC [III–2]

Minimum dose for intervention	Action of protection
50 mSv of total effective dose	Evacuation of the population
10 mSv of total effective dose	Sheltering
50 mSv to the thyroid	Iodine prophylaxis

TABLE III–2. LIMITS FOR THE COMMERCIALIZATION OF FOODSTUFF [III–3]

	Baby feeding	Milk products	Liquids	Others
90Sr	75 Bq/kg	125 Bq/kg	125 Bq/l	125 Bq/kg
131I	150 Bq/kg	500 Bq/kg	500 Bq/l	2000 Bq/kg
Pu	1 Bq/kg	20 Bq/kg	20 Bq/l	80 Bq/kg
Others	400 Bq/kg	1000 Bq/kg	1000 Bq/l	1250 Bq/kg

III–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

The environmental studies for the CEA facilities are conducted with the CERES® platform (‘*Code d’Evaluation Rapide Environnemental et Sanitaire’* for ‘fast software for assessment of the environmental and health impact’) described in Ref [III–4]. This platform has been developed by CEA/DAM (La Direction des applications militaires) and includes software for the assessment of the dose induced by accidental atmospheric release, routine atmospheric release and routine liquid release.

It has a common database containing the properties of about six hundred isotopes and the transfer coefficients of the elements in the food chain (transfer from soil to plants, plants to animals, and food to humans). The dose coefficients are obtained from the French and international regulations. Inhalation and ingestion dose coefficients are obtained from Ref [III–5], external exposure coefficients are obtained from Ref [III–6].

The site characteristics (height of release, source term, meteorological conditions, impact points, diets, etc) have to be defined by the software user or can be chosen from the database specific to the CEA sites. The results of the computations are provided as files (Word and Excel), graphs (Excel) or maps using the Map info system.

The studies of the potential emergency atmospheric releases are conducted with the MITHRA® software of the CERES® platform. The atmospheric transport modelling is carried out using a Gaussian multi puff model. For the standard studies, the model uses standard deviations as defined by the Doury's formulas [III–7], that are functions of the travel time and are adjusted according to the vertical temperature gradient to characterize the atmospheric stability. The standard deviations based on Pasquill's model, Briggs's [III–8] or Turner's [III–9] values are also available if needed for special studies.

These models assume a flat ground and a constant meteorological condition in the entire zone of study. For long releases it is possible to apply a wind meandering factor and a step by step evolution of meteorological conditions (wind speed and direction, stability and rain flowrate are assumed constant during each step).

The user has to take into account the possibility of the effect of the buildings on the effective height of release by adjusting the release height.

MITHRA® provides an assessment of the instantaneous and time-integrated volumetric activities (Bq/m^3 and $Bq{\cdot}s/m^3$), of the deposits on the ground resulting from the mechanism of diffusion, impaction and deposition, and the deposits on the ground resulting from wash out of the puff by rain (Bq/m^2). The depletions due to dry and wet deposition are taken into account. For the aerosol a standard size of 1 micron and a dry deposition velocity of $5.10^{-3} m{\cdot}s^{-1}$ are proposed by default. These values can be modified and the deposition velocity is calculated as a function of the aerosol's size.

Radioactive decay during atmospheric transfer is calculated using the Bateman equations Ref [III–10]. For tritium, a specific module is used to evaluate the dispersion and the transformation of the gaseous form HT into tritiated water Ref [III–11].

Calculations are carried out in a gridded domain for graphic output, at points whose coordinates are set by the user. Similarly, the user specifies the computing times. The default impact assessment time for an accidental release is two days after the beginning of the release.

Reference groups. The dose assessment is performed for some groups of the population which are chosen as representative of the people who receive the most significant dose. It is possible to define the time percentage spent in different exposed zones (maximum 3). Similarly, the percentage of consumption of the different products coming from different locations can be taken into account. The diet habits used in these calculations correspond to the locally produced food.

The assumptions have to be conservative and close to realistic.

Pathway of exposure. In case of accidental atmospheric emissions, the exposure pathways are:

- External exposure by immersion in the plume.
- External exposure by irradiation by the ground deposits.
- Internal exposure by inhalation.
- Internal exposure by intake of vegetables.
- Internal exposure by ingestion of animal products (meat and milk), from animals which have consumed contaminated food.

The internal exposure is taken into account only for the long-term exposure (> 2 days). Usually no sheltering factor is taken into account. The population is assumed to stay outside of their houses.

In case of tritium release the skin-passage pathway is added. Because of the mobility of tritium into the ground and the environment, the accumulation in the ground is neglected.

Breathing rates are chosen corresponding to a moderate activity, according to the Ref [III–12] and they are 1.2 $m^3 \cdot h^{-1}$ for the adults, 0.87 $m^3 \cdot h^{-1}$ for 10 years old children and 0.31 $m^3 \cdot h^{-1}$ for 1 to 2 years old infants.

III–3. RESULTS OF ASSESSMENT

The source term for a total 24-hour release has been modified as presented in Table III–3.

TABLE III–3. SOURCE TERM

Radionuclide	Total release (Bq)
Sr89	2.7e14
Sr90+	2.10e13
Te127m+ (*)	2.43e14
Te129m+	8.4e14
Te132+	1.82e16
I131 gas	1.59e16
I131 org	1.59e16
I123 gas	2.04e16
I133 gas	1.11e16
Xe133	2.87e18
Xe135	3.71e17
Cs134	2.44e14
Cs137+ (*)	1.73e14
Ce144+ (*)	5.24e13
Pu238	1.28e11

Note:

(*) the + sign indicates that the radionuclide is assumed to be in balance with all of or a part of its progenies:

- Ce144+ with Pr144 (98.22%) and Pr144m (1.78%),
- Cs137+ with Ba137m (94.6%),
- Sr90+ with Y90 (100%),
- Te127m+ with Te127 (97.6%),
- Te129m with Te125 (65%),
- Te132+ with I132 (100%).

The doses induced by the progenies are taken into account by the dose coefficient of the original radionuclide. For the other nuclides, the decay is computed during the dispersion of the plume and after deposition. After deposition has taken place, mechanisms other than radioactive decay are not taken into account (washing, ploughing, etc).

The aerosol mean diameter is supposed to be 1 µm. The dry deposition velocity is 5.10^{-3} $m.s^{-1}$ for aerosols. For iodine the dry deposition velocity is 2.10^{-2} $m.s^{-1}$ for the gaseous form and 1.10^{-4} $m.s^{-1}$ for the organic form. There is no deposition for noble gases (Kr, Xe).

For this exercise only 1 year of meteorological data is provided. It is usually considered that it is necessary to have a period three times larger than the return period of the extreme events being considered. Such a short period seems to be inadequate to have a correct evaluation of the intensity for the extreme events.

The class of stability of the atmosphere is obtained by comparing the observed vertical gradient of temperature with the theoretical adiabatic value (-0.5°C/100 m). The atmosphere is considered stable if the vertical gradient of temperature is greater than -0.5°C/100 m, convective otherwise. However, wind roses have been computed for each stability class and presented in Figure III–1 in red – for stable atmosphere, and in blue – for convective atmosphere.

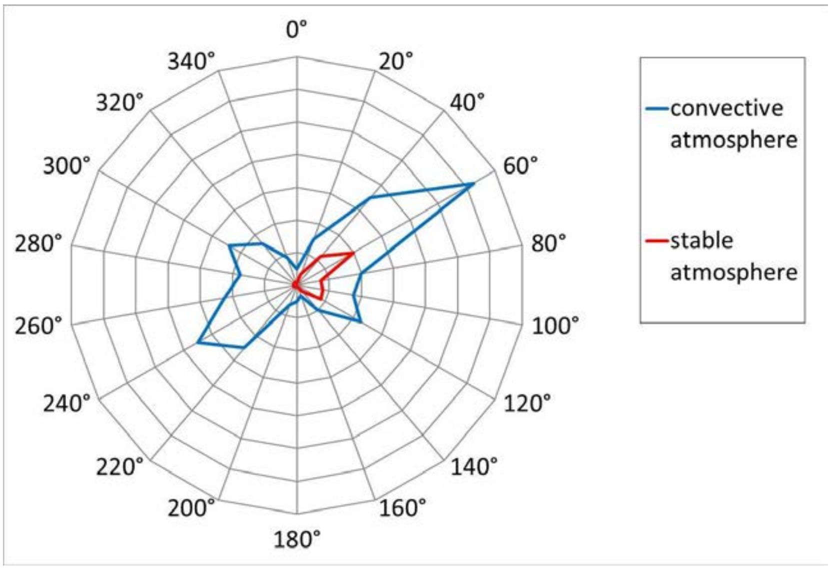

FIG. III–1. Wind rose on the exercise site

The most probable wind directions are north-east (80°) and south west (240°). South-east and north-west directions are also possible. For each stability class the most probable wind speed is sought. Figure III–2 shows the probabillity of each wind speed for stable atmosphere (in red) and convective atmosphere (in blue).

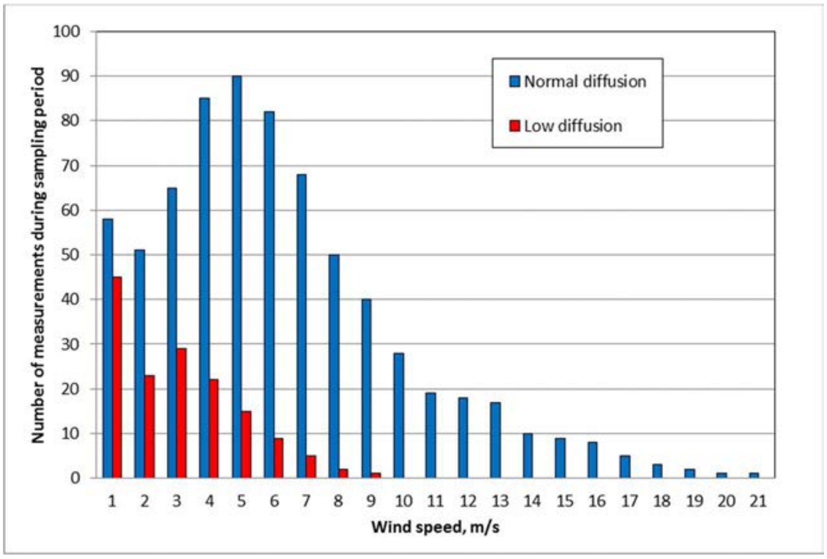

FIG. III–2. Probability of wind speed

The most probable rainfall rate deduced from the meteorological data of the site is 2 mm/h. A rainfall is only possible with non-stable atmosphere. According to these data, the meteorological conditions presented in Table III–4 are chosen for the exercise.

TABLE III–4. METEOROLOGICAL CONDITIONS SELECTED FOR THE EXERCISE

Meteorological condition	Name
Stable atmosphere, low wind (1m/s)	DF1
Convective atmosphere low wind (2 m/s)	DN2
Convective atmosphere, moderate wind (5 m/s)	DN5
Convective atmosphere, strong wind (10 m/s)	DN10
Convective atmosphere, moderate wind (5 m/s) and rainfall (2 mm/h)	DN5p

Maximum total effective doses and maximum doses to thyroid calculated at different distances from the source of release and integrated over 1 day, 2 days and 7 days after release are presented in Table III–5. Table III–6 displays meteorological conditions corresponding to these doses.

TABLE III–5. MAXIMUM DOSES.

Time, days	Distance, km	Dose to adults, mSv		Dose to infants, mSv	
		Total effective	Thyroid	Total effective	Thyroid
1	1.0	7.30E+03	1.00E+05	1.30E+04	2.20E+05
	2.5	2.60E+03	4.00E+04	5.00E+03	8.50E+04
	3.5	1.60E+03	2.40E+04	3.00E+03	5.10E+04
	6.5	5.60E+02	8.40E+03	1.10E+03	1.80E+04
	7.0	4.90E+02	7.30E+03	9.30E+02	1.60E+04
	8.0	3.80E+02	5.80E+03	7.30E+02	1.20E+04
	15	1.20E+02	1.80E+03	2.30E+02	3.90E+03
	50	1.30E+01	2.00E+02	2.50E+01	4.30E+02
2	1.0	8.60E+03	1.00E+05	1.40E+04	2.20E+05
	2.5	2.90E+03	4.40E+04	5.30E+03	8.50E+04
	3.5	1.70E+03	2.40E+04	3.00E+03	5.10E+04
	6.5	6.10E+02	8.40E+03	1.10E+03	1.80E+04
	7.0	5.40E+02	7.40E+03	9.30E+02	1.60E+04
	8.0	4.20E+02	5.80E+03	7.30E+02	1.20E+04
	15	1.30E+02	1.80E+03	2.40E+02	3.90E+03
	50	1.50E+01	2.00E+02	2.70E+01	4.30E+02
7	1.0	1.20E+04	1.00E+05	1.80E+04	2.20E+05
	2.5	3.60E+03	4.10E+04	1.40E+04	8.60E+04
	3.5	2.20E+03	2.40E+04	3.60E+03	5.20E+04
	6.5	7.70E+02	8.60E+03	1.30E+03	1.80E+04
	7.0	6.80E+02	7.50E+03	1.10E+03	1.60E+04
	8.0	5.30E+02	5.90E+03	8.80E+02	1.30E+04
	15	1.70E+02	1.90E+03	2.80E+02	4.00E+03
	50	1.80E+01	2.10E+02	3.00E+01	4.30E+02

The reference groups had to be chosen as possibly exposed to the plume by the north-east wind (probable) and by the south east wind (possible). These correspond to the group 2 (15 000 people at 8 km) and group 3 (50 people at 2.5 km) defined for the exercise. For these localizations three age groups are considered: 1 to 2-year old infants, 10-year old children and adults. The dose coefficients for each age group are obtained from the French regulation Ref [III–5].

The total effective dose and the thyroid dose are computed for a short time exposure (48 hours). This assessment doesn't take into account a potential sheltering by the buildings or the effect of counter measures (evacuation, intake of stable iodine, etc).

TABLE III–6. METEOROLOGICAL CONDITIONS CORRESPONDING TO THE MAXIMUM DOSES

Time, days	Distance, km	Dose to adults, mSv		Dose to infants, mSv	
		Total effective	Thyroid	Total effective	Thyroid
1	1.0	DN5p2	DN5	DN5	DN5
	2.5	DN10	DN10	DN10	DN10
	3.5	DN10	DN10	DN10	DN10
	6.5	DN10	DN10	DN10	DN10
	7.0	DN10	DN10	DN10	DN10
	8.0	DN10	DN10	DN10	DN10
	15	DN10	DN10	DN10	DN10
	50	DN10	DF1	DN10	DN10
2	1.0	DN5p2	DN5	DN5	DN5
	2.5	DN10	DN10	DN10	DN10
	3.5	DN10	DN10	DN10	DN10
	6.5	DN10	DN10	DN10	DN10
	7.0	DN10	DN10	DN10	DN10
	8.0	DN10	DN10	DN10	DN10
	15	DN10	DN10	DN10	DN10
	50	DN10	DF1	DN10	DN10
7	1.0	DN5p2	DN5	DN5p2	DN5
	2.5	DN10	DN10	DF1	DN10
	3.5	DN10	DN10	DN10	DN10
	6.5	DN10	DN10	DN10	DN10
	7.0	DN10	DN10	DN10	DN10
	8.0	DN10	DN10	DN10	DN10
	15	DN10	DN10	DN10	DN10
	50	DN10	DN10	DN10	DN10

Table III–7 presents the total effective dose to the public. The results are computed on the wind axis. To take into account the possible variation of the wind direction during a long release time, a spread factor (SF) is introduced. This factor is 1 for a short release time or very stable wind direction, or 5 for a long release time or a variable wind direction.

TABLE III–7. TOTAL EFFECTIVE DOSE TO THE PUBLIC (mSv)

Meteorological conditions and age groups		Total effective dose (mSv)			
		Point 2		Point 3	
		min (SF=5)	max (SF=1)	min (SF=5)	max (SF=1)
DF1	Infants 1-2y	540	2 700	380	1 900
	Children 10y	480	2 200	320	1 600
	Adult	300	1 500	200	1 000
DN2	Infants 1-2y	340	1 700	182	910
	Children 10y	280	1 400	152	760
	Adult	188	940	100	500
DN5	Infants 1-2y	700	3 500	380	1 900
	Children 10y	580	2 900	320	1 600
	Adult	380	1 900	220	1 100
DN10	Infants 1-2y	1060	5 300	600	3 000
	Children 10y	880	4 400	540	2 700
	Adult	580	2 900	340	1 700
DN5p	Infants 1-2y	740	3 700	400	2 000
	Children 10y	640	3 200	360	1 800
	Adult	440	2 200	260	1 300

The estimated value of the total effective dose is essentially higher than the level associated with the "cliff-edge effect" considered as the limit of potential exposure of the reference group. Calculated doses are higher than the regulatory limits and would require the evacuation of population. In case of such an accident the population has to be evacuated from a large zone including point 2 of the exercise with 15 000 persons. The relative contribution of various radioisotopes is given in Figure III–3 for the adults and in Figure III–4 for the children. The main part of the total effective dose is induced by the inhalation of iodine.

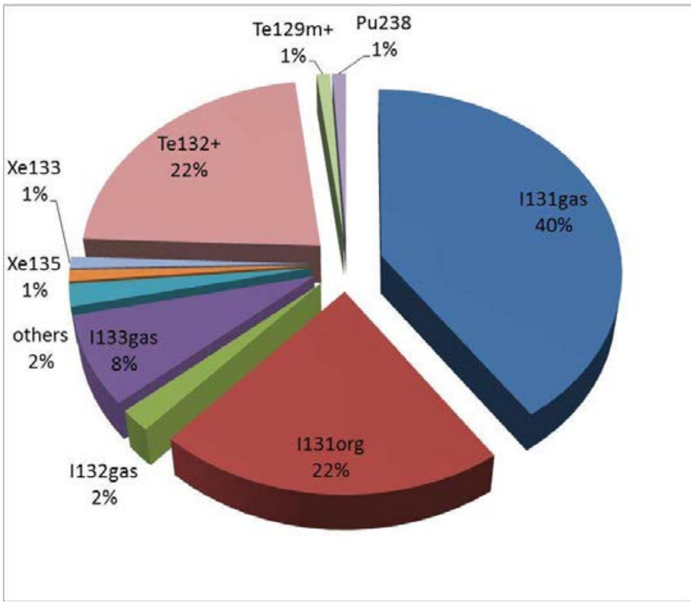

FIG. III–3. Contribution of the radioisotopes to the total effective dose for adults, 2 days, 8 km (point 2)

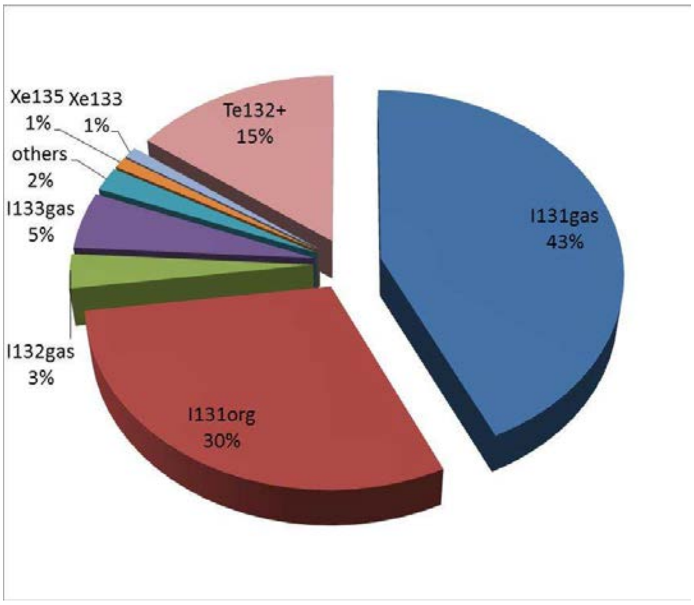

FIG. III–4. Contribution of the radioisotopes to the total effective dose for infants, 2 days, 8 km (point 2)

Table III–8, presents the dose to the thyroid for the public. The thyroid dose is higher than the regulatory prescribed dose. It would induce the distribution and the intake of stable iodine for a large group of population.

TABLE III–8. DOSE TO THE THYROID (mSv)

Meteorological conditions and age groups		Thyroid dose (mSv)			
		Point 2		Point 3	
		min (SF=5)	max (SF=1)	min (SF=5)	max (SF=1)
DF1	Infants 1-2y	8 600	43 000	6 000	31 000
	Children 10y	7 000	35 000	5 000	25 000
	Adult	4 000	20 000	2 800	14 000
DN2	Infants 1-2y	5 400	27 000	3 000	15 000
	Children 10y	4 400	22 000	2 400	12 000
	Adult	2 600	13 000	1 380	6 900
DN5	Infants 1-2y	11 400	57 000	6 200	31 000
	Children 10y	9 200	46 000	5 200	26 000
	Adult	5 200	26 000	3 000	15 000
DN10	Infants 1-2y	17 000	85 000	10 200	51 000
	Children 10y	13 800	69 000	8 400	42 000
	Adult	8 800	44 000	4 800	24 000
DN5p	Infants 1-2y	10 400	52 000	5 600	28 000
	Children 10y	8 400	42 000	4 600	23 000
	Adult	4 800	24 000	2 600	13 000

The activity in the foodstuff is computed for some vegetal products and animal products supposed to be produced at point 3 of the exercise. Most of the values in Tables III–9 and III–10 are beyond the limits defined by Ref [III–3]. According to the French regulation no product would be marketable.

TABLE III–9. ACTIVITY IN VEGETABLE PRODUCTS

	Activity in vegetable products (Bq/kg)						
	carrot	hay	grass	corn	apples	salad	tomato
α aerosols	5.0E+00	3.4E+03	1.4E+03	2.4E+03	2.0E-01	2.3E+02	2.5E+01
β γ aerosols	4.6E+05	3.8E+07	1.6E+07	2.6E+07	9.5E+03	2.5E+06	5.0E+05
Iodine	2.6E+07	7.0E+08	3.0E+08	4.9E+08	1.0E+05	4.7E+07	8.9E+06
Strontium	1.1E+04	7.0E+06	3.0E+06	4.9E+06	1.2E+03	4.7E+05	5.5E+04

TABLE III–10. ACTIVITY IN ANIMAL PRODUCTS

	Activity in animal products (Bq/kg or Bq/l)			
	goat milk	egg	sheep meat	chicken meat
α aerosols	9.50E-02	1.20E-01	3.10E+01	7.10E-01
β γ aerosols	3.60E+06	9.20E+06	2.00E+07	8.80E+06
Iodine	9.00E+08	1.50E+08	8.40E+07.	4.90E+06
Strontium	5.90E+05	9.90E+04	7.00E+06	3.9E+04

In the case of the exercise the calculation of the long-term dose has not been done. Indeed, the conclusion of the short-term dose assessment will induce counter measures like the evacuation of the populations and the prohibition of the consumption and marketing of foodstuffs. A long-term dose assessment does not take into account the effect of these counter measures, thus is not realistic. Furthermore, a long-term dose assessment necessitates considering a food intake that is dependent on the local production and usage factors that are not defined for the exercise.

REFERENCES TO ANNEX III

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ANNEX IV. GERMANY

IV–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

In 1991 the major European electricity producers formed an organization to develop the European Utility Requirements (EUR) document [IV–1]. This document proposes a common set of utility requirements for LWR nuclear power plants. Prior to these requirements, the development, design and licensing of existing LWR plants had been performed on a national basis with little interaction between countries.

The EUR document sets common safety targets which are consistent with the best European and international objectives. It states that these targets are values that are more restrictive than regulatory limits but are judged to be at a level that can be reasonably achieved by modern well-designed plants. Targets are set for normal operation, incident conditions, and accident conditions. For the preliminary design assessment, EUR has proposed criteria in terms of radionuclide releases rather than doses to members of the public. The targets are generally defined as linear combinations of the releases in each of the reference isotopic groups and depend on the category of the accident as determined by the estimated frequency of the initiating event. The detailed methodology can be found in [IV–1].

Germany opted to phase out nuclear power in its territory which implies no construction of new NPPs and shut down of the last currently operating NPP by 2022.

The most recent recommendation by the German Commission on Radiological Protection on “Planning areas for emergency response near nuclear power plants” [IV–2] contains the current philosophy on nuclear emergency management and methodologies to deal with potential accidents and associated risks. The key sentence, describing the change in philosophy is “The range of accidents included in the contingency planning was redefined to more closely reflect an accident's potential impact rather than its likelihood”.

Moving away from the risk as dominating factor, the German Commission on Radiological Protection (SSK) recommends investigating cliff-edge effects independent of their probability to check if the NPP or emergency management is prepared to deal with this. A similar approach was used for the stress test of German NPPs [IV–3].

IV–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

The COSYMA code system is designed for probabilistic risk assessments. This means that the models included within the system only need to be applicable on an average and need not be "correct" at a specific time and location. While this is particularly true of the atmospheric dispersion models, it also applies to some other models. COSYMA uses parameter values which represent the average situation in the region considered, and does not attempt to model the full spatial variation which might be encountered. This means that the COSYMA system is not suitable for use in real time in the event of an accident. The following short description refers to the COSYMA version 90/1 [IV–4].

The COSYMA package includes a set of programs for atmospheric dispersion. They are based on different approximations and are appropriate in different regions or for different applications. The calculations are carried out for each of a number of areas, defined in COSYMA in terms of angular segments and distance bands; throughout each area a uniform level of dose, and hence associated emergency actions and risks, are assumed. The doses in each of these areas are calculated at a single point, the "grid point".

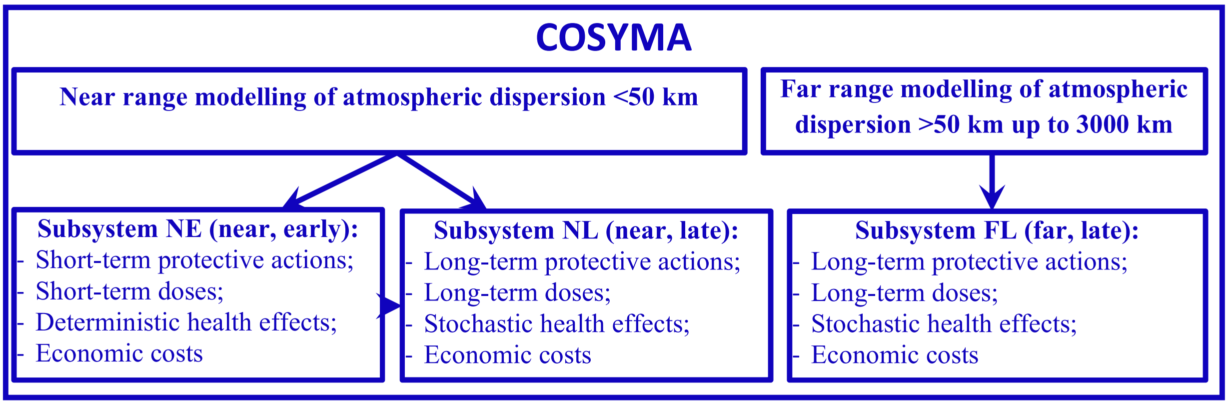

FIG. IV–1. General scheme of the COSYMA code system (modified from [IV–4])

There are many source terms for which there is no need to consider early health effects or the emergency actions intended to reduce the high short-term doses which lead to these effects. As the amount of computation required for these aspects of an analysis can be significant, it is logical to further divide the near distance version of COSYMA into two sub-systems concerned with early and late effects. This emphasis on different distance ranges and different health effects and emergency actions leads to the structure of COSYMA in which there are three principal sub-systems, each of which is an accident consequence assessments (ACA) program for one of the different areas of application. The applications of the different programs are illustrated in Figure IV–1. The three ACA programs designated as the NE, NL and FL sub-systems of COSYMA (where the first letter refers to near or far distance and the second to early or late health effects and the appropriate protective actions) are the main programs within the package.

In addition to the three main sub-systems of COSYMA, the package also contains a number of other programs for particular facets of an analysis.

Major sub-systems' modules and stand-alone programs in COSYMA are briefly described below.

The three sub-systems, NE, NL and FL of COSYMA are written in a modular form to allow the maximum possible flexibility in their use.

The ATMOS module calculates the time-integrals of air concentration and deposition at each point affected by the plume. The dispersion calculations are done for a unit release of a group of idealised nuclides representing a noble gas, an aerosol and the different forms of iodine; these groups of nuclides have different values for the deposition parameters. The CONCEN module combines the results of the atmospheric dispersion calculations (for unit release of idealised nuclides) with the source term information and calculates the air concentrations and deposition for each nuclide at each grid element, including the effects of radioactive decay and daughter build-up during the period of the plume travel. It calculates an effective air concentration which allows other modules to calculate the cloud gamma dose allowing for the finite size of the cloud.

The COSYMA package contains a few alternative dispersion models based on different assumptions and approximations, e.g. the RIMPUFF program can be used instead of the ATMOS module, while COSGAP can replace both the ATMOS and CONCEN modules. ACA calculations can be carried out for sequences of atmospheric conditions in the historical data chosen to represent the range of possible conditions in the data set, or for groups of constant atmospheric conditions. METSAM is a flexible system used for selecting sequences of atmospheric conditions for further analysis with the ACA programs.

Modules POTDOS and POTRSK calculate organ doses and individual health risks assuming no emergency actions. Different times over which the doses are integrated, different exposure pathways, and different health effects are considered. Dose-conversion factors are obtained from pre-calculated data libraries supplied with the package.

The module EARLY in the NE sub-system includes detailed modelling of the effects of early emergency actions in reducing the potential doses. Modules LATDOS and LATRSK in the 'late' sub-systems calculate the doses and individual health risks considering the effects of protective actions.

The program COSING estimates food chain related consequences of the accident. Age-dependent individual ingestion doses and time-dependent individual health risks from ingestion of contaminated foods can be estimated. A detailed breakdown of the contribution of the various foods and nuclides considered to the ingestion dose can also be derived.

Atmospheric dispersion model for the near range

The ATMOS module of the NE and NL sub-systems is based on a Gaussian plume dispersion model (GPM), which allows for hourly changes in atmospheric conditions such as wind vector, diffusion category, and precipitation rate. The diffusion coefficients σ_y, σ_z (m) describing the plume spread in the horizontal and vertical crosswind directions y and z are assumed to be a function of downwind travel distance without direct dependence on travel time. The diffusion coefficients are represented as a power law, showing explicitly the dependence on downwind distance x:

$$\sigma_{y,z} = a_{y,z} \cdot x^{b_{y,z}} \tag{IV–1}$$

Parameters *a* and *b* account for the dependence on the atmospheric stability class, on the surface roughness, and on release height.

At longer distance vertical diffusion is limited by the capping inversion layer at a mixing height which depends on the stability class. This layer is assumed to be impenetrable and totally reflecting. COSYMA then assumes a constant vertical material profile in the plume corresponding to a well-mixed plume between the ground and the capping inversion.

Dry deposition of material from the plume to the surfaces is modelled in COSYMA using three constant deposition velocities for elemental iodine, organically bound iodine, and aerosols. The deposition velocity v_D is defined as the surface contamination rate *($Bq\ m^{-2}\ s^{-1}$)* divided by the concentration *($Bq\ m^{-3}$)* in the air one meter above the surface. Depletion of the plume due to dry deposition of material is modelled using the 'source depletion model', i.e. it is assumed that the deposited material is removed from the whole vertical profile of the plume, not only from the surface layer.

Wet deposition of material from the plume is modelled using the 'washout model'. The washout constant *$\Lambda(s^{-1})$* depends on the precipitation intensity *I* (mm/h):

$$\Lambda = c \cdot I^d \tag{IV–2}$$

where coefficients *c* and *d* depend on the material to be washed out. The depletion of the plume due to wet deposition of material is modelled by assuming that the material is washed out and removed from the whole vertical profile of the plume. The fraction of material remaining in the plume after the time *t* is

$$f(t) = e^{-\Lambda}\ . \tag{IV–3}$$

IV–3. RESULTS OF ASSESSMENT

Calculations were performed with the COSYMA system using the weather data and the source term from the exercise. The weather data are categorized into 144 classes with the relevant probabilities of occurrence. A representative weather sequence has been selected for the model runs. This is done automatically by a pre-processor of the COSYMA system.

Doses are calculated for adults and one-year old infants as indicated in Tables IV–1 to IV–11 for various percentiles. For convenience in comparing results between different national case studies, the doses in Tables IV–1 to IV–9 are presented at the distances defined in the task setting. Complementary information on the doses from ground after 70 years exposure and doses from ingestion is provided at the standard grid used in COSYMA comprising the distance bands ranging from 250m up to 87.5 kilometres.

In all tables the percentiles are derived by sorting the results in ascending order. Each result is weighted by the probability of its occurrence. In this way, the 144 results can be sorted in the various percentiles/ fractiles and used in the tables. The percentile/ fractile of 99% means that 99% of the results are below that value and only one percent is equal to or above that value. All tables show the dose to an individual.

The following tables contain doses for adults and one-year old infants. Maximum values may be an order of magnitude higher than the mean values. This is attributed to the fact that maximum doses are often obtained with stable dispersion conditions and/or heavy rain events. Rain is a particularly important factor for estimation of doses from the ground.

The time dependency of doses from the ground shows the importance of short-lived nuclides. This is seen while comparing the integrated dose from 7 days and over 70 years. This resulting difference is smaller and thus less significant than the difference between 1 and 7 days.

The dose from ingestion dominates the dose. However due to the monitoring of contamination levels in the food and food restrictions which will be introduced after an emergency, the estimated contribution from ingestion is limited. Therefore, often ingestion doses are excluded from the assessments. Using the concentration levels of radionuclides in food, doses would be limited to 5 mSv per year.

Depending on the distance, doses to either adults or to infants are higher. Higher in all cases are doses to the thyroid due to the higher sensitivity of an infant. In general the most sensitive groups are used for an assessment, thus calculations cannot be limited to one age group only.

The total effective dose for adults is the result of the three exposure pathways: inhalation, external exposure from cloud pass, and external exposure from 7 days from ground without shielding. For the highest percentiles, the dose from ground shows the highest contribution; for the 95th percentile, inhalation and ground are similar and for the mean, the inhalation contributes more to the total – all for 1 km distance. The contribution from cloud is always much smaller and, typically for the near range, is of no importance. Further away (typically 50 km), exposure from cloud passage contributes more, but is never higher than about 10% of the total effective dose.

In case other integration times for the exposure from ground are considered, the contribution from ground is roughly one half or one quarter of that of the seven days, for two days and for one day, respectively.

In case of doses to a one-year old infant, the total dose would be dominated by inhalation as the dose from inhalation is roughly one order of magnitude higher than the one for adults. The contribution from the other pathways would be only slightly increased as the dose conversion factors for external irradiation do not differ significantly between infants and adults (roughly 30% higher for infants).

TABLE IV–1. EFFECTIVE DOSE TO ADULTS FROM CLOUD, Sv

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	8.77E-02	6.25E-03	8.27E-02	5.55E-02	3.09E-02	2.09E-02
2.5	4.46E-02	2.09E-03	3.71E-02	2.20E-02	1.19E-02	7.01E-03
3.5	2.81E-02	1.18E-03	2.43E-02	1.30E-02	6.73E-03	3.98E-03
6.5	1.49E-02	4.92E-04	1.36E-02	7.31E-03	2.76E-03	1.45E-03
7	1.45E-02	4.45E-04	1.28E-02	6.56E-03	2.49E-03	1.31E-03
8	1.38E-02	3.59E-04	1.13E-02	4.95E-03	2.00E-03	1.08E-03
15	7.90E-03	1.47E-04	5.45E-03	1.93E-03	7.77E-04	4.44E-04
50	9.94E-04	2.07E-05	5.98E-04	2.94E-04	1.53E-04	6.11E-05

TABLE IV–2. EFFECTIVE DOSE TO ADULTS FROM INHALATION, Sv

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	1.44E+00	6.18E-02	1.12E+00	6.54E-01	3.56E-01	2.16E-01
2.5	4.12E-01	1.44E-02	2.98E-01	1.83E-01	9.18E-02	4.60E-02
3.5	2.24E-01	6.94E-03	1.72E-01	9.05E-02	4.25E-02	2.20E-02
6.5	8.30E-02	2.26E-03	7.06E-02	3.39E-02	1.36E-02	6.51E-03
7	7.86E-02	2.01E-03	6.49E-02	2.99E-02	1.19E-02	5.77E-03
8	7.23E-02	1.56E-03	5.50E-02	2.24E-02	9.01E-03	4.52E-03
15	3.07E-02	5.50E-04	2.11E-02	7.09E-03	3.01E-03	1.55E-03
50	2.76E-03	7.91E-05	1.94E-03	1.17E-03	5.32E-04	2.43E-04

TABLE IV–3. EFFECTIVE DOSE TO INFANTS (1-YEAR OLD) FROM INHALATION, Sv

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	1.08E+01	4.87E-01	8.65E+00	5.03E+00	2.83E+00	1.70E+00
2.5	2.91E+00	1.10E-01	2.25E+00	1.36E+00	6.88E-01	3.65E-01
3.5	1.51E+00	5.24E-02	1.27E+00	6.71E-01	3.25E-01	1.65E-01
6.5	5.77E-01	1.66E-02	4.90E-01	2.31E-01	9.87E-02	4.84E-02
7	5.47E-01	1.46E-02	4.48E-01	2.04E-01	8.71E-02	4.28E-02
8	4.97E-01	1.13E-02	3.75E-01	1.59E-01	6.76E-02	3.35E-02
15	1.98E-01	3.99E-03	1.45E-01	4.95E-02	2.22E-02	1.14E-02
50	1.87E-02	5.69E-04	1.47E-02	8.87E-03	3.77E-03	1.64E-03

TABLE IV–4. EFFECTIVE DOSE TO ADULTS FROM GROUND, Sv (1 DAY EXPOSURE TIME)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	7.72E-01	1.75E-02	4.32E-01	1.78E-01	9.49E-02	6.02E-02
2.5	2.28E-01	4.22E-03	1.10E-01	5.05E-02	2.54E-02	1.40E-02
3.5	1.03E-01	2.14E-03	5.60E-02	2.85E-02	1.26E-02	6.87E-03
6.5	5.33E-02	7.32E-04	2.52E-02	9.85E-03	4.01E-03	2.06E-03
7	5.01E-02	6.56E-04	2.38E-02	8.82E-03	3.57E-03	1.83E-03
8	4.35E-02	5.28E-04	2.21E-02	7.11E-03	2.82E-03	1.45E-03
15	1.79E-02	2.00E-04	8.49E-03	3.02E-03	1.02E-03	5.38E-04
50	4.95E-03	3.23E-05	1.72E-03	5.34E-04	1.93E-04	7.87E-05

TABLE IV–5. EFFECTIVE DOSE TO ADULTS FROM GROUND, Sv (2 DAYS EXPOSURE TIME)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	1.29E+00	2.78E-02	7.08E-01	2.84E-01	1.50E-01	9.53E-02
2.5	3.87E-01	6.78E-03	1.87E-01	8.08E-02	4.02E-02	2.25E-02
3.5	1.77E-01	3.47E-03	9.51E-02	4.60E-02	1.99E-02	1.10E-02
6.5	9.24E-02	1.19E-03	4.29E-02	1.63E-02	6.64E-03	3.34E-03
7	8.68E-02	1.07E-03	4.06E-02	1.46E-02	5.93E-03	2.98E-03
8	7.55E-02	8.61E-04	3.81E-02	1.18E-02	4.69E-03	2.38E-03
15	3.09E-02	3.27E-04	1.47E-02	5.11E-03	1.66E-03	8.56E-04
50	8.52E-03	5.28E-05	2.93E-03	8.65E-04	3.13E-04	1.25E-04

TABLE IV–6. EFFECTIVE DOSE TO ADULTS FROM GROUND, Sv (7 DAYS EXPOSURE TIME)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	2.80E+00	5.86E-02	1.51E+00	5.93E-01	3.19E-01	2.01E-01
2.5	8.41E-01	1.44E-02	4.09E-01	1.73E-01	8.60E-02	4.71E-02
3.5	3.86E-01	7.40E-03	2.08E-01	9.84E-02	4.33E-02	2.33E-02
6.5	2.03E-01	2.55E-03	9.37E-02	3.49E-02	1.42E-02	7.00E-03
7	1.91E-01	2.29E-03	8.88E-02	3.14E-02	1.27E-02	6.22E-03
8	1.66E-01	1.84E-03	8.34E-02	2.55E-02	1.00E-02	4.97E-03
15	6.79E-02	7.00E-04	3.29E-02	1.09E-02	3.57E-03	1.80E-03
50	1.86E-02	1.13E-04	6.26E-03	1.89E-03	6.54E-04	2.67E-04

TABLE IV–7. DOSE TO THYROID, Sv (ADULTS)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	1.65E+01	7.79E-01	1.37E+01	8.19E+00	4.54E+00	2.79E+00
2.5	4.12E+00	1.70E-01	3.41E+00	2.03E+00	1.04E+00	5.58E-01
3.5	2.05E+00	7.98E-02	1.86E+00	9.92E-01	5.01E-01	2.54E-01
6.5	7.92E-01	2.43E-02	6.63E-01	3.26E-01	1.43E-01	7.33E-02
7	7.47E-01	2.14E-02	6.02E-01	2.89E-01	1.26E-01	6.46E-02
8	6.67E-01	1.66E-02	5.00E-01	2.27E-01	9.66E-02	5.01E-02
15	2.69E-02	8.25E-04	2.28E-02	1.31E-02	5.44E-03	2.32E-03

TABLE IV–8. DOSE TO THYROID, Sv (INFANTS OF 1 YEAR)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	1.71E+02	8.01E+00	1.00E+02	8.46E+01	4.65E+01	2.83E+01
2.5	4.30E+01	1.75E+00	3.57E+01	2.10E+01	1.09E+01	5.78E+00
3.5	2.13E+01	8.23E-01	1.95E+01	1.04E+01	5.16E+00	2.62E+00
6.5	8.27E+00	2.51E-01	6.94E+00	3.40E+00	1.50E+00	7.50E-01
7	7.81E+00	2.22E-01	6.30E+00	3.02E+00	1.31E+00	6.65E-01
8	6.99E+00	1.72E-01	5.23E+00	2.35E+00	1.01E+00	5.26E-01
15	2.54E+00	5.99E-02	2.06E+00	7.29E-01	3.30E-01	1.76E-01
50	2.78E-01	8.53E-03	2.38E-01	1.34E-01	5.44E-02	2.38E-02

TABLE IV–9. TOTAL EFFECTIVE DOSE TO ADULTS, Sv (EXPOSURE PATHWAYS: INHALATION, CLOUD, GROUND 7 DAYS)

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
1	4.33E+00	1.27E-01	2.71E+00	1.30E+00	7.05E-01	4.38E-01
2.5	1.30E+00	3.09E-02	7.44E-01	3.78E-01	1.90E-01	1.00E-01
3.5	6.38E-01	1.55E-02	4.04E-01	2.02E-01	9.25E-02	4.92E-02
6.5	3.01E-01	5.30E-03	1.78E-01	7.62E-02	3.05E-02	1.50E-02
7	2.84E-01	4.74E-03	1.67E-01	6.78E-02	2.71E-02	1.33E-02
8	2.52E-01	3.76E-03	1.50E-01	5.29E-02	2.10E-02	1.06E-02
15	1.06E-01	1.40E-03	5.94E-02	1.99E-02	7.35E-03	3.79E-03
50	2.24E-02	2.13E-04	8.80E-03	3.36E-03	1.34E-03	5.71E-04

TABLE IV–10. EFFECTIVE DOSE FROM GROUND AFTER 70 YEARS EXPOSURE, ADULTS, Sv

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
0.250	0.2804E+02	0.9099E+00	0.1820E+02	0.8128E+01	0.4571E+01	0.3090E+01
0.400	0.1872E+02	0.4873E+00	0.1072E+02	0.4467E+01	0.2512E+01	0.1622E+01
0.625	0.1224E+02	0.2667E+00	0.6457E+01	0.2570E+01	0.1413E+01	0.9120E+00
0.875	0.8686E+01	0.1670E+00	0.4571E+01	0.1698E+01	0.9120E+00	0.5754E+00
1.15	0.6471E+01	0.1129E+00	0.3388E+01	0.1230E+01	0.6166E+00	0.3890E+00
1.55	0.4574E+01	0.7315E-01	0.2455E+01	0.8318E+00	0.4266E+00	0.2455E+00
2.10	0.3177E+01	0.4654E-01	0.1479E+01	0.5888E+00	0.2754E+00	0.1479E+00
2.70	0.1957E+01	0.3065E-01	0.9772E+00	0.3802E+00	0.1820E+00	0.9772E-01
3.70	0.9453E+00	0.1651E-01	0.5129E+00	0.2455E+00	0.9550E-01	0.4898E-01
4.90	0.6901E+00	0.1041E-01	0.4266E+00	0.1549E+00	0.5623E-01	0.2951E-01
6.55	0.5905E+00	0.6550E-02	0.2754E+00	0.9120E-01	0.3715E-01	0.1698E-01
8.75	0.4365E+00	0.4096E-02	0.2344E+00	0.5888E-01	0.2138E-01	0.9772E-02
11.5	0.3023E+00	0.2753E-02	0.1413E+00	0.4074E-01	0.1349E-01	0.6918E-02
15.5	0.1927E+00	0.1776E-02	0.9120E-01	0.3020E-01	0.8511E-02	0.4266E-02
21	0.1699E+00	0.1119E-02	0.5754E-01	0.1905E-01	0.5495E-02	0.2818E-02
27	0.9643E-01	0.7502E-03	0.4074E-01	0.1148E-01	0.3802E-02	0.1820E-02
37	0.3856E-01	0.4514E-03	0.2512E-01	0.7413E-02	0.2455E-02	0.1122E-02
49	0.5398E-01	0.3198E-03	0.1905E-01	0.5754E-02	0.1738E-02	0.7079E-03
65.5	0.2910E-01	0.1922E-03	0.1202E-01	0.3388E-02	0.9120E-03	0.4365E-03
87.5	0.1797E-01	0.1215E-03	0.7762E-02	0.2399E-02	0.6761E-03	0.2239E-03

TABLE IV–11. EFFECTIVE DOSE FROM INGESTION, ADULTS, Sv

Radius, km	Max doses	Mean doses	Fractile 99.9	Fractile 99.0	Fractile 95.0	Fractile 90.0
0.250	0.1164E+03	0.4073E+01	0.8913E+02	0.4898E+02	0.2042E+02	0.1259E+02
0.400	0.7656E+02	0.2150E+01	0.5129E+02	0.2630E+02	0.1122E+02	0.6761E+01
0.625	0.4982E+02	0.1158E+01	0.2951E+02	0.1413E+02	0.6607E+01	0.3631E+01
0.875	0.3496E+02	0.7125E+00	0.1995E+02	0.8913E+01	0.4169E+01	0.2188E+01
1.15	0.2542E+02	0.4729E+00	0.1445E+02	0.5754E+01	0.2754E+01	0.1413E+01
1.55	0.1729E+02	0.2977E+00	0.8913E+01	0.3548E+01	0.1738E+01	0.8913E+00
2.10	0.1144E+02	0.1835E+00	0.5623E+01	0.2455E+01	0.1096E+01	0.5248E+00
2.70	0.7026E+01	0.1176E+00	0.3631E+01	0.1622E+01	0.6918E+00	0.3236E+00
3.70	0.3057E+01	0.5955E-01	0.1950E+01	0.8511E+00	0.3715E+00	0.1585E+00
4.90	0.2098E+01	0.3665E-01	0.1288E+01	0.5248E+00	0.2188E+00	0.9333E-01
6.55	0.1704E+01	0.2258E-01	0.8710E+00	0.3388E+00	0.1202E+00	0.5370E-01
8.75	0.1205E+01	0.1315E-01	0.6310E+00	0.2138E+00	0.6607E-01	0.3020E-01
11.5	0.8929E+00	0.8732E-02	0.3020E+00	0.1349E+00	0.4786E-01	0.1995E-01
15.5	0.4536E+00	0.5651E-02	0.2239E+00	0.1000E+00	0.2818E-01	0.1318E-01
21	0.2957E+00	0.3550E-02	0.1380E+00	0.5370E-01	0.1950E-01	0.8710E-02
27	0.2935E+00	0.2414E-02	0.7762E-01	0.4074E-01	0.1175E-01	0.5888E-02
37	0.1163E+00	0.1348E-02	0.5248E-01	0.2399E-01	0.7244E-02	0.3388E-02
49	0.1522E+00	0.9671E-03	0.5012E-01	0.1950E-01	0.4786E-02	0.2042E-02
65.5	0.7810E-01	0.5262E-03	0.2951E-01	0.1202E-01	0.2630E-02	0.1175E-02
87.5	0.4710E-01	0.3199E-03	0.1905E-01	0.7586E-02	0.1585E-02	0.5129E-03

REFERENCES TO ANNEX IV

[IV–1] EUROPEAN UTILITY REQUIREMENTS, European Utility Requirements for LWR Nuclear Power Plants, Volume 2, Generic Nuclear Island Requirements, Revision D (2012). http://www.europeanutilityrequirements.org/Documentation/EURdocument/RevisionD/Volume2.aspx

[IV–2] GERMAN COMMISSION ON RADIOLOGICAL PROTECTION, Planning Areas for Emergency Response near Nuclear Power Plants, SSK 2014. 268th meeting of GCRP (2014).

[IV–3] FEDERAL MINISTRY FOR ENVIRONMENT, NATURE CONSERVATION AND NUCLEAR SAFETY, EU Stress test: National Report of Germany, BMU (2012).

[IV–4] HASEMANN, I., JONES, J., COSYMA: User Guide. Report, EUR 13045, KfK-4331B.CEC, Brussels (1990).

ANNEX V. INDIA

V–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

Estimation of dose to the public through atmospheric releases under potential accidents from a power reactor was performed in order to compare various methodologies adopted by the participants from different Member States. A hypothetical accident in a reactor was assumed and the radioactive releases to the environment through the atmospheric route were considered for the assessment. The relevant input parameters to be used such as meteorological data, environmental data and the radiological data were identified and a standard set of data was provided to the participants for this assessment. Each participant was advised to conduct the dose assessment using their own computational aids and tools and to present the results in terms of dose to the public at pre-designated distances. Participants were also requested to consider a risk-based approach, if such a system is used in their country's regulation.

The source term used for the accident under assessment is given in the Table V–1. Fifteen radiologically significant nuclides, including three fission product noble gases, eleven solid fission products and one fissile material (fuel) were considered for the estimation of the offsite dose.

TABLE V–1. ENVIRONMENTAL RELEASE

Significant nuclide No.	Radionuclide	Release (Bq)
1	Kr-88	3.04E+14
2	Xe-133	2.87E+18
3	Xe-135	3.71E+17
4	Cs-134	2.44E+14
5	Cs-137	1.73E+14
6	Sr-89	2.70E+14
7	Sr-90	2.10E+13
8	I-131	1.59E+16
9	I-132	2.04E+16
10	I-133	1.11E+16
11	Te-127m	2.43E+14
12	Te-129m	8.40E+14
13	Te-132	1.82E+16
14	Ce-144	5.24E+13
15	Pu-239	1.47E+10

The release is assumed to occur at a height of 35 m above ground. Depletion of the radioactivity due to radiological decay was considered in the calculation.

A complete set of meteorological data observed for one full year at a typical site was provided to all the participants. The data included hourly average values of wind direction, wind speed (for three different heights), stability category (based on Pasquill-Gifford classification), temperature (at three different elevations), solar insolation, barometric pressure, relative humidity and precipitation rates. As the accident release is considered only for 24 hours, choosing the weather data for the calculation requires careful scrutiny of the data to identify the contiguous 24-hour meteorological data set that would result in the maximum offsite doses. The regulatory guide in India suggests that for the accident conditions the combination of the weather that results in the highest offsite radiological consequences should be assumed. Accordingly, in the calculations, the direction sector was considered to be unchanged during the release duration. The wind speed and stability category were also assumed to remain unchanged throughout the release period and the offsite doses estimated accordingly. Corrections due to plume depletion by dry deposition were considered in the calculation. No rain was considered in the calculation.

The Atomic Energy Regulatory Board (AERB) in India has published several codes and guides indicating the requirements for siting a nuclear power plant in India. The AERB regulatory guide Ref [V–1] on the consenting process for nuclear power plants and research reactors specifies criteria with respect to the probability of the events that could result in off-site radiological consequences.

The dose limit in the case of the accident that is being considered is 100 mSv effective dose and 500 mSv equivalent dose (Thyroid) to the maximally exposed individual at the site boundary. Collective dose to public has not been considered as part of regulatory requirement. As in many of the countries the dose to human beings is taken as the requirement for compliance.

In July 2014, the Atomic Energy Regulatory Board in India published a safety code on evaluation of sites for nuclear facilities [V–2] wherein the radiological dose criteria for various categories of accidents in nuclear reactors were specified. Ref [V-2] states that in case of a severe accident the release of radioactive materials should cause no permanent relocation of population. The need for offsite interventions should be limited in area and time.

It may be noted that the regulation mandates the licensee to undertake the offsite dose assessments even for severe accidents in order to identify the magnitude of the exposures involved and the distance up to which protective actions are warranted so that a comprehensive emergency preparedness plan can be established.

The risk-based approach has not been considered in the regulatory framework for licensing sites and nuclear facilities in India.

The Atomic Energy Regulatory Board, during 2014 published a guideline [V–3] with an objective to provide criteria for establishing emergency preparedness and response plans at nuclear and radiation facilities to mitigate the radiological consequences following a nuclear accident or radiological emergency situation. The document also provides guidance for establishing operational criteria that include operational intervention levels (OILs), emergency action levels (EALs), specific observables and other indicators on the scene to facilitate the decision-making process during an emergency situation.

For emergency response plans the reference dose levels for the public are set typically between an effective dose of 20 mSv and 100 mSv, expressed in terms of residual dose, which includes dose contributions via all exposure pathways. During the emergency phase, a reference level between 20 and 100 mSv per year should be used to implement protective actions driven by urgency, taking into account the prevailing conditions. The protection strategy should be optimized to reduce the exposures below the reference level. Once the emergency is over, a reference level for the existing exposure situations should be used between 1 and 20 mSv per year depending upon the situation. Effort should be taken to reduce the radiation exposure. The generic criteria both for avoiding or minimizing the deterministic effects and for reducing the stochastic risk for accidental exposures are given in Tables V–2 and V–3.

TABLE V–2. GENERIC CRITERIA FOR ACUTE DOSES FOR WHICH PROTECTIVE ACTIONS AND OTHER RESPONSE ACTIONS ARE TO BE TAKEN UNDER ANY CIRCUMSTANCES TO AVOID OR TO MINIMIZE SEVERE DETERMINISTIC EFFECTS

Generic Criteria		Examples of protective actions and other response actions
External acute exposure (<10 hours)		
Whole Body (Bone Marrow)	1 Sv	If the dose is projected: − Take precautionary urgent protective actions immediately (even under difficult conditions) to keep doses below the generic criteria − Provide public information and warnings − Carry out urgent decontamination If the dose has been received: − Perform immediate medical examination, consultation and indicated medical treatment − Carry out contamination control − Carry out immediate decorporation (if applicable) − Carry out registration for long term health monitoring (medical follow-up) − Provide comprehensive psychological counselling
Skin	10 Sv to 100 cm^2	
Internal Exposure from acute intake (Delivered in 30 days)		
Thyroid	2 Sv	
Lung	30 Sv	

TABLE V–3. GENERIC CRITERIA FOR PROTECTIVE ACTIONS AND OTHER RESPONSE ACTIONS IN EMERGENCY EXPOSURE SITUATIONS TO REDUCE THE RISK OF STOCHASTIC EFFECTS

Generic Criteria		Examples of protective actions and other response actions
Projected dose that exceeds the following generic criteria: Take urgent protective actions/Protective actions and other response actions		
Thyroid dose	50 mSv in the first 7 days	Urgent protective actions: Iodine thyroid blocking
Whole body dose	100 mSv in the first 7 days	Urgent protective actions: Sheltering; evacuation; decontamination; restriction on consumption of food, milk and water; contamination control; public reassurance
Whole body dose	100 mSv per annum	Early Protective Actions: Temporary relocation; decontamination; replacement of food, milk and water; public reassurance
Dose that has been received and that exceeds the following generic criteria: Take longer term medical actions to detect and to effectively treat radiation induced health effects		
Whole body dose	100 mSv in a month	Screening based on equivalent doses to specific radiosensitive organs (as a basis for medical follow-up), counselling

V–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

The computation of the offsite doses is done using an in-house developed spread sheet-based software. The calculation adopts a simple, standardized Gaussian plume model for the estimation of the concentration and the consequent doses with correction for dry deposition [V–4, V–5]. The cloud shine doses are also estimated individually for all the isotopes for all the distances involved. The pathways of exposure considered are through (i) inhalation (ii) cloud shine and (iii) ground shine. Unlike the inhalation and cloud shine doses which are prompt and likely to continue as long as the duration of the release, the exposure from the ground shine pathway continues for longer periods of time depending on the occupancy of the individuals.

The inhalation and the cloud shine doses are short term exposures and they are estimated with no credit for the period of occupancy by the public outdoors and the shielding offered to the personnel due to indoor occupancy. The occupancy factor outdoors was considered as 1.0 to make the estimates conservative. The dose conversion factors required for the calculations for various nuclides and pathways of exposure are taken from an IAEA guide [V–6]. Dose estimation is carried out imagining a hypothetical adult assumed to be residing at the site boundary and beyond. Though long-term site specific meteorology is available, the worst combination of weather that results in the highest dose to the public is considered for the dose assessment. As the release duration is short, i.e. about 24 hours, using the single stability category, single wind speed and wind direction is recommended by the regulatory guides. It is well recognised that such extreme assumptions would result in higher dose estimates. But such estimates indicate the upper bound values of the off-site doses for the distances involved, so as to establish a comprehensive emergency preparedness plan by the licensee. There could be scenarios with long term release of radioactivity to the environment, wherein it would be appropriate to use frequency weighted weather data, which is generated from the long term annual meteorological measurements, specific to the site.

Accident consequences are expressed only in terms of doses and not in terms of health effects or risk estimates, since such an approach is not recommended by the regulatory body in India.

V–3. RESULTS OF ASSESSMENT

It is known that the values assumed for the meteorological parameters influence the environmental doses significantly. Accordingly, the calculations are done for all stability categories to show the variations. The wind speed is also considered to be the lowest, i.e. 1 m/s though the annual frequency of its occurrence could be very low. To maximise the estimated doses, the wind direction is also assumed to be constant, whereas in realistic cases the probability of wind direction being the same for 24-hour periods could be very small. It is also noted that the probability of combination of wind being in single direction, having a very low wind speed of 1 m/s, and having one weather stability category could be extremely small. However, considering the accident scenario for which the release period is considered to be 24 hours, the bulk of the release could occur within the initial few hours when such combination of weather could be feasible. Hence the assumption of a single direction, single wind speed and stability category is generally considered in the dose estimates.

The dose calculation is performed for different pathways of exposures namely, inhalation, cloud shine, ground shine (exposure from contaminated ground surfaces) and from ingestion of iodine through the "grass-cow-milk" route. The inhalation and the cloud shine doses are of finite nature and the exposure pathways cease to exist as soon as the release of radioactivity from the plant stops. As the release duration is considered to be 24 hours, the integration time for the estimation of the exposure is taken as one day only. While in the case of cloud shine the effective dose is estimated, for inhalation the committed effective dose is calculated. For ground shine, the exposure time determines the cumulative exposure received by the individual. In the current exercise an exposure time of 24 hours is used for the estimation. Since all the NPPs have an exclusion zone of a minimum of 1 km for new plants and 1.5 km for old plants, the results are given for distances beyond 1 km where the general public is assumed to reside and have access with no restrictions.

The concentration of the radionuclides at the specified location is estimated using the standard Gaussian plume model. The hypothetical individual is assumed to be continuously present in the location and breathe the contaminated air for the entire period of the release. The estimated inhalation doses for all the radionuclides considered, for 1 to 50 km distance and for various stability categories are given in Tables V–4 to V–11. The total dose received through the inhalation route is given in Table V–4 and in Figure V–1.

TABLE V–4. INHALATION DOSE (Sv) FROM ALL RADIONUCLIDES (I, Cs, Ce, Sr, Te, Pu)

Distance (km)	Stability categories					
	A	B	C	D	E	F
1	2.20E-01	1.10E+00	2.30E+00	4.11E+00	4.28E+00	1.65E+00
2.5	1.37E-02	1.76E-01	4.55E-01	1.29E+00	2.23E+00	3.12E+00
3.5	6.28E-03	8.60E-02	2.27E-01	6.57E-01	1.16E+00	1.86E+00
7	3.33E-03	2.09E-02	6.09E-02	2.08E-01	3.91E-01	7.29E-01
8	2.94E-03	1.57E-02	4.57E-02	1.49E-01	2.66E-01	4.70E-01
15	1.64E-03	4.34E-03	1.39E-02	5.27E-02	9.76E-02	1.78E-01
50	5.18E-04	5.32E-04	1.11E-03	2.17E-03	1.41E-03	5.13E-04

TABLE V–5. INHALATION DOSE (Sv) FROM I

Distance (km)	A	B	C	D	E	F
1	1.60E-01	7.99E-01	1.67E+00	2.99E+00	3.11E+00	1.20E+00
2.5	9.99E-03	1.28E-01	3.31E-01	9.39E-01	1.62E+00	2.27E+00
3.5	4.57E-03	6.25E-02	1.65E-01	4.77E-01	8.41E-01	1.36E+00
7	2.42E-03	1.52E-02	4.42E-02	1.51E-01	2.84E-01	5.29E-01
8	2.14E-03	1.14E-02	3.32E-02	1.08E-01	1.93E-01	3.41E-01
15	1.19E-03	3.14E-03	1.01E-02	3.82E-02	7.08E-02	1.29E-01
50	3.75E-04	3.85E-04	8.06E-04	1.57E-03	1.02E-03	3.71E-04

TABLE V–6. EQUIVALENT DOSE (Sv) TO THYROID DUE TO INHALATION OF I

Distance (km)	A	B	C	D	E	F
1	4.00E+00	2.00E+01	4.18E+01	7.48E+01	7.79E+01	3.01E+01
2.5	2.50E-01	3.20E+00	8.27E+00	2.35E+01	4.06E+01	5.67E+01
3.5	1.14E-01	1.56E+00	4.12E+00	1.19E+01	2.10E+01	3.39E+01
7	6.04E-02	3.79E-01	1.11E+00	3.78E+00	7.10E+00	1.32E+01
8	5.34E-02	2.85E-01	8.29E-01	2.70E+00	4.83E+00	8.54E+00
15	2.97E-02	7.86E-02	2.52E-01	9.55E-01	1.77E+00	3.22E+00
50	9.37E-03	9.62E-03	2.01E-02	3.92E-02	2.55E-02	9.27E-03

TABLE V–7. INHALATION DOSE (Sv) FROM Cs

Distance (km)	A	B	C	D	E	F
1	2.84E-03	1.41E-02	2.97E-02	5.30E-02	5.52E-02	2.13E-02
2.5	1.78E-04	2.28E-03	5.89E-03	1.67E-02	2.89E-02	4.04E-02
3.5	8.15E-05	1.12E-03	2.94E-03	8.52E-03	1.50E-02	2.42E-02
7	4.36E-05	2.73E-04	7.97E-04	2.72E-03	5.12E-03	9.54E-03
8	3.86E-05	2.06E-04	5.99E-04	1.95E-03	3.49E-03	6.17E-03
15	2.19E-05	5.77E-05	1.85E-04	7.02E-04	1.30E-03	2.37E-03
50	7.36E-06	7.56E-06	1.58E-05	3.08E-05	2.00E-05	7.28E-06

TABLE V–8. INHALATION DOSE (Sv) FROM Sr

Distance (km)	A	B	C	D	E	F
1	6.47E-03	3.23E-02	6.77E-02	1.21E-01	1.26E-01	4.87E-02
2.5	4.06E-04	5.20E-03	1.34E-02	3.81E-02	6.60E-02	9.22E-02
3.5	1.86E-04	2.55E-03	6.72E-03	1.94E-02	3.43E-02	5.52E-02
7	9.93E-05	6.23E-04	1.82E-03	6.21E-03	1.17E-02	2.18E-02
8	8.80E-05	4.69E-04	1.37E-03	4.46E-03	7.96E-03	1.41E-02
15	4.98E-05	1.32E-04	4.23E-04	1.60E-03	2.96E-03	5.40E-03
50	1.67E-05	1.72E-05	3.60E-05	7.02E-05	4.56E-05	1.66E-05

TABLE V–9. INHALATION DOSE (Sv) FROM Te

Distance (km)	A	B	C	D	E	F
1	4.70E-02	2.35E-01	4.92E-01	8.79E-01	9.15E-01	3.54E-01
2.5	2.94E-03	3.77E-02	9.73E-02	2.76E-01	4.78E-01	6.68E-01
3.5	1.35E-03	1.84E-02	4.85E-02	1.41E-01	2.48E-01	3.99E-01
7	7.13E-04	4.47E-03	1.31E-02	4.46E-02	8.38E-02	1.56E-01
8	6.30E-04	3.36E-03	9.79E-03	3.19E-02	5.70E-02	1.01E-01
15	3.52E-04	9.30E-04	2.99E-03	1.13E-02	2.09E-02	3.81E-02
50	1.10E-04	1.13E-04	2.37E-04	4.62E-04	3.00E-04	1.09E-04

TABLE V–10. INHALATION DOSE (Sv) FROM Ce

Distance (km)	A	B	C	D	E	F
1	3.27E-03	1.63E-02	3.42E-02	6.12E-02	6.37E-02	2.46E-02
2.5	2.05E-04	2.63E-03	6.80E-03	1.93E-02	3.34E-02	4.66E-02
3.5	9.41E-05	1.29E-03	3.40E-03	9.83E-03	1.73E-02	2.79E-02
7	5.03E-05	3.15E-04	9.20E-04	3.14E-03	5.91E-03	1.10E-02
8	4.45E-05	2.37E-04	6.91E-04	2.26E-03	4.03E-03	7.12E-03
15	2.52E-05	6.66E-05	2.14E-04	8.10E-04	1.50E-03	2.73E-03
50	8.48E-06	8.72E-06	1.82E-05	3.56E-05	2.31E-05	8.39E-06

TABLE V–11. INHALATION DOSE (Sv) FROM Pu

Distance (km)	A	B	C	D	E	F
1	2.77E-04	1.38E-03	2.90E-03	5.18E-03	5.39E-03	2.08E-03
2.5	1.74E-05	2.23E-04	5.75E-04	1.63E-03	2.83E-03	3.95E-03
3.5	7.97E-06	1.09E-04	2.88E-04	8.33E-04	1.47E-03	2.36E-03
7	4.26E-06	2.67E-05	7.79E-05	2.66E-04	5.00E-04	9.32E-04
8	3.77E-06	2.01E-05	5.85E-05	1.91E-04	3.41E-04	6.03E-04
15	2.14E-06	5.64E-06	1.81E-05	6.86E-05	1.27E-04	2.31E-04
50	7.19E-07	7.39E-07	1.55E-06	3.01E-06	1.96E-06	7.12E-07

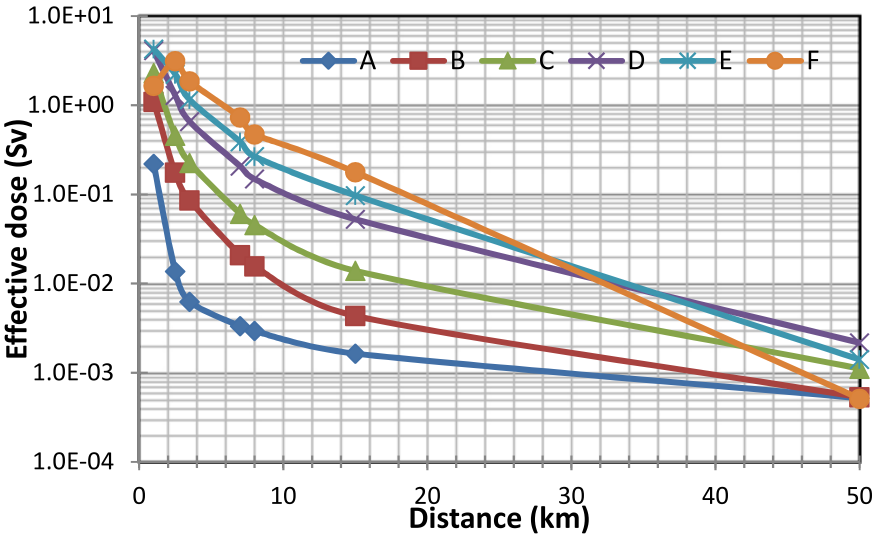

FIG. V–1. Effective dose through inhalation from all radionuclides for different stability categories

As expected the estimated doses vary significantly with weather categories and decrease with increasing downwind distance, with doses varying rapidly for the weather stability category A compared to F. Except for the closer distances, the dose from the stability category F is higher than that of all the other categories. The maximum dose at the distance of 1 km is about 4.28 Sv for weather category E and 0.220 Sv for weather category A, without introduction of any counter measures in both cases. The relative contribution of various radioisotopes in the inhalation pathway is given in Figure V–2. The inhalation exposure from the iodine accounted for the maximum of 72.8% of the total inhalation exposures while isotopes of tellurium accounted for 21.4%, isotopes of strontium accounted for about 2.9%, the isotopes of cerium accounted for 1.5%, isotopes of caesium accounted for 1.3% with marginal contribution from plutonium. The equivalent dose to the thyroid at 1 km distance is 4 Sv for category A and 78 Sv for category E stability category. Fission product noble gases are not considered in the evaluation since they do not contribute inhalation doses.

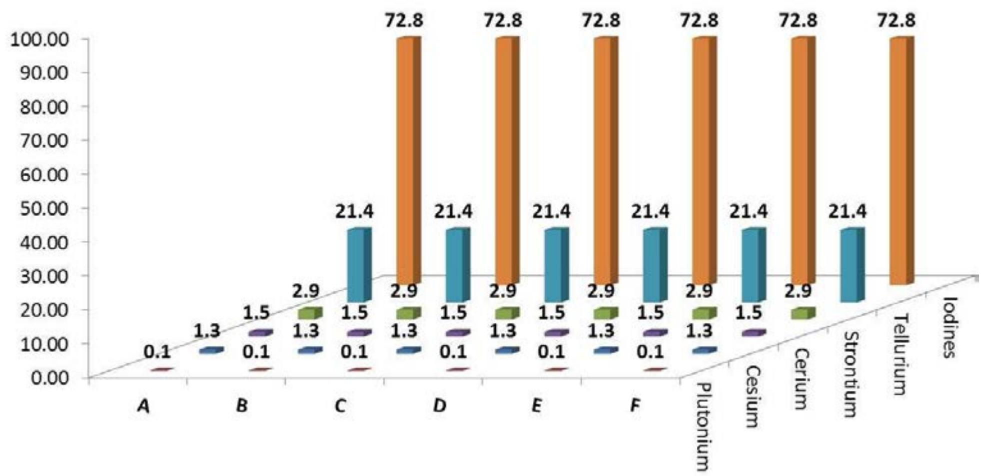

FIG. V–2. Radionuclide-wise contribution (%) to effective dose from inhalation at 1 km from release

TABLE V–12. CLOUD GAMMA DOSE (Sv) – NOBLE GASES (Kr88, Xe-133, Xe-135), I, Te AND OTHERS

Distance (km)	A	B	C	D	E	F
1	4.21E-02	1.57E-01	2.61E-01	4.06E-01	4.95E-01	5.43E-01
2.5	3.01E-03	3.64E-02	8.28E-02	1.80E-01	2.64E-01	3.64E-01
3.5	1.55E-03	1.96E-02	5.03E-02	1.23E-01	1.96E-01	2.84E-01
7	8.15E-04	5.03E-03	1.56E-02	5.44E-02	9.55E-02	1.55E-01
8	7.07E-04	3.77E-03	1.26E-02	4.55E-02	8.15E-02	1.35E-01
15	3.71E-04	1.00E-03	3.79E-03	1.90E-02	3.81E-02	6.86E-02
50	9.76E-05	1.32E-04	3.45E-04	3.04E-03	7.83E-03	1.63E-02

TABLE V–13. CLOUD GAMMA DOSE (Sv) – NOBLE GASES (KR88, XE-133 AND XE-135)

Distance (km)	A	B	C	D	E	F
1	3.13E-02	1.17E-01	1.94E-01	3.01E-01	3.68E-01	4.03E-01
2.5	2.28E-03	2.76E-02	6.28E-02	1.36E-01	2.00E-01	2.76E-01
3.5	1.19E-03	1.51E-02	3.86E-02	9.44E-02	1.51E-01	2.18E-01
7	6.48E-04	4.00E-03	1.24E-02	4.33E-02	7.60E-02	1.23E-01
8	5.68E-04	3.03E-03	1.01E-02	3.65E-02	6.55E-02	1.08E-01
15	3.12E-04	8.44E-04	3.19E-03	1.60E-02	3.21E-02	5.77E-02
50	8.77E-05	1.18E-04	3.10E-04	2.73E-03	7.04E-03	1.47E-02

TABLE V–14. CLOUD GAMMA DOSE (Sv) FROM I

Distance (km)	A	B	C	D	E	F
1	9.90E-03	3.69E-02	6.14E-02	9.54E-02	1.16E-01	1.28E-01
2.5	6.62E-04	8.00E-03	1.82E-02	3.96E-02	5.81E-02	8.01E-02
3.5	3.27E-04	4.13E-03	1.06E-02	2.59E-02	4.13E-02	5.98E-02
7	1.47E-04	9.08E-04	2.81E-03	9.82E-03	1.72E-02	2.79E-02
8	1.22E-04	6.52E-04	2.18E-03	7.87E-03	1.41E-02	2.33E-02
15	4.88E-05	1.32E-04	4.99E-04	2.50E-03	5.02E-03	9.03E-03
50	6.92E-06	9.33E-06	2.44E-05	2.15E-04	5.55E-04	1.16E-03

TABLE V–15. CLOUD GAMMA DOSE (Sv) FROM Te

Distance (km)	A	B	C	D	E	F
1	8.32E-04	3.10E-03	5.16E-03	8.02E-03	9.78E-03	1.07E-02
2.5	6.11E-05	7.39E-04	1.68E-03	3.65E-03	5.36E-03	7.40E-03
3.5	3.20E-05	4.05E-04	1.04E-03	2.54E-03	4.05E-03	5.86E-03
7	1.77E-05	1.09E-04	3.39E-04	1.18E-03	2.07E-03	3.36E-03
8	1.56E-05	8.29E-05	2.77E-04	1.00E-03	1.79E-03	2.97E-03
15	8.78E-06	2.37E-05	8.97E-05	4.50E-04	9.03E-04	1.62E-03
50	2.69E-06	3.62E-06	9.49E-06	8.36E-05	2.16E-04	4.50E-04

TABLE V–16. CLOUD GAMMA DOSE (Sv) FROM OTHERS

Distance (km)	A	B	C	D	E	F
1	8.47E-05	3.16E-04	5.26E-04	8.16E-04	9.96E-04	1.09E-03
2.5	6.24E-06	7.54E-05	1.72E-04	3.73E-04	5.48E-04	7.56E-04
3.5	3.28E-06	4.15E-05	1.06E-04	2.60E-04	4.15E-04	6.00E-04
7	1.83E-06	1.13E-05	3.49E-05	1.22E-04	2.14E-04	3.47E-04
8	1.61E-06	8.58E-06	2.86E-05	1.04E-04	1.86E-04	3.07E-04
15	9.23E-07	2.50E-06	9.43E-06	4.73E-05	9.50E-05	1.71E-04
50	3.06E-07	4.12E-07	1.08E-06	9.52E-06	2.46E-05	5.12E-05

The cloud shine doses are estimated for all the radioisotopes released, for various stability categories and for 1 to 50 km distance. The occupancy factor of the hypothetical person outdoors is taken as 1.0. The estimated doses are given in Tables V–12 to V–16. The estimated dose at 1.0 km distance is 42.1 mSv under stability category A and 543 mSv under stability category F. Fission product noble gases contribute to about 75.7% of the total, iodine isotopes – 22%, tellurium isotopes – 2.03% and the others contribute the rest. Figure V–3 gives the total dose through the cloud shine pathway for various distances and stability categories, while Figure V–4 gives the relative contribution of the various nuclides at a typical distance of 1 km.

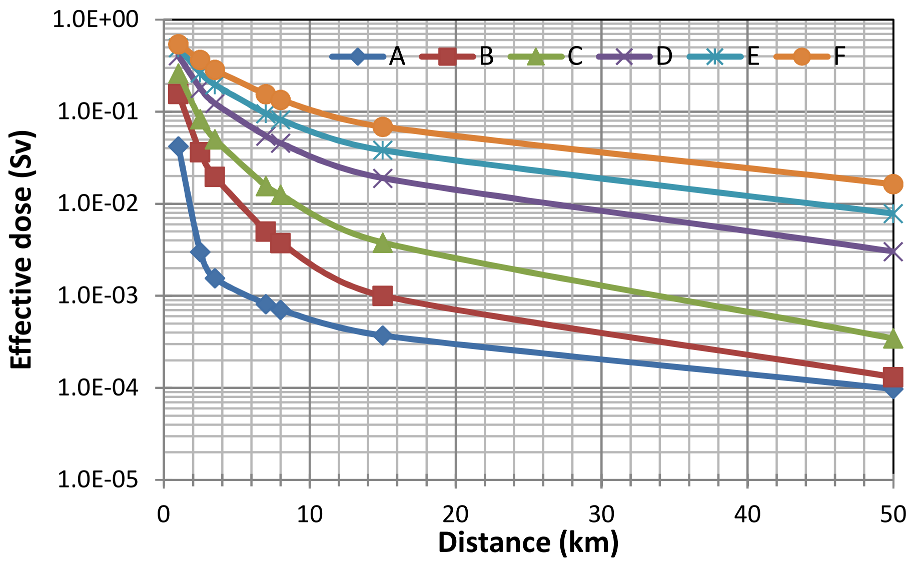

FIG. V–3. Effective dose through cloud-shine from all the radionuclides at different stability categories

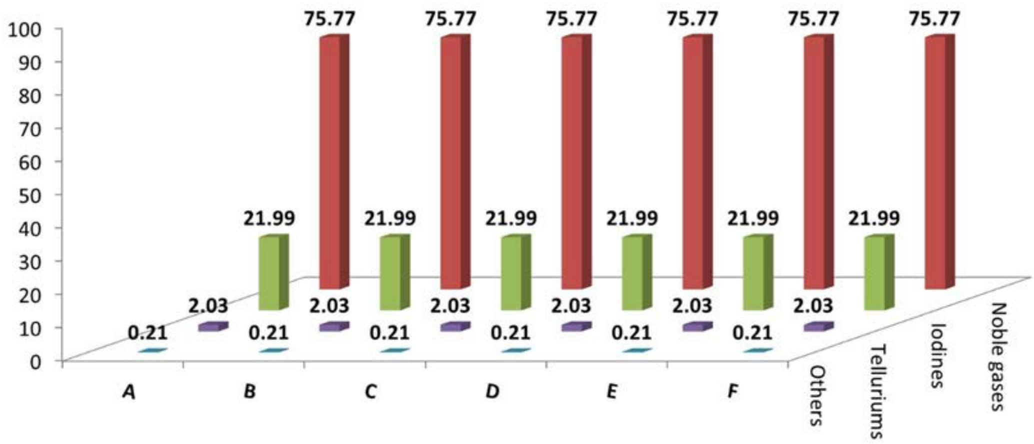

FIG. V–4. Radionuclide-wise contribution (%) to effective dose from plume (gamma) at 1 km from release

The ground deposited activity is estimated using the default deposition velocity recommended for the exercise for all the radionuclides, except for fission product noble gases. The exposure rate from the contaminated ground surface is estimated using the standard dose conversion factors derived for unit deposited activity (Sv/h)/(Bq/sq.m) taken from IAEA guide [V–7]. The integration time is taken as 24 hours and 7 days following the event of continuous exposure. The cumulative effective dose estimated for 24 hours and 7 days of cumulative exposure considering all the particulate radionuclides for various distances and stability categories are given in Tables V–17 and V–18. In view of the long-term nature of the exposure the deposited activity is depleted to account for the removal through weathering processes. The weathering half-life values for the isotopes, corresponding to grass medium, are taken form IAEA-TECDOC-1616 [V–8]. It may be noted from Table V–17 that at 1 km distance the dose varies between 111 mSv to 833 mSv for stability categories A and E, with stability category E resulting in higher exposures. Similarly, the cumulative external exposure for 7 days integration period at 1 km distance, with an occupancy factor of 1.0, with due correction for decay due to radiological as well as weathering process, is 531 mSv for category A and 10.3 Sv for category E. Figures V–5 and V–6 give the estimated cumulative doses for various distances for all the radionuclides for the cases of 24 hours and 7 days. Tellurium isotopes contribute to about 64.6 % of the doses, iodine isotopes contribute to about 33.9% with very small contributions from the other nuclides. This profile would change significantly with time due to the decay of the short-lived isotopes. This can be seen from the values of ground doses integrated for 7 days, wherein the contribution from tellurium is 79%, from iodine is 19% with marginal contributions from others. Figures V–7 and V–8 give the relative contribution of the various isotopes for the integration periods of 24 hours and 7 days.

TABLE V–17. GAMMA DOSE (Sv) FROM GROUND DEPOSITED ACTIVITY FROM ALL ISOTOPES, FOR 24 HOURS

Distance (km)	A	B	C	D	E	F
1	1.11E-01	5.53E-01	1.16E+00	2.07E+00	2.16E+00	8.33E-01
2.5	6.79E-03	8.70E-02	2.25E-01	6.38E-01	1.10E+00	1.54E+00
3.5	3.07E-03	4.21E-02	1.11E-01	3.21E-01	5.66E-01	9.11E-01
7	1.57E-03	9.87E-03	2.88E-02	9.84E-02	1.85E-01	3.44E-01
8	1.38E-03	7.35E-03	2.14E-02	6.98E-02	1.25E-01	2.20E-01
15	7.35E-04	1.94E-03	6.24E-03	2.36E-02	4.37E-02	7.97E-02
50	2.16E-04	2.22E-04	4.64E-04	9.05E-04	5.88E-04	2.14E-04

TABLE V–18. GAMMA DOSE (Sv) FROM GROUND DEPOSITED ACTIVITY FROM ALL ISOTOPES, FOR 7 DAYS

Distance (km)	A	B	C	D	E	F
1	5.31E-01	2.65E+00	5.55E+00	9.91E+00	1.03E+01	3.99E+00
2.5	3.30E-02	4.23E-01	1.09E+00	3.10E+00	5.37E+00	7.50E+00
3.5	1.51E-02	2.06E-01	5.44E-01	1.58E+00	2.78E+00	4.47E+00
7	7.93E-03	4.98E-02	1.45E-01	4.96E-01	9.32E-01	1.74E+00
8	7.00E-03	3.73E-02	1.09E-01	3.55E-01	6.33E-01	1.12E+00
15	3.87E-03	1.02E-02	3.28E-02	1.24E-01	2.30E-01	4.19E-01
50	1.19E-03	1.23E-03	2.57E-03	5.00E-03	3.25E-03	1.18E-03

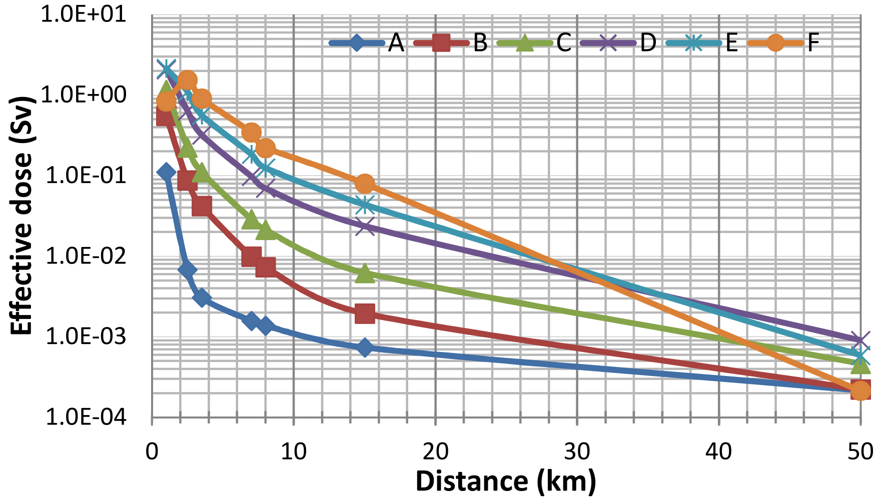

FIG. V–5. Effective dose through exposure to ground deposited activity in first 24 hours

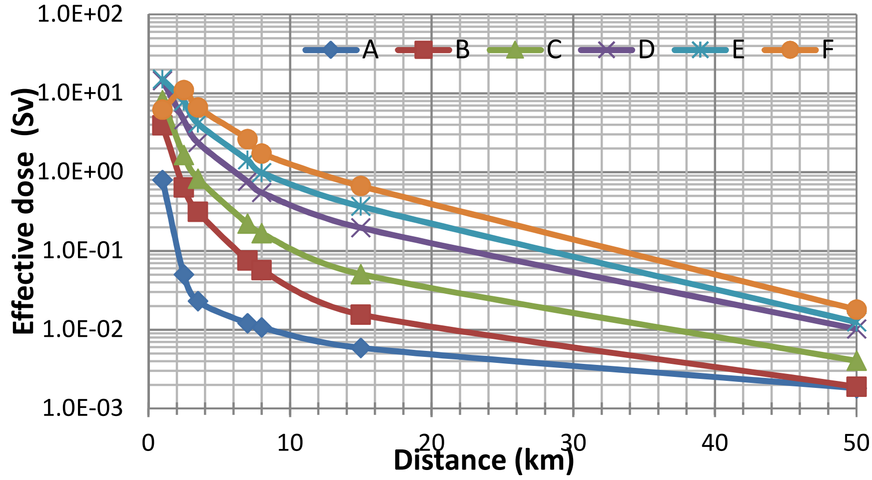

FIG. V–6. Total effective dose (Sv) from all the pathways of exposure (ground shine for 7 days)

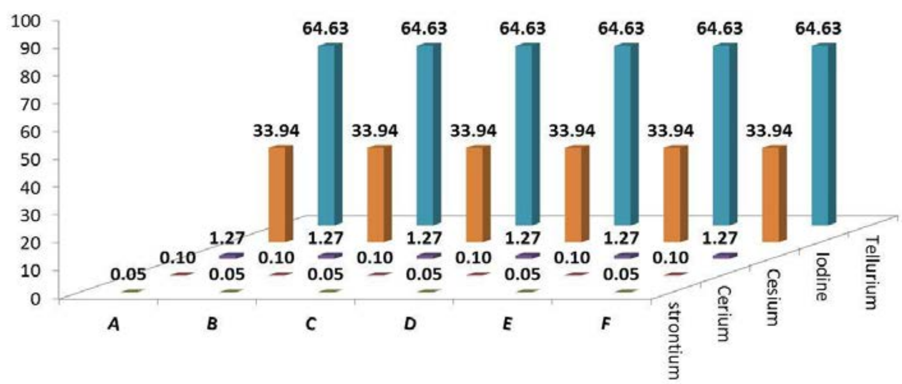

FIG. V–7. Radionuclide-wise contribution of effective dose from ground shine at 1 km from release (24 hours)

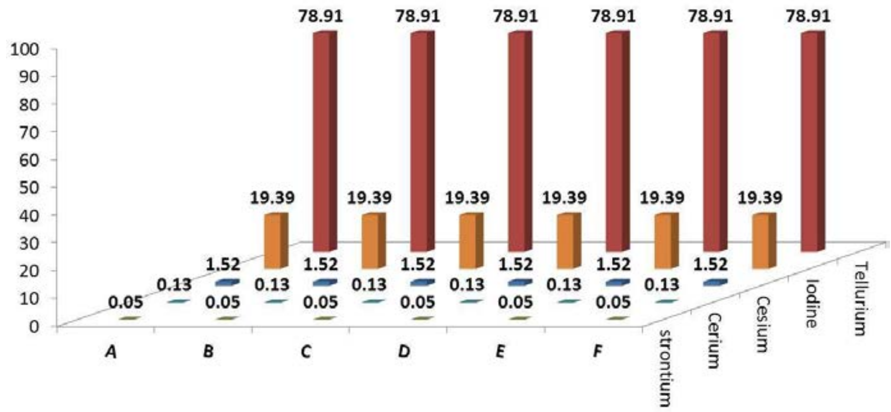

FIG. V–8. Radionuclide-wise contribution of effective dose from ground shine at 1 km from release (7 days)

The total effective dose from all the pathways due to all radionuclides is given in Tables V–19 and V–20 and in Figures V–9 and V–10. In the case of doses estimation for a 24-hour integration period for ground shine doses, the total dose at 1 km distance from all the pathways and from all the radionuclides is 373 mSv under stability category A and 6.93 Sv under category E. In the case of 7 days of integration period assumed for ground shine, the total dose from all the pathways is 793 mSv under category A and 15.1 Sv under category F. In the total dose estimated, dose through the inhalation pathway contributes to about 59% of the doses, cloud gamma contributing to about 13% and ground shine contributing to about 28 % each.

TABLE V–19. TOTAL DOSE (Sv) FROM ALL RADIONUCLIDES AND ALL PATHWAYS, 24 HOURS GROUND SHINE

Distance (km)	A	B	C	D	E	F
1	3.73E-01	1.81E+00	3.72E+00	6.59E+00	6.93E+00	3.03E+00
2.5	2.35E-02	2.99E-01	7.63E-01	2.11E+00	3.60E+00	5.03E+00
3.5	1.09E-02	1.48E-01	3.88E-01	1.10E+00	1.92E+00	3.06E+00
7	5.71E-03	3.58E-02	1.05E-01	3.61E-01	6.71E-01	1.23E+00
8	5.03E-03	2.68E-02	7.97E-02	2.64E-01	4.72E-01	8.25E-01
15	2.75E-03	7.28E-03	2.39E-02	9.53E-02	1.79E-01	3.26E-01
50	8.32E-04	8.86E-04	1.92E-03	6.11E-03	9.83E-03	1.71E-02

TABLE V–20. TOTAL DOSE (Sv) FROM ALL RADIONUCLIDES AND ALL PATHWAYS, 7 DAYS GROUND SHINE

Distance (km)	A	B	C	D	E	F
1	7.93E-01	3.90E+00	8.11E+00	1.44E+01	1.51E+01	6.19E+00
2.5	4.98E-02	6.35E-01	1.63E+00	4.57E+00	7.87E+00	1.10E+01
3.5	2.29E-02	3.12E-01	8.21E-01	2.35E+00	4.13E+00	6.62E+00
7	1.21E-02	7.57E-02	2.22E-01	7.59E-01	1.42E+00	2.62E+00
8	1.06E-02	5.67E-02	1.67E-01	5.49E-01	9.80E-01	1.72E+00
15	5.88E-03	1.56E-02	5.05E-02	1.96E-01	3.66E-01	6.66E-01
50	1.81E-03	1.89E-03	4.03E-03	1.02E-02	1.25E-02	1.80E-02

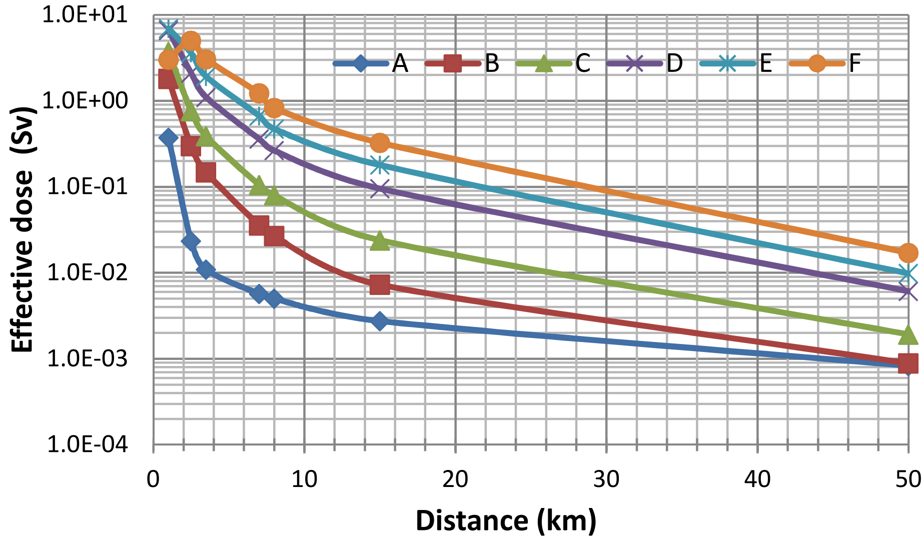

FIG. V–9. Total effective dose (Sv) from all the pathways of exposure (ground shine for 24 hours)

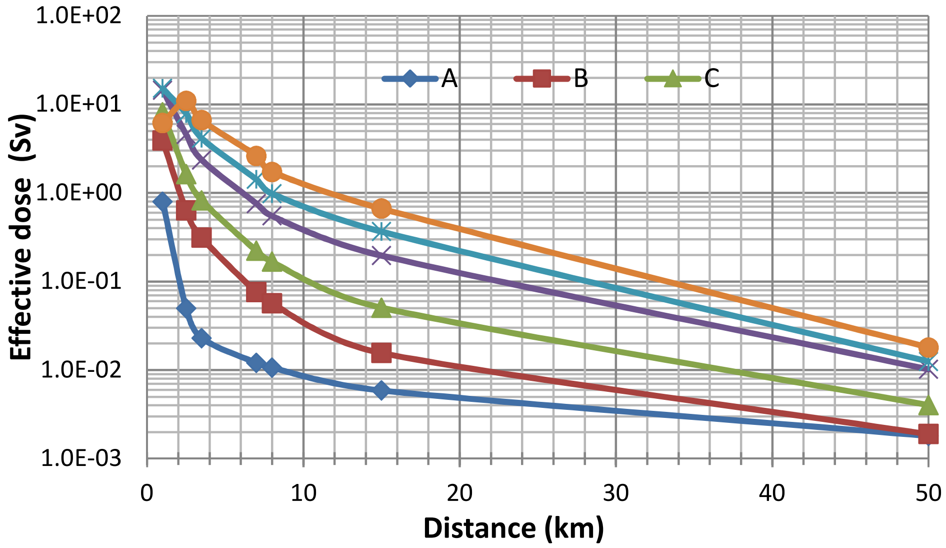

FIG. V–10. Total effective dose (Sv) from all the pathways of exposure (ground shine for 7 Days)

Dose estimation is done for all the major pathways of exposure for the accidental release under consideration. However, for ensuring compliance, doses that are beyond the exclusion boundary are taken for regulatory compliance, especially for public doses. Accordingly, the results are given for distances beyond 1 km. The dose estimates are upper bound values since the assumptions used for the meteorological parameters are highly conservative. The estimates indicate that without protective actions, the projected doses, including from inhalation and cloud shine, are orders of magnitude higher compared to the regulatory prescribed doses. This estimate presumes that the dose from the ingestion pathway, which starts to manifest in the intermediate or the late phase of the accident, has been totally prevented. This approach has been adopted in Ref [V–9].

The national regulatory standards allow taking credit for the protective actions that could be implemented in the public domain to reduce the projected doses. In the present case under assessment, since there is a reasonable warning time of 24 hours available between the shutdown of the reactor and the release of activity into the environment, urgent protective actions could be implemented promptly and a significant fraction of the dose, even from the inhalation and cloud shine, could be averted. Though the distances requiring protective actions such as sheltering and evacuation appear to be larger, (about 15 to 20 km), since only one direction sector is considered to be affected, the effective area for which the protective actions are to be implemented would be smaller. If more direction sectors are involved, then the distances to which protective actions are to be implemented would be smaller and could be managed by the emergency preparedness plan.

In the ENV-PE exercise, following India's national regulatory requirements for the estimation of offsite doses to the public, the use of single category of weather, unit wind speed and single wind direction is assumed. Since the releases are assumed to occur within a period of 24 hours invariant weather conditions are proposed. This approach generally yields unreasonably higher dose estimates, especially for prolonged releases. Nevertheless, this approach was adopted since under a severe accident scenario, the bulk of the releases could occur within a few hours following the accident wherein the meteorological parameters assumed could remain invariant.

An alternate methodology involving use of frequency distribution of the persistency data for the wind direction, stability category and wind speed can be incorporated into the calculation. This could result in a more realistic dose estimate. Such a scheme requires site specific meteorological data collected over long periods of time to get the representative annual average data set. Alternatively, from the hourly meteorological data set given in the exercise, (which consist of 8760 data points) a contiguous 24-hour data set could be taken and the dilution factors could be established assuming the standard Gaussian plume model for unit release rate. The dilution factor values could be sorted out to find the 24-hour bin that results in the lowest dilution factor amongst the data set generated. The 24-hour data set thus identified could be used to estimate the public doses in order to make the estimates more realistic. The proposed scheme needs to be validated before being applied for regulatory screening of plants for licensing purposes.

The regulatory system in India adopts a deterministic approach for the estimation of the dose from potential releases under accident conditions unlike a few other countries wherein a semi-probabilistic or probabilistic approach is adopted. For environmental dose assessment under severe accident conditions, application of probabilistic methodology with adoption of a risk-based approach can yield more realistic results. Nevertheless, the dose assessment with conservative assumptions shall also be carried out to identify the magnitude of exposures involved and the extent of the area involved in aiding the licensee the build a comprehensive emergency preparedness plan.

REFERENCES TO ANNEX V

[V–1] ATOMIC ENERGY REGULATORY BOARD, Consenting Process for Nuclear Power Plants and Research Reactors, AERB/NPP&RR/SG/G-1, AERB, Mumbai (2007).
[V–2] ATOMIC ENERGY REGULATORY BOARD, Site Evaluation of Nuclear Facilities, AERB/NF/SC/S (Rev.1), AERB, Mumbai (2014).
[V–3] ATOMIC ENERGY REGULATORY BOARD, Site Considerations of Nuclear Power Plants for Off-Site Emergency Preparedness AERB/NPP/SG/S-8, AERB, Mumbai (2005).
[V–4] ATOMIC ENERGY REGULATORY BOARD, Atmospheric Dispersion and Modelling AERB/NF/SG/S-1, AERB, Mumbai (2008).
[V–5] HUKOO, R., BAPAT, V., SHIRVAIKAR, V., Emergency Dose Evaluation Manual, BARC-1412, BARC, Mumbai (1988).

[V–6] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. IAEA Safety Standards Series. General Safety Requirements Part 3. No. GSR Part 3, IAEA, Vienna (2014).

[V–7] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Models for use in Assessing the Impact of Discharge of Radioactive Substance to the Environment, Safety Report Series 19, IAEA, Vienna (2001).

[V–8] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009).

[V–9] U.S. NUCLEAR REGULATORY COMMISSION, State-of-the-Art Reactor Consequence Analyses Project. Surry Integrated Analysis. NUREG-CR/7110, Vol 2, U.S. NRC, Washington (2013).

ANNEX VI. ISRAEL

VI–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

An estimation of dose and risk for members of the public (via a representative person for assessing doses) as a result of a postulated accident in a nuclear reactor was performed in order to compare various methodologies adopted by the participants from the various Member States in the INPRO-ENV team. The radioactive releases to the environment through the atmospheric route were considered for the assessment. The relevant input parameters to be used such as meteorological data, environmental data and the radiological data were identified, and a standard set of data was provided to the participants for the assessment. Each participant was advised to take cognizance of their country's respective regulatory requirements.

The national regulation of Israel [VI–1] requires the risk *R* from nuclear reactor accidents for the representative person for assessing doses to be less than 10^{-7} per year. Assuming that Beyond Design Basis Accident (BDBA) frequencies *f* lay in a range between 10^{-4} to 10^{-6} per year and that the risk coefficient[10] (*R.C)* is 0.07 Sv^{-1} [VI–2], additional dose limits *D* apply:

- An effective dose of 10 mSv is the maximum permissible dose for the representative person for assessing doses in a BDBA with a probability of 10^{-4} – 10^{-5} per year.
- A BDBA with a probability < 10^{-5} per year may lead to permissible doses higher than 10 mSv (but lower than 100 mSv) for the representative person.
- Only a rare accident with a probability of ~10^{-6} per year may lead to permissible doses higher than 100 mSv for the representative person.

All of these dose limits are derived using Eq. (VI–1):

$$D = \frac{R}{R.C \cdot f} \qquad \text{(VI–1)}$$

The methodology to obtain the safety target from the regulatory requirement involves a combination of deterministic criteria based on dose limits and probabilistic criteria based on risk requirements. Probabilistic requirements are normally applied when deterministic criteria are not met.

TABLE VI–1. INTERVENTION LEVELS FOR THE PUBLIC IN ISRAEL [VI–3]

Minimum dose for intervention	Action of protection
50 mSv total effective dose	Evacuation of the population
10 mSv total effective dose	Sheltering
50 mSv to the thyroid	Iodine prophylaxis

Table VI–1 taken from Ref [VI–3] shows that the maximum individual effective dose which does not require interventions in Israel is 10 mSv. If by using a deterministic assessment it is found that the TEDE (Total Effective Dose Equivalent) for the representative person for assessing doses is lower than 10 mSv, then there is no need to perform additional probabilistic assessments, because it meets the basic criteria requirement of the regulatory body. On the other hand, if by using a deterministic assessment it is found that the TEDE for the representative person is higher than 10 mSv, additional probabilistic assessments need to be performed, which involve the meteorological probabilities, the risk coefficients and the probability of the accident. Calculations which take into account all these probabilistic parameters need to meet the risk criteria (risk < 10^{-7} per year).

[10]The risk coefficient is a value used by the ICRP in Ref [VI–2] to weigh all increases in risk including cases of sufferings from a disease (with or without latent deaths). This means that the suffering caused from exposure to 1 Sv is equivalent to 7% rise in the risk of cancer.

VI–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

Based on the methodology aforementioned, estimation of dose and risk to the public from atmospheric releases from a hypothetical accident in a reactor was performed.

Step 1: Deterministic Approach

A map of a hypothetic site defined and prepared for the exercise was presented in Section 3.1. The map specifies the locations of the cities and urbanizations with data about population, size of the area, the distance and the angle from the point of release (the reactor) on the map.

The original source term which was provided for the participants was taken from the SOARCA study and includes 69 radionuclides. The source term release was divided into 24 plume segments. Each segment is characterized by a release fraction, plume release times, plume heat content plume release height, plume mass density, plume mass flow rate and plume segment duration. Later an Excel file was provided, according to the decision of the ENV-PE team, with a recalculated source term which included only 14 radiologically significant radionuclides. The source term used for the accident is given in Table VI–2. It has been also agreed among ENV-PE exercise participants to use 1 μm AMAD particle size if needed for the exercise.

TABLE VI–2. SOURCE TERM

Radionuclide	Total release (Bq)	Material type / Absorption type
Sr-89	2.70E+14	Aerosol / Slow
Sr-90	2.10E+13	Aerosol / Slow
Te-127m	2.43E+14	Aerosol / Moderate
Te-129m	8.40E+14	Aerosol / Moderate
Te-132	1.82E+16	Aerosol / Moderate
Xe-133	2.87E+18	
Xe-135	3.71E+17	
Cs-134	2.44E+14	Aerosol / Fast
Cs-137	1.73E+14	Aerosol / Fast
Ce-144	5.24E+13	Aerosol / Slow
Pu-238	1.28E+11	Aerosol/ Slow
I-131	1.59E+16	Elemental iodine
I-132	2.04E+16	Elemental iodine
I-133	1.11E+16	Elemental iodine

A complete set of meteorological data observed for one full year at the hypothetical exercise site was provided to all the participants. The full list of the parameters of the meteorological data set includes:

- Month, Day, Hour;
- Wind speed and direction at 80 m and 10 m altitude;
- Temperature at 80 m and 10 m altitudes;
- Humidity (relative) and pressure (mmHg);
- Solar irradiation and precipitation (mm);
- Pasquill-Gifford Category.

For the deterministic step conservative meteorological conditions were chosen:

- Stability class F - the most stable condition amongst the stability categories (very common condition for night and early day hours).
- 2 m/s wind speed (low wind – typical and strict value for class F).
- 100 m inversion height - The inversion height was not included in the meteorological exercise data provided but the Israeli regulator requires this data as well. Furthermore, it constitutes an additional conservative assumption for the deterministic assessment. Since

the data were not provided, a 100 m inversion height was chosen as a reasonable condition for stability class F.

The given release height of the source term was 8.4 m. It was decided by the group to use 35 m as an effective release height due to heat rise. Wind direction at 35 m was assumed to be constant at 10 m height.

Atmospheric dispersion calculations are performed by using a Gaussian plume model to find the TEDE (sum of exposure from inhalation, submersion and ground shine) for the representative person for assessing doses. This model includes the assumption of a flat ground and constant meteorological conditions in the entire zone under consideration. Two main assumptions were made when using the model to find the TEDE:

- Constant wind direction towards the areas around the reactor.
- The public is not protected at all (i.e. no credit given for protective actions).

Step 2: Probabilistic Approach

When the estimated TEDE for the representative person for assessing doses is higher than 10 mSv, additional probabilistic risk assessments, which involve the meteorological probability, the risk coefficient and the accident probability need to be performed. Calculations which take into account all these probabilistic parameters need to meet the risk criteria (risk < 10^{-7} per year).

For the exercise only one year of meteorological data was provided. The regulator in Israel allows taking into account meteorological probability in the calculation of the total risk, only if the meteorological data were taken over a minimum of 5 consecutive years. For the purpose of the exercise, it will be considered that the meteorological data is an average of 5 consecutive years.

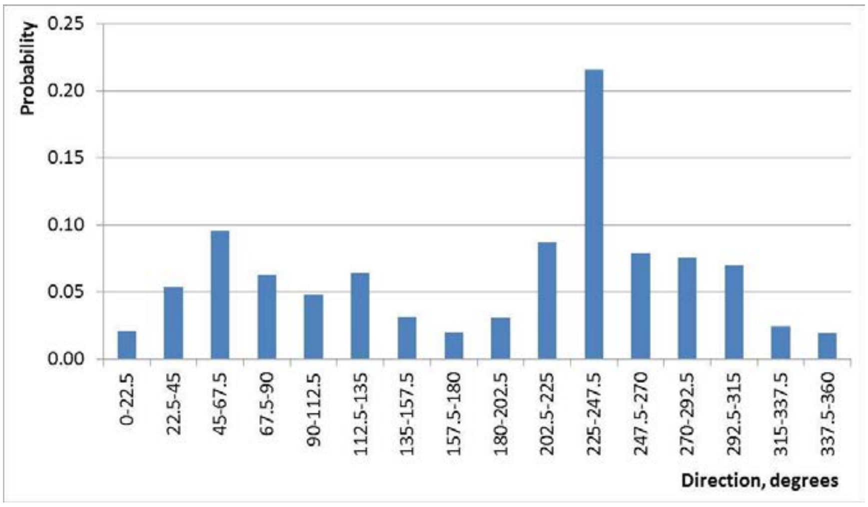

FIG. VI–1. Wind Direction Distribution

The one year of meteorological data provided was used to build a wind direction distribution which was used in the risk calculation. Figure VI–1 shows the wind direction distribution performed (16 intervals of direction and the probability of each one of them).

The meteorological probability, *M.R*, the risk coefficient, *R.C*, the accident probability, *A.P*, and the TEDE which were all calculated in step 1 (the deterministic approach), were taken into account in the risk *R* calculation by using Eq. (VI–2):

$$R = TEDE \cdot M.R \cdot R.C \cdot A.P \quad \text{(VI–2)}$$

VI–3. REPRESENTATIVE PERSON / CRITICAL GROUP FOR THE EXERCISE

The TEDE and risk have to be calculated for all populated, defined and formal areas in a given region. The representative person for assessing doses will be located at the highest TEDE/risk area.

The critical group to consider should be infants between 1 to 2 years old. Breathing rate of 8.6E-5 m^3s^{-1} was chosen according to the ICRP recommendations [VI–4] for moderate activity for children 1 to 2 years old.

Collective dose to the public has not been considered as it is not required by the regulator.

VI–4. RESULTS OF ASSESSMENT

Step 1: Deterministic Approach.

TEDE and dose to thyroid were calculated for infants and adults, after 1 day, 2 days and 7 days of exposure (sum of exposure from inhalation, submersion and ground shine) for 1 km distance from the accident point and for all the populated, defined and formal areas in the map. The results are presented in Tables VI–3 to VI–8 below.

TABLE VI–3. TEDE AND DOSE TO THYROID FOR INFANTS AFTER 1 DAY OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	1.10E+00	3.40E-02	8.69E-02	1.2E+00	2.1E+00
3	2.5	3.90E+00	1.28E-01	3.22E-01	4.4E+00	7.4E+00
5	3.5	3.19E+00	1.10E-01	2.62E-01	3.6E+00	6.0E+00
4	6.5	1.62E+00	6.62E-02	1.31E-01	1.8E+00	3.1E+00
6	7	1.48E+00	6.19E-02	1.20E-01	1.7E+00	2.8E+00
2	8	1.26E+00	5.48E-02	1.01E-01	1.4E+00	2.4E+00
1	15	4.46E-01	3.01E-02	3.50E-02	5.1E-01	8.6E-01
8	50	1.86E-02	1.09E-02	1.78E-03	3.1E-02	4.5E-02

TABLE VI–4. TEDE AND DOSE TO THYROID FOR INFANTS AFTER 2 DAYS OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	1.10E+00	3.40E-02	1.27E-01	1.3E+00	2.1E+00
3	2.5	3.90E+00	1.28E-01	4.71E-01	4.5E+00	7.5E+00
5	3.5	3.19E+00	1.10E-01	3.85E-01	3.7E+00	6.2E+00
4	6.5	1.62E+00	6.62E-02	1.94E-01	1.9E+00	3.1E+00
6	7	1.48E+00	6.19E-02	1.77E-01	1.7E+00	2.9E+00
2	8	1.26E+00	5.48E-02	1.51E-01	1.5E+00	2.5E+00
1	15	4.46E-01	3.01E-02	5.32E-02	5.3E-01	8.8E-01
8	50	1.86E-02	1.09E-02	3.05E-03	3.3E-02	4.7E-02

TABLE VI–5. TEDE AND DOSE TO THYROID FOR INFANTS AFTER 7 DAYS OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	1.10E+00	3.40E-02	2.45E-01	1.4E+00	2.2E+00
3	2.5	3.90E+00	1.28E-01	9.16E-01	4.9E+00	8.0E+00
5	3.5	3.19E+00	1.10E-01	7.51E-01	4.1E+00	6.5E+00
4	6.5	1.62E+00	6.62E-02	3.83E-01	2.1E+00	3.3E+00
6	7	1.48E+00	6.19E-02	3.51E-01	1.9E+00	3.0E+00
2	8	1.26E+00	5.48E-02	2.99E-01	1.6E+00	2.6E+00
1	15	4.46E-01	3.01E-02	1.08E-01	5.8E-01	9.3E-01
8	50	1.86E-02	1.09E-02	6.97E-03	3.6E-02	5.1E-02

TABLE VI–6. TEDE AND DOSE TO THYROID FOR ADULTS AFTER 1 DAY OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	4.30E-01	3.40E-02	8.69E-02	5.5E-01	7.7E+00
3	2.5	1.54E+00	1.28E-01	3.22E-01	2.0E+00	2.7E+01
5	3.5	1.27E+00	1.10E-01	2.62E-01	1.6E+00	2.2E+01
4	6.5	6.66E-01	6.62E-02	1.31E-01	8.6E-01	1.1E+01
6	7	6.12E-01	6.19E-02	1.20E-01	7.9E-01	1.0E+01
2	8	5.26E-01	5.48E-02	1.01E-01	6.8E-01	8.8E+00
1	15	2.05E-01	3.01E-02	3.50E-02	2.7E-01	3.1E+00
8	50	2.16E-02	1.09E-02	1.78E-03	3.4E-02	1.4E-01

TABLE VI–7. TEDE AND DOSE TO THYROID FOR ADULTS AFTER 2 DAYS OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	4.30E-01	3.40E-02	1.27E-01	5.9E-01	7.7E+00
3	2.5	1.54E+00	1.28E-01	4.71E-01	2.1E+00	2.7E+01
5	3.5	1.27E+00	1.10E-01	3.85E-01	1.8E+00	2.2E+01
4	6.5	6.66E-01	6.62E-02	1.94E-01	9.3E-01	1.1E+01
6	7	6.12E-01	6.19E-02	1.77E-01	8.5E-01	1.0E+01
2	8	5.26E-01	5.48E-02	1.51E-01	7.3E-01	8.9E+00
1	15	2.05E-01	3.01E-02	5.32E-02	2.9E-01	3.1E+00
8	50	2.16E-02	1.09E-02	3.05E-03	3.6E-02	1.4E-01

TABLE VI–8. TEDE AND DOSE TO THYROID FOR ADULTS AFTER 7 DAYS OF EXPOSURE

Area Number	Distance, km	Inhalation, Sv	Submersion, Sv	Ground Shine, Sv	TEDE, Sv	Thyroid, Sv
-	1	4.30E-01	3.40E-02	2.45E-01	7.1E-01	7.8E+00
3	2.5	1.54E+00	1.28E-01	9.16E-01	2.6E+00	2.8E+01
5	3.5	1.27E+00	1.10E-01	7.51E-01	2.1E+00	2.3E+01
4	6.5	6.66E-01	6.62E-02	3.83E-01	1.1E+00	1.2E+01
6	7	6.12E-01	6.19E-02	3.51E-01	1.0E+00	1.1E+01
2	8	5.26E-01	5.48E-02	2.99E-01	8.8E-01	9.0E+00
1	15	2.05E-01	3.01E-02	1.08E-01	3.4E-01	3.2E+00
8	50	2.16E-02	1.09E-02	6.97E-03	4.0E-02	1.4E-01

The TEDE for infants after 48 hours of exposure (sum of exposure from inhalation, submersion and ground shine) which is calculated for the populated areas, is presented in Table VI–4. The maximum TEDE was calculated at 2.2 km distance (4.6 Sv). According to the results, the representative person for assessing doses is located at area number 3 (2.5 km from the accident point). Since the TEDE for the representative person for assessing doses is higher than 10 mSv additional probabilistic assessment is required.

Step 2: Probabilistic Approach.

When the estimated TEDE for the representative person is higher than 10 mSv, additional probabilistic risk assessments need to be performed, which involve the meteorological probability *M.P*, the risk coefficient *R.C* and the accident probability *A.P*. Calculations which take into account all of these probabilistic parameters need to meet the risk criteria (risk < 10^{-7} per year).

Accordingly, the risks calculated by Eq. (VI–2) for infants and adults, after 1 day, 2 days and 7 days of exposure, at the populated areas, are presented in Table VI–11 to Table VI–16.

TABLE VI–11. RISK FOR INFANTS AFTER 1 DAY OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	4.4E+00	1.11E-08
5	160	3.5	0.020	0.07	1.5E-6	3.6E+00	7.56E-09
4	40	6.5	0.053	0.07	1.5E-6	1.8E+00	1.00E-08
6	115	7	0.064	0.07	1.5E-6	1.7E+00	1.14E-08
2	220	8	0.087	0.07	1.5E-6	1.4E+00	1.28E-08
1	300	15	0.071	0.07	1.5E-6	5.1E-01	3.80E-09
8	140	50	0.031	0.07	1.5E-6	3.1E-02	1.01E-10

TABLE VI–12. RISK FOR INFANTS AFTER 2 DAYS OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	4.5E+00	1.13E-08
5	160	3.5	0.020	0.07	1.5E-6	3.7E+00	7.77E-09
4	40	6.5	0.053	0.07	1.5E-6	1.9E+00	1.06E-08
6	115	7	0.064	0.07	1.5E-6	1.7E+00	1.14E-08
2	220	8	0.087	0.07	1.5E-6	1.5E+00	1.37E-08
1	300	15	0.071	0.07	1.5E-6	5.3E-01	3.95E-09
8	140	50	0.031	0.07	1.5E-6	3.3E-02	1.07E-10

TABLE VI–13. RISK FOR INFANTS AFTER 7 DAYS OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	4.9E+00	1.23E-08
5	160	3.5	0.020	0.07	1.5E-6	4.1E+00	8.61E-09
4	40	6.5	0.053	0.07	1.5E-6	2.1E+00	1.17E-08
6	115	7	0.064	0.07	1.5E-6	1.9E+00	1.28E-08
2	220	8	0.087	0.07	1.5E-6	1.6E+00	1.46E-08
1	300	15	0.071	0.07	1.5E-6	5.8E-01	4.32E-09
8	140	50	0.031	0.07	1.5E-6	3.6E-02	1.17E-10

TABLE VI–14. RISK FOR ADULTS AFTER 1 DAY OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	2.0E+00	5.04E-09
5	160	3.5	0.020	0.07	1.5E-6	1.6E+00	3.36E-09
4	40	6.5	0.053	0.07	1.5E-6	8.6E-01	4.79E-09
6	115	7	0.064	0.07	1.5E-6	7.9E-01	5.31E-09
2	220	8	0.087	0.07	1.5E-6	6.8E-01	6.21E-09
1	300	15	0.071	0.07	1.5E-6	2.7E-01	2.01E-09
8	140	50	0.031	0.07	1.5E-6	3.4E-02	1.11E-10

TABLE VI–15. RISK FOR ADULTS AFTER 2 DAYS OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	2.1E+00	5.29E-09
5	160	3.5	0.020	0.07	1.5E-6	1.8E+00	3.78E-09
4	40	6.5	0.053	0.07	1.5E-6	9.3E-01	5.18E-09
6	115	7	0.064	0.07	1.5E-6	8.5E-01	5.71E-09
2	220	8	0.087	0.07	1.5E-6	7.3E-01	6.67E-09
1	300	15	0.071	0.07	1.5E-6	2.9E-01	2.16E-09
8	140	50	0.031	0.07	1.5E-6	3.6E-02	1.17E-10

TABLE VI–16. RISK FOR ADULTS AFTER 7 DAYS OF EXPOSURE

Area number	Sector, °	Distance, km	M.P	R.C, Sv^{-1}	A.P, $Year^{-1}$	TEDE, Sv	Risk, $Year^{-1}$
3	330	2.5	0.024	0.07	1.5E-6	2.6E+00	6.55E-09
5	160	3.5	0.020	0.07	1.5E-6	2.1E+00	4.41E-09
4	40	6.5	0.053	0.07	1.5E-6	1.1E+00	6.12E-09
6	115	7	0.064	0.07	1.5E-6	1.0E+00	6.72E-09
2	220	8	0.087	0.07	1.5E-6	8.8E-01	8.04E-09
1	300	15	0.071	0.07	1.5E-6	3.4E-01	2.53E-09
8	140	50	0.031	0.07	1.5E-6	4.0E-02	1.30E-10

According to the risk results the representative person for assessing doses is located at area number 2 - the area with the highest risk (8 km from the accident point). The total risk for all the scenarios which were calculated for the representative person, considering all the probability parameters, was lower than 1E-7 per year.

REFERENCES TO ANNEX VI

[VI–1] ISRAEL ATOMIC ENERGY COMMISSION, Requirements to Safety Assessment, Licensing and Safety Division, IAEC, Tel Aviv (2011).

[VI–2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP), The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Elsevier (2007).

[VI–3] ISRAEL ATOMIC ENERGY COMMISSION, Ionizing radiation protection standard, IAEC, Tel Aviv (2014).

[VI–4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP), Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66. Pergamon Press (1994).

ANNEX VII. RUSSIAN FEDERATION

This Annex considers potential exposure to the public (sections VII-1 to VII-3) and non-human biota (sections VII-4 to VII-6).

VII–1. STRUCTURE OF CONSIDERATION OF POTENTIAL EXPOSURES TO PUBLIC

In Russia the decision making on protective measures for the public in case of a major nuclear emergency with radioactive contamination of territories has to be performed based on the estimation of the predicted dose prevented by protective actions and contamination levels with levels A and B (Table VII–1).

TABLE VII–1. CRITERIA FOR URGENT DECISION MAKING IN THE INITIAL PERIOD OF A RADIATION ACCIDENT [VII–1]

Protective measures		Prevented dose for the first 10 days, mSv			
		Whole body		Thyroid, lungs, skin	
		Level A	Level B	Level A	Level B
Shelter		5	50	50	500
Iodine prophylactics:	Adults	-	-	250*	2 500*
	Children	-	-	100*	1 000*
Evacuation		50	500	500	5 000

* Only for thyroid

TABLE VII–2. NECESSITY OF PROTECTIVE MEASURES. DOSE TO THE WHOLE BODY TO BE AVERTED IN THE FIRST TEN DAYS (mSv)

Dist. (km)	A	B	C	D	E	F
0.1	2.03E+04	5.67E+03	4.47E+02	4.23E+00	2.39E-06	1.95E-22
0.2	1.77E+04	1.66E+04	7.97E+03	1.49E+03	2.85E+01	1.48E-05
0.3	9.96E+03	1.29E+04	9.53E+03	3.77E+03	8.67E+02	3.18E-01
0.5	4.11E+03	6.62E+03	6.45E+03	4.14E+03	4.40E+03	1.68E+02
1.0	1.14E+03	2.12E+03	2.43E+03	2.09E+03	5.09E+03	3.72E+03
1.5	5.39E+02	1.05E+03	1.27E+03	1.18E+03	3.53E+03	5.95E+03
2.0	3.21E+02	6.39E+02	7.90E+02	7.72E+02	2.49E+03	6.11E+03
2.5	2.15E+02	4.36E+02	5.48E+02	5.50E+02	1.86E+03	5.54E+03
3.0	1.57E+02	3.20E+02	4.08E+02	4.17E+02	1.44E+03	4.85E+03
3.5	1.21E+02	2.48E+02	3.18E+02	3.30E+02	1.16E+03	4.19E+03
5.0	6.72E+01	1.39E+02	1.81E+02	1.94E+02	6.94E+02	2.76E+03
6.5	4.44E+01	9.20E+01	1.21E+02	1.32E+02	4.77E+02	1.93E+03
7.0	3.96E+01	8.22E+01	1.09E+02	1.19E+02	4.30E+02	1.73E+03
8.0	3.24E+01	6.71E+01	8.93E+01	9.87E+01	3.56E+02	1.41E+03
10.0	2.35E+01	4.83E+01	6.47E+01	7.27E+01	2.60E+02	9.89E+02
15.0	1.37E+01	2.72E+01	3.71E+01	4.27E+01	1.49E+02	4.96E+02
20.0	1.00E+01	1.85E+01	2.55E+01	2.98E+01	1.02E+02	2.91E+02
30.0	7.43E+00	1.13E+01	1.55E+01	1.84E+01	6.09E+01	1.31E+02
50.0	5.06E+00	6.79E+00	9.04E+00	1.04E+01	3.36E+01	4.29E+01

Note:

- The decision about shelter is made according the minimax principles and substantiation policy with the consideration of the particular situation and local conditions
- Radiation shelter is necessary
- Evacuation is necessary

If the level of radiation exposure prevented by protective countermeasure does not exceed level A, then there is no need to apply any such protective actions, which would impact socio-economic activities and normal civic life of people in that territory. If the level of radiation exposure prevented by protective actions exceeds level A, but does not exceed level B, then the decision on implementation of protective actions is made according to the principles of substantiation and optimization policy with consideration of the specific situation and local conditions. If the level of radiation exposure prevented by the protective countermeasure, is equal to or exceeds level B, it is necessary to implement the necessary counter measures, even if they impact normal public life and socio-economic activities of the territory [VII–1].

Table VII–2 presents the necessity of implementation of protective actions for different distances. It can also be seen that the need of protective measures depends on the stability category (A to F).

VII–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED FOR IMPACT ASSESSMENT FOR THE PUBLIC

The procedure of environmental contamination calculation and impact assessment for the public to substantiate protective measures in case of an emergency at a radiation hazardous facility is implemented in the program tool Express [VII–2] developed by SI SPA “Typhoon”.

Express is based on the computer system RECASS which is an independent programming tool with an integral cartographic component. It was developed for the calculation of radioactivity of the substances in the atmosphere and on the underlying terrain, as well as for assessment of their exposure to the public in case of an emergency at a radiation hazardous facility, causing the emission and transport of radioactive substances in the atmosphere. The main aim of the contamination calculation and impact assessment is to substantiate counter measures for population protection at early stages of the accident. Express includes:

- A model of atmospheric transfer and deposition on underlying terrain of the radioactive substances, released by one or several sources into the atmospheric boundary layer.
- A model of the transport of contamination through air and water in case contaminated air is emitted into the atmosphere with temperature different than the temperature of the environment;
- A model of formation and transformation of daughter radionuclides;
- A model of radiation doses calculation;
- A module for the calculation of zones for application of protective measures;
- Supplemental information on dose factors and radiative properties for 404 radionuclides;
- An integrated cartographic subsystem, based on use of programming components of the geo-information system MapX 5.0 of the MapInfo corporation;
- An algorithm, that calculates the contribution of daughter radionuclides, which appear due to radioactive decay, into the radiation dose.

The Gaussian model of atmospheric dispersion was used as the model of pollutant transport and dispersion. Standard information on meteorological conditions and a minimum expert dataset of release source parameters are used as input data. Stability categories were analyzed, and the average wind speed (at 10 m height) for each category was determined (Table VII–3).

TABLE VII–3. AVERAGE WIND SPEED FOR STABILITY CATEGORIES

Stability category	Wind velocity, m/s
A	1.6
B	2.0
C	3.4
D	6.5
E	3.8
F	1.2

VII–3. RESULTS OF ASSESSMENT FOR THE PUBLIC

According to Russian national regulation standards [VII–1] doses were calculated for 10 days for the following exposure pathways: cloud, inhalation and ground. Also, doses to the thyroid for adults and children (1-2 years old) were calculated for various distances (Tables VII–4 to VII–9).

TABLE VII–4. INHALATION DOSE FOR ADULTS (mSv) AFTER 10-DAY EXPOSURE

Dist. (km)	A	B	C	D	E	F
0.1	1.01E+04	2.83E+03	2.23E+02	2.11E+00	1.19E-06	9.72E-23
0.2	8.81E+03	8.31E+03	3.98E+03	7.43E+02	1.42E+01	7.41E-06
0.3	4.97E+03	6.44E+03	4.76E+03	1.88E+03	4.33E+02	1.59E-01
0.5	2.05E+03	3.30E+03	3.22E+03	2.07E+03	2.20E+03	8.39E+01
1.0	5.68E+02	1.06E+03	1.21E+03	1.04E+03	2.54E+03	1.86E+03
1.5	2.68E+02	5.23E+02	6.31E+02	5.91E+02	1.76E+03	2.97E+03
2.0	1.60E+02	3.18E+02	3.93E+02	3.85E+02	1.24E+03	3.05E+03
2.5	1.07E+02	2.17E+02	2.73E+02	2.74E+02	9.23E+02	2.76E+03
3.0	7.83E+01	1.59E+02	2.03E+02	2.08E+02	7.16E+02	2.41E+03
3.5	6.02E+01	1.23E+02	1.58E+02	1.64E+02	5.75E+02	2.08E+03
5.0	3.34E+01	6.90E+01	8.99E+01	9.64E+01	3.44E+02	1.36E+03
6.5	2.21E+01	4.57E+01	6.04E+01	6.59E+01	2.36E+02	9.41E+02
7.0	1.97E+01	4.08E+01	5.41E+01	5.92E+01	2.13E+02	8.42E+02
8.0	1.61E+01	3.33E+01	4.44E+01	4.91E+01	1.76E+02	6.85E+02
10.0	1.17E+01	2.40E+01	3.22E+01	3.61E+01	1.28E+02	4.76E+02
15.0	6.84E+00	1.35E+01	1.84E+01	2.12E+01	7.32E+01	2.33E+02
20.0	5.00E+00	9.19E+00	1.27E+01	1.48E+01	4.98E+01	1.34E+02
30.0	3.71E+00	5.58E+00	7.70E+00	9.11E+00	2.96E+01	5.71E+01
50.0	2.53E+00	3.38E+00	4.48E+00	5.18E+00	1.62E+01	1.66E+01

TABLE VII–5. CLOUD GAMMA DOSE (mSv) AFTER 10-DAY EXPOSURE

Dist. (km)	A	B	C	D	E	F
0.1	8.94E+02	2.50E+02	1.97E+01	1.86E-01	1.05E-07	8.57E-24
0.2	7.81E+02	7.34E+02	3.51E+02	6.56E+01	1.26E+00	6.53E-07
0.3	4.43E+02	5.72E+02	4.21E+02	1.66E+02	3.81E+01	1.40E-02
0.5	1.84E+02	2.96E+02	2.86E+02	1.83E+02	1.94E+02	7.37E+00
1.0	5.16E+01	9.61E+01	1.09E+02	9.28E+01	2.26E+02	1.63E+02
1.5	2.45E+01	4.81E+01	5.72E+01	5.29E+01	1.58E+02	2.62E+02
2.0	1.46E+01	2.94E+01	3.59E+01	3.46E+01	1.13E+02	2.73E+02
2.5	9.83E+00	2.02E+01	2.50E+01	2.47E+01	8.50E+01	2.53E+02
3.0	7.17E+00	1.49E+01	1.86E+01	1.88E+01	6.67E+01	2.26E+02
3.5	5.51E+00	1.15E+01	1.46E+01	1.49E+01	5.41E+01	2.00E+02
5.0	3.06E+00	6.50E+00	8.38E+00	8.82E+00	3.32E+01	1.41E+02
6.5	2.02E+00	4.33E+00	5.65E+00	6.06E+00	2.32E+01	1.06E+02
7.0	1.78E+00	3.87E+00	5.06E+00	5.46E+00	2.10E+01	9.69E+01
8.0	1.46E+00	3.17E+00	4.17E+00	4.54E+00	1.76E+01	8.28E+01
10.0	1.06E+00	2.28E+00	3.04E+00	3.35E+00	1.32E+01	6.34E+01
15.0	6.18E-01	1.30E+00	1.75E+00	1.98E+00	7.90E+00	3.88E+01
20.0	4.47E-01	8.68E-01	1.21E+00	1.40E+00	5.61E+00	2.74E+01
30.0	3.25E-01	5.32E-01	7.32E-01	8.71E-01	3.58E+00	1.69E+01
50.0	2.15E-01	3.19E-01	4.33E-01	5.03E-01	2.19E+00	9.38E+00

TABLE VII–6. GAMMA DOSE (mSv) FROM GROUND DEPOSITED ACTIVITY AFTER 10-DAY EXPOSURE

Dist. (km)	A	B	C	D	E	F
0.1	9.27E+03	2.59E+03	2.04E+02	1.93E+00	1.09E-06	8.89E-23
0.2	8.06E+03	7.60E+03	3.64E+03	6.80E+02	1.30E+01	6.78E-06
0.3	4.55E+03	5.89E+03	4.35E+03	1.72E+03	3.96E+02	1.45E-01
0.5	1.88E+03	3.02E+03	2.94E+03	1.89E+03	2.01E+03	7.67E+01
1.0	5.20E+02	9.68E+02	1.11E+03	9.54E+02	2.32E+03	1.70E+03
1.5	2.46E+02	4.80E+02	5.78E+02	5.41E+02	1.61E+03	2.72E+03
2.0	1.46E+02	2.92E+02	3.61E+02	3.52E+02	1.14E+03	2.79E+03
2.5	9.85E+01	1.99E+02	2.50E+02	2.51E+02	8.47E+02	2.53E+03
3.0	7.18E+01	1.46E+02	1.86E+02	1.90E+02	6.58E+02	2.21E+03
3.5	5.52E+01	1.13E+02	1.45E+02	1.51E+02	5.29E+02	1.91E+03
5.0	3.07E+01	6.34E+01	8.27E+01	8.85E+01	3.17E+02	1.26E+03
6.5	2.03E+01	4.20E+01	5.54E+01	6.05E+01	2.18E+02	8.78E+02
7.0	1.81E+01	3.75E+01	4.96E+01	5.44E+01	1.96E+02	7.87E+02
8.0	1.48E+01	3.06E+01	4.07E+01	4.51E+01	1.62E+02	6.43E+02
10.0	1.07E+01	2.20E+01	2.95E+01	3.32E+01	1.19E+02	4.50E+02
15.0	6.27E+00	1.24E+01	1.69E+01	1.95E+01	6.81E+01	2.24E+02
20.0	4.58E+00	8.46E+00	1.16E+01	1.36E+01	4.65E+01	1.30E+02
30.0	3.39E+00	5.14E+00	7.07E+00	8.38E+00	2.77E+01	5.68E+01
50.0	2.31E+00	3.09E+00	4.13E+00	4.76E+00	1.52E+01	1.69E+01

TABLE VII–7. TOTAL DOSE (mSv) FROM ALL PATHWAYS AFTER 10-DAY EXPOSURE

Dist. (km)	A	B	C	D	E	F
0.1	2.03E+04	5.67E+03	4.47E+02	4.23E+00	2.39E-06	1.95E-22
0.2	1.77E+04	1.66E+04	7.97E+03	1.49E+03	2.85E+01	1.48E-05
0.3	9.96E+03	1.29E+04	9.53E+03	3.77E+03	8.67E+02	3.18E-01
0.5	4.11E+03	6.62E+03	6.45E+03	4.14E+03	4.40E+03	1.68E+02
1.0	1.14E+03	2.12E+03	2.43E+03	2.09E+03	5.09E+03	3.72E+03
1.5	5.39E+02	1.05E+03	1.27E+03	1.18E+03	3.53E+03	5.95E+03
2.0	3.21E+02	6.39E+02	7.90E+02	7.72E+02	2.49E+03	6.11E+03
2.5	2.15E+02	4.36E+02	5.48E+02	5.50E+02	1.86E+03	5.54E+03
3.0	1.57E+02	3.20E+02	4.08E+02	4.17E+02	1.44E+03	4.85E+03
3.5	1.21E+02	2.48E+02	3.18E+02	3.30E+02	1.16E+03	4.19E+03
5.0	6.72E+01	1.39E+02	1.81E+02	1.94E+02	6.94E+02	2.76E+03
6.5	4.44E+01	9.20E+01	1.21E+02	1.32E+02	4.77E+02	1.93E+03
7.0	3.96E+01	8.22E+01	1.09E+02	1.19E+02	4.30E+02	1.73E+03
8.0	3.24E+01	6.71E+01	8.93E+01	9.87E+01	3.56E+02	1.41E+03
10.0	2.35E+01	4.83E+01	6.47E+01	7.27E+01	2.60E+02	9.89E+02
15.0	1.37E+01	2.72E+01	3.71E+01	4.27E+01	1.49E+02	4.96E+02
20.0	1.00E+01	1.85E+01	2.55E+01	2.98E+01	1.02E+02	2.91E+02
30.0	7.43E+00	1.13E+01	1.55E+01	1.84E+01	6.09E+01	1.31E+02
50.0	5.06E+00	6.79E+00	9.04E+00	1.04E+01	3.36E+01	4.29E+01

TABLE VII–8. DOSE TO THYROID AFTER 10-DAY EXPOSURE, ADULTS, Sv

Dist. (km)	A	B	C	D	E	F
1	9.50	18.00	20.00	18.00	43.00	31.00
2	2.70	5.30	6.60	6.50	21.00	51.00
3	1.30	2.70	3.40	3.50	12.00	40.00
4	0.81	1.70	2.10	2.30	8.00	30.00
5	0.56	1.20	1.50	1.60	5.80	23.00
6	0.42	0.87	1.10	1.20	4.40	18.00
7	0.33	0.68	0.91	0.99	3.60	14.00
8	0.27	0.56	0.74	0.82	2.90	11.00
10	0.19	0.40	0.54	0.60	2.10	7.80
12	0.15	0.31	0.42	0.47	1.70	5.70
14	0.12	0.25	0.34	0.39	1.30	4.30
16	0.11	0.21	0.28	0.33	1.10	3.40
20	0.08	0.15	0.21	0.25	0.83	2.20
25	0.07	0.12	0.16	0.19	0.62	1.40
30	0.06	0.09	0.13	0.15	0.49	0.91
40	0.05	0.07	0.09	0.11	0.35	0.46
50	0.04	0.06	0.08	0.09	0.27	0.26

TABLE VII–9. DOSE TO THYROID AFTER 10-DAY EXPOSURE, CHILDREN (1-2 YEARS OLD), Sv

Dist. (km)	A	B	C	D	E	F
1	21.00	39.00	45.00	39.00	95.00	70.00
2	6.00	12.00	15.00	14.00	46.00	110.00
3	2.90	5.90	7.60	7.80	27.00	90.00
4	1.80	3.70	4.80	5.00	18.00	67.00
5	1.20	2.60	3.40	3.60	13.00	50.00
6	0.93	1.90	2.50	2.80	9.80	39.00
7	0.73	1.50	2.00	2.20	7.90	31.00
8	0.60	1.20	1.70	1.80	6.50	25.00
10	0.43	0.89	1.20	1.30	4.80	17.00
12	0.34	0.69	0.93	1.10	3.70	13.00
14	0.28	0.55	0.75	0.86	3.00	9.60
16	0.24	0.46	0.63	0.73	2.50	7.40
20	0.19	0.34	0.47	0.55	1.80	4.80
25	0.16	0.26	0.36	0.42	1.40	3.00
30	0.14	0.21	0.29	0.34	1.10	2.00
40	0.11	0.15	0.21	0.24	0.77	1.00
50	0.09	0.12	0.17	0.19	0.59	0.56

For convenience of comparison of the results between different national case studies the doses in Tables VII–10 to VII–30 are presented at 1, 2 and 7 days after the release at the distances defined in the task setting. Pathways considered in calculation involve inhalation, cloud immersion and ground exposure. Potential precipitation effects have been omitted.

TABLE VII–10. TOTAL EFFECTIVE DOSE (1 DAY, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	6.86E+02	1.28E+03	1.46E+03	1.26E+03	3.07E+03	2.24E+03
2.5	1.29E+02	2.62E+02	3.30E+02	3.31E+02	1.12E+03	3.33E+03
3.5	7.26E+01	1.49E+02	1.91E+02	1.98E+02	6.96E+02	2.52E+03
6.5	2.65E+01	5.51E+01	7.30E+01	7.97E+01	2.87E+02	1.15E+03
7	2.36E+01	4.92E+01	6.53E+01	7.16E+01	2.59E+02	1.03E+03
8	1.93E+01	4.01E+01	5.36E+01	5.94E+01	2.14E+02	8.45E+02
15	7.85E+00	1.60E+01	2.22E+01	2.56E+01	8.93E+01	2.94E+02
50	2.11E+00	3.16E+00	4.87E+00	6.15E+00	1.87E+01	2.23E+01

TABLE VII–11. TOTAL EFFECTIVE DOSE (2 DAYS, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	7.85E+02	1.46E+03	1.67E+03	1.44E+03	3.50E+03	2.56E+03
2.5	1.48E+02	3.00E+02	3.77E+02	3.78E+02	1.28E+03	3.81E+03
3.5	8.30E+01	1.70E+02	2.18E+02	2.27E+02	7.96E+02	2.88E+03
6.5	3.04E+01	6.31E+01	8.35E+01	9.11E+01	3.28E+02	1.32E+03
7	2.65E+01	5.64E+01	7.48E+01	8.19E+01	2.96E+02	1.18E+03
8	2.21E+01	4.60E+01	6.14E+01	6.78E+01	2.45E+02	9.68E+02
15	9.34E+00	1.86E+01	2.54E+01	2.93E+01	1.02E+02	3.40E+02
50	3.34E+00	4.54E+00	6.11E+00	7.13E+00	2.29E+01	3.06E+01

TABLE VII–12. TOTAL EFFECTIVE DOSE (7 DAYS, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.06E+03	1.97E+03	2.26E+03	1.94E+03	4.73E+03	3.45E+03
2.5	2.00E+02	4.05E+02	5.09E+02	5.11E+02	1.72E+03	5.15E+03
3.5	1.12E+02	2.30E+02	2.95E+02	3.06E+02	1.08E+03	3.89E+03
6.5	4.12E+01	8.54E+01	1.13E+02	1.29E+02	4.43E+02	1.79E+03
7	3.67E+01	7.63E+01	1.01E+02	1.11E+02	3.99E+02	1.60E+03
8	3.01E+01	6.23E+01	8.29E+01	9.16E+01	3.31E+02	1.31E+03
15	1.27E+01	2.52E+01	3.44E+01	3.96E+01	1.39E+02	4.60E+02
50	4.67E+00	6.28E+00	8.37E+00	9.68E+00	3.12E+01	4.01E+01

TABLE VII–13. TOTAL EFFECTIVE DOSE (1 DAY, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.30E+03	2.42E+03	2.78E+03	2.40E+03	5.83E+03	4.26E+03
2.5	2.46E+02	4.97E+02	6.25E+02	6.29E+02	2.11E+03	6.33E+03
3.5	1.37E+02	2.83E+02	3.62E+02	3.77E+02	1.32E+03	4.76E+03
6.5	5.04E+01	1.05E+02	1.39E+02	1.51E+02	5.42E+02	2.16E+03
7	4.49E+01	9.32E+01	1.24E+02	1.35E+02	4.88E+02	1.93E+03
8	3.68E+01	7.61E+01	1.02E+02	1.12E+02	4.03E+02	1.57E+03
15	1.50E+01	3.03E+01	4.21E+01	4.86E+01	1.68E+02	5.33E+02
50	4.04E+00	6.00E+00	9.22E+00	1.16E+01	3.46E+01	3.48E+01

TABLE VII–14. TOTAL EFFECTIVE DOSE (2 DAYS, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.40E+03	2.60E+03	2.99E+03	2.58E+03	6.26E+03	4.58E+03
2.5	2.65E+02	5.35E+02	6.72E+02	6.76E+02	2.27E+03	6.81E+03
3.5	1.48E+02	3.04E+02	3.89E+02	4.06E+02	1.42E+03	5.12E+03
6.5	5.43E+01	1.13E+02	1.49E+02	1.62E+02	5.83E+02	2.33E+03
7	4.78E+01	1.00E+02	1.34E+02	1.46E+02	5.25E+02	2.08E+03
8	3.96E+01	8.20E+01	1.09E+02	1.21E+02	4.34E+02	1.69E+03
15	1.67E+01	3.32E+01	4.53E+01	5.23E+01	1.81E+02	5.81E+02
50	6.02E+00	8.12E+00	1.09E+01	1.27E+01	4.00E+01	4.61E+01

TABLE VII–15. TOTAL EFFECTIVE DOSE (7 DAYS, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.67E+03	3.11E+03	3.58E+03	3.08E+03	7.49E+03	5.47E+03
2.5	3.17E+02	6.40E+02	8.04E+02	8.09E+02	2.72E+03	8.15E+03
3.5	1.77E+02	3.64E+02	4.66E+02	4.85E+02	1.70E+03	6.13E+03
6.5	6.51E+01	1.35E+02	1.78E+02	2.00E+02	6.98E+02	2.80E+03
7	5.80E+01	1.20E+02	1.60E+02	1.74E+02	6.28E+02	2.50E+03
8	4.76E+01	9.83E+01	1.31E+02	1.45E+02	5.20E+02	2.03E+03
15	2.01E+01	3.98E+01	5.43E+01	6.26E+01	2.17E+02	7.01E+02
50	7.35E+00	9.86E+00	1.32E+01	1.52E+01	4.83E+01	5.56E+01

TABLE VII–16. DOSE TO THYROID (1 DAY, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	9.05E+03	1.68E+04	1.93E+04	1.67E+04	4.05E+04	2.97E+04
2.5	1.71E+03	3.45E+03	4.34E+03	4.37E+03	1.47E+04	4.40E+04
3.5	9.58E+02	1.96E+03	2.52E+03	2.62E+03	9.16E+03	3.30E+04
6.5	3.52E+02	7.26E+02	9.60E+02	1.05E+03	3.75E+03	1.48E+04
7	3.13E+02	6.48E+02	8.60E+02	9.44E+02	3.37E+03	1.32E+04
8	2.56E+02	5.29E+02	7.05E+02	7.82E+02	2.79E+03	1.07E+04
15	1.04E+02	2.11E+02	2.92E+02	3.37E+02	1.15E+03	3.55E+03
50	2.86E+01	4.21E+01	6.42E+01	8.11E+01	2.35E+02	1.96E+02

TABLE VII–17. DOSE TO THYROID (2 DAYS, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	9.15E+03	1.70E+04	1.96E+04	1.68E+04	4.10E+04	3.00E+04
2.5	1.73E+03	3.49E+03	4.39E+03	4.42E+03	1.49E+04	4.45E+04
3.5	9.69E+02	1.99E+03	2.54E+03	2.65E+03	9.26E+03	3.34E+04
6.5	3.56E+02	7.34E+02	9.71E+02	1.06E+03	3.79E+03	1.50E+04
7	3.17E+02	6.55E+02	8.70E+02	9.54E+02	3.41E+03	1.34E+04
8	2.59E+02	5.35E+02	7.13E+02	7.90E+02	2.82E+03	1.09E+04
15	1.10E+02	2.17E+02	2.96E+02	3.41E+02	1.17E+03	3.63E+03
50	4.02E+01	5.37E+01	7.14E+01	8.29E+01	2.56E+02	2.46E+02

TABLE VII–18. DOSE TO THYROID (7 DAYS, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	9.44E+03	1.76E+04	2.02E+04	1.74E+04	4.23E+04	3.04E+04
2.5	1.79E+03	3.60E+03	4.53E+03	4.56E+03	1.53E+04	4.59E+04
3.5	1.00E+03	2.05E+03	2.62E+03	2.73E+03	9.55E+03	3.44E+04
6.5	3.67E+02	7.58E+02	1.00E+03	1.09E+03	3.91E+03	1.55E+04
7	3.27E+02	6.76E+02	8.98E+02	9.84E+02	3.52E+03	1.38E+04
8	2.67E+02	5.52E+02	7.36E+02	8.15E+02	2.91E+03	1.12E+04
15	1.13E+02	2.24E+02	3.05E+02	3.52E+02	1.21E+03	3.76E+03
50	4.16E+01	5.55E+01	7.38E+01	8.56E+01	2.64E+02	2.56E+02

TABLE VII–19. DOSE TO THYROID (1 DAY, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	2.07E+04	3.86E+04	4.43E+04	3.81E+04	9.28E+04	6.80E+04
2.5	3.92E+03	7.90E+03	9.95E+03	1.00E+04	3.37E+04	1.01E+05
3.5	2.19E+03	4.50E+03	5.76E+03	6.00E+03	2.10E+04	7.56E+04
6.5	8.05E+02	1.66E+03	2.20E+03	2.40E+03	8.58E+03	3.34E+04
7	7.18E+02	1.48E+03	1.97E+03	2.16E+03	7.72E+03	3.03E+04
8	5.86E+02	1.21E+03	1.62E+03	1.79E+03	6.38E+03	2.46E+04
15	2.39E+02	4.83E+02	6.69E+02	7.72E+02	2.64E+03	8.10E+03
50	6.52E+01	9.60E+01	1.47E+02	1.86E+02	5.37E+02	4.39E+02

TABLE VII–20. DOSE TO THYROID (2 DAYS, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	2.08E+04	3.88E+04	4.45E+04	3.83E+04	9.33E+04	6.83E+04
2.5	3.94E+03	7.94E+03	1.00E+04	1.01E+04	3.38E+04	1.01E+05
3.5	2.20E+03	4.52E+03	5.79E+03	6.03E+03	2.11E+04	7.59E+04
6.5	8.09E+02	1.67E+03	2.21E+03	2.41E+03	8.62E+03	3.41E+04
7	7.21E+02	1.49E+03	1.98E+03	2.17E+03	7.76E+03	3.04E+04
8	5.89E+02	1.22E+03	1.62E+03	1.80E+03	6.41E+03	2.47E+04
15	2.50E+02	4.93E+02	6.72E+02	7.76E+02	2.66E+03	8.24E+03
50	9.11E+01	1.22E+02	1.62E+02	1.89E+02	5.81E+02	5.48E+02

TABLE VII–21. DOSE TO THYROID (7 DAYS, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	2.11E+04	3.93E+04	4.51E+04	3.89E+04	9.46E+04	6.92E+04
2.5	3.99E+03	8.05E+03	1.01E+04	1.02E+04	3.43E+04	1.03E+05
3.5	2.24E+03	4.58E+03	5.87E+03	6.12E+03	2.14E+04	7.70E+04
6.5	8.20E+02	1.69E+03	2.24E+03	2.45E+03	8.74E+03	3.46E+04
7	7.31E+02	1.51E+03	2.01E+03	2.20E+03	7.87E+03	3.09E+04
8	5.98E+02	1.23E+03	1.65E+03	1.82E+03	6.50E+03	2.50E+04
15	2.53E+02	5.00E+02	6.82E+02	7.87E+02	2.69E+03	8.36E+03
50	9.24E+01	1.24E+02	1.65E+02	1.91E+02	5.89E+02	5.58E+02

TABLE VII–22. EFFECTIVE DOSE FROM GROUND DEPOSITION (1 DAY), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	6.65E+01	1.24E+02	1.43E+02	1.23E+02	2.99E+02	2.18E+02
2.5	1.24E+01	2.52E+01	3.19E+01	3.23E+01	1.08E+02	3.20E+02
3.5	6.84E+00	1.42E+01	1.84E+01	1.93E+01	6.73E+01	2.40E+02
6.5	2.42E+00	5.10E+00	6.92E+00	7.69E+00	2.73E+01	1.07E+02
7	2.14E+00	4.53E+00	6.18E+00	6.91E+00	2.46E+01	9.56E+01
8	1.73E+00	3.66E+00	5.04E+00	5.71E+00	2.02E+01	7.73E+01
15	6.65E-01	1.38E+00	2.01E+00	2.42E+00	8.20E+00	2.51E+01
50	1.39E-01	2.25E-01	3.92E-01	5.33E-01	1.51E+00	1.28E+00

TABLE VII–23. EFFECTIVE DOSE FROM GROUND DEPOSITION (2 DAYS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.65E+02	3.07E+02	3.52E+02	3.03E+02	7.37E+02	5.38E+02
2.5	3.10E+01	6.29E+01	7.91E+01	7.97E+01	2.68E+02	8.00E+02
3.5	1.73E+01	3.57E+01	4.58E+01	4.78E+01	1.67E+02	6.03E+02
6.5	6.29E+00	1.31E+01	1.74E+01	1.91E+01	6.86E+01	2.74E+02
7	5.03E+00	1.17E+01	1.56E+01	1.72E+01	6.17E+01	2.46E+02
8	4.56E+00	9.51E+00	1.28E+01	1.42E+01	5.10E+01	2.00E+02
15	1.88E+00	3.78E+00	5.24E+00	6.11E+00	2.12E+01	6.82E+01
50	5.97E-01	8.38E-01	1.20E+00	1.45E+00	4.49E+00	4.63E+00

TABLE VII–24. EFFECTIVE DOSE FROM GROUND DEPOSITION (7 DAYS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	4.39E+02	8.17E+02	9.37E+02	8.05E+02	1.96E+03	1.43E+03
2.5	8.31E+01	1.68E+02	2.11E+02	2.12E+02	7.15E+02	2.14E+03
3.5	4.65E+01	9.56E+01	1.22E+02	1.27E+02	4.46E+02	1.61E+03
6.5	1.71E+01	3.54E+01	4.67E+01	5.72E+01	1.84E+02	7.40E+02
7	1.52E+01	3.16E+01	4.18E+01	4.59E+01	1.65E+02	6.64E+02
8	1.25E+01	2.58E+01	3.43E+01	3.80E+01	1.37E+02	5.42E+02
15	5.27E+00	1.04E+01	1.42E+01	1.64E+01	5.74E+01	1.88E+02
50	1.92E+00	2.58E+00	3.46E+00	4.00E+00	1.28E+01	1.41E+01

TABLE VII–25. EFFECTIVE DOSE FROM CLOUD (1 DAY), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	5.16E+01	9.61E+01	1.09E+02	9.28E+01	2.26E+02	1.63E+02
2.5	9.83E+00	2.02E+01	2.50E+01	2.47E+01	8.50E+01	2.53E+02
3.5	5.51E+00	1.15E+01	1.46E+01	1.49E+01	5.41E+01	2.00E+02
6.5	2.02E+00	4.33E+00	5.65E+00	6.06E+00	2.32E+01	1.06E+02
7	1.78E+00	3.87E+00	5.06E+00	5.46E+00	2.10E+01	9.69E+01
8	1.46E+00	3.17E+00	4.17E+00	4.54E+00	1.76E+01	8.28E+01
15	5.95E-01	1.28E+00	1.75E+00	1.98E+00	7.90E+00	3.84E+01
50	1.55E-01	2.53E-01	3.93E-01	4.98E-01	2.04E+00	7.57E+00

TABLE VII–26. EFFECTIVE DOSE FROM CLOUD (2 DAYS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	5.16E+01	9.61E+01	1.09E+02	9.28E+01	2.26E+02	1.63E+02
2.5	9.83E+00	2.02E+01	2.50E+01	2.47E+01	8.50E+01	2.53E+02
3.5	5.51E+00	1.15E+01	1.46E+01	1.49E+01	5.41E+01	2.00E+02
6.5	2.02E+00	4.33E+00	5.65E+00	6.06E+00	2.32E+01	1.06E+02
7	1.78E+00	3.87E+00	5.06E+00	5.46E+00	2.10E+01	9.69E+01
8	1.46E+00	3.17E+00	4.17E+00	4.54E+00	1.76E+01	8.28E+01
15	6.18E-01	1.30E+00	1.75E+00	1.98E+00	7.90E+00	3.88E+01
50	2.15E-01	3.19E-01	4.33E-01	5.03E-01	2.19E+00	9.38E+00

TABLE VII–27. EFFECTIVE DOSE FROM INHALATION (1 DAY, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	5.68E+02	1.06E+03	1.21E+03	1.04E+03	2.54E+03	1.86E+03
2.5	1.07E+02	2.17E+02	2.73E+02	2.74E+02	9.23E+02	2.76E+03
3.5	6.02E+01	1.23E+02	1.58E+02	1.64E+02	5.75E+02	2.08E+03
6.5	2.21E+01	4.57E+01	6.04E+01	6.59E+01	2.36E+02	9.41E+02
7	1.97E+01	4.08E+01	5.41E+01	5.92E+01	2.13E+02	8.42E+02
8	1.61E+01	3.33E+01	4.44E+01	4.91E+01	1.76E+02	6.85E+02
15	6.59E+00	1.33E+01	1.84E+01	2.12E+01	7.32E+01	2.30E+02
50	1.82E+00	2.68E+00	4.08E+00	5.12E+00	1.51E+01	1.34E+01

TABLE VII–28. EFFECTIVE DOSE FROM INHALATION (2 DAYS, ADULTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	5.68E+02	1.06E+03	1.21E+03	1.04E+03	2.54E+03	1.86E+03
2.5	1.07E+02	2.17E+02	2.73E+02	2.74E+02	9.23E+02	2.76E+03
3.5	6.02E+01	1.23E+02	1.58E+02	1.64E+02	5.75E+02	2.08E+03
6.5	2.21E+01	4.57E+01	6.04E+01	6.59E+01	2.36E+02	9.41E+02
7	1.97E+01	4.08E+01	5.41E+01	5.92E+01	2.13E+02	8.42E+02
8	1.61E+01	3.33E+01	4.44E+01	4.91E+01	1.76E+02	6.85E+02
15	6.84E+00	1.35E+01	1.84E+01	2.12E+01	7.32E+01	2.33E+02
50	2.53E+00	3.38E+00	4.48E+00	5.18E+00	1.62E+01	1.66E+01

TABLE VII–29. EFFECTIVE DOSE FROM INHALATION (1 DAY, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.18E+03	2.20E+03	2.53E+03	2.18E+03	5.30E+03	3.88E+03
2.5	2.24E+02	4.52E+02	5.68E+02	5.72E+02	1.92E+03	5.76E+03
3.5	1.25E+02	2.57E+02	3.29E+02	3.43E+02	1.20E+03	4.32E+03
6.5	4.60E+01	9.51E+01	1.26E+02	1.37E+02	4.91E+02	1.95E+03
7	4.10E+01	8.48E+01	1.13E+02	1.23E+02	4.42E+02	1.74E+03
8	3.36E+01	6.93E+01	9.24E+01	1.02E+02	3.65E+02	1.41E+03
15	1.37E+01	2.76E+01	3.83E+01	4.42E+01	1.52E+02	4.69E+02
50	3.75E+00	5.52E+00	8.43E+00	1.06E+01	3.10E+01	2.59E+01

TABLE VII–30. EFFECTIVE DOSE FROM INHALATION (2 DAYS, INFANTS), mSv

Distance, km	Stability category					
	A	B	C	D	E	F
1	1.18E+03	2.20E+03	2.53E+03	2.18E+03	5.30E+03	3.88E+03
2.5	2.24E+02	4.52E+02	5.68E+02	5.72E+02	1.92E+03	5.76E+03
3.5	1.25E+02	2.57E+02	3.29E+02	3.43E+02	1.20E+03	4.32E+03
6.5	4.60E+01	9.51E+01	1.26E+02	1.37E+02	4.91E+02	1.95E+03
7	4.10E+01	8.48E+01	1.13E+02	1.23E+02	4.42E+02	1.74E+03
8	3.36E+01	6.93E+01	9.24E+01	1.02E+02	3.65E+02	1.41E+03
15	1.42E+01	2.81E+01	3.83E+01	4.42E+01	1.52E+02	4.74E+02
50	5.21E+00	6.96E+00	9.27E+00	1.07E+01	3.33E+01	3.21E+01

VII–4. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION FOR BIOTA

According to Ref [VII–3], the term environmental protection may be taken to include the prevention of the contamination of environmental media that are considered to constitute environmental resources (such as soil, water, sediment, and air) of human value with the objective of ‘protecting’ them for the future. A typical example is that of guarding against the risk of contamination of ground water with radionuclides from waste disposal. In such cases the ‘object’ of protection (for example, groundwater) is not itself ‘harmed’ by exposure to ionizing radiation, and the concern is essentially that of the future use of the resource by humans. It thus forms part of the framework of human protection. In the same manner, however, these resources also form part of the network of exposure media for non-human biota. As such, protection of such resources is also a mechanism for limiting exposures for both humans and biota. Environmental media are therefore considered as pathways of exposure, whereas the recommendations relating to protection are derived from an understanding of effects in, and the sensitivity of, the organisms living in the environment.

The main objective of the current part of the annex is to give an example of the biota considering approach in cases of emergencies. The impact due to potential accidents could play a role in the early stages of a decision process for instance, to select a good site or to define simple practical measures to mitigate the potential consequences of accidents to biota[11].

VII–5. METHODOLOGY FOR BIOTA CONSIDERATION

VII–5.1. Representative organisms

The representative organisms are located in the vicinity of the source – around the release point – where the highest environmental activity concentrations could occur. Ref [VII–3] indicates that a representative organism is “a particular species or group of organisms selected during a site-specific assessment, taking account of their assumed location with respect to the source”. The actual choice of representative organisms was made according the recommendations of Ref [VII–4]. The pine tree is considered to be a reference object because of its high radio sensitivity, and grasses were considered in order to compare the impact to these plant objects.

All grasses belong to the same family, the Poaceae (formerly the Gramineae). Grasses of one or another form are the predominant plants throughout much of the terrestrial environment. They have a worldwide distribution and occur naturally in a wide variety of forms, including reeds and bamboos, as well as the more familiar cereal crops, and are the dominant plants of natural pasture land. They serve as food for a wide range of herbivorous mammals, including

[11]Animals are not considered in this study. The model for animals has to account for several complementary factors, e.g. habitat, potential migration and food chains.

(as herbage) domesticated forms of cattle, sheep, and horses. They are also the basic food crop for humans all over the world. Their biology has therefore been well studied, including their accumulation of a wide range of chemicals. Their life cycle is highly seasonal.

Reference Wild Grass is assumed to have the characteristics of a 'barley-type' wild grass with a flowering spikelet carried on a stalk above the ground. It is a perennial. The grass meristem is modelled as an infinite homogeneous layer with a density of 13.7 kg/m^3. The layer has a thickness of 10 cm and overlays the air/ground interface.

Pine trees (family Pinacea) occur naturally across the whole of the Northern hemisphere, from the Arctic Circle to just south of the Equator, in a wide variety of environments. They have also been introduced into many countries of the Southern hemisphere. They have been used extensively by man for building materials, for fuel, and for resin. They have been well studied with regard to their physiology and general biology, and are easily cultivated. In addition, a large amount of information is available with regard to exposure to radiation and its effects.

Reference Pine Tree is taken to have the characteristics of a large tree growing in a temperate region. It attains reproductive maturity at 10 years and lives for 200 years. Young trees grow at the rate of 1 m/a. Pine Trees produce cones that are ovoid, taking 18 months to mature. For external exposure assessment, the homogeneous plant layer was 10-m-height with a density of 2.4 kg/m^3 [VII–5].

VII–5.2. Model description

Calculation of the surface activity caused by the passage of the radioactive cloud from an atmospheric release source was carried out by means of the tool Express [VII–2].

To describe the processes of radioactive substances transmission in a forest ecosystem the vertical migration model was developed. The model structure is presented at Figure VII–1.

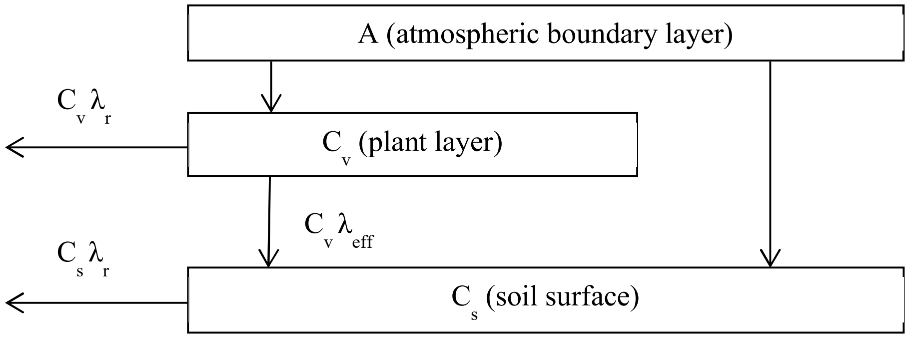

FIG. VII–1. Structure of the vertical radionuclide migration model (modified from [VII–6]).

The model considers processes such as radionuclide interception by plant layer, deposition on soil surface, ecological self-purification and radionuclide decay [VII–7]. The complex of specified processes can be described by the following differential equation system:

$$\begin{cases} \frac{dC_v}{dt} = -\lambda_{eff} C_v \\ \frac{dC_s}{dt} = \lambda_{ec} C_v - \lambda_r C_s \end{cases}, \qquad \text{(VII–1);}$$

where C_s – radionuclides concentration on the soil surface, (Bq/m^2); C_v – radionuclides concentration in plant layer, (Bq/m^2); λ_{ec} – ecological decay constant, day^{-1}; λ_r – radionuclide decay constant, day^{-1}, λ_{eff} – effective ecological decay constant ($\lambda_{eff} = \lambda_{ec} + \lambda_r$), day^{-1}.

The following correlations were admitted as initial conditions:

$$C_v = A\,K_z \qquad \text{(VII–2);}$$

$$C_s = A\,(1 - K_z) \qquad \text{(VII–3);}$$

where A is radionuclide fallout density, (Bq/m^2); K_z is fraction of the radionuclides intercepted by the plant layer (0.9 for conifers and 0.2 for grasses).

In terms of dosimetric terminology, plant layer containing radionuclides could be presented as continued thick radioactive source. It is supposed that radionuclides are homogeneously distributed within this source. Dose calculation for plants were performed by the following equations:

$$D_c(t) = C_v(t) \cdot \frac{K_c}{\rho h} \qquad \text{(VII–4);}$$

$$D_s(t) = C_s(t) \cdot K_s \qquad \text{(VII–5);}$$

where D_c – dose rates from the radionuclides in plant layer, µGy/day; D_s – dose rates from the radionuclides on the soil surface, µGy/day; K_c – dose conversion coefficient for external irradiation of trees from the radionuclides intercepted by tree canopies, (µGy/day)/(Bq/kg) [VII–5]; K_s – dose conversion coefficient for external irradiation of trees from the radionuclides deposited on soil surface, (µGy/day)/(Bq/m^2) [VII–5]; h – height of the plants, m; ρ – density of the homogeneous air-vegetation layer, kg/m^3.

VII–6. RESULTS OF ASSESSMENT FOR BIOTA

The exposure scenario and the source term are described in Section 3.

The most frequent atmospheric category according to the meteorological data used in the exercise was F (3468 out of total 8760 hours). The height of the atmospheric boundary level was assumed as 200 m according to Ref [VII–2]. The minimum wind speed under such conditions is 0 m/s. Due to the conservative approach, wind velocity should be minimum. The code allows a minimum wind velocity of 0.5 m/s, hence this value was used in the study. The effective height of the release was assumed to be 35 m.

Dose rates were estimated for Wild Grass and Pine Trees for a period of 1 year for distances of 1.75 km, 5 km, 10 km, 20 km, 30 km, 40 km and 50 km. The results are presented in Table VII–32.

TABLE VII–32. EXTERNAL DOSES ACCUMULATED IN ONE YEAR AND AVERAGE DOSE RATES

Distance,	Wild Grass		Pine Trees	
km	Dose, mGy	Dose rates, mGy/day	Dose, mGy	Dose rates, mGy/day
1.75	1.17E+05	3.20E+02	2.64E+04	7.22E+01
5	3.99E+04	1.09E+02	9.00E+03	2.46E+01
10	9.61E+03	2.63E+01	2.17E+03	5.93E+00
20	1.48E+03	4.04E+00	3.41E+02	9.31E-01
30	3.83E+02	1.05E+00	9.09E+01	2.48E-01
40	1.27E+02	3.46E-01	3.13E+01	8.54E-02
50	4.78E+01	1.31E-01	1.23E+01	3.35E-02

As it is seen from the table the highest annual dose both for grass and trees is observed at a distance of 1.75 km.

Table VII–33 is based on information from Ref [VII–3] providing a review of all of the known data on the effects of radiation relevant to the Reference Animal or Plants (RAPs) and information summarised in terms of increasing orders of magnitude of dose [VII–4]. From these compilations, a band of dose rate for each RAP, spanning one order of magnitude, was selected for the purposes of providing a starting point for considering what action, if any, should be carried out. These bands are called Derived Consideration Reference Levels (DCRLs). A DCRL is “a band of dose rate within which there is some chance of deleterious effect from ionising radiation occurring to individuals of that type of Reference Animal or Plant”. The values themselves are very similar to those which have recently been derived by other reviews and analyses of radiation effects data from a wider range of biota.

TABLE VII–33. DOSE RATES AND EFFECTS FOR REFERENCE PINE TREE AND WILD GRASS [VII–3].

Dose rate (mGy/day)	Reference Pine tree	Reference wild grass
> 1000	Mortality (5 to 16 Gy LD50[1])	Mortality (16 to 22 Gy LD50[1])
100 – 1000	Mortality of some trees after prolonged exposure	Reduced reproductive capacity
10 – 100	Mortality of some trees after very long exposure. Growth defects. Reduced reproductive success	Reduced reproductive capacity
1 – 10	Morbidity as expressed through anatomical and morphological damage. Prolonged exposure leads to reduced reproductive success	No information
0.1 – 1	No information	No information
0.01 – 0.1	No information	No information
< 0.01	Natural background	Natural background

Note: [1] - LD50 – lethal dose for 50% of samples.

According to Table VII–32 it is obvious that at the point of maximum dose rates different effects for pine trees and grass occurred. At distances 1.75, 5 and 10 km there would be reduced reproductive capacity for trees and grasses. For some individual organisms of trees there could be observed mortality and growth defects at distances of 1.75 and 5 km.

The following conclusions can be made from the previous discussions:

In considering the effects of radiation on the population, it is essential to specify the precise characteristics of the considered population, the fraction of the population known or assumed to be exposed to different dose rates, their total dose and the stages in the life cycle receiving the relevant dose, plus any other factors of relevance. That is why for the current situation it is difficult to give a detailed assessment of the damage to the population and the mean dose-rates are to be considered as screening values.

Estimated levels of radiation impact on biota for the considered accident confirms the necessity of studies of consequences for environmental components resulting from potential accidental releases from nuclear facilities. One of the issues of such studies could be the criteria for impact assessment for accidental situations, as most of the used criteria are derived for prolonged exposures.

Such a methodology with one reference object can be used for comparative analysis for different nuclear facilities in terms of accidental exposures.

REFERENCES TO ANNEX VII

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ANNEX VIII. SPAIN

VIII–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

In the Table VIII–1 the Spanish radiological quantitative criteria for the protective actions in the case of a radiological emergency are presented.

TABLE VIII–1. QUANTITATIVE RADIOLOGICAL CRITERIA [VIII–1, VIII–2]

Countermeasure	Radiological criteria (*)
Sheltering	10 mSv effective avertible dose in 2 days Preventively this measure can be adopted at lower doses for shorter periods
Iodine prophylaxis	100 mSv equivalent dose to the thyroid
Evacuation	50 mSv avertible effective dose in less than a week This measure may be adopted at lower doses for shorter periods if evacuation is simple
Temporary relocation	30 mSv avertible effective dose for the first month and 10 mSv next month. Ending of relocation for avertible dose <10 mSv
Permanent relocation	If avertible dose doesn't decrease <10 mSv to 1 or 2 years or if it exceeds 1 Sv / lifetime dose
Zoning / Remoteness of people	<100 μSv/h for public <5 mSv/h for intervention staff

Note: (*) The Nuclear Safety Council can define different values if the analysis of the specific circumstances of the emergency conclude the convenience to optimize the generic values indicated.

VIII–2. DESCRIPTION OF METHODOLOGIES APPLIED FOR ASSESSMENT OF RADIOLOGICAL IMPACT FROM POTENTIAL EXPOSURE

In this case study a potential impact is assessed by a proposed methodology for estimation of the impact's magnitude. Also the acceptability of this impact is analysed based on the general requirement that an accident at a Nuclear Energy System will not cause the need for public relocation or evacuation protective actions beyond the site boundary [VIII–3] and, on the other hand, based on a risk curve criterion for the public [VIII–4], where acceptability of the dose depends on the probability of release category occurrence.

Two state of the art models have been used in the study of the magnitude of consequences of the postulated category of accident. One is the WinMACCS code with probabilistic approach, with a broader view on the problems, but more general models, and another one is the JRODOS code with more emphasis on the specific problem using electronic maps from the Environmental Systems Research Institute [VIII-5] as background for results and for input information.

For the probabilistic analysis of consequences from potential exposure such phenomena as atmospheric dispersion, deposition of airborne materials, resuspension, and migration through the food chains are modelled by the WinMACCS code version 3.7.0 [VIII–6]. The WinMACCS code (last updated MACCS code) has been developed since 1990 to support probabilistic safety assessment (PSA) efforts [VIII–7] and became one of the most commonly used codes for such purposes, along with other codes such as COSYMA (CEC), OSCAAR (Japan) and others.

The computer code MACCS (MELCOR Accident Consequence Code Systems) was developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (NRC) to simulate the impact of severe accidents at nuclear power plants on the surrounding environment and to analyse the off-site consequences of an accidental atmospheric release of radioactive material. Designed primarily as a probabilistic risk assessment (PRA) tool, MACCS2 can sample annual weather data and generate statistics that describe the effects of weather variations at the time of a release. MACCS2 results include land contamination areas and levels of contamination, doses to individuals and populations, health effects and risks, and economic losses resulting from an accident. MACCS2 is the code used by the NRC to support Level-3 PRAs and has been applied in a study for risk-informed emergency response guidance [VIII–8].

The time scale after the accident is divided in the code into three phases: emergency, intermediate, and long-term phases, and the region surrounding the reactor is split into a polar coordinate grid. WinMACCS estimates transport, dispersion and deposition of the radioactive materials released from the reactor. The doses are estimated from all exposure pathways: cloud-shine, plume inhalation, ground-shine, resuspension, skin dose from the material deposited on the skin, and ingestion of contaminated foods. The mitigation of the dose is considered by the protective actions (evacuation, sheltering, iodine tablets administration, post-accident relocation of the people, and disposal of the food products) [VIII–8].

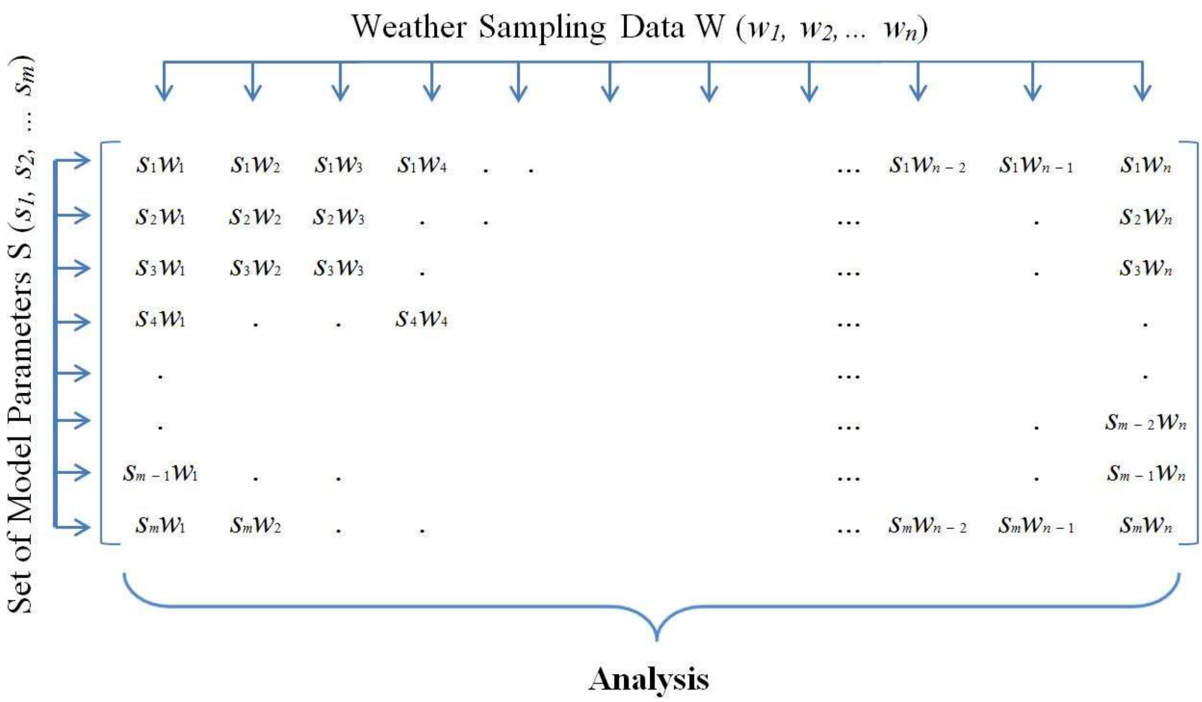

FIG. VIII–1. Conceptual scheme of the modelling with the WinMACCS code

The WinMACCS code accounts for the uncertainty in weather, and so random weather sampling addressed the uncertainty in health effects from accidental releases caused by weather variability. Also, the code permits evaluation of the impact of uncertainty of the model parameters by introducing random sampling distribution for key model parameters [VIII–8]. In Figure VIII–1 the main concept of the modelling with the WinMACCS code is presented.

Additionally, the JRODOS code [VIII–9] has been applied for the deterministic modelling of off-site consequences for the critical meteorological conditions. RODOS is the European Real-time On-line Decision Support System for off-site emergency management which provides consistent and comprehensive information on the present and future radiological situation, and provides methodological support for taking decisions on emergency response strategies regarding the extent, and the benefits and drawbacks, of emergency actions and protective actions [VIII–9, VIII–10]. Over the last years the RODOS system has been re-engineered, and in 2008 JRODOS – a Java-based product – was released [VIII–11]. The implementation of the RODOS and JRODOS systems in the emergency centre in Spain was performed [VIII–12] and the system was used for different case studies and scenarios [VIII–13] where it proved to be a flexible and effective tool to support emergency preparedness.

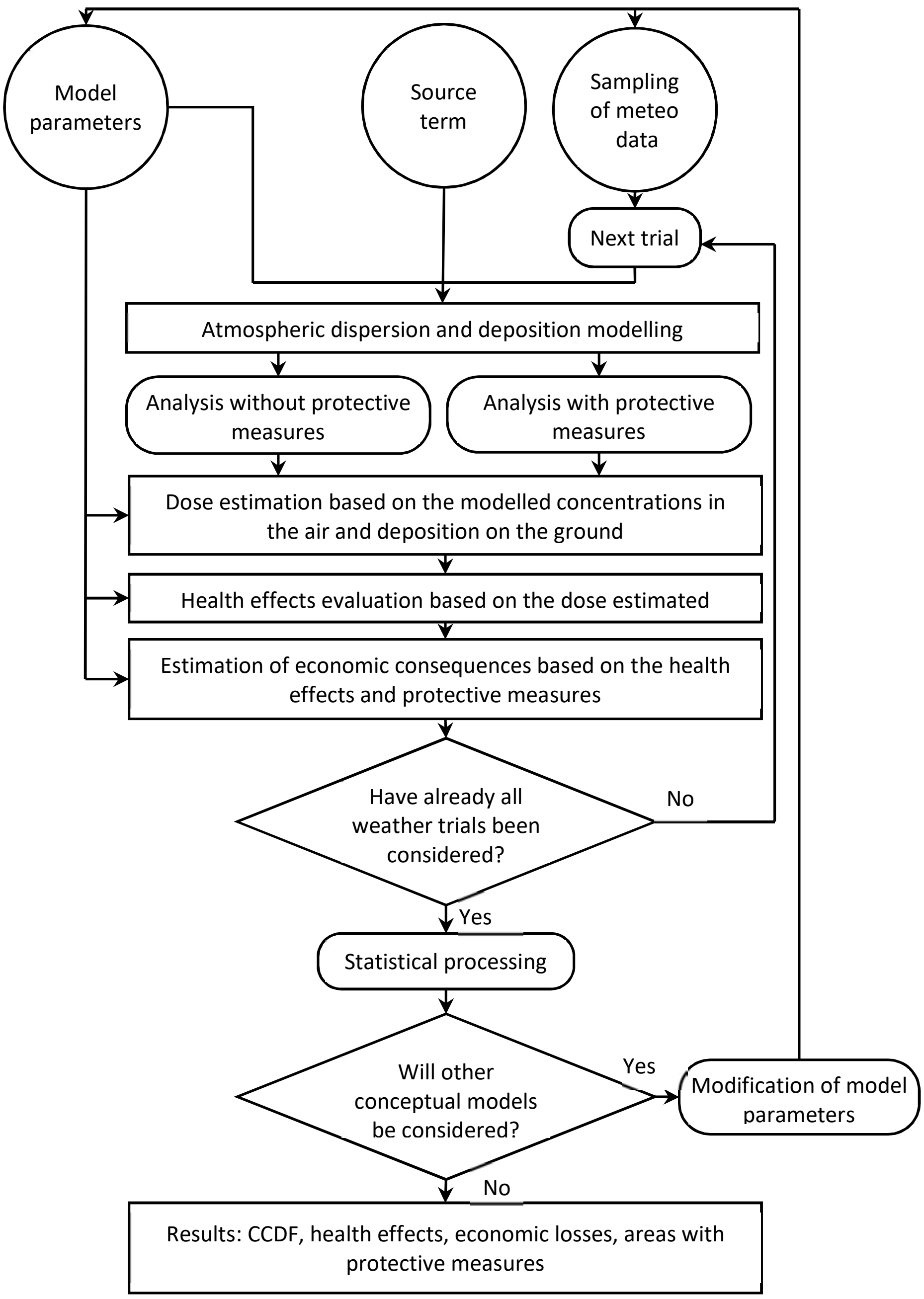

FIG. VIII–2. Frame of the probabilistic consequence analysis

A flowchart diagram illustrating basic steps in the probabilistic analysis of consequences from radioactive release is presented in Figure VIII–2. In the beginning of the study an appropriate scenario should be defined with the meteorological data accumulated for at least one year with an hourly step interval, the corresponding source term, and other input information and model parameters. Based on this information the iterations for considered weather sampling (8760 sequences) are fulfilled with calculations for each trial of the atmospheric dispersion and deposition, providing estimation of the doses and health effects. This modelling takes into account the weather uncertainty in correspondent location to estimate the probability of consequences. Thereafter the received array of results is subjected to statistical processing. If uncertainty of the model parameters is taken into account, more cycles of iterated calculations should be made with the same procedure of the consequence estimation.

The above described consequences are evaluated on a polar grid (r, θ) around the release location. The results are produced for each of the grid elements for a large number of weather conditions. This produces a distribution of individual risk at each grid element.

This study (similarly as Ref [VIII–14, VIII–15]) is focused on the peak doses in all directions of wind rose at each distance and for each weather sequence. Peak dose means the maximum dose around the compass under all meteorological sampling options [VIII–16]. Then the samples of peak dose values are statistically processed to get the estimation of the percentiles, and complementary cumulative distribution functions (CCDFs).

Based on the meteorological sampling of site-specific data and the application of dose and/or health effects models, the complementary cumulative distribution functions (CCDFs) are built by the WinMACCS code for various characteristics of consequences distribution. The 50th (median), 90th, 95th, 99th, and 99.5th percentile doses are provided in the output along with the mean and the peak values.

Risk indicators and a risk-informed approach to estimate potential exposure are presented below.

To analyse the acceptability of a NES for one release category such an approach can be proposed. First, a certain scenario with release category and its frequency is selected, then the hourly meteorological data for one year typical for this site is prepared. The PSA Level 3 is fulfilled with the results of plots showing families of doses (doses vs. distance) as percentiles based on the sample of the weather conditions, 50th, 95th, 99th and peak consequences.

The next step is identification of the distances where doses exceed the limits for such protective actions as evacuation and relocation. In other words, each plot of dose will be compared against the dose limit. If the doses do not reach the limits for evacuation and relocation at any area, then the installation can be acceptable. For all locations where doses exceed the limits, the distances should be analysed. If dose limits are reached or exceeded for the off-site zone, then it implies that the evacuation or relocation of the public would be necessary and such a NES facility is not acceptable. In other words, one should identify areas where the evacuation limits may be exceeded.

On the other hand the risk indicator from the release which occurred at a specific location (with typical meteorological conditions in this location) can be estimated as a product of 95th percentile of the assessed dose (which itself includes risk concept, as was received based on the weather sampling), the probability of occurrence of the release of considered category and the risk coefficient for stochastic effects (see Eq. (VIII–1)). The nominal risk coefficient for stochastic effects was taken as 0.057 Sv^{-1} (including cancer and heritable effects) [VIII–17]. The probability of occurrence of the release category was considered to be $1.5 \cdot 10^{-6}$ [VIII–18].

$$Risk_n = P(RC)^n \cdot D \cdot f(D) \quad \text{(VIII–1)}$$

where $Risk_n$ is the individual risk from the Release Category *n*; $P(RC)^n$ is the probability of occurrence of the Release category *n*; D is the effective dose (95th percentile based on weather sampling); and $f(D)$ is the nominal risk coefficient for stochastic effects of received doses.

The results of the dose and risk estimation are presented in the following sections in the exercise description.

To analyse an installation for general acceptability the whole risk from this installation should be defined, taking into account all possible release categories. Risk can be expressed as "set of triplets" [VIII–19]:

$$Risk = \{S_{i}, P_{i}, X_i\} \quad i = 1, 2, \ldots, N \qquad \text{(VIII–2)}$$

where S_i is i-th scenario description; P_i is the probability of scenario i; and X_i is the consequence or magnitude of damage of i-th scenario.

So, for estimation of the total risk from an installation, it is important to include a complete set of scenarios or categories of releases. As it is impossible to include all releases, the general set of N important categories is included and residual category $N+1$ is added [VIII–19]. Each of these triplets should be analysed for acceptability. In this work only one release category (only one triplet) is considered as an example. This triplet was analysed based on the acceptance criteria curve developed by Argentina (Annex I).

VIII–3. RESULTS OF ASSESSMENT

This study is mostly focused on the assessment of criteria formulated for relocation and evacuation of population. Dose integrated over 7 days and the lifetime dose were analysed. When dose criteria are exceeded in an off-site zone the evacuation or relocation of the public will be necessary. The potential ingestion of radionuclides has been omitted here assuming that uncontaminated food and water could be supplied when needed to avoid ingestion of radionuclides.

The calculation of radiation doses considers five pathways: (1) direct external exposure to radioactive material in the plume (cloud-shine), (2) exposure from inhalation of radionuclides in the cloud (cloud inhalation), (3) exposure to radioactive material deposited on the ground (ground-shine), (4) inhalation of resuspended material (resuspension inhalation), and (5) skin dose from material deposited on the skin [VIII–20].

To check if the evacuation countermeasure will be necessary, a calculation was made for a 7 days period, as in accordance with Spanish legislation the necessity of this countermeasure depends on the 7 days integrated dose, and the dose limit is 50 mSv Ref [VIII–1, VIII–2]. For convenience of the result comparison between different national case studies the doses in Table VIII–2 are presented at the locations defined in the task setting. To define the area of potential evacuation a more detailed distribution of the same total effective doses is presented in Table VIII–3. Values greater than 50 mSv (criterion for evacuation) are highlighted with grey.

TABLE VIII–2. TOTAL EFFECTIVE DOSE AT POPULATED AREAS (7 DAYS), Sv

Distance, km	Percentiles			
	90th	95th	99th	Max
1.0	3.48E-01	3.78E-01	4.57E-01	5.90E-01
2.5	1.80E-01	2.17E-01	3.01E-01	4.19E-01
3.5	1.40E-01	1.70E-01	2.38E-01	3.50E-01
6.5	9.46E-02	1.11E-01	1.55E-01	2.46E-01
7	7.10E-02	8.64E-02	1.12E-01	1.80E-01
8	5.07E-02	6.14E-02	8.57E-02	1.27E-01
15	2.79E-02	3.39E-02	5.04E-02	6.56E-02
50	3.25E-03	3.87E-03	6.59E-03	9.22E-03

TABLE VIII–3. TOTAL EFFECTIVE DOSE (7 DAYS), Sv

Distance, km	Mean	50th	90th	95th	99th	99.5th	Peak consequence	Peak trial
0-0.1	1.99E+00	1.94E+00	2.36E+00	2.53E+00	2.99E+00	3.08E+00	3.61E+00	6679
0.1-0.5	5.60E-01	5.31E-01	7.29E-01	7.68E-01	8.66E-01	9.13E-01	1.08E+00	6417
0.5-1.0	2.68E-01	2.49E-01	3.48E-01	3.78E-01	4.57E-01	4.96E-01	5.90E-01	6417
1.0-1.5	1.86E-01	1.70E-01	2.66E-01	3.02E-01	3.36E-01	3.52E-01	4.53E-01	6335
1.5-2.0	1.51E-01	1.25E-01	2.30E-01	2.60E-01	3.18E-01	3.34E-01	4.42E-01	6333
2.0-3.0	1.16E-01	1.05E-01	1.80E-01	2.17E-01	3.01E-01	3.17E-01	4.19E-01	7818
3.0-4.0	8.62E-02	7.82E-02	1.40E-01	1.70E-01	2.38E-01	2.68E-01	3.50E-01	6332
4.0-5.0	6.69E-02	5.99E-02	1.14E-01	1.35E-01	2.00E-01	2.13E-01	3.00E-01	7817
5.0-6.0	5.33E-02	4.82E-02	9.46E-02	1.11E-01	1.55E-01	1.78E-01	2.46E-01	7817
6.0-8.0	3.92E-02	3.37E-02	7.10E-02	8.64E-02	1.12E-01	1.21E-01	1.80E-01	7817
8.0-10.0	2.77E-02	2.40E-02	5.07E-02	6.14E-02	8.57E-02	9.70E-02	1.27E-01	7817
10-16	1.56E-02	1.27E-02	2.79E-02	3.39E-02	5.04E-02	5.25E-02	6.56E-02	7817
16-20	9.29E-03	8.22E-03	1.61E-02	2.04E-02	3.02E-02	3.16E-02	4.04E-02	6350
20-25	6.32E-03	5.59E-03	1.14E-02	1.36E-02	2.02E-02	2.12E-02	2.77E-02	8512
25-30	4.43E-03	3.73E-03	8.05E-03	9.68E-03	1.18E-02	1.28E-02	1.97E-02	6352
30-40	2.76E-03	2.34E-03	5.14E-03	6.06E-03	9.67E-03	1.04E-02	1.32E-02	6351
40-50	1.73E-03	1.33E-03	3.25E-03	3.87E-03	6.59E-03	7.26E-03	9.22E-03	6350
50-60	1.18E-03	9.57E-04	2.22E-03	2.63E-03	4.67E-03	5.31E-03	7.18E-03	6349
60-80	7.16E-04	5.45E-04	1.27E-03	1.54E-03	2.93E-03	3.72E-03	5.92E-03	6345

The values highlighted in grey are those which exceed 50 mSv and for which it will be necessary to consider evacuation of the people. It can also be seen for this scenario that the evacuation could be necessary up to the distance 10-16 km. On the other hand, for the 50th percentile, the distance where the dose criterion was met is greater than 6 km, which is high frequency and large distance, so evacuation of an off-site area, outside the site boundary will be necessary.

An example of the CCDF function as probability of dose exceeding the distance of 5 km is shown in Figure VIII–3, where it can be seen that with probability of 1 the peak dose will exceed 10 mSv at this distance.

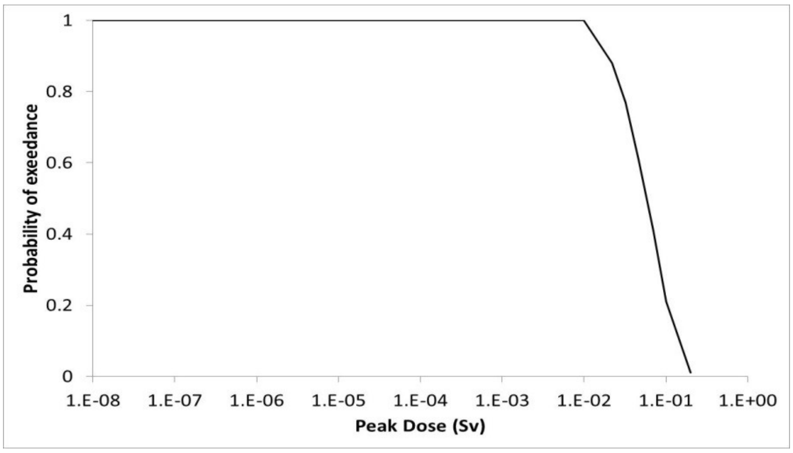

FIG. VIII–3. CCDF of peak dose (7 days doses) on the distance 5 km

Lifetime dose is used to determine the need for mitigative actions and for calculation of the cancer induction and population dose results. It represents the 50-year dose commitment, received from the sum of the following pathways: cloud-shine and inhalation doses during plume passage, projected ground-shine dose for the duration of the emergency phase, and resuspension inhalation dose for the duration of the emergency phase. Dose conversion factors from Ref [VIII–21] were used for the calculation.

TABLE VIII–4. PEAK EFFECTIVE LIFETIME DOSES (Sv)

Distance , km	Mean	50th	90th	95th	99th	99.5th	Peak consequence	Peak trial
0-0.1	7.86E+00	7.30E+00	1.13E+01	1.28E+01	1.69E+01	1.91E+01	2.96E+01	3005
0.1-0.5	2.02E+00	1.77E+00	2.81E+00	3.22E+00	4.22E+00	4.74E+00	6.87E+00	3004
0.5-1.0	7.47E-01	6.77E-01	1.06E+00	1.23E+00	1.73E+00	2.00E+00	2.72E+00	3005
1.0-1.5	4.08E-01	3.53E-01	6.12E-01	7.32E-01	1.00E+00	1.08E+00	1.57E+00	6678
1.5-2.0	2.77E-01	2.39E-01	4.31E-01	5.26E-01	7.31E-01	8.23E-01	1.10E+00	3003
2.0-3.0	1.80E-01	1.42E-01	2.92E-01	3.48E-01	5.07E-01	5.59E-01	7.83E-01	3003
3.0-4.0	1.15E-01	9.59E-02	1.90E-01	2.29E-01	3.24E-01	3.62E-01	5.38E-01	3003
4.0-5.0	8.16E-02	6.78E-02	1.31E-01	1.63E-01	2.48E-01	2.89E-01	3.87E-01	3002
5.0-6.0	6.15E-02	5.10E-02	1.03E-01	1.22E-01	1.85E-01	2.07E-01	2.96E-01	6674
6.0-8.0	4.31E-02	3.50E-02	7.29E-02	9.00E-02	1.16E-01	1.27E-01	2.02E-01	6673
8.0-10.0	2.98E-02	2.40E-02	5.12E-02	6.30E-02	9.62E-02	1.06E-01	1.55E-01	6673
10-16	1.71E-02	1.32E-02	3.03E-02	3.74E-02	5.66E-02	6.47E-02	9.25E-02	4629
16-20	1.07E-02	8.29E-03	1.96E-02	2.39E-02	3.55E-02	4.13E-02	6.95E-02	4628
20-25	7.76E-03	5.92E-03	1.34E-02	1.71E-02	2.67E-02	3.06E-02	4.48E-02	4629
25-30	5.90E-03	4.34E-03	1.10E-02	1.36E-02	2.14E-02	2.44E-02	3.64E-02	3644
30-40	4.15E-03	3.08E-03	7.99E-03	1.03E-02	1.55E-02	1.85E-02	2.55E-02	2995
40-50	2.92E-03	2.12E-03	5.64E-03	7.21E-03	1.13E-02	1.38E-02	3.09E-02	6667
5060	2.19E-03	1.54E-03	4.29E-03	5.56E-03	8.29E-03	9.55E-03	1.40E-02	2204
60-80	1.57E-03	1.11E-03	3.20E-03	3.98E-03	5.93E-03	6.78E-03	1.10E-02	7074

The statistically processed results of the lifetime peak doses are presented in Table VIII–4. Doses exceeding the limit of permanent relocation (1 Sv) are highlighted in grey. In continuation the family curves of doses (95th, 99th percentiles) versus distance are plotted and solved for the limit dose (1 Sv) in Figure VIII–4. So, it can be seen that in the worst-case the zone of relocation will not exceed 2 km, and in 5% of the cases it will exceed 1 km.

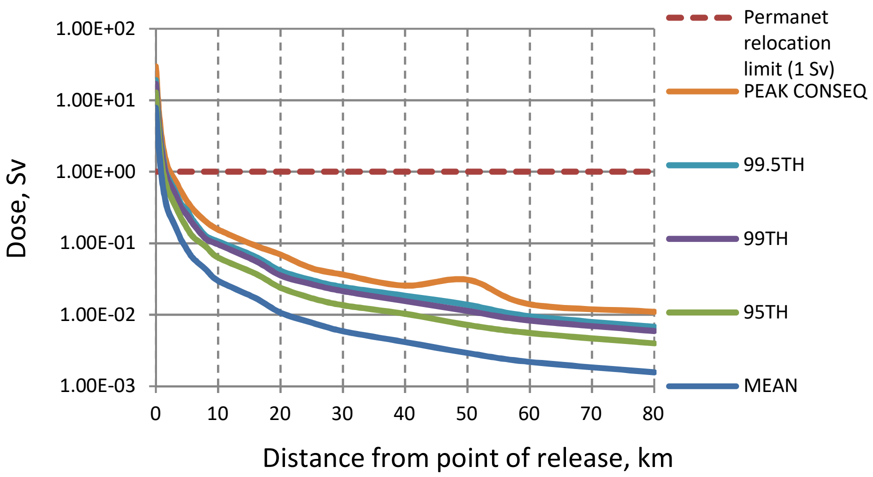

FIG. VIII–4. Effective Lifetime dose dependent on distance from point of release

This is the approach similar to that presented in Ref [VIII–22], only with the different objective of the assessment of potential exposure. In Ref [VIII–22] the main objective was the definition of Emergency Planning Zones or revising of emergency management requirements for new generation reactors.

A comparison was also made between the 7-days and lifetime doses for the 95th percentile (Figure VIII–5), and it can be seen that there is not a big difference, especially for the distance of 4 – 10 km from the point of release, because of the big contribution of the iodine component in this release.

Other useful information that can be extracted from the results of the 'peak trial' (Tables VIII–3, VIII–4) is about the hourly weather conditions which can give the highest consequences. Simulation for a whole year was carried out using the total set of 8760 trials. At different distances from the point of release, 7-days' doses achieved maximum values for 6332 – 8512 trials, which means that the critical period is the autumn (from September to December). For lifetime dose (except ingestion pathway), the more critical time of the release is considered from April until September. The most critical trial for 7-days doses is for the distances 4-16 km from the point of release (Table VIII–3) is the trial 7817, which can lead to the need for extensive evacuation. This trial was analysed in more details with the JRODOS system [VIII–9], which permits the use of more sophisticated atmospheric dispersion modelling and achieves clearer visualization using the standard ESRI of geographical maps etc. This approach is an example of graded dose and risk consequence analysis using two tools, WinMACCS and JRODOS.

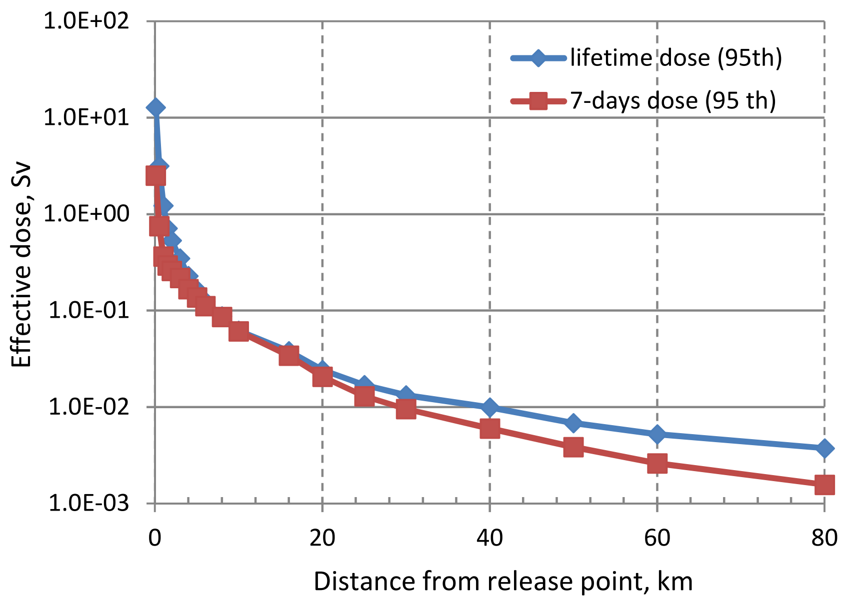

FIG. VIII–5. Comparison of the 7-days and lifetime doses (95th percentile)

The calculation was made for a fictitious site with a defined source term which was used as an input fractions released out of the inventory for selected release group of MELCOR_10_GROUP. The land use type 'everywhere grassland or unidentified area' was used. Actual geographical and land use GIS maps of the site should be used for a real case study. The size and location of the evacuation zone was estimated using the tool DIPCOT [VIII–23]. The evacuation criterion of 50 mSv can be achieved in the territory extending up to about 10 km from the release point. This exercise was carried out to demonstrate the possibility of using other tools with more detailed modelling of certain atmospheric conditions, while the WinMACCS code was used for probabilistic modelling.

The risk indicator was calculated as the product of lifetime effective dose (50, 90 and 95 percentiles); the nominal risk coefficient for stochastic effects, and the probability of occurrence of the release category (see Eq. (VIII–1)). The results of the calculation are provided in Table VIII–5.

TABLE VIII–5. RISK INDICATORS CALCULATED FOR DIFFERENT DOSE PERCENTILES

Distance, km	Risk indicators		
	50th percentile	90 th percentile	95 th percentile
0.1	6,24E-07	9,66E-07	1,1E-06
0.5	1,51E-07	2,40E-07	2,8E-07
1	5,79E-08	9,06E-08	1,1E-07
1.5	3,02E-08	5,23E-08	6,3E-08
2	2,04E-08	3,69E-08	4,5E-08
3	1,21E-08	2,50E-08	3,0E-08
4	8,20E-09	1,62E-08	2,0E-08
5	5,80E-09	1,12E-08	1,4E-08
6	4,36E-09	8,81E-09	1,0E-08
8	2,99E-09	6,23E-09	7,7E-09
10	2,05E-09	4,38E-09	5,4E-09
16	1,13E-09	2,59E-09	3,2E-09
20	7,09E-10	1,68E-09	2,0E-09
25	5,06E-10	1,15E-09	1,5E-09
30	3,71E-10	9,41E-10	1,2E-09
40	2,63E-10	6,83E-10	8,8E-10

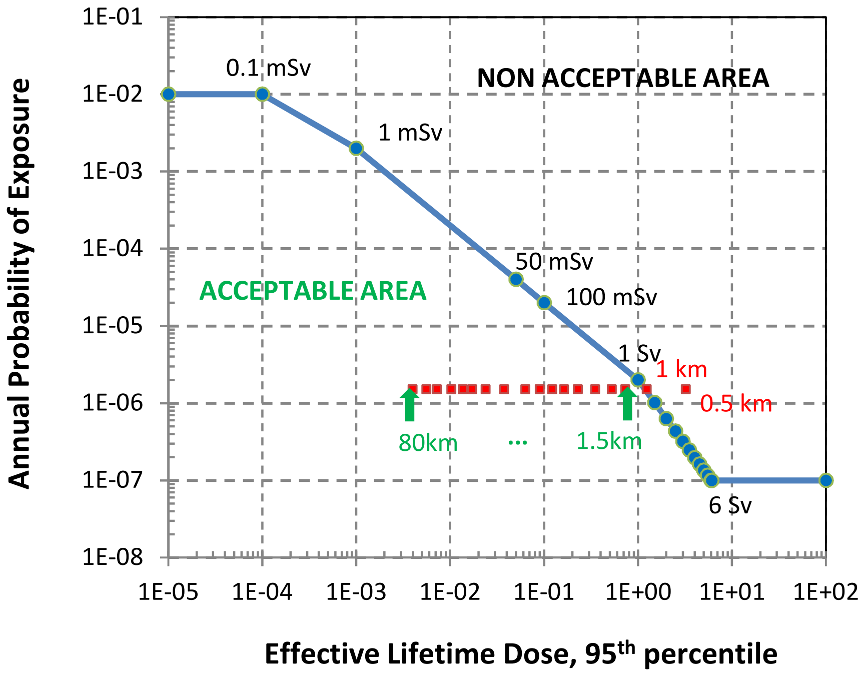

FIG. VIII–6. Comparison of lifetime doses depending on distance from point of release with risk curve criteria as a function of annual probability of the release

The values of doses (95th percentile) were located on the graph with the curve of risk acceptance criteria developed by Argentina (Annex I) and modified to adopt it to Spanish national requirements (see Figure VIII–6). The following representation of the acceptance risk curve can be considered [VIII–16]:

$$R = \begin{cases} 10^{-2} \text{ for } D \le 0.1\ mSv \\ \mathrm{D}\ \cdot 0.057 \text{ for } 0.1mSv < D < 1Sv \\ D^{a}\ \cdot 0.057 \text{ for } 1Sv \le D \le 6Sv \\ 10^{-7} \text{ for } D > 6Sv \end{cases} \qquad \text{(VIII–3)}$$

where *R* is annual probability of exposure; *D* is effective dose; *a* is power function's parameter.

The first horizontal segment has truncated the function at the probability of exposure 10^{-2} to consider any installation with high probability of accident as not acceptable. Appropriate constraints for individual dose should be selected. The release of effluents from an NPP had been established at the doses constraint of 0.1 mSv per year as used in Spain.

The values of the doses for different distances from the point of release are shown on the graph (see also Ref [VIII–16]). Only one point falls directly into the non-acceptable area (0.5 km) and another one (1 km) falls on the limit risk line. Therefore, it can be estimated that the risk value is exceeded for very short distances from the point of release (which can be practically without habitants and can be considered an exclusion zone around of the plant).

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ANNEX IX. UKRAINE

IX–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

Exposure under accident conditions and potential exposure are regulated by the following Ukrainian documents:

- Radiation safety standards of Ukraine (NRBU-97) [IX–1];
- Radiation safety standards of Ukraine, addition: Radiation protection from sources of potential exposure (NRBU-97/D-2000) [IX–2];
- General safety regulations of nuclear power plants (ZPBU-2008) [IX–3].

Ref [IX–1] establishes requirements for introduction of protective actions (countermeasures) in accident conditions. Ref [IX–2] defines four groups of potential exposure sources:

- 1st group – sources that may cause exposure of an individual or a limited group of people (covers industrial accidents, radiation injuries of members of the public under accidental contact with orphan sources);
- 2nd group – sources associated with radiation accidents for which consequences can be exposure of a significant contingent of members of the public and/or radioactive contamination of the environment;
- 3rd group – sources of potential exposure due to natural disasters or abnormal processes related to events that may occur in the future (including distant future) at any facility or installation released from regulatory control, as well as inadvertent human interventions (this type of situations should be taken into account during the design of repositories of radioactive waste);
- 4th group – sources of potential exposure of patients undergoing radiotherapy or radio diagnostic procedures.

Ref [IX–2] contains numerical limits for sources of potential exposure of the 1st group which are provided in Tables IX–1, IX–2.

TABLE IX–1. REFERENCE PROBABILITIES OF CRITICAL EVENTS FOLLOWED BY POTENTIAL EXPOSURE OF MEMBERS OF THE PUBLIC FROM THE SOURCES OF THE 1ST GROUP

Effective doses of potential exposure, mSv per event	Reference probability, a^{-1}
≤ 50	$1 \cdot 10^{-2}$
> 50*	$2 \cdot 10^{-5}$

* Probability of events which can lead to lethal doses (short term) should not exceed 5×10^{-7} a^{-1} (negligible risk)

TABLE IX–2. REFERENCE PROBABILITIES OF CRITICAL EVENTS FOLLOWED BY POTENTIAL EXPOSURE OF WORKERS FROM THE SOURCES OF THE 1ST GROUP

Potential exposure		Reference probability, a^{-1}
Effective dose	≤ 100 mSv per event	$1 \cdot 10^{-2}$
	> 100 mSv per event	$2 \cdot 10^{-4}$
Equivalent dose	150 – 500 mSv per event	$2 \cdot 10^{-4}$
Absorbed dose	> 1000 mGy per event	$5 \cdot 10^{-7}$

It should be noted that these limits are established for an individual or a limited group of people. They cannot be applied for large-scale radiation accidents at nuclear power plants.

At the same time, Ref [IX–2] doesn't establish similar criteria for sources of potential exposure of the 2nd group and declares that such criteria should be specified in separate documents currently missing.

Ref [IX–3] establishes criteria for safety of power units of NPPs. These criteria are specified for a frequency of significant degradation of the reactor core (SDRC) and for a frequency of limiting emergency release (LER). Both terms are defined in Ref [IX–3]. SDRC is the damage exceeding the maximum designed limit of the fuel degradation. LER is the emergency release of radioactive materials achieving evacuation criteria at the border of the sanitary protective zone of NPP.

The criteria for frequencies of the SDRC and the LER are different for operating and new NPPs. The criteria for the safety of operating power units are the following:

- frequency of SDRC should not exceed $10^{-4}a^{-1}$;
- frequency of LER should not exceed $10^{-5}a^{-1}$.

The criteria for the safety of new power units are 10 times more restrictive:

- frequency of SDRC should not exceed $10^{-5}a^{-1}$;
- frequency of LER should not exceed $10^{-6}a^{-1}$.

ZPBU-2008 also indicates the target frequencies for operating power units:

- for SDRC – not more than $10^{-5}a^{-1}$;
- for LER – not more than $10^{-6}a^{-1}$;

and for new NPPs:

- for SDRC – not more than $5{\cdot}10^{-6}a^{-1}$;
- for LER – not more than $10^{-7}a^{-1}$.

Safety requirements for site selection for a nuclear power plant [IX–4] further elaborate on Ref [IX–3] criteria related to LER. According to Ref [IX–4], the size of the observation area is determined so that under beyond design basis accidents (BDBA) with the LER the doses to the public at the border and beyond the observation area do not exceed the criteria for the introduction of emergency protective actions specified in Ref [IX–1]. Requirements for the determination of the sizes and boundaries for the observation area of a nuclear power plant [IX–5] specify that such a requirement should be applied only for BDBAs without the SDRC and the LER.

Currently, the size of the observation area around each Ukrainian NPP is 30 km. Criteria for emergency protective actions (according to Ref [IX–1]) are presented in Table IX–3. Ref [IX–1] also establishes criteria for urgent protective actions (Table IX–4).

TABLE IX–3. CRITERIA FOR EMERGENCY PROTECTIVE ACTIONS (DOSES AVERTED DURING FIRST 2 WEEKS AFTER AN ACCIDENT)

Protective action		Lower boundaries of justification			Levels of unconditional justification		
		to whole body, mSv	to thyroid, mGy	to skin, mGy	to whole body, mSv	to thyroid, mGy	to skin, mGy
Sheltering		5	50	100	50	300	500
Evacuation		50	300	500	500	1 000	3 000
Iodine prophylaxis	children	–	50 *	–	–	200 *	–
	adults	–	200 *	–	–	500 *	–
Outdoor restriction	children	1	20	50	10	100	300
	adults	2	100	200	20	300	1000

* the committed dose of internal exposure from iodine radioisotopes absorbed in the body during the first two weeks after beginning of the accident.

TABLE IX–4. CRITERIA FOR URGENT PROTECTIVE ACTIONS FOR ACUTE EXPOSURE

Organ / tissue	Predicted absorbed dose for 2 days, Gy
Whole body (bone marrow)	1
Lung	6
Skin	3
Thyroid	5
Eye lens	2
Gonads	2
Fetus	0.1

According to Ref [IX–1], emergency protective actions are defined as protective actions, the implementation of which is aimed to prevent deterministic effects. Urgent protective actions are protective actions introduction of which is intended to prevent acute and/or chronic exposure of members of the public which would cause acute clinical radiation effects.

The term “urgent” means not only unconditional justification of intervention but that any delay with the decision and implementation of protective actions creates a threat of severe radiation injuries for the exposed population. In this sense “urgent protective actions” require a much quicker response than even those identified as “emergency protective actions”.

The information above shows the following situation in Ukrainian regulation regarding limitation of potential exposure for large-scale radiation accidents at nuclear power plants:

- There are limitations for frequencies of significant degradation of the reactor core and limiting emergency release of radioactive substances into the environment (in terms of events per reactor per year). These limitations are applicable to operating and designed power units;
- There are limitations of doses only for BDBAs without significant degradation of the reactor core. Compliance with these should be demonstrated at the design stage;
- Risk assessments (in terms of the product of probability and dose) are not defined and are not used.

IX–2. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED

The source term should include all data necessary to calculate dispersion and environmental transfer of radionuclides for the application of the results in dosimetric assessments. Amounts of released radionuclides, their physical and chemical forms, particle sizes (or particle size distributions) are important components of the source term.

The amounts of released radionuclides were calculated based on Section 3.2. Calculations were performed according to the ICRP Publication 107 [IX–6]. They considered decay of initial (parent) radionuclides and contributions of progenies. Results for all 24 stages (each stage corresponds to 1 hour) are given in Tables IX–5 to IX–7.

TABLE IX–5. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 1 – 8), Bq

Radionuclide	1	2	3	4	5	6	7	8
Co-58	3.27E+07	6.68E+07	1.15E+08	1.32E+08	1.44E+08	1.38E+08	1.29E+08	1.11E+08
Co-60	1.83E+08	3.73E+08	6.41E+08	7.39E+08	8.08E+08	7.71E+08	7.23E+08	6.22E+08
Kr-85	1.14E+14	2.63E+14	5.13E+14	6.64E+14	8.14E+14	8.69E+14	9.12E+14	8.76E+14
Kr-85m	5.55E+13	1.10E+14	1.84E+14	2.04E+14	2.15E+14	1.96E+14	1.76E+14	1.44E+14
Kr-88	1.44E+13	2.61E+13	3.98E+13	4.04E+13	3.90E+13	3.26E+13	2.67E+13	2.00E+13
Rb-86	3.30E+10	7.09E+10	1.30E+11	1.59E+11	1.87E+11	1.93E+11	1.95E+11	1.78E+11
Rb-88	2.66E+10	4.49E+10	6.45E+10	6.22E+10	5.75E+10	4.66E+10	3.68E+10	2.63E+10
Sr-89	3.32E+12	7.07E+12	1.28E+13	1.55E+13	1.79E+13	1.82E+13	1.81E+13	1.67E+13
Sr-90	2.56E+11	5.47E+11	9.90E+11	1.20E+12	1.39E+12	1.41E+12	1.41E+12	1.29E+12
Sr-91	6.50E+11	1.29E+12	2.17E+12	2.45E+12	2.64E+12	2.49E+12	2.32E+12	1.98E+12
Sr-92	5.12E+09	8.40E+09	1.17E+10	1.09E+10	9.82E+09	7.66E+09	5.88E+09	4.14E+09
Y-90	2.79E+09	5.92E+09	1.07E+10	1.28E+10	1.46E+10	1.46E+10	1.44E+10	1.31E+10
Y-91	4.60E+10	9.79E+10	1.76E+11	2.12E+11	2.42E+11	2.42E+11	2.39E+11	2.16E+11
Y-91m	4.33E+09	8.57E+09	1.44E+10	1.60E+10	1.71E+10	1.59E+10	1.46E+10	1.23E+10
Y-92	1.01E+09	1.78E+09	2.66E+09	2.65E+09	2.52E+09	2.08E+09	1.70E+09	1.27E+09
Y-93	9.26E+09	1.84E+10	3.09E+10	3.47E+10	3.71E+10	3.47E+10	3.20E+10	2.70E+10
Zr-95	1.39E+12	2.87E+12	5.00E+12	5.83E+12	6.46E+12	6.26E+12	5.92E+12	5.18E+12
Zr-97	4.83E+11	9.55E+11	1.60E+12	1.79E+12	1.90E+12	1.77E+12	1.61E+12	1.35E+12
Nb-95	3.58E+12	7.29E+12	1.25E+13	1.44E+13	1.58E+13	1.51E+13	1.41E+13	1.22E+13
Nb-95m	6.92E+09	1.46E+10	2.59E+10	3.08E+10	3.47E+10	3.40E+10	3.28E+10	2.90E+10
Nb-97	1.27E+12	2.48E+12	4.08E+12	4.52E+12	4.74E+12	4.34E+12	3.90E+12	3.22E+12
Mo-99	2.98E+12	6.03E+12	1.02E+13	1.17E+13	1.26E+13	1.19E+13	1.11E+13	9.43E+12
Tc-99m	2.87E+12	5.79E+12	9.84E+12	1.12E+13	1.22E+13	1.15E+13	1.07E+13	9.08E+12
Ru-103	7.24E+11	1.49E+12	2.59E+12	3.01E+12	3.33E+12	3.22E+12	3.06E+12	2.66E+12
Ru-105	8.62E+09	1.52E+10	2.26E+10	2.25E+10	2.14E+10	1.77E+10	1.43E+10	1.07E+10
Ru-106	2.24E+11	4.61E+11	8.02E+11	9.33E+11	1.03E+12	9.97E+11	9.48E+11	8.27E+11
Rh-103m	7.15E+11	1.47E+12	2.56E+12	2.98E+12	3.29E+12	3.18E+12	3.02E+12	2.63E+12
Rh-105	3.21E+11	6.49E+11	1.11E+12	1.26E+12	1.37E+12	1.30E+12	1.21E+12	1.04E+12
Rh-106	2.24E+11	4.61E+11	8.02E+11	9.33E+11	1.03E+12	9.97E+11	9.48E+11	8.27E+11
Te-127	6.41E+12	1.30E+13	2.24E+13	2.58E+13	2.84E+13	2.72E+13	2.58E+13	2.26E+13
Te-127m	3.69E+12	7.75E+12	1.37E+13	1.62E+13	1.84E+13	1.81E+13	1.76E+13	1.58E+13
Te-129	8.10E+12	1.70E+13	3.01E+13	3.56E+13	4.02E+13	3.96E+13	3.85E+13	3.44E+13
Te-129m	1.28E+13	2.69E+13	4.77E+13	5.64E+13	6.37E+13	6.28E+13	6.10E+13	5.46E+13
Te-131	6.20E+12	1.27E+13	2.21E+13	2.55E+13	2.82E+13	2.72E+13	2.58E+13	2.26E+13
Te-131m	2.76E+13	5.66E+13	9.80E+13	1.13E+14	1.25E+14	1.21E+14	1.15E+14	1.00E+14
Te-132	2.99E+14	6.22E+14	1.09E+15	1.28E+15	1.44E+15	1.40E+15	1.35E+15	1.20E+15
I-131	1.43E+14	3.18E+14	6.01E+14	7.65E+14	9.25E+14	9.86E+14	1.02E+15	9.52E+14
I-132	1.94E+14	4.30E+14	8.07E+14	1.02E+15	1.23E+15	1.30E+15	1.34E+15	1.24E+15
I-133	1.34E+14	2.90E+14	5.32E+14	6.56E+14	7.71E+14	7.97E+14	8.02E+14	7.24E+14
I-135	1.95E+13	3.93E+13	6.70E+13	7.69E+13	8.41E+13	8.09E+13	7.57E+13	6.35E+13
Xe-131m	7.49E+12	1.79E+13	3.62E+13	4.84E+13	6.12E+13	6.74E+13	7.28E+13	7.19E+13
Xe-133	2.22E+16	5.13E+16	9.97E+16	1.29E+17	1.57E+17	1.67E+17	1.75E+17	1.67E+17
Xe-133m	1.22E+14	2.86E+14	5.65E+14	7.42E+14	9.20E+14	9.93E+14	1.05E+15	1.02E+15
Xe-135	5.04E+15	1.10E+16	2.03E+16	2.49E+16	2.88E+16	2.90E+16	2.86E+16	2.58E+16
Xe-135m	2.34E+14	4.88E+14	8.56E+14	9.98E+14	1.10E+15	1.06E+15	9.99E+14	8.62E+14
Cs-134	2.77E+12	5.96E+12	1.09E+13	1.34E+13	1.58E+13	1.63E+13	1.65E+13	1.51E+13
Cs-136	9.50E+11	2.04E+12	3.74E+12	4.58E+12	5.38E+12	5.54E+12	5.60E+12	5.11E+12
Cs-137	1.95E+12	4.21E+12	7.72E+12	9.48E+12	1.12E+13	1.15E+13	1.17E+13	1.07E+13
Ba-137m	3.25E+11	6.94E+11	1.26E+12	1.52E+12	1.76E+12	1.78E+12	1.78E+12	1.64E+12

TABLE IX–5. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 1 – 8), Bq (cont.)

Radionuclide	1	2	3	4	5	6	7	8
Ba-139	1.36E+07	1.80E+07	–	–	–	–	–	–
Ba-140	5.72E+12	1.22E+13	2.20E+13	2.65E+13	3.07E+13	3.10E+13	3.10E+13	2.84E+13
La-140	6.49E+10	1.38E+11	2.48E+11	2.97E+11	3.40E+11	3.39E+11	3.34E+11	3.03E+11
La-141	6.03E+08	1.07E+09	1.62E+09	1.63E+09	1.57E+09	1.31E+09	1.08E+09	8.21E+08
La-142	4.01E+05	5.43E+05	6.16E+05	4.68E+05	3.48E+05	–	–	–
Ce-141	1.36E+12	2.80E+12	4.87E+12	5.68E+12	6.29E+12	6.10E+12	5.76E+12	5.04E+12
Ce-143	7.48E+11	1.51E+12	2.58E+12	2.94E+12	3.20E+12	3.04E+12	2.81E+12	2.41E+12
Ce-144	9.69E+11	2.00E+12	3.48E+12	4.06E+12	4.50E+12	4.36E+12	4.12E+12	3.61E+12
Pr-143	5.41E+10	1.15E+11	2.07E+11	2.48E+11	2.84E+11	2.84E+11	2.80E+11	2.53E+11
Pr-144	4.03E+10	8.56E+10	1.54E+11	1.85E+11	2.12E+11	2.12E+11	2.09E+11	1.90E+11
Pr-144m	3.93E+08	8.36E+08	1.51E+09	1.81E+09	2.07E+09	2.07E+09	2.04E+09	1.85E+09
Nd-147	2.25E+10	4.77E+10	8.57E+10	1.03E+11	1.17E+11	1.17E+11	1.15E+11	1.04E+11
Pm-147	1.83E+07	4.03E+07	7.51E+07	9.33E+07	1.10E+08	1.14E+08	1.16E+08	1.08E+08
Np-239	1.17E+13	2.38E+13	4.10E+13	4.73E+13	5.18E+13	4.96E+13	4.63E+13	4.01E+13
Pu-238	2.36E+09	4.86E+09	8.48E+09	9.89E+09	1.10E+10	1.06E+10	1.01E+10	8.81E+09
Pu-239	2.72E+08	5.59E+08	9.75E+08	1.14E+09	1.26E+09	1.22E+09	1.16E+09	1.01E+09
Pu-240	3.32E+08	6.84E+08	1.19E+09	1.39E+09	1.54E+09	1.50E+09	1.42E+09	1.24E+09
Pu-241	9.63E+10	1.98E+11	3.46E+11	4.03E+11	4.47E+11	4.34E+11	4.10E+11	3.59E+11
Am-241	4.07E+06	8.65E+06	1.56E+07	1.87E+07	2.14E+07	2.14E+07	2.11E+07	1.92E+07
Cm-242	1.34E+09	2.85E+09	5.13E+09	6.16E+09	7.04E+09	7.04E+09	6.95E+09	6.30E+09
Cm-244	1.33E+08	2.84E+08	5.11E+08	6.14E+08	7.02E+08	7.02E+08	6.93E+08	6.28E+08

TABLE IX–6. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 9 – 16), Bq

Radionuclide	9	10	11	12	13	14	15	16
Co-58	9.83E+07	8.64E+07	7.32E+07	6.61E+07	5.99E+07	4.90E+07	4.45E+07	4.04E+07
Co-60	5.51E+08	4.85E+08	4.11E+08	3.71E+08	3.36E+08	2.75E+08	2.50E+08	2.27E+08
Kr-85	8.60E+14	8.42E+14	7.91E+14	7.94E+14	7.93E+14	7.18E+14	7.18E+14	7.16E+14
Kr-85m	1.22E+14	1.02E+14	8.23E+13	7.09E+13	6.05E+13	4.69E+13	4.03E+13	3.44E+13
Kr-88	1.54E+13	1.18E+13	8.72E+12	6.88E+12	5.37E+12	3.81E+12	2.99E+12	2.33E+12
Rb-86	1.68E+11	1.58E+11	1.44E+11	1.41E+11	1.38E+11	1.24E+11	1.22E+11	1.22E+11
Rb-88	1.94E+10	1.44E+10	1.03E+10	7.94E+09	6.10E+09	4.26E+09	3.32E+09	2.59E+09
Sr-89	1.58E+13	1.50E+13	1.38E+13	1.35E+13	1.32E+13	1.17E+13	1.15E+13	1.14E+13
Sr-90	1.23E+12	1.17E+12	1.07E+12	1.05E+12	1.03E+12	9.10E+11	8.97E+11	8.85E+11
Sr-91	1.75E+12	1.55E+12	1.32E+12	1.21E+12	1.10E+12	9.05E+11	8.31E+11	7.62E+11
Sr-92	3.04E+09	2.22E+09	1.58E+09	1.20E+09	8.99E+08	6.13E+08	4.65E+08	3.56E+08
Y-90	1.22E+10	1.14E+10	1.03E+10	9.94E+09	9.61E+09	8.43E+09	8.22E+09	8.00E+09
Y-91	2.02E+11	1.89E+11	1.70E+11	1.64E+11	1.59E+11	1.39E+11	1.36E+11	1.32E+11
Y-91m	1.07E+10	9.29E+09	7.82E+09	7.04E+09	6.32E+09	5.16E+09	4.69E+09	4.25E+09
Y-92	9.81E+08	7.58E+08	5.68E+08	4.54E+08	3.62E+08	2.62E+08	2.12E+08	1.70E+08
Y-93	2.36E+10	2.06E+10	1.74E+10	1.57E+10	1.42E+10	1.16E+10	1.06E+10	9.63E+09
Zr-95	4.66E+12	4.19E+12	3.63E+12	3.37E+12	3.11E+12	2.61E+12	2.44E+12	2.26E+12
Zr-97	1.16E+12	1.00E+12	8.37E+11	7.45E+11	6.60E+11	5.32E+11	4.77E+11	4.25E+11
Nb-95	1.08E+13	9.46E+12	8.02E+12	7.24E+12	6.57E+12	5.38E+12	4.89E+12	4.43E+12
Nb-95m	2.64E+10	2.38E+10	2.06E+10	1.91E+10	1.77E+10	1.48E+10	1.37E+10	1.27E+10
Nb-97	2.74E+12	2.31E+12	1.88E+12	1.63E+12	1.42E+12	1.11E+12	9.71E+11	8.44E+11
Mo-99	8.26E+12	7.19E+12	6.03E+12	5.39E+12	4.84E+12	3.92E+12	3.52E+12	3.16E+12
Tc-99m	7.95E+12	6.93E+12	5.81E+12	5.19E+12	4.66E+12	3.78E+12	3.40E+12	3.05E+12
Ru-103	2.39E+12	2.14E+12	1.85E+12	1.71E+12	1.58E+12	1.32E+12	1.23E+12	1.14E+12

TABLE IX–6. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 9 – 16), Bq (cont.)

Radionuc lide	9	10	11	12	13	14	15	16
Ru-105	8.19E+09	6.28E+09	4.66E+09	3.70E+09	2.91E+09	2.09E+09	1.66E+09	1.32E+09
Ru-106	7.41E+11	6.65E+11	5.75E+11	5.32E+11	4.91E+11	4.12E+11	3.82E+11	3.54E+11
Rh-103m	2.36E+12	2.11E+12	1.83E+12	1.69E+12	1.56E+12	1.31E+12	1.21E+12	1.12E+12
Rh-105	9.11E+11	8.01E+11	6.80E+11	6.17E+11	5.59E+11	4.60E+11	4.19E+11	3.81E+11
Rh-106	7.41E+11	6.65E+11	5.75E+11	5.32E+11	4.91E+11	4.12E+11	3.82E+11	3.54E+11
Te-127	2.03E+13	1.83E+13	1.59E+13	1.49E+13	1.39E+13	1.18E+13	1.12E+13	1.06E+13
Te-127m	1.45E+13	1.34E+13	1.19E+13	1.13E+13	1.08E+13	9.31E+12	8.94E+12	8.60E+12
Te-129	3.17E+13	2.92E+13	2.59E+13	2.47E+13	2.35E+13	2.03E+13	1.94E+13	1.87E+13
Te-129m	5.02E+13	4.63E+13	4.10E+13	3.91E+13	3.72E+13	3.21E+13	3.08E+13	2.96E+13
Te-131	2.03E+13	1.83E+13	1.59E+13	1.48E+13	1.38E+13	1.16E+13	1.09E+13	1.03E+13
Te-131m	9.02E+13	8.13E+13	7.05E+13	6.58E+13	6.12E+13	5.17E+13	4.85E+13	4.56E+13
Te-132	1.10E+15	1.00E+15	8.80E+14	8.33E+14	7.85E+14	6.73E+14	6.40E+14	6.10E+14
I-131	9.13E+14	8.78E+14	8.15E+14	8.13E+14	8.10E+14	7.33E+14	7.36E+14	7.41E+14
I-132	1.18E+15	1.13E+15	1.04E+15	1.04E+15	1.03E+15	9.24E+14	9.22E+14	9.22E+14
I-133	6.74E+14	6.29E+14	5.67E+14	5.48E+14	5.30E+14	4.66E+14	4.54E+14	4.43E+14
I-135	5.50E+13	4.77E+13	4.01E+13	3.61E+13	3.24E+13	2.65E+13	2.41E+13	2.18E+13
Xe-131m	7.25E+13	7.29E+13	7.02E+13	7.22E+13	7.39E+13	6.84E+13	7.00E+13	7.14E+13
Xe-133	1.64E+17	1.60E+17	1.50E+17	1.49E+17	1.49E+17	1.34E+17	1.34E+17	1.33E+17
Xe-133m	1.01E+15	9.94E+14	9.39E+14	9.47E+14	9.51E+14	8.64E+14	8.67E+14	8.68E+14
Xe-135	2.38E+16	2.19E+16	1.94E+16	1.83E+16	1.71E+16	1.45E+16	1.36E+16	1.27E+16
Xe-135m	7.62E+14	6.71E+14	5.68E+14	5.14E+14	4.61E+14	3.76E+14	3.39E+14	3.04E+14
Cs-134	1.42E+13	1.35E+13	1.23E+13	1.20E+13	1.18E+13	1.06E+13	1.05E+13	1.04E+13
Cs-136	4.81E+12	4.54E+12	4.13E+12	4.04E+12	3.96E+12	3.53E+12	3.49E+12	3.47E+12
Cs-137	1.01E+13	9.52E+12	8.69E+12	8.51E+12	8.36E+12	7.47E+12	7.41E+12	7.38E+12
Ba-137m	1.56E+12	1.48E+12	1.36E+12	1.34E+12	1.30E+12	1.15E+12	1.14E+12	1.12E+12
Ba-139	–	–	–	–	–	–	–	–
Ba-140	2.69E+13	2.55E+13	2.34E+13	2.29E+13	2.23E+13	1.97E+13	1.94E+13	1.91E+13
La-140	2.82E+11	2.63E+11	2.38E+11	2.29E+11	2.21E+11	1.94E+11	1.89E+11	1.84E+11
La-141	6.42E+08	5.03E+08	3.82E+08	3.10E+08	2.50E+08	1.84E+08	1.51E+08	1.23E+08
La-142	–	–	–	–	–	–	–	–
Ce-141	4.53E+12	4.07E+12	3.53E+12	3.27E+12	3.02E+12	2.53E+12	2.36E+12	2.20E+12
Ce-143	2.12E+12	1.87E+12	1.59E+12	1.44E+12	1.31E+12	1.08E+12	9.82E+11	8.94E+11
Ce-144	3.25E+12	2.92E+12	2.54E+12	2.35E+12	2.17E+12	1.83E+12	1.70E+12	1.58E+12
Pr-143	2.36E+11	2.20E+11	1.99E+11	1.92E+11	1.85E+11	1.62E+11	1.58E+11	1.54E+11
Pr-144	1.77E+11	1.65E+11	1.49E+11	1.44E+11	1.39E+11	1.22E+11	1.19E+11	1.16E+11
Pr-144m	1.73E+09	1.61E+09	1.46E+09	1.41E+09	1.36E+09	1.19E+09	1.16E+09	1.13E+09
Nd-147	9.68E+10	9.02E+10	8.13E+10	7.83E+10	7.55E+10	6.61E+10	6.43E+10	6.24E+10
Pm-147	1.04E+08	9.98E+07	9.26E+07	9.17E+07	9.10E+07	8.19E+07	8.17E+07	8.15E+07
Np-239	3.56E+13	3.17E+13	2.71E+13	2.49E+13	2.27E+13	1.88E+13	1.74E+13	1.59E+13
Pu-238	7.93E+09	7.13E+09	6.19E+09	5.74E+09	5.30E+09	4.46E+09	4.16E+09	3.87E+09
Pu-239	9.12E+08	8.20E+08	7.11E+08	6.60E+08	6.10E+08	5.12E+08	4.78E+08	4.45E+08
Pu-240	1.12E+09	1.00E+09	8.70E+08	8.07E+08	7.46E+08	6.27E+08	5.85E+08	5.44E+08
Pu-241	3.23E+11	2.91E+11	2.52E+11	2.34E+11	2.16E+11	1.82E+11	1.69E+11	1.58E+11
Am-241	1.79E+07	1.67E+07	1.51E+07	1.46E+07	1.41E+07	1.24E+07	1.21E+07	1.18E+07
Cm-242	5.88E+09	5.49E+09	4.96E+09	4.79E+09	4.63E+09	4.06E+09	3.96E+09	3.86E+09
Cm-244	5.86E+08	5.48E+08	4.95E+08	4.78E+08	4.62E+08	4.06E+08	3.95E+08	3.85E+08

TABLE IX–7. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 17 – 24), Bq

Radionuclide	17	18	19	20	21	22	23	24
Co-58	3.45E+07	2.94E+07	2.72E+07	2.42E+07	2.21E+07	1.83E+07	8.13E+06	5.64E+05
Co-60	1.94E+08	1.66E+08	1.53E+08	1.36E+08	1.24E+08	1.03E+08	4.58E+07	3.18E+06
Kr-85	6.71E+14	6.26E+14	6.30E+14	6.12E+14	6.10E+14	5.50E+14	2.58E+14	1.83E+13
Kr-85m	2.75E+13	2.20E+13	1.91E+13	1.59E+13	1.35E+13	1.04E+13	4.38E+12	2.97E+11
Kr-88	1.71E+12	1.24E+12	9.94E+11	7.55E+11	5.84E+11	4.14E+11	1.68E+11	1.11E+10
Rb-86	1.13E+11	1.04E+11	9.96E+10	9.20E+10	8.68E+10	7.47E+10	3.39E+10	2.37E+09
Rb-88	1.88E+09	1.36E+09	1.02E+09	7.44E+08	5.51E+08	3.69E+08	1.47E+08	8.49E+06
Sr-89	1.05E+13	9.57E+12	9.07E+12	8.16E+12	7.55E+12	6.50E+12	3.07E+12	2.21E+11
Sr-90	8.22E+11	7.47E+11	7.08E+11	6.38E+11	5.90E+11	5.08E+11	2.41E+11	1.73E+10
Sr-91	6.58E+11	5.57E+11	4.92E+11	4.12E+11	3.55E+11	2.84E+11	1.28E+11	9.02E+09
Sr-92	2.53E+08	1.78E+08	1.28E+08	9.05E+07	6.43E+07	4.38E+07	1.51E+07	2.54E+06
Y-90	7.34E+09	6.73E+09	6.66E+09	6.37E+09	6.26E+09	5.57E+09	2.60E+09	1.84E+08
Y-91	1.21E+11	1.11E+11	1.10E+11	1.05E+11	1.03E+11	9.20E+10	4.29E+10	3.03E+09
Y-91m	3.62E+09	3.10E+09	2.85E+09	2.54E+09	2.32E+09	1.93E+09	8.53E+08	5.91E+07
Y-92	1.28E+08	9.71E+07	7.95E+07	6.28E+07	5.07E+07	3.72E+07	1.51E+07	1.03E+06
Y-93	8.25E+09	7.08E+09	6.55E+09	5.86E+09	5.37E+09	4.47E+09	1.98E+09	1.38E+08
Zr-95	1.98E+12	1.73E+12	1.64E+12	1.49E+12	1.39E+12	1.18E+12	5.29E+11	3.68E+10
Zr-97	3.57E+11	3.00E+11	2.72E+11	2.38E+11	2.13E+11	1.73E+11	7.55E+10	5.20E+09
Nb-95	3.78E+12	3.23E+12	2.99E+12	2.66E+12	2.43E+12	2.02E+12	8.94E+11	6.20E+10
Nb-95m	1.11E+10	9.66E+09	9.10E+09	8.26E+09	7.67E+09	6.48E+09	2.91E+09	2.03E+08
Nb-97	6.91E+11	5.67E+11	5.03E+11	4.30E+11	3.76E+11	3.00E+11	1.29E+11	8.86E+09
Mo-99	2.67E+12	2.26E+12	2.07E+12	1.82E+12	1.65E+12	1.35E+12	5.95E+11	4.12E+10
Tc-99m	2.58E+12	2.18E+12	1.99E+12	1.76E+12	1.59E+12	1.30E+12	5.74E+11	3.97E+10
Ru-103	9.88E+11	8.62E+11	8.12E+11	7.36E+11	6.82E+11	5.74E+11	2.57E+11	1.78E+10
Ru-105	9.77E+08	7.32E+08	5.92E+08	4.59E+08	3.63E+08	2.62E+08	1.05E+08	6.93E+06
Ru-106	3.08E+11	2.69E+11	2.54E+11	2.30E+11	2.13E+11	1.80E+11	8.05E+10	5.59E+09
Rh-103m	9.76E+11	8.52E+11	8.03E+11	7.27E+11	6.74E+11	5.68E+11	2.54E+11	1.76E+10
Rh-105	3.25E+11	2.78E+11	2.57E+11	2.29E+11	2.08E+11	1.72E+11	7.58E+10	5.24E+09
Rh-106	3.08E+11	2.69E+11	2.54E+11	2.30E+11	2.13E+11	1.80E+11	8.05E+10	5.59E+09
Te-127	9.40E+12	8.43E+12	8.12E+12	7.58E+12	7.30E+12	6.32E+12	2.90E+12	2.04E+11
Te-127m	7.76E+12	7.05E+12	6.88E+12	6.51E+12	6.34E+12	5.54E+12	2.57E+12	1.80E+11
Te-129	1.69E+13	1.53E+13	1.49E+13	1.41E+13	1.37E+13	1.20E+13	5.56E+12	3.91E+11
Te-129m	2.67E+13	2.43E+13	2.37E+13	2.24E+13	2.18E+13	1.90E+13	8.81E+12	6.19E+11
Te-131	9.05E+12	8.04E+12	7.67E+12	7.09E+12	6.74E+12	5.77E+12	2.63E+12	1.84E+11
Te-131m	4.02E+13	3.57E+13	3.41E+13	3.15E+13	3.00E+13	2.56E+13	1.17E+13	8.15E+11
Te-132	5.46E+14	4.92E+14	4.76E+14	4.46E+14	4.31E+14	3.73E+14	1.72E+14	1.21E+13
I-131	6.99E+14	6.43E+14	6.19E+14	5.74E+14	5.43E+14	4.69E+14	2.13E+14	1.49E+13
I-132	8.66E+14	7.92E+14	7.58E+14	6.98E+14	6.57E+14	5.64E+14	2.55E+14	1.78E+13
I-133	4.06E+14	3.62E+14	3.39E+14	3.04E+14	2.79E+14	2.34E+14	1.04E+14	7.22E+12
I-135	1.86E+13	1.55E+13	1.35E+13	1.13E+13	9.60E+12	7.49E+12	3.16E+12	2.15E+11
Xe-131m	6.84E+13	6.51E+13	6.69E+13	6.62E+13	6.72E+13	6.18E+13	2.94E+13	2.09E+12
Xe-133	1.24E+17	1.15E+17	1.15E+17	1.12E+17	1.11E+17	9.94E+16	4.66E+16	3.29E+15
Xe-133m	8.15E+14	7.61E+14	7.68E+14	7.46E+14	7.43E+14	6.70E+14	3.15E+14	2.23E+13
Xe-135	1.12E+16	9.76E+15	9.21E+15	8.36E+15	7.78E+15	6.56E+15	2.94E+15	2.04E+14
Xe-135m	2.56E+14	2.15E+14	1.95E+14	1.70E+14	1.52E+14	1.24E+14	5.39E+13	3.71E+12
Cs-134	9.75E+12	8.93E+12	8.58E+12	7.94E+12	7.50E+12	6.47E+12	2.94E+12	2.05E+11
Cs-136	3.24E+12	2.96E+12	2.84E+12	2.62E+12	2.47E+12	2.12E+12	9.63E+11	6.73E+10
Cs-137	6.89E+12	6.31E+12	6.07E+12	5.61E+12	5.31E+12	4.57E+12	2.08E+12	1.45E+11
Ba-137m	1.04E+12	9.47E+11	8.98E+11	8.09E+11	7.48E+11	6.45E+11	3.05E+11	2.19E+10

TABLE IX–7. AMOUNTS OF RELEASED RADIONUCLIDES (STAGES 17 – 24), Bq (cont.)

Radionuclide	17	18	19	20	21	22	23	24
Ba-139	–	–	–	–	–	–	–	–
Ba-140	1.77E+13	1.60E+13	1.52E+13	1.36E+13	1.26E+13	1.08E+13	5.11E+12	3.67E+11
La-140	1.68E+11	1.54E+11	1.52E+11	1.45E+11	1.43E+11	1.27E+11	5.91E+10	4.17E+09
La-141	9.41E+07	7.25E+07	6.03E+07	4.84E+07	3.97E+07	2.96E+07	1.22E+07	8.33E+05
La-142	–	–	–	–	–	–	–	–
Ce-141	1.92E+12	1.68E+12	1.59E+12	1.44E+12	1.35E+12	1.14E+12	5.11E+11	3.56E+10
Ce-143	7.66E+11	6.57E+11	6.09E+11	5.43E+11	4.97E+11	4.12E+11	1.82E+11	1.26E+10
Ce-144	1.39E+12	1.21E+12	1.15E+12	1.05E+12	9.77E+11	8.27E+11	3.71E+11	2.58E+10
Pr-143	1.41E+11	1.29E+11	1.28E+11	1.22E+11	1.20E+11	1.07E+11	4.97E+10	3.51E+09
Pr-144	1.07E+11	9.77E+10	9.67E+10	9.26E+10	9.09E+10	8.10E+10	3.78E+10	2.67E+09
Pr-144m	1.04E+09	9.55E+08	9.45E+08	9.05E+08	8.88E+08	7.91E+08	3.69E+08	2.61E+07
Nd-147	5.72E+10	5.23E+10	5.16E+10	4.93E+10	4.83E+10	4.29E+10	2.00E+10	1.41E+09
Pm-147	7.66E+07	7.18E+07	7.25E+07	7.10E+07	7.11E+07	6.47E+07	3.06E+07	2.17E+06
Np-239	1.38E+13	1.19E+13	1.11E+13	1.00E+13	9.26E+12	7.74E+12	3.44E+12	2.39E+11
Pu-238	3.38E+09	2.96E+09	2.80E+09	2.55E+09	2.39E+09	2.02E+09	9.06E+08	6.31E+07
Pu-239	3.89E+08	3.40E+08	3.22E+08	2.93E+08	2.74E+08	2.32E+08	1.04E+08	7.26E+06
Pu-240	4.76E+08	4.17E+08	3.94E+08	3.59E+08	3.36E+08	2.84E+08	1.28E+08	8.88E+06
Pu-241	1.38E+11	1.21E+11	1.14E+11	1.04E+11	9.73E+10	8.24E+10	3.69E+10	2.57E+09
Am-241	1.08E+07	9.92E+06	9.82E+06	9.41E+06	9.23E+06	8.23E+06	3.84E+06	2.71E+05
Cm-242	3.54E+09	3.25E+09	3.21E+09	3.08E+09	3.02E+09	2.69E+09	1.25E+09	8.86E+07
Cm-244	3.54E+08	3.24E+08	3.21E+08	3.07E+08	3.02E+08	2.69E+08	1.25E+08	8.86E+06

Ten bins are used for the characterization of particle size distribution. Each bin is characterized by the mean particle size and the deposition velocity for particles. The data for all ten bins are presented in Table IX–8.

TABLE IX–8. PARTICLE SIZES AND DEPOSITION VELOCITIES

Group	Mass mean diameter, µm	Deposition velocity, mm/s
Bin 1	0.15	0.535
Bin 2	0.29	0.491
Bin 3	0.53	0.643
Bin 4	0.99	1.08
Bin 5	1.8	2.12
Bin 6	3.4	4.34
Bin 7	6.4	8.37
Bin 8	11.9	13.7
Bin 9	22.1	17.0
Bin 10	41.2	17.0

The data about initial particle size distributions are important for the calculation of atmospheric transfer of the released particles. The data can also be used for the assessments of the mass mean diameters for aerosols in the initial state and in due course during atmospheric transfer. Data on the particle sizes for aerosols of 8 element groups present in the release are provided in terms of fractions distributed by 10 bins as shown in Figure IX–1.

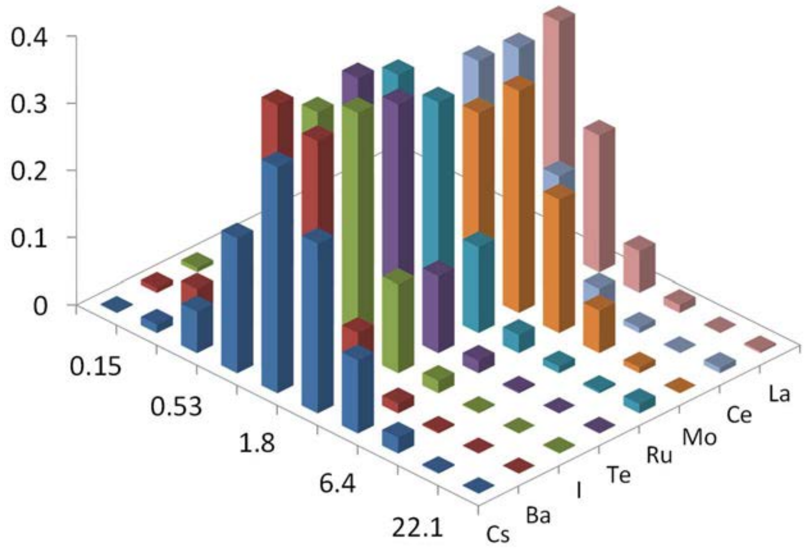

FIG. IX–1. Initial particle size distributions for 8 element groups

Figure IX–2 provides the same distributions normalized by bin sizes. This method of presentation is more correct if these curves are discussed as functions of density distributions, the area under which should be equal to 1.0.

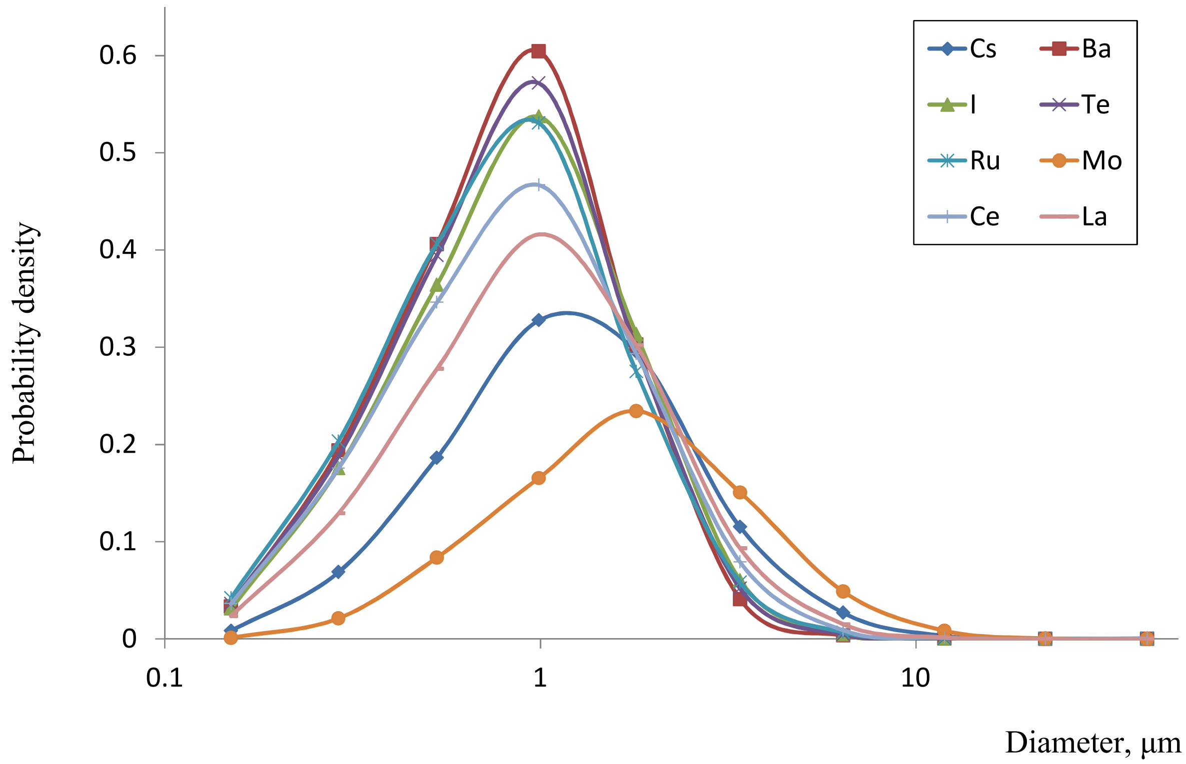

FIG. IX–2. Initial particle size distributions in logarithmic scale for 8 element groups (normalized by bin sizes)

According to the data about particle size distributions, mass mean diameters for initial aerosols of 8 element groups were calculated (Table IX–9). As can be seen from Table IX–9, the mass mean diameters for aerosols of 7 element groups are in a small range from 1.5 µm (Ba group) to 2.8 µm (Cs group). Only the mass mean diameter for aerosols of Mo groups is slightly larger (3.9 µm).

TABLE IX–9. MASS MEAN DIAMETERS FOR ELEMENT GROUPS

Group	Mass mean diameter, µm
Cs	2.8
Ba	1.5
I	1.7
Te	1.6
Ru	2.3
Mo	3.9
Ce	2.2
La	2.3

Table IX–10 contains mass mean diameters for aerosols of I-131 changed during atmospheric transfer. Values were calculated considering deposition velocities that are different for particles of different sizes (Table IX–8). The reduction of the mass mean diameter is relatively small, it is about 5% for transfer time = 2.1 h (for 2 m/s it corresponds to a transfer distance = 15 km, where T1 is located).

TABLE IX–10. CHANGES OF MASS MEAN DIAMETER FOR AEROSOLS OF I-131 DURING ATMOSPHERIC TRANSFER (WIND SPEED = 2 $m{\cdot}s^{-1}$)

Transfer distance (transfer time)	Mass mean diameter, µm
0 (no transfer)	1.70
1 km (8.3 min)	1.68
3 km (25 min)	1.65
7 km (58 min)	1.63
15 km (2.1 h)	1.61

All the above-mentioned assessments are important for further calculations of internal doses formed by radionuclides after the emergency release. The default AMAD is taken to be 1 µm for environmental exposure. So typically, inhalation dose coefficients (e_{inh}) for AMAD = 1 µm are used for the dose calculation to the public. It is reasonable to compare e_{inh} for different AMADs with e_{inh}(1 µm)in order to determine what AMAD should be used for the analysed emergency case.

Results of such a comparison for several radionuclides are presented in Figure IX–3 (recommended default absorption types [IX–7, IX–8] were used for comparison). The most significant differences (several times) are observed for submicron particles (from ~0.003 µm to ~0.1 µm). But for AMADs from 0.3 µm to 3 µm the ratio e_{inh}(AMAD) / e_{inh}(1 µm) differs from 1 by no more than ~30–40%.

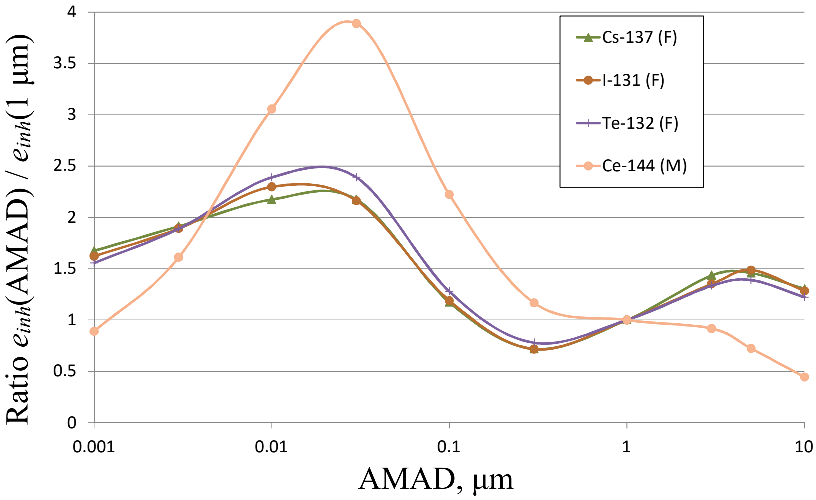

FIG. IX–3. Ratio e_{inh}(AMAD) / e_{inh}(1 µm) for different radionuclides (reference age 'Adult')

Taking into account the results of this e_{inh} comparison, results about small changes of mean particle sizes during atmospheric transfer, and general uncertainty for the determination of particle size in the initial discharge, it is reasonable to use $e_{inh}(1\mu m)$ for calculations of internal doses due to inhalation. Moreover, the treatment of aerosols as lognormally distributed with AMAD = 1 µm and application of average deposition velocity (without a detailed examination of 10 separate bins and subsequent merger of all of them) gives an appropriate assessment for concentrations of radionuclides in the air.

For the ENV-PE exercise purpose, two different approaches were used for calculations:

– deterministic assessment;
– probabilistic assessment.

The deterministic assessment was performed according to Ref [IX-5]. This approach can be described briefly as a calculation of the worst cases for all distances from the release point. Calculations should be done for six categories (from A to F) and for wind speeds of 0.5 $m \times s^{-1}$ and higher. It is assumed that all those meteorological data are stable during the release and atmospheric dispersion. Results are the highest doses for all of the cases above. The similar approach is typically used for the emergency assessments in Ukraine.

The probabilistic assessment was made for 8760 different scenarios. The initial time for each scenario corresponds to each separate hour in a calendar year. Meteorological data described in Section 4.2.1 were used for all the scenarios. Probabilistic assessment is not clearly regulated in Ukrainian legislation. It can be performed, but the question is how to interpret the results (distributions, percentiles, etc.). The probabilistic assessment presented below has been performed for the ENV-PE exercise purpose only.

The software system for operative analysis of the radiation situation due to an accident at an NPP in Ukraine (SOARS) was used for probabilistic calculations. SOARS was developed by the Radiation Protection Institute (Kyiv, Ukraine) for dose calculation and to support decisions about protective actions (countermeasures) under accident situations.

SOARS is intended for the calculation of the consequences of atmospheric releases from an NPP within its observation area at an early stage of the accident. It includes the following main modules:

– module for calculation of the atmospheric transport and the fallout to the ground surface;
– module for calculation of the external doses from the radioactive clouds;
– module for calculation of the external doses from the fallout to the ground surface;
– module for calculation of the internal doses due to inhalation;
– module for calculation of the internal doses due to ingestion of contaminated food;
– module for protective actions.

The atmospheric transport module in SOARS calculates the field of volume specific activities of radionuclides in the surface layer of the air and surface specific activities of radionuclides in the fallout to the ground surface. It is based on a time-dependent model of atmospheric dispersion. In contrast to the standard Gaussian model of atmospheric dispersion [IX–9], time-dependent atmospheric transport models can be applied in situations characterized by a rapidly changing trend of release and under conditions with changing of meteorological fields during the time of pollutant transport (essentially, speed and direction of the wind). Prolonged non-stationary release of radionuclides is modelled by a sequence of discrete releases ("puffs") emitted from the source during some (sufficiently small) intervals. Description of the model applied in SOARS for the calculation of the volume specific activity of radionuclides in the air is given in Ref. [IX–10]. This approach allows increasing the range of applicability of the model for the transport distances within the supervised area of an NPP. Descriptions of other SOARS's modules are presented in Ref. [IX–11, IX–12].

SOARS was installed at the Rivne NPP (4 units) in 2003. It was commended by experts from the International Atomic Energy Agency during the OSART (Operational Safety Review Team) mission and also by experts of WANO (World Association of Nuclear Operators) missions. In 2007 the Ukrainian utility Energoatom decided to use SOARS as a site (plant) decision support system in the event of radiation accidents at all 4 operating Ukrainian NPPs (15 units). The activity was finalized in 2014. SOARS fully complies with the requirements of NRBU-97.

The source term for the calculation contains 70 radionuclides (Tables IX–5 to IX–7). It should be noted that the majority of radionuclides in this list form a very small contribution to the total doses (absorbed, equivalent and effective doses). SOARS has a tool for the analysis of a source term to identify the most important radionuclides (for the early stage of an accident, up to 30 days). The tool gives a possibility to eliminate radionuclides whose contributions are negligible (with an indication of the maximum assessment of their contribution) and to optimize calculation procedures.

The analysis tool was applied to the source term (Tables IX–5 to IX–7). External exposure (from the cloud, from deposition to the soil) and internal exposure (inhalation, ingestion) were considered for up to one month after the accident. After the analysis the list was reduced to 14 radionuclides: Sr-89, Sr-90, Te-127m, Te-129m, Te-132, I-131, I-132, I-133, Xe-133, Xe-135, Cs-134, Cs-137, Ce-144, and Pu-238.

The contribution of other radionuclides to the total effective dose is less than 4%, and to the dose to the thyroid it is less than 0.6%. The reduced list is presented in Tables IX–11 to IX–13.

TABLE IX–11. AMOUNTS OF RELEASED RADIONUCLIDES FROM 'REDUCED' LIST (STAGES 1–8), Bq

Radionuclide	1	2	3	4	5	6	7	8
Sr-89	3.32E+12	7.07E+12	1.28E+13	1.55E+13	1.79E+13	1.82E+13	1.81E+13	1.67E+13
Sr-90	2.56E+11	5.47E+11	9.90E+11	1.20E+12	1.39E+12	1.41E+12	1.41E+12	1.29E+12
Te-127m	3.69E+12	7.75E+12	1.37E+13	1.62E+13	1.84E+13	1.81E+13	1.76E+13	1.58E+13
Te-129m	1.28E+13	2.69E+13	4.77E+13	5.64E+13	6.37E+13	6.28E+13	6.10E+13	5.46E+13
Te-132	2.99E+14	6.22E+14	1.09E+15	1.28E+15	1.44E+15	1.40E+15	1.35E+15	1.20E+15
I-131	1.43E+14	3.18E+14	6.01E+14	7.65E+14	9.25E+14	9.86E+14	1.02E+15	9.52E+14
I-132	1.94E+14	4.30E+14	8.07E+14	1.02E+15	1.23E+15	1.30E+15	1.34E+15	1.24E+15
I-133	1.34E+14	2.90E+14	5.32E+14	6.56E+14	7.71E+14	7.97E+14	8.02E+14	7.24E+14
Xe-133	2.22E+16	5.13E+16	9.97E+16	1.29E+17	1.57E+17	1.67E+17	1.75E+17	1.67E+17
Xe-135	5.04E+15	1.10E+16	2.03E+16	2.49E+16	2.88E+16	2.90E+16	2.86E+16	2.58E+16
Cs-134	2.77E+12	5.96E+12	1.09E+13	1.34E+13	1.58E+13	1.63E+13	1.65E+13	1.51E+13
Cs-137	1.95E+12	4.21E+12	7.72E+12	9.48E+12	1.12E+13	1.15E+13	1.17E+13	1.07E+13
Ce-144	9.69E+11	2.00E+12	3.48E+12	4.06E+12	4.50E+12	4.36E+12	4.12E+12	3.61E+12
Pu-238	2.36E+09	4.86E+09	8.48E+09	9.89E+09	1.10E+10	1.06E+10	1.01E+10	8.81E+09

TABLE IX–12. AMOUNTS OF RELEASED RADIONUCLIDES FROM ‘REDUCED’ LIST (STAGES 9–16), Bq

Radionuclide	9	10	11	12	13	14	15	16
Sr-89	1.58E+13	1.50E+13	1.38E+13	1.35E+13	1.32E+13	1.17E+13	1.15E+13	1.14E+13
Sr-90	1.23E+12	1.17E+12	1.07E+12	1.05E+12	1.03E+12	9.10E+11	8.97E+11	8.85E+11
Te-127m	1.45E+13	1.34E+13	1.19E+13	1.13E+13	1.08E+13	9.31E+12	8.94E+12	8.60E+12
Te-129m	5.02E+13	4.63E+13	4.10E+13	3.91E+13	3.72E+13	3.21E+13	3.08E+13	2.96E+13
Te-132	1.10E+15	1.00E+15	8.80E+14	8.33E+14	7.85E+14	6.73E+14	6.40E+14	6.10E+14
I-131	9.13E+14	8.78E+14	8.15E+14	8.13E+14	8.10E+14	7.33E+14	7.36E+14	7.41E+14
I-132	1.18E+15	1.13E+15	1.04E+15	1.04E+15	1.03E+15	9.24E+14	9.22E+14	9.22E+14
I-133	6.74E+14	6.29E+14	5.67E+14	5.48E+14	5.30E+14	4.66E+14	4.54E+14	4.43E+14
Xe-133	1.64E+17	1.60E+17	1.50E+17	1.49E+17	1.49E+17	1.34E+17	1.34E+17	1.33E+17
Xe-135	2.38E+16	2.19E+16	1.94E+16	1.83E+16	1.71E+16	1.45E+16	1.36E+16	1.27E+16
Cs-134	1.42E+13	1.35E+13	1.23E+13	1.20E+13	1.18E+13	1.06E+13	1.05E+13	1.04E+13
Cs-137	1.01E+13	9.52E+12	8.69E+12	8.51E+12	8.36E+12	7.47E+12	7.41E+12	7.38E+12
Ce-144	3.25E+12	2.92E+12	2.54E+12	2.35E+12	2.17E+12	1.83E+12	1.70E+12	1.58E+12
Pu-238	7.93E+09	7.13E+09	6.19E+09	5.74E+09	5.30E+09	4.46E+09	4.16E+09	3.87E+09

TABLE IX–13. AMOUNTS OF RELEASED RADIONUCLIDES FROM ‘REDUCED’ LIST (STAGES 17–24), Bq

Radionuclide	17	18	19	20	21	22	23	24
Sr-89	1.05E+13	9.57E+12	9.07E+12	8.16E+12	7.55E+12	6.50E+12	3.07E+12	2.21E+11
Sr-90	8.22E+11	7.47E+11	7.08E+11	6.38E+11	5.90E+11	5.08E+11	2.41E+11	1.73E+10
Te-127m	7.76E+12	7.05E+12	6.88E+12	6.51E+12	6.34E+12	5.54E+12	2.57E+12	1.80E+11
Te-129m	2.67E+13	2.43E+13	2.37E+13	2.24E+13	2.18E+13	1.90E+13	8.81E+12	6.19E+11
Te-132	5.46E+14	4.92E+14	4.76E+14	4.46E+14	4.31E+14	3.73E+14	1.72E+14	1.21E+13
I-131	6.99E+14	6.43E+14	6.19E+14	5.74E+14	5.43E+14	4.69E+14	2.13E+14	1.49E+13
I-132	8.66E+14	7.92E+14	7.58E+14	6.98E+14	6.57E+14	5.64E+14	2.55E+14	1.78E+13
I-133	4.06E+14	3.62E+14	3.39E+14	3.04E+14	2.79E+14	2.34E+14	1.04E+14	7.22E+12
Xe-133	1.24E+17	1.15E+17	1.15E+17	1.12E+17	1.11E+17	9.94E+16	4.66E+16	3.29E+15
Xe-135	1.12E+16	9.76E+15	9.21E+15	8.36E+15	7.78E+15	6.56E+15	2.94E+15	2.04E+14
Cs-134	9.75E+12	8.93E+12	8.58E+12	7.94E+12	7.50E+12	6.47E+12	2.94E+12	2.05E+11
Cs-137	6.89E+12	6.31E+12	6.07E+12	5.61E+12	5.31E+12	4.57E+12	2.08E+12	1.45E+11
Ce-144	1.39E+12	1.21E+12	1.15E+12	1.05E+12	9.77E+11	8.27E+11	3.71E+11	2.58E+10
Pu-238	3.38E+09	2.96E+09	2.80E+09	2.55E+09	2.39E+09	2.02E+09	9.06E+08	6.31E+07

The assessment above was performed assuming that all radionuclides are released as aerosols (particles). However, the accidental release of iodine can also occur in other forms. The U.S. Regulatory Guides [IX–13, IX–14] state the following breakdown for released iodine: 91% in the form of elemental iodine, 5% in the form of particulate iodine, and 4% in the form of organic iodide. Report [IX–15] declares that “present knowledge may not support this distribution of iodine forms and the static state throughout the duration of an accident”. Nevertheless, the breakdown from Refs [IX–13, IX–14] was used for the calculation as it leads to more conservative assessments.

The following dry deposition velocity values were used for non-aerosols:

– for elemental iodine = 20 $mm\cdot s^{-1}$;
– for methyl iodide = 0.1 $mm\cdot s^{-1}$.

For such a breakdown, discussion about particle distributions is a minor question, because the elemental iodine (I-131, etc) will be the most important contributor to the total doses.

Table IX–14 presents the summary of total release values (during 24 hours) and ICRP material types for the calculation. Iodine aerosols and organic forms of I-132 and I-133 were removed from the list because their contributions to the total doses were very low. With such assumptions, the contribution of all removed radionuclides to the total effective dose is less than 3%, and to the dose to the thyroid it is less than 0.5%.

TABLE IX–14. TOTAL RELEASE VALUES AND MATERIAL TYPES

Radionuclide	Release, Bq	Material type / Absorption type
Sr-89	2.70E+14	Aerosol / Slow
Sr-90	2.10E+13	Aerosol / Slow
Te-127m	2.43E+14	Aerosol / Moderate
Te-129m	8.40E+14	Aerosol / Moderate
Te-132	1.82E+16	Aerosol / Moderate
Xe-133	2.87E+18	-
Xe-135	3.71E+17	-
Cs-134	2.44E+14	Aerosol / Fast
Cs-137	1.73E+14	Aerosol / Fast
Ce-144	5.24E+13	Aerosol / Slow
Pu-238	1.28E+11	Aerosol / Slow
I-131	1.45E+16	Elemental iodine
I-131	7.96E+14	Aerosol / Fast
I-131	6.37E+14	Methyl iodide
I-132	1.85E+16	Elemental iodine
I-133	1.01E+16	Elemental iodine

All the assumptions described above were applied for deterministic and probabilistic assessments. Doses for both approaches were calculated for 6 reference ages.

IX–3. RESULTS OF DETERMINISTIC ASSESSMENTS

Results of deterministic assessments are provided in Tables IX–15 to IX–17. Table IX–15 contains predicted doses to the whole body with a breakdown according to pathways. Table IX–16 presents total predicted doses to the whole body for four different time periods for 6 reference ages. Table IX–17 gives predicted internal doses to the thyroid due to inhalation.

TABLE IX–15. PREDICTED DOSES TO THE WHOLE BODY, Gy

Pathway, reference age or time period		Distance, km							
		1	2.5	3.5	6.5	7	8	15	50
Cloud		0.589	0.354	0.263	0.148	0.138	0.120	0.059	0.015
Inhalation	3 mo	5.21	2.96	2.08	1.00	0.893	0.714	0.209	0.023
	1 y	8.66	4.92	3.45	1.66	1.48	1.18	0.341	0.036
	5 y	8.31	4.71	3.30	1.58	1.41	1.12	0.319	0.032
	10 y	7.53	4.28	3.00	1.45	1.29	1.03	0.302	0.033
	15 y	6.44	3.66	2.57	1.24	1.11	0.886	0.261	0.029
	Adults	4.72	2.69	1.89	0.920	0.822	0.660	0.200	0.024
Ground	1 day	1.01	0.569	0.396	0.189	0.169	0.135	0.041	0.005
	2 days	1.57	0.894	0.627	0.307	0.276	0.224	0.073	0.010
	7 days	3.21	1.84	1.30	0.651	0.586	0.479	0.164	0.024
	14 days	4.28	2.46	1.74	0.865	0.778	0.634	0.213	0.030

The initial purpose was to calculate the doses and compare them with the criteria for emergency protective actions (doses averted during the first two weeks after an accident) defined in Ukrainian regulation (Table IX–3). However, it was discovered that assessed doses were higher than those criteria. The obtained doses were even higher than the criteria for urgent protective actions for acute exposure (predicted absorbed dose for two days) at least for distances up to 15 km.

TABLE IX–16. TOTAL PREDICTED DOSES TO THE WHOLE BODY, Gy

Time period	Reference age	Distance, km							
		1	2.5	3.5	6.5	7	8	15	50
1 d	3 mo	6.81	3.88	2.74	1.34	1.20	0.970	0.310	0.042
	1 y	10.3	5.84	4.11	2.00	1.78	1.43	0.441	0.056
	5 y	9.91	5.64	3.96	1.92	1.71	1.38	0.419	0.052
	10 y	9.13	5.20	3.66	1.79	1.60	1.29	0.402	0.052
	15 y	8.04	4.58	3.23	1.58	1.41	1.14	0.361	0.048
	Adults	6.32	3.61	2.55	1.26	1.13	0.916	0.301	0.043
2 d	3 mo	7.37	4.21	2.97	1.46	1.31	1.06	0.341	0.047
	1 y	10.8	6.17	4.34	2.11	1.89	1.52	0.473	0.060
	5 y	10.5	5.96	4.19	2.04	1.82	1.47	0.451	0.057
	10 y	9.69	5.53	3.89	1.90	1.70	1.38	0.434	0.057
	15 y	8.60	4.91	3.46	1.70	1.52	1.23	0.393	0.053
	Adults	6.88	3.94	2.78	1.38	1.24	1.00	0.332	0.048
7 d	3 mo	9.00	5.15	3.64	1.80	1.62	1.31	0.432	0.061
	1 y	12.5	7.11	5.01	2.46	2.20	1.78	0.563	0.074
	5 y	12.1	6.91	4.87	2.38	2.13	1.72	0.541	0.070
	10 y	11.3	6.48	4.57	2.25	2.01	1.63	0.524	0.071
	15 y	10.2	5.86	4.14	2.04	1.83	1.49	0.484	0.067
	Adults	8.52	4.89	3.46	1.72	1.55	1.26	0.423	0.062
14 d	3 mo	10.1	5.77	4.08	2.01	1.81	1.47	0.481	0.067
	1 y	13.5	7.73	5.45	2.67	2.39	1.93	0.613	0.080
	5 y	13.2	7.53	5.30	2.59	2.32	1.88	0.591	0.076
	10 y	12.4	7.09	5.00	2.46	2.21	1.79	0.574	0.077
	15 y	11.3	6.47	4.57	2.25	2.02	1.64	0.533	0.073
	Adults	9.59	5.50	3.89	1.93	1.74	1.42	0.472	0.068

TABLE IX–17. PREDICTED DOSES TO THE THYROID (INTERNAL EXPOSURE), Gy

Reference age	Distance, km							
	1	2.5	3.5	6.5	7	8	15	50
3 mo	93.0	52.5	36.7	17.2	15.3	12.1	3.16	0.248
1 y	160	90.0	62.9	29.5	26.1	20.5	5.28	0.389
5 y	153	86.4	60.3	28.2	25.0	19.6	5.02	0.359
10 y	133	75.2	52.5	24.6	21.7	17.1	4.38	0.314
15 y	114	64.4	45.0	21.0	18.6	14.6	3.73	0.265
Adults	80.0	45.1	31.5	14.8	13.0	10.3	2.63	0.191

For BDBAs at nuclear power plants, the Ukrainian regulation specifies limitations of frequencies of significant degradation of the reactor core and limitations of limiting emergency release of the radioactive substances into the environment. Limitations of doses are applicable only for BDBAs without significant degradation of the reactor core. If the considered accident is a BDBA with significant degradation of the reactor core, then for compliance with regulatory requirements it is enough to demonstrate that the frequency is below the level specified in Ref [IX–3].

IX–4. RESULTS OF PROBABILISTIC ASSESSMENTS

SOARS is developed for calculation of the consequences of atmospheric releases from NPPs within their observation areas (i.e., up to 30 km). Dose assessments were performed by SOARS for 7 settlements: T1 (15 km), T2 (8 km), T3 (2.5 km), T4 (6.5 km), T5 (3.5 km), T6 (7 km), T7 (1 km). Locations of the settlements and a wind rose are shown in Figure IX–4.

As it was expected, the most important contributor to the total doses is I-131. The maximum doses for children are calculated for a reference age ‘1 year’. Therefore only doses to the thyroid and to the whole body are provided in this subsection (for reference ages ‘1 year’ and ‘adult’). Ukrainian regulation doesn’t declare any statements about involving dose distributions in the analysis. However, such distributions can potentially be an important part of the study, so they are shown in Figures IX–5 to IX–18. The summary is presented in Table IX–18, which contains 90^{th}, 95^{th}, 99^{th} percentiles and maximum for doses to the thyroid and to the whole body.

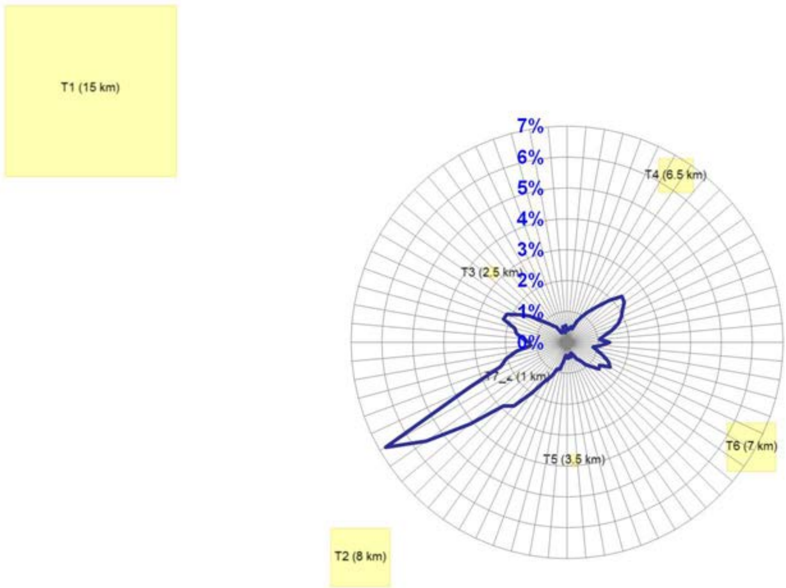

FIG. IX–4. Wind rose (by wind directions at height = 10 m)

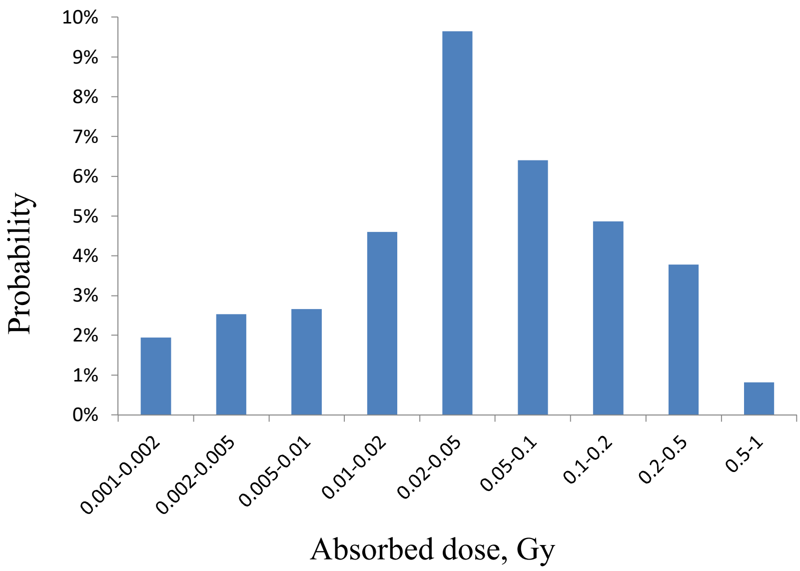

FIG. IX–5. Distribution of absorbed doses to thyroid for children (1 y) (T1, 15 km), Gy

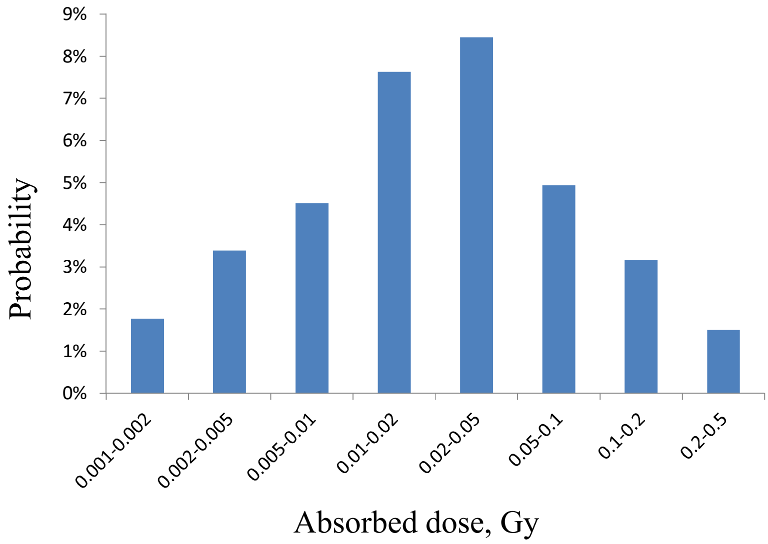

FIG. IX–6. Distribution of absorbed doses to thyroid for adults (T1, 15 km), Gy

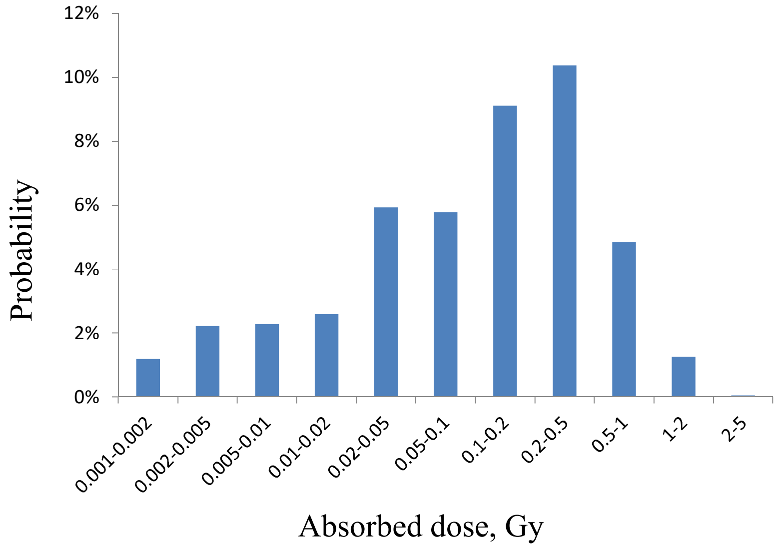

FIG. IX–7. Distribution of absorbed doses to thyroid for children (1 y) (T2, 8 km), Gy

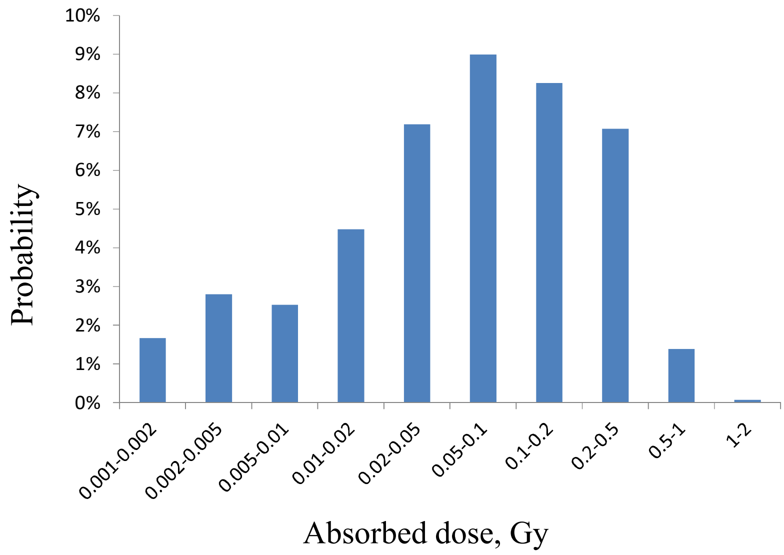

FIG. IX–8. Distribution of absorbed doses to thyroid for adults (T2, 8 km), Gy

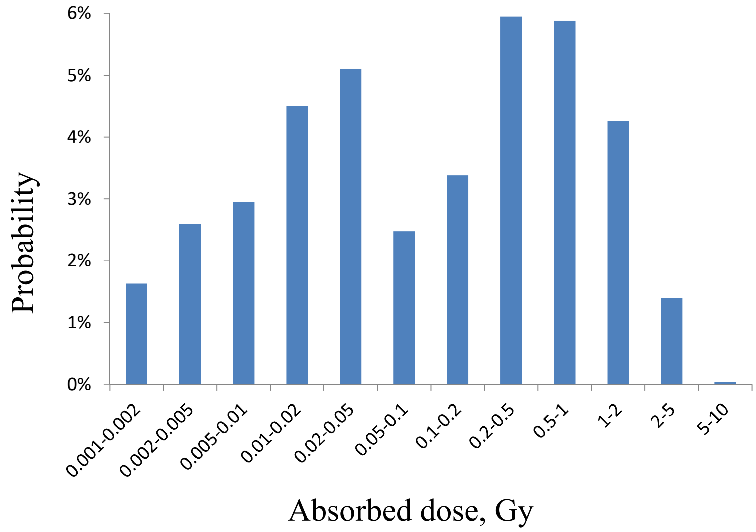

FIG. IX–9. Distribution of absorbed doses to thyroid for children (1 y) (T3, 2.5 km), Gy

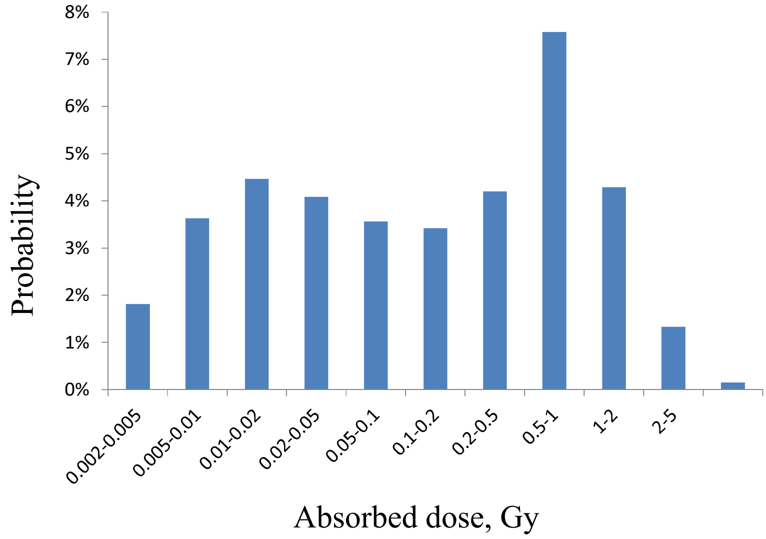

FIG. IX–10. Distribution of absorbed doses to thyroid for adults (T3, 2.5 km), Gy

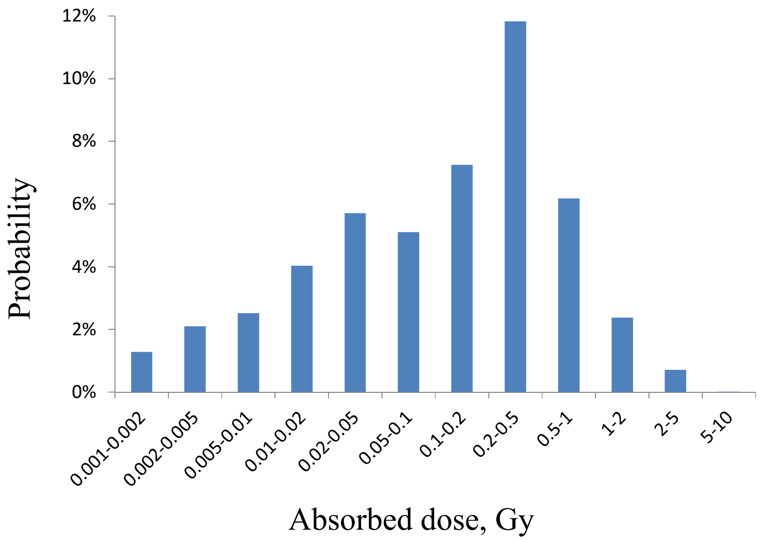

FIG. IX–11. Distribution of absorbed doses to thyroid for children (1 y) (T4, 6.5 km), Gy

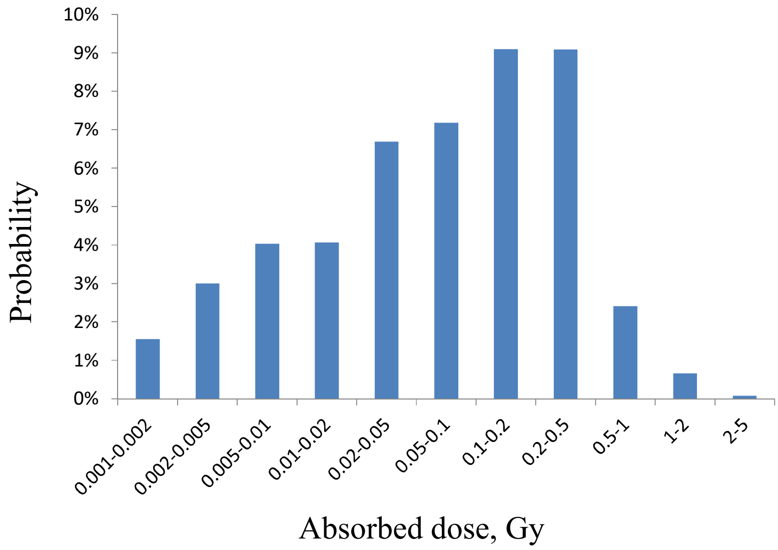

FIG. IX–12. Distribution of absorbed doses to thyroid for adults (T4, 6.5 km), Gy

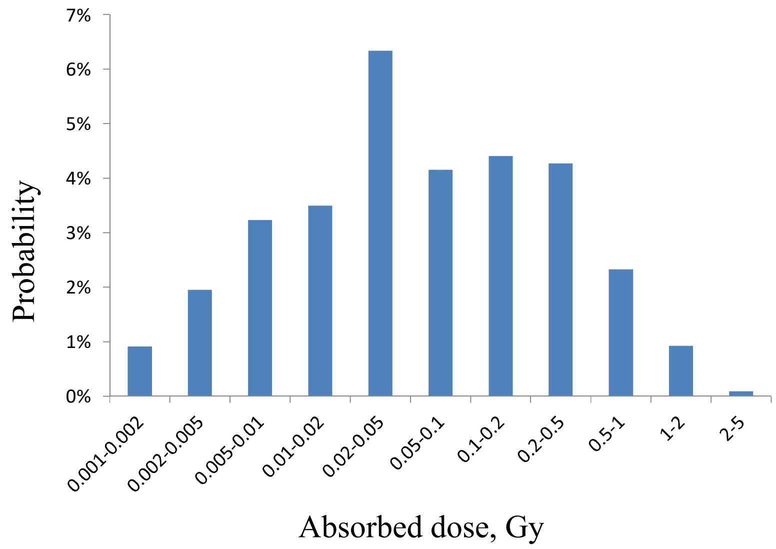

FIG. IX–13. Distribution of absorbed doses to thyroid for children (1 y) (T5, 3.5 km), Gy

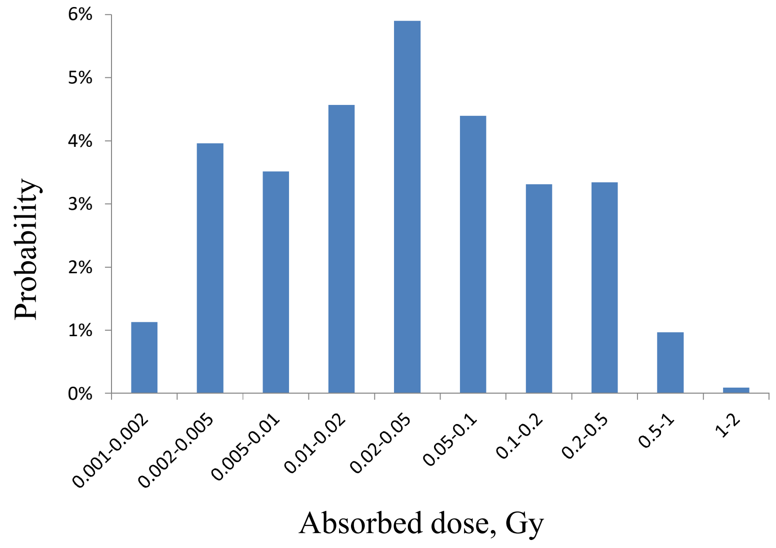

FIG. IX–14. Distribution of absorbed doses to thyroid for adults (T5, 3.5 km), Gy

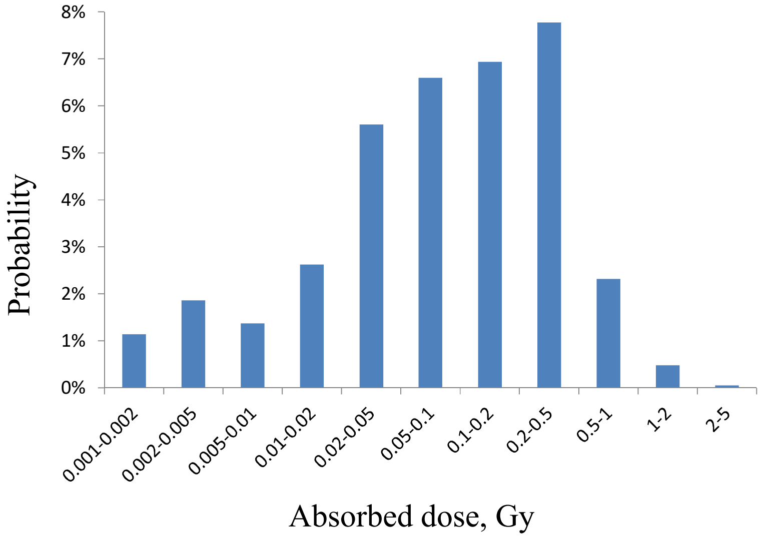

FIG. IX–15. Distribution of absorbed doses to thyroid for children (1 y) (T6, 7 km), Gy

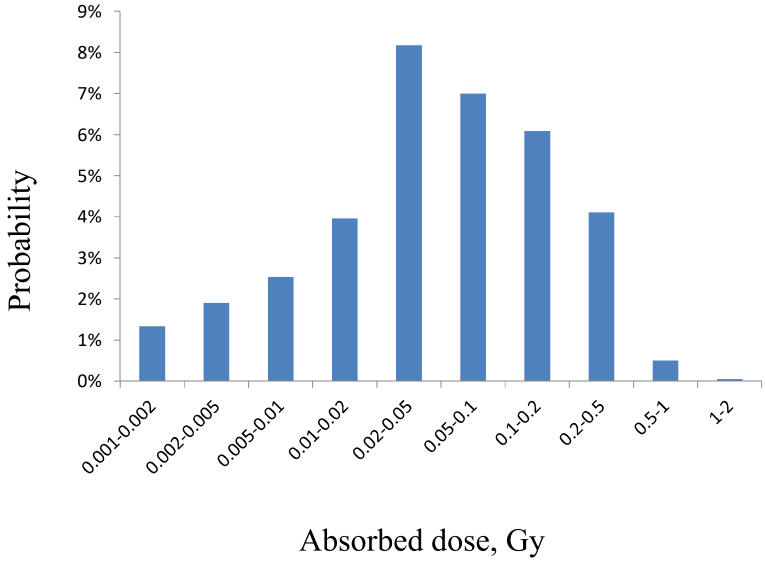

FIG. IX–16. Distribution of absorbed doses to thyroid for adults (T6, 7 km), Gy

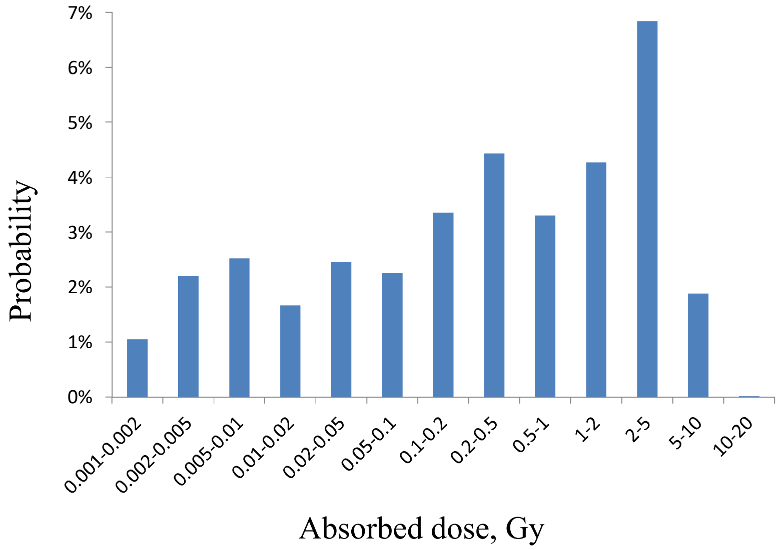

FIG. IX–17. Distribution of absorbed doses to thyroid for children (1 y) (T7, 1 km), Gy

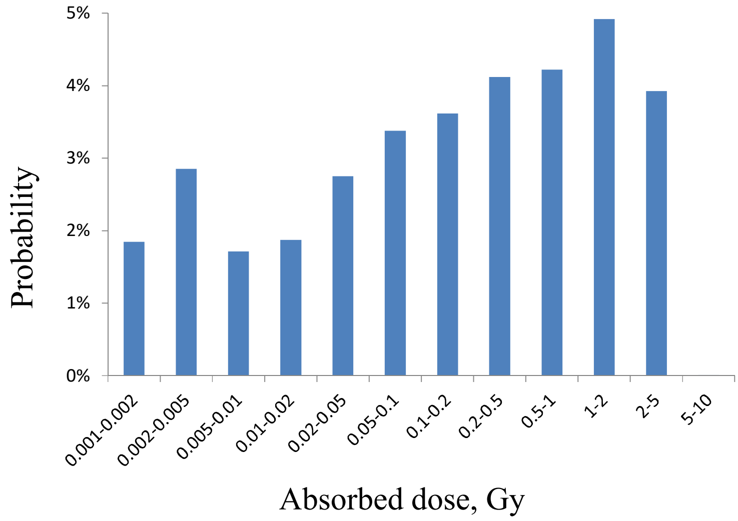

FIG. IX–18. Distribution of absorbed doses to thyroid for adults (T7, 1 km), Gy

TABLE IX–18. PREDICTED DOSES (DURING FIRST 2 DAYS), Gy

Organ/tissue		T7 (1 km)	T3 (2.5 km)	T5 (3.5 km)	T4 (6.5 km)	T6 (7 km)	T2 (8 km)	T1 (15 km)
Thyroid (children, 1 y)	Max	10	8.5	3.2	7.8	2.2	2.1	0.83
	99^{tho}%	5.8	2.4	1.0	1.7	0.80	1.1	0.47
	95^{tho}%	3.4	1.1	0.34	0.77	0.38	0.58	0.19
	90^{tho}%	1.7	0.61	0.13	0.47	0.22	0.34	0.091
Thyroid (adults)	Max	5.2	4.3	1.6	4.0	1.2	1.2	0.42
	99^{tho}%	2.9	1.2	0.51	0.87	0.40	0.55	0.24
	95^{tho}%	1.7	0.55	0.17	0.39	0.19	0.29	0.095
	90^{tho}%	0.84	0.31	0.68	0.24	0.11	0.17	0.046
Whole body (children, 1 y)	Max	0.73	0.64	0.46	0.62	0.31	0.62	0.11
	99^{tho}%	0.40	0.17	0.065	0.12	0.057	0.079	0.035
	95^{tho}%	0.24	0.076	0.024	0.055	0.027	0.04	0.014
	90^{tho}%	0.11	0.042	0.0097	0.033	0.015	0.024	0.0067
Whole body (adults)	Max	0.48	0.53	0.41	0.53	0.26	0.59	0.095
	99^{tho}%	0.26	0.11	0.049	0.084	0.037	0.051	0.023
	95^{tho}%	0.15	0.049	0.016	0.036	0.017	0.026	0.0093
	90^{tho}%	0.074	0.027	0.0063	0.021	0.0099	0.016	0.0044

According to the results, for each of the settlements, there are meteorological conditions under which criteria for emergency protective actions can be exceeded. Moreover, for three settlements (T7 (1 km), T3 (2.5 km), T4(6.5km)) criteria for urgent protective actions can be exceeded. All conclusions above were made on the basis of maximal doses. If a probabilistic approach is applied, the situation would be slightly more optimistic. For example, for 99th percentiles, criteria for urgent protective actions may be exceeded only for T7 (1 km). For 95th percentiles, there are no settlements for which such criteria can be exceeded.

As it was already stated above, use of dose distributions (e.g. percentiles) is not clearly defined in Ukrainian regulation, so typically maximum doses (and the deterministic approach) are used as a basis for decision making.

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ANNEX X. UNITED KINGDOM

X–1. STRUCTURE OF POTENTIAL EXPOSURES CONSIDERATION

The UK Regulator, ONR (Office for Nuclear Regulation), uses Safety Assessment Principles (SAPs) [X–1], together with the supporting Technical Assessment Guides (TAGs), to guide regulatory decision making in the process of granting permits for nuclear facilities. The TAG on radiological analysis for fault conditions [X–2] states:

> “[Para. 5.14]
>
> The maximum dose to a person off the site should generally be determined assuming the person is directly downwind of the airborne release. The location should be chosen to be conservative for an analysis in support of a DBA, and best estimate for input to a PSA or a SAA. In estimating the societal risk (Target 9) dose to the many persons on and off the site needs to be considered.
>
> …….
>
> [Para. 5.26]
>
> Best-estimate methods and data should preferably be used for the radiological analysis in the PSA and should:
>
> - assume the weather conditions that give a best estimate dose, usually category D weather,
> - assume a hypothetical person located at the nearest habitation or location where occupancy is likely e.g. workplace or at a distance of 1 kilometre from the facility, or at the point of greatest dose if that is further away,
> - assume the hypothetical person to be directly downwind of the release for the duration of the release, except for extended faults where realistic occupancy factors may be assumed after a suitable interval,
> - take account of the likelihood of the different weather conditions and wind directions, including wind rose data, that are most relevant for the site,
> - take account of only those protective actions that are highly likely to be implemented. In the case of the most exposed individual member of the public, it will be difficult to provide justification for short term protective actions such as shelter, evacuation and administration of stable iodine.”

Since this scenario is a severe accident, a best estimate approach was adopted and Category D weather with a windspeed of 5 m/s was used. Ordinarily, as no credit for protective actions can be taken (see extract from TAG above), an integration time for the ground gamma dose from deposited activity would be 50 years with an allowance for occupancy; however, for the purposes of this comparison exercise, integration periods of 1 day and 7 days were used.

The UK Regulator’s Safety Assessment Principles [X–1] provide nine numerical targets against which doses and risks from new and existing facilities (not just NPPs) are assessed. Targets 1-3 concern normal operation and Targets 4-9 concern accidental releases.

Target 4 is a facility-based target for both on-site and off-site consequences from design basis events. The Target is in the form of dose targets (on or off-site) for initiating fault frequencies in various bands. The assessments against this Target should be deterministic and on a conservative basis.

Targets 5 and 6 concern the risk and dose respectively to workers on site from all accidents – design basis and beyond design basis.

Target 7 is a target for the individual risk of death to a person off site, from accidents at the site resulting in exposure to ionising radiation. As a site target, the risks from all facilities on site need to be included.

Target 8 is a set of frequency targets for off-site dose from accidents on an individual facility. It comprises a series of frequency targets for all events leading to an off-site dose in a specified band (the frequencies for all events in that band being summed).

Target 9 is a societal risk target for the site – namely: a target for the total risk of 100 or more fatalities, either immediate or eventual, from accidents at the site resulting in exposure to ionising radiation.

Each target has two levels – a Basic Safety Level (BSL) and a Basic Safety Objective (BSO) on which ONR elaborates as follows in the SAPs [X–1]:

> "[Para. 698]
>
> It is ONR's policy that a new facility or activity should at least meet the BSLs. However, even if the BSLs are met, the risks may not be ALARP; in such cases the designer/dutyholder must reduce the risks further. Deciding when the level of risk is ALARP needs to be justified by the designer/dutyholder on a case-by-case basis, applying the legal test of gross disproportion. A graded approach should be used so that the higher the risk (or hazard), the greater the degree of disproportion applied, and the more robust the argument needed to justify not implementing additional safety measures.
>
> …….
>
> [Para. 701]
>
> The BSOs form benchmarks that reflect modern safety standards and expectations. The BSOs also recognise that there is a level beyond which further consideration of the safety case would not be a reasonable use of ONR resources, compared with the benefit of applying these resources to areas of higher risk. Inspectors therefore need not seek further improvements from the designer/dutyholder but can confine themselves to assessing the validity of the arguments presented. The dutyholder, however, is not given the option of stopping at this level. ALARP considerations may be such that the dutyholder is justified in stopping before reaching the BSO, but if it is reasonably practicable to provide a higher standard of safety, then the dutyholder must do so by law."

Table X–1 below summarizes the guidance on numerical targets applicable for off-site releases. These figures are termed basic safety levels which represent a level that it is considered a new facility should meet; basic safety objectives are set more stringent, for instance at lower levels (generally a factor of 100 lower) and mark the start of what is considered broadly acceptable. There are also targets for workers on-site.

TABLE X–1. NUMERICAL TARGETS FOR POTENTIAL EXPOSURES OFF-SITE

Target	Applicability	Numerical values (Basic Safety Level)	
Target 4	Design Basis fault sequences	1 mSv for initiating fault frequencies exceeding $1 \cdot 10^{-3}$ a^{-1} 10 mSv for initiating fault frequencies between $1 \cdot 10^{-3}$ and $1 \cdot 10^{-4}$ a^{-1} 100 mSv for initiating fault frequencies between $1 \cdot 10^{-4}$and $1 \cdot 10^{-5}$ a^{-1}	
Target 7	Individual risk of death from accidents	$1 \cdot 10^{-4}$ a^{-1}	
Target 8	Frequency-dose targets (all accidents)	Effective dose, mSv	Total predicted frequency, a^{-1}
		0.1–1	1
		1–10	$1 \cdot 10^{-1}$
		10–100	$1 \cdot 10^{-2}$
		100–1000	$1 \cdot 10^{-3}$
		> 1000	$1 \cdot 10^{-4}$
Target 9	Total risk of 100 or more fatalities (immediate or eventual)	$1 \cdot 10^{-5}$ a^{-1}	

For the ENV-PE exercise the appropriate targets for assessment are Targets 7, 8, and 9; Targets 5 and 6 for on-site dose and risk respectively would also have to be addressed but since this exercise concerns only off-site consequences they are not considered further here. Target 8 requires a deterministic assessment and the methodologies applied and the results are described in Section X.3 and X.4 respectively below. A probabilistic assessment (Level 3 PSA) would be required to assess this facility and site against Targets 7 and 9 and this is described in Section X.5 with the results in Section X.6 below.

X–2. CRITERIA FOR IMPLEMENTATION OF PROTECTIVE ACTIONS

The UK National Radiological Protection Board (NRPB) (now Public Health England) has recommended quantitative criteria for the introduction of protective actions to protect the public in the event of an accident [X–3]. These criteria are termed Emergency Reference Levels (ERLs) and for each countermeasure are specified in terms of the dose to an individual that could be averted if that countermeasure were implemented.

An upper and lower ERL is specified for each countermeasure. The NRPB states:

> "The lower ERL is the dose level below which the countermeasure should not be introduced because, in the Board's judgement, it would be very unlikely to be justified to do so. If estimated averted doses exceed the lower ERL, implementation of the countermeasure should be considered but is not essential. The upper ERL is the dose level at which the Board expects every effort to be made to introduce the countermeasure unless it would clearly contravene the principles of justification and optimisation to do so."

The ERLs for each countermeasure are reproduced in Table X–2.

TABLE X–2. EMERGENCY REFERENCE LEVELS

Countermeasure	Dose Equivalent Level, mSv	
	Lower ERL	Upper ERL
Stable iodine (thyroid dose)	30	300
Sheltering (whole body)	3	30
Sheltering (thyroid, lungs, and skin)	30	300
Evacuation (whole body)	30	300
Evacuation (thyroid, lungs, and skin)	300	3000

In addition, Euratom Council Regulation 2016/52 [X–4] lays down the maximum permitted levels of radioactive contamination in food and animal feed which may be placed on the market following a release of radioactivity into the environment.

TABLE X–3. COUNCIL FOOD INTERVENTION LEVELS (CFILs)

Isotope group/Food group	Food (Bq/kg)			
	Infant food	Dairy produce	Other food except minor food	Liquid food
Sum of the isotopes of strontium, notably Sr-90	75	125	750	125
Sum of the isotopes of iodine, notably I-131	150	500	2000	500
Sum of alpha-emitting isotopes of plutonium and trans-plutonium elements, notably Pu-239, Am-241	1	20	80	20
Sum of all other nuclides of half-life greater than 10 days, notably Cs-134, Cs-137	400	1000	1250	1000

The levels are set to restrict the dose from ingestion of contaminated food to less than 1 mSv per year on the assumption that 10 % of food consumed annually is contaminated. However, different assumptions apply to infants under 1 year leading to corresponding lower levels for infant food.

There are limits for iodine isotopes, strontium isotopes, alpha emitting nuclides and other nuclides (notably Cs-137 and Cs-134).

Food exceeding these levels – known as Council Food Intervention Levels (CFILs) – is prohibited from being placed on the market in the European Union. The levels are shown in Table X–3.

X–3. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED FOR THE DETERMINISTIC ASSESSMENT

For the deterministic dose calculations, a simple Gaussian atmospheric dispersion model modified to account for dry and wet deposition and building wake effects was used. The models used are described in reports issued by the UK National Radiological Protection Board (NRPB) (now Public Health England) [X–5 to X–8].

The dose per unit inhalation values used were obtained from Annex G and Annex H of ICRP 119 [X–9], which is a compilation of dose coefficients for intakes of radionuclides by workers and members of the public, and conversion coefficients for use in occupational radiological protection against external radiation from ICRP-72 [X–10] and ICRP-74 [X–11].

The main assumptions and parameter values used in the analysis are presented in Table X–4.

TABLE X–4. MAIN ASSUMPTIONS AND PARAMETER VALUES USED IN ANALYSIS

Parameter	Value
Source Term	Reduced source term
Release height	35 m (isolated stack release)
Release duration (for wind meander)	1 hour
Heat content of plume	0
Pasquill Category and windspeed at 10m	D5 (Category D with a windspeed of 5 m/s)
Rainfall rate	0 mm/hour
Terrain type (surface roughness length)	Parkland/open suburbia (0.4 m)
Adult breathing rate	0.92 m^3/hour
Infant breathing rate	0.22 m^3/hour
Location and shielding factors	None applied (i.e. exposed person is assumed to be outside for whole duration of release and subsequent period – 1 or 7 days)
Dose coefficients	ICRP-119
Chemical form for iodine	All elemental iodine
Dry deposition velocities:	
Particulate	$1 \cdot 10^{-3}$ m/s
Elemental iodine	$3 \cdot 10^{-3}$ m/s

TABLE X–4. MAIN ASSUMPTIONS AND PARAMETER VALUES USED IN ANALYSIS (cont.)

Parameter	Value
Lung absorption type:	Based on ICRP-71 [X–12] guidance
Strontium	M (moderate rate of absorption) - deposited materials that have intermediate rates of absorption into blood from the respiratory tract
Tellurium	M
Caesium	F (fast rate of absorption) - deposited materials that are readily absorbed into blood from the respiratory tract
Cerium	M
Plutonium	M
Iodine	V (very fast absorption) - deposited materials that, for dosimetric purposes, are assumed to be instantaneously absorbed into body fluids from the respiratory tract; this only applies to certain gases and vapours

X–4. RESULTS OF THE DETERMINISTIC ASSESSMENT

The Total Effective Dose and Thyroid Dose for adults and infants for each integration period for the distances specified above were calculated and the results are shown in Table X–5 to Table X–7 below.

TABLE X–5. TOTAL EFFECTIVE DOSE TO ADULTS, Sv

Weather category	D5				D5			
Integration Period	1 day				7 day			
Pathway / Distance, km	Inhalation	Cloud gamma	Deposited gamma	Total	Inhalation	Cloud gamma	Deposited gamma	Total
1.0	1.06E+00	1.01E-01	4.68E-02	1.20E+00	1.06E+00	1.01E-01	1.65E-01	1.32E+00
2.5	2.72E-01	2.61E-02	1.20E-02	3.11E-01	2.72E-01	2.61E-02	4.27E-02	3.41E-01
3.5	1.60E-01	1.53E-02	7.04E-03	1.82E-01	1.60E-01	1.53E-02	2.51E-02	2.00E-01
6.5	5.99E-02	5.70E-03	2.62E-03	6.83E-02	5.99E-02	5.70E-03	9.40E-03	7.50E-02
7.0	5.34E-02	5.07E-03	2.33E-03	6.07E-02	5.34E-02	5.07E-03	8.37E-03	6.68E-02
8.0	4.33E-02	4.10E-03	1.88E-03	4.93E-02	4.33E-02	4.10E-03	6.79E-03	5.42E-02
15.0	1.66E-02	1.54E-03	7.08E-04	1.88E-02	1.66E-02	1.54E-03	2.60E-03	2.07E-02
50.0	2.88E-03	2.46E-04	1.14E-04	3.25E-03	2.88E-03	2.46E-04	4.48E-04	3.58E-03

TABLE X–6. TOTAL EFFECTIVE DOSE TO INFANTS, Sv

Weather category	D5				D5			
Integration Period	1 day				7 day			
Pathway / Distance, km	Inhalation	Cloud gamma	Deposited gamma	Total	Inhalation	Cloud gamma	Deposited gamma	Total
1.0	1.99E+00	1.01E-01	4.68E-02	2.13E+00	1.99E+00	1.01E-01	1.65E-01	2.25E+00
2.5	5.12E-01	2.61E-02	1.20E-02	5.50E-01	5.12E-01	2.61E-02	4.27E-02	5.80E-01
3.5	3.00E-01	1.53E-02	7.04E-03	3.23E-01	3.00E-01	1.53E-02	2.51E-02	3.41E-01
6.5	1.13E-01	5.70E-03	2.62E-03	1.21E-01	1.13E-01	5.70E-03	9.40E-03	1.28E-01
7.0	1.00E-01	5.07E-03	2.33E-03	1.08E-01	1.00E-01	5.07E-03	8.37E-03	1.14E-01
8.0	8.12E-02	4.10E-03	1.88E-03	8.72E-02	8.12E-02	4.10E-03	6.79E-03	9.21E-02
15.0	3.11E-02	1.54E-03	7.08E-04	3.33E-02	3.11E-02	1.54E-03	2.60E-03	3.52E-02
50.0	5.39E-03	2.46E-04	`1.14E-04	5.75E-03	5.39E-03	2.46E-04	4.48E-04	6.09E-03

TABLE X–7. THYROID DOSE TO ADULTS AND INFANTS (INHALATION ONLY), Sv

Weather category	D5	D5
Age group	Adult	Infant
Pathway	Thyroid	Thyroid
Distance, km		
1.0	1.79E+01	3.65E+01
2.5	4.61E+00	9.42E+00
3.5	2.71E+00	5.53E+00
6.5	1.01E+00	2.07E+00
7.0	9.02E-01	1.84E+00
8.0	7.32E-01	1.49E+00
15.0	2.80E-01	5.72E-01
50.0	4.86E-02	9.90E-02

Figure X–1 to Figure X–4 show plume centreline plots of the total effective dose up to 2km for 1 and 7 day integration periods showing the contribution of each pathway and nuclide. Inhalation is the dominant pathway and I-131 is the dominant nuclide.

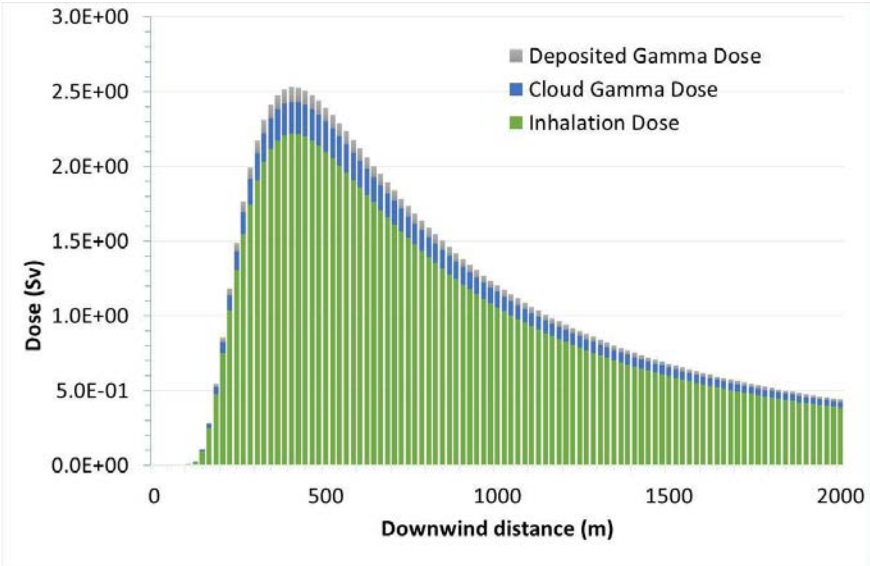

FIG. X–1. Total Effective Dose, Adult, 1-day integration period

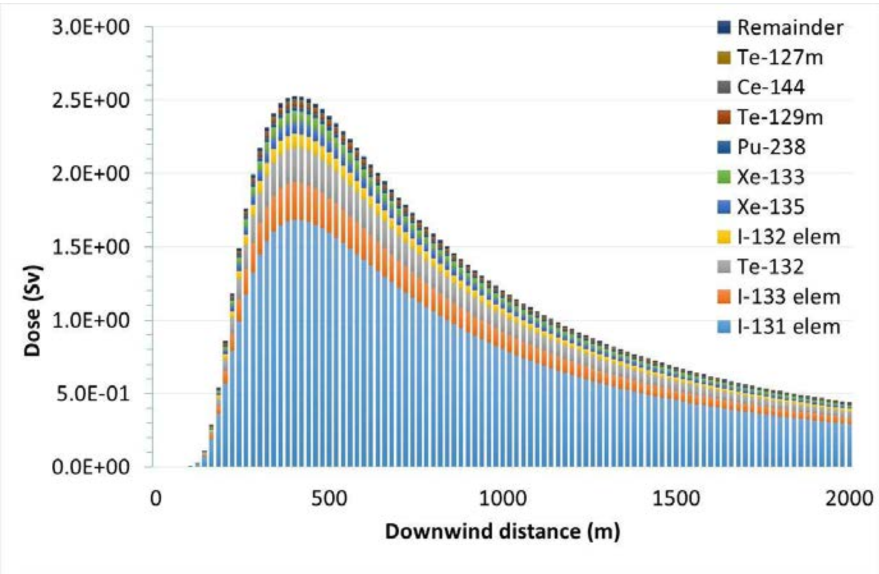

FIG. X–2. Total Effective Dose, Adult, 1 day integration period

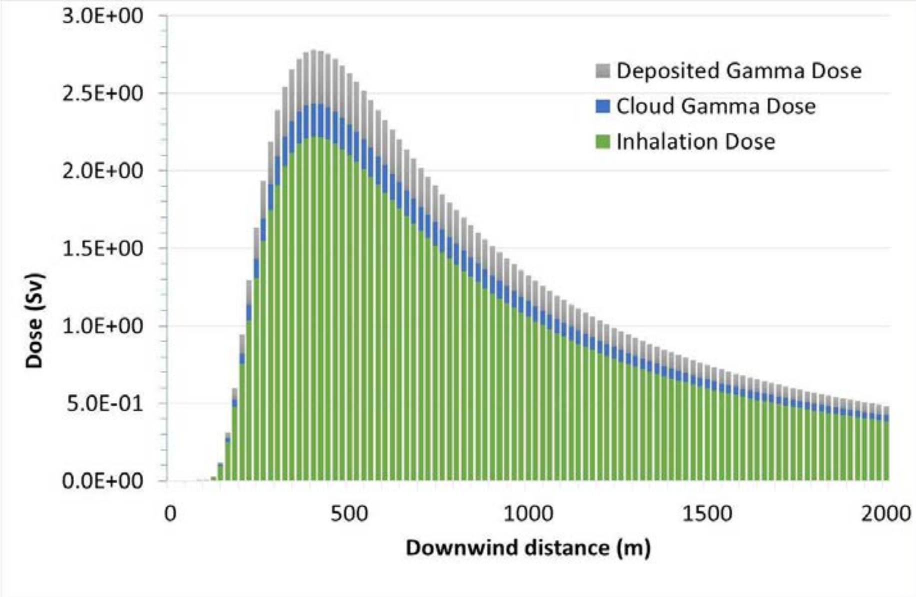

FIG. X–3. Total Effective Dose, Adult, 7-day integration period

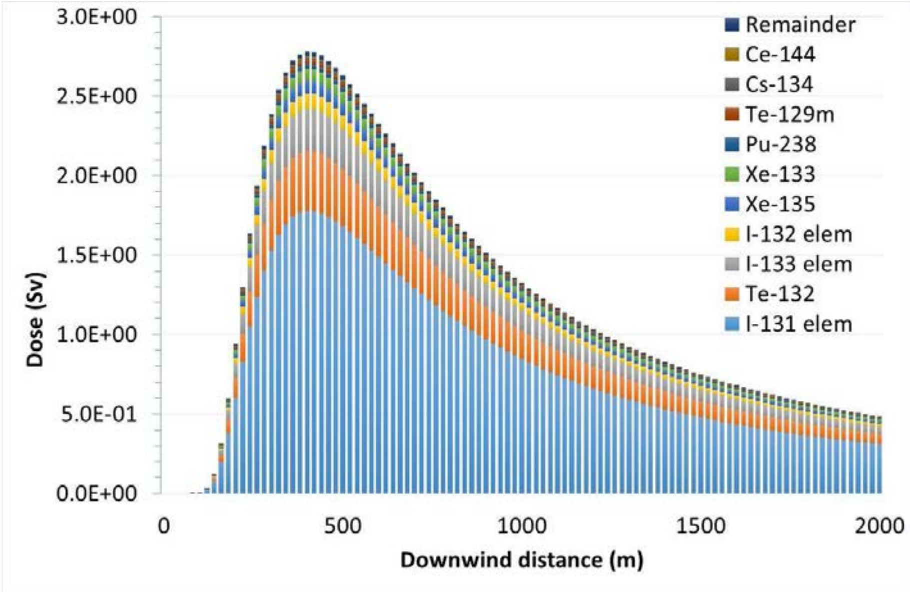

FIG. X–4. Total Effective Dose, Adult, 7-day integration period

The off-site dose calculated above is greater than 1 Sv which puts this event in the top dose band of Target 8 (see Figure X–5 below). In addition to the dose calculated above, the contribution from ingestion dose would also have to be added and dose from deposited activity would have to be integrated for a period significantly longer than 7 days. However, as the event is already in the top band, this does not affect assessment against this Target.

Although the assessment against this Target should be on a best-estimate basis, ONR states [X–2] that 'only those protective actions that are highly likely to be implemented' should be credited and adds 'it will be difficult to provide justification for short term protective actions such as shelter, evacuation and administration of stable iodine'. The rational for this is that the doses evaluated on this basis can be seen as a surrogate for the economic consequences of an accident with each dose band related in an approximate fashion to the off-site actions which could be expected following an accident (see insert after Para. 751 in the SAPs [X–1]). This is also why the integration period for the deposited activity should be significantly longer than 7 days since evacuation in this period would be difficult to justify as 'highly likely to be implemented'. For the assessment for this exercise no sheltering or normal occupancy (time spent indoors) was assumed for the 1 or 7 day exposure. If integration times of a year or longer were required – as would be the case for assessment against Target 8 – then normal occupancy could be assumed.

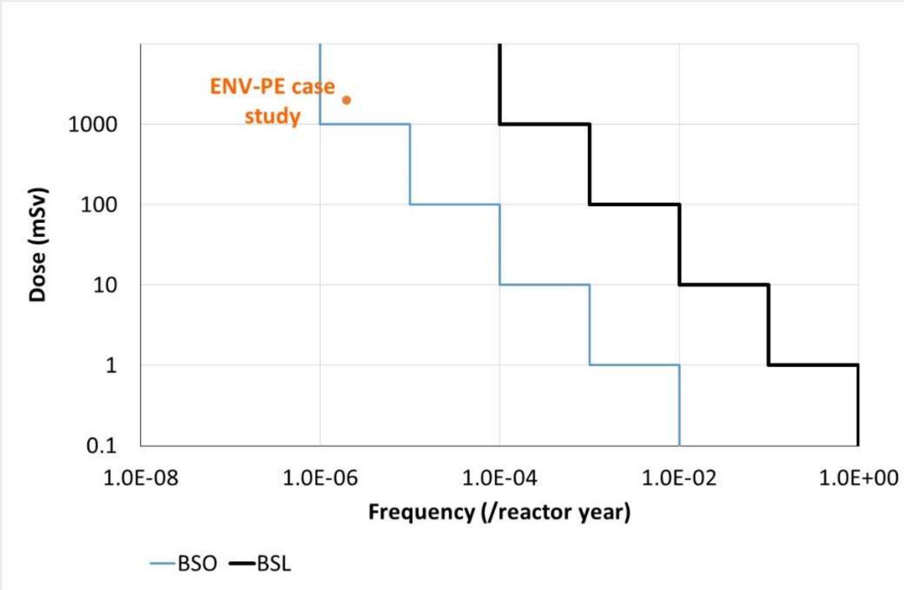

FIG. X–5. Assessment against UK Target 8

This is only one scenario and all the other events would have to be included (as well as design-basis faults) and the frequencies summed for their respective dose bands. Only then would it be possible to determine if the BSL had been exceeded; however, this scenario on its own has exceeded the BSO.

X–5. DESCRIPTION OF MODELS OR METHODOLOGIES APPLIED FOR THE PROBABILISTIC ASSESSMENT

The PC-COSYMA Code [X–13] was used to perform these assessments. Version 2.03 was used which was updated in 2007 by the UK Health Protection Agency (HPA) (now Public Health England) to include:

- the then latest available dose coefficients and data provided in ICRP Publication 72 [X–10]
- UK specific cancer risk factors [X–14]
- UK population distribution dataset based on 2001 census data
- UK datasets from 2003 agricultural survey data– the original PC COSYMA assumption related to foodstuff contamination and dose from ingestion of the contaminated foodstuff was that most of the food is produced and consumed locally to the area contaminated; this assumption is not valid for the UK as the majority of food consumed is grown on a commercial basis and is distributed nationally to consumers.

For this exercise, the UK-specific risk factors [X–14] and the population data provided were used. No information on agricultural production and food consumption rates in the local population was provided so ingestion dose was not calculated.

PC-COSYMA calculates short term doses (to consider deterministic health effects) integrated over a time specified by the user, up to 365 days and long-term doses integrated for a period of

50 years, to consider stochastic health effects. For the comparison exercise integration periods of 1, 2, and 7 days were used.

The meteorological dataset supplied was used; this contained hourly data for a period of one year although longer periods would normally be used in this type of assessment. However, even one year of hourly data has 8760 sets of meteorological conditions and so it would be impractical to perform dispersion and dose/risk calculation for each one. Instead probabilistic accident consequences assessment tools sample from the dataset to broadly account for the range of conditions that may be present when an accident occurs.

In PC-COSYMA the user can specify a meteorological sampling scheme by using the sampling options available within the code or by providing a user defined scheme. Two sampling schemes can be selected – 'cyclic' or 'stratified'. Cyclic sampling is the simpler method, allowing sampling every n^{th} sequence. This method tends to sample the more common types of weather sequence frequently whilst potentially overlooking the more unusual ones. Stratified sampling is designed to ensure infrequent conditions that might lead to high consequence are not missed. Representative sampling ensures that most of the possible weather sequences have been considered in estimating accident consequence endpoints.

TABLE X–8. MAIN ASSUMPTIONS AND PARAMETER VALUES USED IN ANALYSIS

Parameter	Value
Source Term	Reduced source term
Release height	35 m (isolated stack release)
Release duration	Six one-hour segments representing the six four phases for 24-hour duration of the release
Heat content of plume	0
Pasquill Category and windspeed at 10m	Sampled from the meteorological data file
Rainfall rate	Sampled from the meteorological data file
Terrain type (surface roughness length)	Parkland/open suburbia (0.4 m)
Adult breathing rate	0.92 m^3/hour
Infant breathing rate	Infant doses not calculated as PC-COSYMA only has adult dose coefficients
Location and shielding factors	None applied (i.e. exposed person is assumed to be outside for whole duration of release and subsequent period – 1 or 7 days)
Dose coefficients	ICRP-72
Risk coefficients	UK-specific [X–14]
Chemical form for iodine	All elemental iodine
Dry deposition velocities:	
Particulate	$1 \cdot 10^{-3}$ m/s
Elemental iodine	$3 \cdot 10^{-3}$ m/s
Lung absorption type:	Based on ICRP-71 [X–12] guidance
Strontium	M
Tellurium	M
Caesium	F
Cerium	M
Plutonium	M
Iodine	V

Sensitivity studies on different sampling schemes available in COSYMA indicate that the ranges of predicted consequences from different sampling schemes are comparable with the ranges arising from variations in the same sampling scheme, e.g. varying the number of sequences in a cyclic sampling scheme.

The cyclic sampling scheme was used in this assessment. 144 samples from the 8760 weather sequences were taken with 61 hours between sequences; 61 (a prime number) is chosen to avoid sampling the same time of day too many times as would be the case if a number divisible by 4 or 6 were used for example. 144 is the maximum number of sequences the code will allow; whereas fewer than 50 sequences are not considered representative. For each sequence sampled the first hour is selected and dispersion and dose/risk calculations are performed for each of the six phases using the meteorological data for the hour corresponding to the timing of that phase. Each release phase has to be one-hour duration and the phases do not need to relate to consecutive hours.

Three options are possible for modelling the dispersion of the six phases:

a. The wind direction remains constant throughout the duration of the six phases (all release phases travel in the direction of the first hour of the first phase).
b. As above but each phase has a wind direction corresponding to the first hour of that phase and doesn't change during the transit of that phase.
c. The wind direction changes corresponding to the meteorological data (hourly changes in wind direction are considered for each hour of each phase).

For this analysis the third option was chosen (see Table X–8).

X–6. RESULTS OF THE PROBABILISTIC ASSESSMENT

The results are presented in Tables X–9 to X–16 and Figures X–6 to X–13 showing the percentiles as a function of distance for each integration period. Results are given for total effective dose, cloud-shine, inhalation dose, and ground-shine individually. All results are for adults as PC-COSYMA does not give doses for other age groups.

For each distance band, PC-COSYMA calculates the dose for the radial sectors (72 in this case) for each of 144 meteorological sequences sampled, and from these 72·144 values PC-COSYMA determines the percentiles.

TABLE X–9. INDIVIDUAL ORGAN DOSES FOR EFF. DOSE (CONTRIBUTION FROM INHALATION IS COMMITTED TO AGE 70 YEARS), 1 DAY INTEGRATION TIME, NO SHIELDING, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	1.53E+01	3.54E-01	5.75E+00	2.04E+00	1.00E+00	2.14E-03
1.00	4.47E+00	8.84E-02	1.59E+00	5.13E-01	2.34E-01	9.33E-05
1.50	2.49E+00	4.87E-02	8.71E-01	2.82E-01	1.26E-01	2.75E-05
2.10	2.00E+00	2.65E-02	4.68E-01	1.51E-01	6.92E-02	2.57E-06
2.80	8.56E-01	1.67E-02	2.95E-01	9.33E-02	4.27E-02	1.05E-06
3.70	7.57E-01	1.15E-02	2.19E-01	6.17E-02	2.69E-02	3.55E-07
4.90	5.83E-01	7.09E-03	1.20E-01	3.47E-02	1.62E-02	-
6.55	3.23E-01	4.13E-03	7.41E-02	2.09E-02	1.00E-02	-
8.75	2.11E-01	2.43E-03	4.17E-02	1.29E-02	5.62E-03	-
11.50	1.43E-01	1.46E-03	2.40E-02	7.59E-03	3.47E-03	-
15.50	1.18E-01	7.76E-04	1.23E-02	4.17E-03	1.95E-03	-
21.00	8.25E-02	4.63E-04	7.41E-03	2.46E-03	1.23E-03	-
28.00	4.56E-02	3.07E-04	5.37E-03	1.70E-03	7.94E-04	-
37.00	1.78E-02	1.93E-04	3.63E-03	1.10E-03	5.01E-04	-
50.00	1.70E-02	1.25E-04	2.34E-03	7.59E-04	2.75E-04	-

TABLE X–10. INDIVIDUAL ORGAN DOSES FOR EFF. DOSE (CONTRIBUTION FROM INHALATION IS COMMITTED TO AGE 70 YEARS), 2 DAY INTEGRATION TIME, NO SHIELDING, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	1.66E+01	3.86E-01	6.46E+00	2.24E+00	1.10E+00	2.19E-03
1.00	4.88E+00	9.70E-02	1.74E+00	5.62E-01	2.57E-01	9.55E-05
1.50	2.72E+00	5.36E-02	9.55E-01	3.09E-01	1.38E-01	2.88E-05
2.10	2.33E+00	2.95E-02	5.25E-01	1.66E-01	7.76E-02	2.63E-06
2.80	9.37E-01	1.85E-02	3.39E-01	1.05E-01	4.68E-02	1.05E-06
3.70	9.06E-01	1.29E-02	2.46E-01	7.08E-02	3.02E-02	3.55E-07
4.90	6.31E-01	7.96E-03	1.38E-01	3.98E-02	1.82E-02	-
6.55	3.48E-01	4.66E-03	8.51E-02	2.40E-02	1.15E-02	-
8.75	2.28E-01	2.77E-03	4.79E-02	1.45E-02	6.46E-03	-
11.50	1.54E-01	1.67E-03	2.95E-02	8.51E-03	3.89E-03	-
15.50	1.27E-01	9.00E-04	1.51E-02	4.79E-03	2.24E-03	-
21.00	8.85E-02	5.40E-04	9.33E-03	2.82E-03	1.38E-03	-
28.00	4.89E-02	3.61E-04	6.76E-03	1.95E-03	9.12E-04	-
37.00	2.09E-02	2.24E-04	4.17E-03	1.29E-03	5.62E-04	-
50.00	1.83E-02	1.47E-04	2.69E-03	8.51E-04	3.09E-04	-

TABLE X–11. INDIVIDUAL ORGAN DOSES FOR EFF. DOSE (CONTRIBUTION FROM INHALATION IS COMMITTED TO AGE 70 YEARS), 7 DAY INTEGRATION TIME, NO SHIELDING, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	2.04E+01	4.78E-01	7.94E+00	2.75E+00	1.35E+00	2.24E-03
1.00	6.06E+00	1.22E-01	2.19E+00	7.24E-01	3.16E-01	9.77E-05
1.50	3.41E+00	6.80E-02	1.23E+00	3.98E-01	1.74E-01	3.02E-05
2.10	3.25E+00	3.80E-02	6.61E-01	2.14E-01	9.55E-02	2.69E-06
2.80	1.27E+00	2.38E-02	4.37E-01	1.35E-01	5.89E-02	1.10E-06
3.70	1.33E+00	1.69E-02	3.31E-01	8.91E-02	3.72E-02	3.72E-07
4.90	7.67E-01	1.05E-02	1.91E-01	5.13E-02	2.29E-02	-
6.55	4.72E-01	6.20E-03	1.20E-01	3.16E-02	1.45E-02	-
8.75	4.36E-01	3.73E-03	6.76E-02	1.95E-02	8.51E-03	-
11.50	1.85E-01	2.29E-03	4.27E-02	1.12E-02	5.13E-03	-
15.50	1.53E-01	1.26E-03	2.24E-02	6.31E-03	2.95E-03	-
21.00	1.06E-01	7.63E-04	1.29E-02	3.89E-03	1.82E-03	-
28.00	7.14E-02	5.16E-04	9.55E-03	2.63E-03	1.23E-03	-
37.00	3.09E-02	3.13E-04	5.75E-03	1.74E-03	7.24E-04	-
50.00	3.42E-02	2.09E-04	3.98E-03	1.15E-03	4.07E-04	-

TABLE X.12. INDIVIDUAL ORGAN DOSES FOR EFFECTIVE DOSE/CLOUDSHINE, 1/2/7 DAY INTEGRATION TIME, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	4.27E-01	1.76E-02	1.82E-01	9.33E-02	5.62E-02	1.74E-03
1.00	1.97E-01	6.37E-03	7.94E-02	3.63E-02	2.00E-02	7.94E-05
1.50	1.52E-01	4.12E-03	5.89E-02	2.40E-02	1.20E-02	2.29E-05
2.10	1.06E-01	2.62E-03	3.63E-02	1.55E-02	7.94E-03	2.00E-06
2.80	7.51E-02	1.88E-03	2.95E-02	1.05E-02	5.25E-03	8.13E-07
3.70	6.30E-02	1.45E-03	2.51E-02	7.94E-03	3.72E-03	2.82E-07
4.90	7.01E-02	1.00E-03	1.74E-02	5.25E-03	2.40E-03	-
6.55	4.79E-02	6.39E-04	1.15E-02	3.31E-03	1.55E-03	-
8.75	2.78E-02	4.01E-04	7.24E-03	2.14E-03	9.12E-04	-
11.50	2.24E-02	2.50E-04	4.47E-03	1.32E-03	5.62E-04	-
15.50	2.37E-02	1.30E-04	2.09E-03	6.46E-04	3.02E-04	-
21.00	1.47E-02	6.03E-05	9.33E-04	3.09E-04	1.59E-04	-
28.00	6.98E-03	3.95E-05	6.61E-04	2.19E-04	1.02E-04	-
37.00	2.79E-03	2.62E-05	4.68E-04	1.48E-04	6.61E-05	-
50.00	2.83E-03	1.69E-05	3.24E-04	1.02E-04	3.98E-05	-

TABLE X.13. INDIVIDUAL ORGAN DOSES FOR EFFECTIVE DOSE/INHALATION (CONTRIBUTION FROM INHALATION IS COMMITTED TO AGE 70 YEARS), 1 DAY INTEGRATION TIME, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	1.29E+01	2.89E-01	4.90E+00	1.66E+00	7.94E-01	2.40E-06
1.00	3.66E+00	6.92E-02	1.29E+00	3.89E-01	1.82E-01	-
1.50	1.98E+00	3.72E-02	6.92E-01	2.14E-01	9.33E-02	-
2.10	1.43E+00	1.96E-02	3.47E-01	1.10E-01	5.01E-02	-
2.80	6.60E-01	1.21E-02	2.24E-01	6.76E-02	3.02E-02	-
3.70	5.53E-01	8.08E-03	1.55E-01	4.27E-02	1.86E-02	-
4.90	4.61E-01	4.84E-03	8.32E-02	2.40E-02	1.07E-02	-
6.55	2.48E-01	2.72E-03	5.13E-02	1.38E-02	6.31E-03	-
8.75	1.61E-01	1.55E-03	2.88E-02	7.76E-03	3.47E-03	-
11.50	1.06E-01	8.98E-04	1.45E-02	4.47E-03	2.04E-03	-
15.50	8.04E-02	4.68E-04	7.24E-03	2.46E-03	1.15E-03	-
21.00	5.90E-02	2.92E-04	4.90E-03	1.59E-03	7.76E-04	-
28.00	3.38E-02	1.91E-04	3.24E-03	1.07E-03	4.90E-04	-
37.00	1.30E-02	1.23E-04	2.34E-03	7.24E-04	3.09E-04	-
50.00	1.22E-02	7.73E-05	1.55E-03	4.79E-04	1.66E-04	-

TABLE X–14. INDIVIDUAL ORGAN DOSES FOR EFFECTIVE DOSE/GROUNDSHINE, 1 DAY INTEGRATION TIME, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	2.28E+00	4.76E-02	7.94E-01	2.75E-01	1.26E-01	3.89E-07
1.00	8.39E-01	1.29E-02	2.40E-01	7.24E-02	3.02E-02	-
1.50	5.11E-01	7.34E-03	1.35E-01	4.07E-02	1.66E-02	-
2.10	4.67E-01	4.31E-03	7.76E-02	2.24E-02	9.33E-03	-
2.80	2.31E-01	2.70E-03	5.25E-02	1.41E-02	5.89E-03	-
3.70	2.12E-01	1.99E-03	4.17E-02	9.55E-03	3.80E-03	-
4.90	1.19E-01	1.26E-03	2.51E-02	5.89E-03	2.34E-03	-
6.55	9.21E-02	7.67E-04	1.62E-02	3.39E-03	1.45E-03	-
8.75	1.00E-01	4.82E-04	9.77E-03	2.24E-03	8.71E-04	-
11.50	4.30E-02	3.07E-04	6.46E-03	1.45E-03	5.25E-04	-
15.50	2.50E-02	1.77E-04	3.63E-03	8.13E-04	3.09E-04	-
21.00	1.67E-02	1.10E-04	2.14E-03	4.57E-04	1.86E-04	-
28.00	1.59E-02	7.68E-05	1.59E-03	3.09E-04	1.29E-04	-
37.00	5.55E-03	4.40E-05	8.32E-04	2.00E-04	7.24E-05	-
50.00	8.08E-03	3.07E-05	6.17E-04	1.32E-04	4.07E-05	-

TABLE X–15. INDIVIDUAL ORGAN DOSES FOR EFFECTIVE DOSE/GROUNDSHINE, 2 DAY INTEGRATION TIME, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	3.86E+00	7.91E-02	1.32E+00	4.57E-01	2.14E-01	6.61E-07
1.00	1.43E+00	2.15E-02	3.98E-01	1.20E-01	5.01E-02	-
1.50	8.74E-01	1.23E-02	2.24E-01	6.92E-02	2.82E-02	-
2.10	7.91E-01	7.25E-03	1.32E-01	3.72E-02	1.55E-02	-
2.80	3.99E-01	4.54E-03	8.71E-02	2.34E-02	9.77E-03	-
3.70	3.62E-01	3.36E-03	7.08E-02	1.62E-02	6.31E-03	-
4.90	2.03E-01	2.12E-03	4.27E-02	9.77E-03	3.89E-03	-
6.55	1.58E-01	1.30E-03	2.75E-02	5.62E-03	2.46E-03	-
8.75	1.74E-01	8.18E-04	1.66E-02	3.80E-03	1.45E-03	-
11.50	7.44E-02	5.22E-04	1.10E-02	2.46E-03	8.71E-04	-
15.50	4.32E-02	3.01E-04	6.31E-03	1.38E-03	5.13E-04	-
21.00	2.88E-02	1.87E-04	3.63E-03	7.59E-04	3.09E-04	-
28.00	2.73E-02	1.31E-04	2.75E-03	5.13E-04	2.14E-04	-
37.00	9.50E-03	7.48E-05	1.41E-03	3.31E-04	1.23E-04	-
50.00	1.41E-02	5.23E-05	1.05E-03	2.19E-04	6.92E-05	-

TABLE X–16. INDIVIDUAL ORGAN DOSES FOR EFFECTIVE DOSE/GROUNDSHINE, 7 DAY INTEGRATION TIME, Sv

RADIUS (km)	MAX. DOSES	MEAN DOSES	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	8.45E+00	1.71E-01	2.82E+00	9.77E-01	4.57E-01	1.41E-06
1.00	3.14E+00	4.66E-02	8.71E-01	2.63E-01	1.07E-01	2.09E-08
1.50	1.92E+00	2.67E-02	4.79E-01	1.48E-01	6.03E-02	-
2.10	1.72E+00	1.58E-02	2.88E-01	8.13E-02	3.39E-02	-
2.80	8.81E-01	9.89E-03	1.91E-01	5.13E-02	2.09E-02	-
3.70	7.91E-01	7.31E-03	1.51E-01	3.47E-02	1.38E-02	-
4.90	4.44E-01	4.62E-03	9.33E-02	2.14E-02	8.51E-03	-
6.55	3.47E-01	2.83E-03	5.89E-02	1.23E-02	5.25E-03	-
8.75	3.82E-01	1.79E-03	3.63E-02	8.32E-03	3.16E-03	-
11.50	1.63E-01	1.14E-03	2.40E-02	5.37E-03	1.91E-03	-
15.50	9.47E-02	6.59E-04	1.38E-02	2.95E-03	1.12E-03	-
21.00	6.34E-02	4.10E-04	7.94E-03	1.66E-03	6.76E-04	-
28.00	5.97E-02	2.86E-04	6.03E-03	1.12E-03	4.68E-04	-
37.00	2.08E-02	1.64E-04	3.09E-03	7.24E-04	2.69E-04	-
50.00	3.14E-02	1.15E-04	2.29E-03	4.79E-04	1.51E-04	-

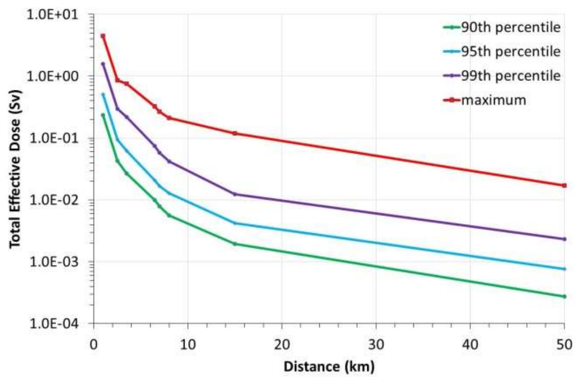

FIG. X–6. Total effective dose (1-day integration for deposited activity) for different percentiles

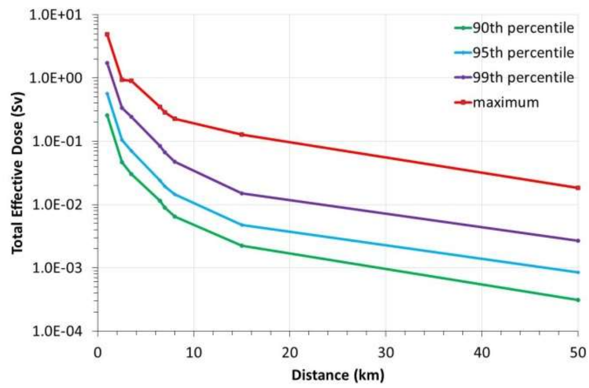

FIG. X–7. Total effective dose (2-day integration for deposited activity) for different percentiles

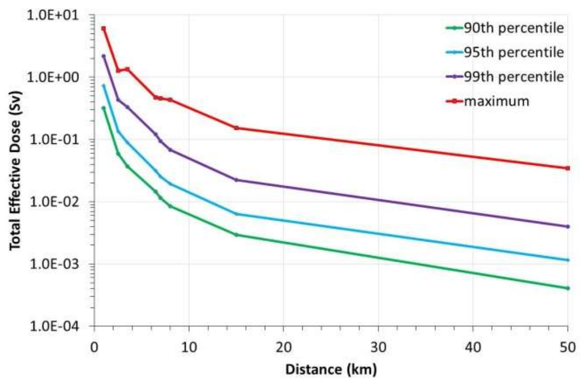

FIG. X–8. Total effective dose (7 day integration for deposited activity) for different percentiles

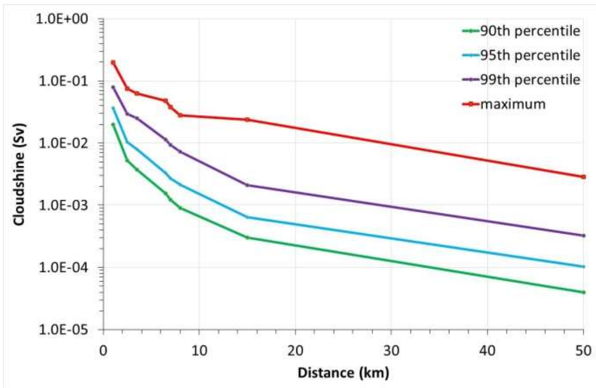

FIG. X–9. Cloud-shine dose for different percentiles

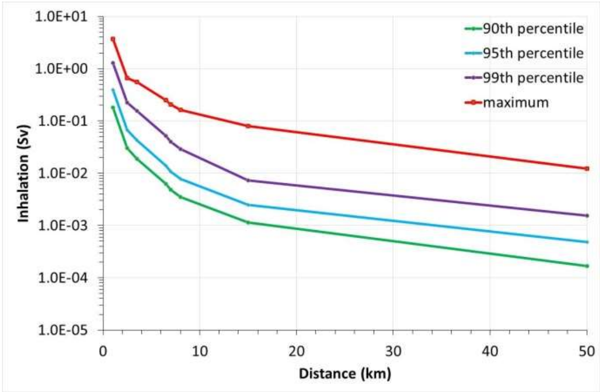

FIG. X–10. Inhalation dose for different percentiles (adult)

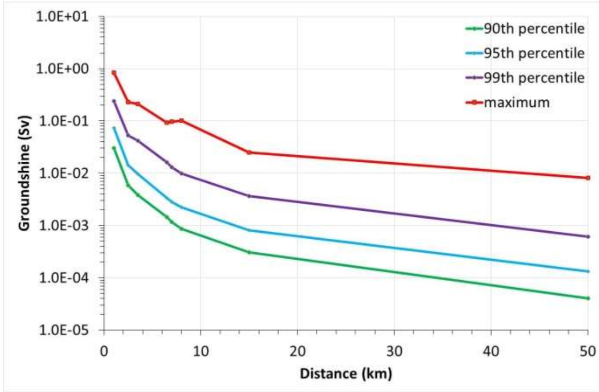

FIG. X–11. Ground-shine dose (1-day integration for deposited activity) for different percentiles

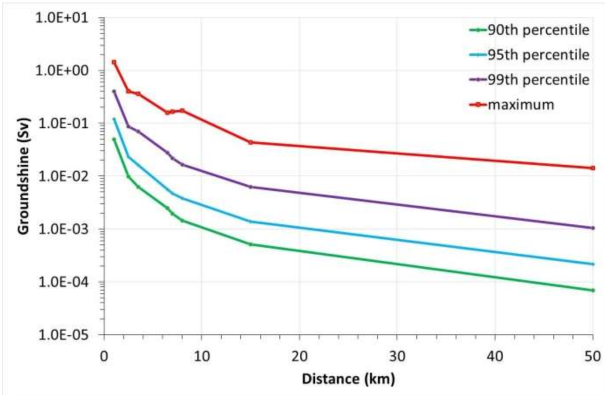

FIG. X–12. Ground-shine dose (2-day integration for deposited activity) for different percentiles

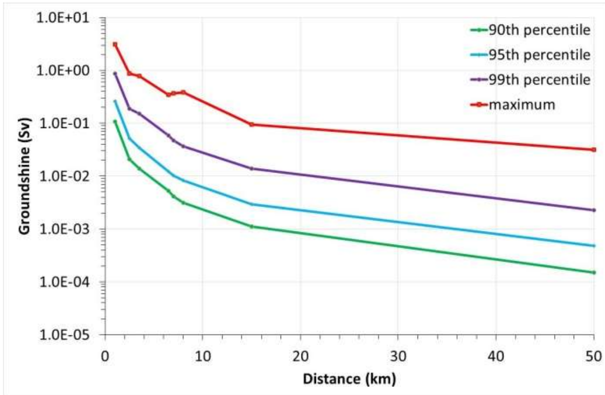

FIG. X–13. Ground-shine dose (7day integration for deposited activity) for different percentiles

In the UK regulatory context, for the assessment against Targets 7 and 9, the results above would not be used. The individual and societal risk need to be calculated and different assumptions to those used above need to be made. For example, the risk calculations need to be performed for a 50-year integration period for deposited dose but normal occupancy (fraction of time spent indoors) can be assumed.

Therefore another set of PC-COSYMA calculations was performed and the results, as required for an assessment against Targets 7 and 9, are given in Tables X–17 and X–18. These calculations do take account of the population distribution and wind rose as supplied for the exercise.

Conditional individual risks are given at various distances from the release site to illustrate how the individual risk varies with distance over the range of interest. Assessment against Target 7 for individual risk requires the risk to the most exposed person to be calculated; that is the most exposed person of the population groups identified. The closest habitation listed in Table 1 in Section 3.1 is at 1 km; therefore, the value for the individual risk at 1 km is used here as the main reference point for the assessment against Target 7.

The conditional individual risks given in Table X–17 are the sum of the conditional individual risk of early (deterministic) health effects leading to fatality and conditional individual risk of late (stochastic) health effects leading to fatality. For the accident scenario given here the conditional individual risk of early (deterministic) health effects leading to a fatality is zero. It is noted that the UK assessment results presented here are based on no off-site protective actions being considered. However, for a realistic assessment against Targets 7 and 9, minimal off-site protective actions would be considered, i.e. food restrictions to comply with legally mandated CFILs (as discussed above) although ingestion dose is not considered here as food production data were not available.

TABLE X–17. CONDITIONAL INDIVIDUAL RISK OF HEALTH EFFECTS (DETERMINISTIC AND STOCHASTIC) LEADING TO FATALITY

RADIUS (km)	MAX. RISK	MEAN RISK	FRACTILE 99.0	FRACTILE 95.0	FRACTILE 90.0	FRACTILE 50.0
0.40	3.52E-01	9.53E-03	1.55E-01	5.50E-02	2.69E-02	3.89E-05
1.00	1.28E-01	2.59E-03	4.68E-02	1.51E-02	6.61E-03	1.66E-06
1.50	7.86E-02	1.48E-03	2.63E-02	8.51E-03	3.63E-03	-
2.10	7.73E-02	8.49E-04	1.51E-02	4.68E-03	2.04E-03	-
2.80	3.43E-02	5.37E-04	1.02E-02	2.95E-03	1.26E-03	-
3.70	3.43E-02	3.89E-04	7.41E-03	2.00E-03	8.13E-04	-
4.90	1.86E-02	2.45E-04	4.79E-03	1.18E-03	5.13E-04	-
6.55	1.38E-02	1.47E-04	3.09E-03	7.08E-04	3.16E-04	-
8.75	1.36E-02	9.08E-05	1.74E-03	4.68E-04	1.91E-04	-
11.50	5.74E-03	5.66E-05	1.10E-03	2.63E-04	1.18E-04	-
15.50	3.83E-03	3.18E-05	6.03E-04	1.51E-04	6.76E-05	-
21.00	2.44E-03	1.96E-05	3.47E-04	9.33E-05	4.17E-05	-
28.00	2.24E-03	1.35E-05	2.57E-04	6.31E-05	2.88E-05	-
37.00	8.27E-04	8.09E-06	1.45E-04	4.27E-05	1.66E-05	-
50.00	1.30E-03	5.64E-06	1.07E-04	2.82E-05	9.55E-06	-

The assessment against Target 7 is then performed using the product of the conditional individual risk at 1 km (mean value) and the frequency for each release category, summed over all release categories/faults considered in the PSA.

For the scenario considered in this exercise, the estimated frequency is stated in Section 3.2 as $1 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$ /a. Combining this with the conditional mean risk at 1 km from Table X–17 above of $2.59 \cdot 10^{-3}$ gives the individual risk to the most exposed person from this one scenario as $2.6 \cdot 10^{-9}$ per year to $5.2 \cdot 10^{-9}$ per year. This is well below the BSO of 10^{-6} per year; however, the risks from all other accident scenarios for this reactor and from any other facilities on the same site need to be summed to get total individual risk.

For comparison against Target 9, the probability of greater than 100 fatalities – both short term (deterministic) and the notional late fatalities (stochastic) – for on-site workers and in the population needs to be calculated. No details of the on-site workforce were available but since in this scenario the release was elevated (35 m) their exposure should not be significant.

The results for this scenario shown in Table X–18 below – based on the population and meteorological data supplied – indicate that the 100 fatalities threshold has been exceeded for the higher percentiles but not for the mean number.

TABLE X–18. STATISTICAL QUANTITIES OF THE NUMBER OF DETERMINISTIC (EARLY) AND STOCHASTIC (LATE) HEALTH EFFECTS IN THE POPULATION (MORTALITY)

Health effects	Early mortality	Late mortality	Total
MAX. NUMBER	0.00E+00	1.56E+02	1.56E+02
MEAN NUMBER	0.00E+00	1.69E+01	1.69E+01
FRACTILE 99.0	0.00E+00	1.48E+02	1.48E+02
FRACTILE 95.0	0.00E+00	9.12E+01	9.12E+01
FRACTILE 90.0	0.00E+00	5.25E+01	5.25E+01
FRACTILE 50.0	0.00E+00	5.13E+00	5.13E+00
Probability of exceeding 100 fatalities			3.47E-02

The conditional probability of exceeding 100 fatalities for this scenario is given in Table X–18 as $3.47 \cdot 10^{-2}$. Combining this with the scenario frequency gives a probability of exceeding 100 fatalities of $3.5 \cdot 10^{-8}$ to $6.9 \cdot 10^{-8}$ per year. This is below the Target 9 BSO of 10^{-7} per year but is a significant fraction of it for only one scenario (35-70%). Again, as for Target 7, the risks from all other accident scenarios for this reactor and from any other facilities on the same site would need to be summed to get the total risk for comparison with the Target 9.

Of course, any judgement on the acceptability of this NPP would be a matter for the regulators. However, when assessed against ONR's Targets using methodologies and assumptions typically applied in the UK for Targets 7, 8, and 9, and interpreting ONR's guidance, the conclusion of the assessors in this exercise is that the results are below the BSL for all Targets and only for Target 8 is the BSO exceeded. A full analysis would have to be performed looking at a full spectrum of accident scenarios. A justification would also need to be made to show that the risks had been reduced to a level as low as reasonably practicable (ALARP); the standards expected would be higher for a new plant. In addition, if there were other facilities on the site such as other units, the risks for these would also need to be included for assessment against Targets 7 and 9 which are for the site as a whole.

In the discussion above, the need for a full assessment rather than just examining a single scenario is mentioned several times. To give some idea of the way the results of the assessments for individual scenarios would be combined together Figures X–14, X–15, and X–16 show some fabricated results for Targets 8, 7, and 9 respectively.

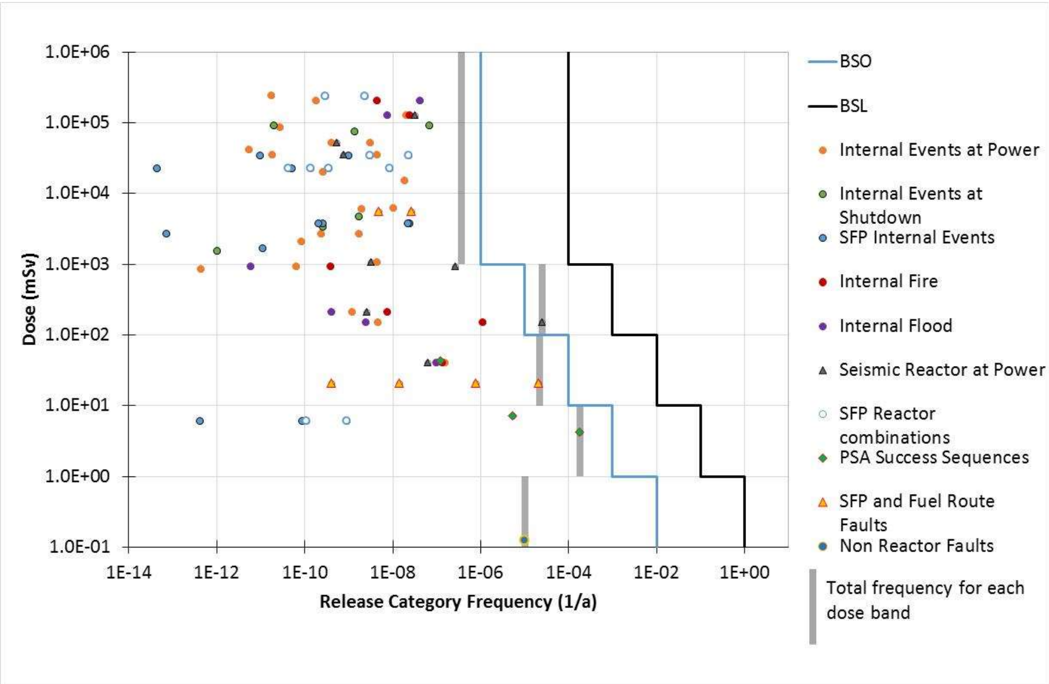

FIG. X–14. Fabricated Target 8 Assessment Results for Illustrative Purposes (50 year integration time)

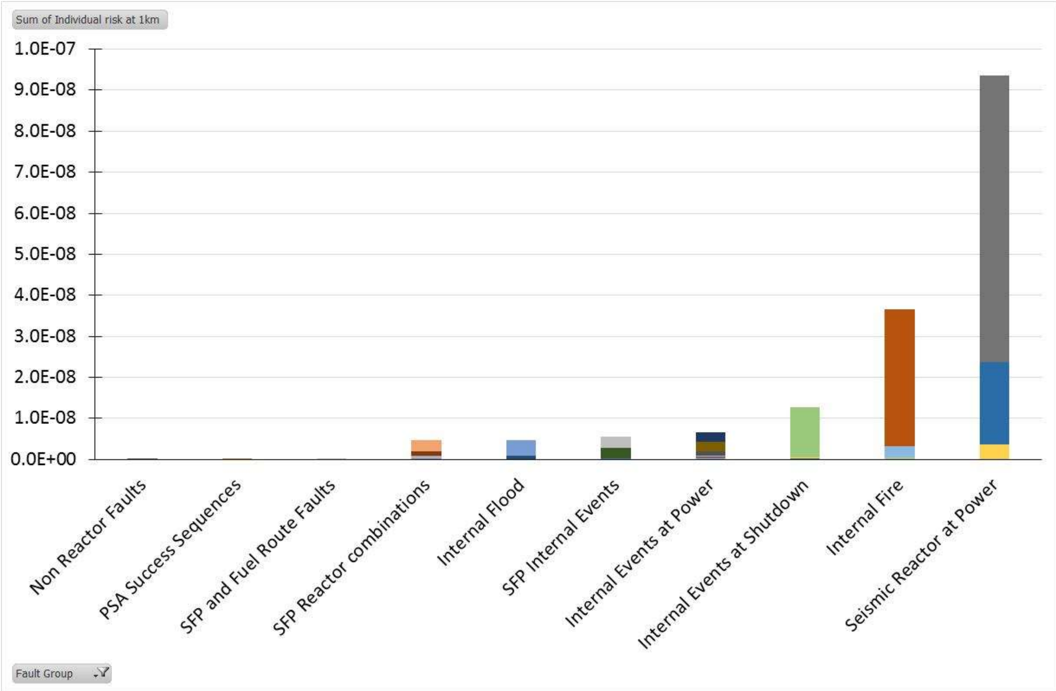

FIG. X–15. Fabricated Target 7 Assessment Results for Illustrative Purposes

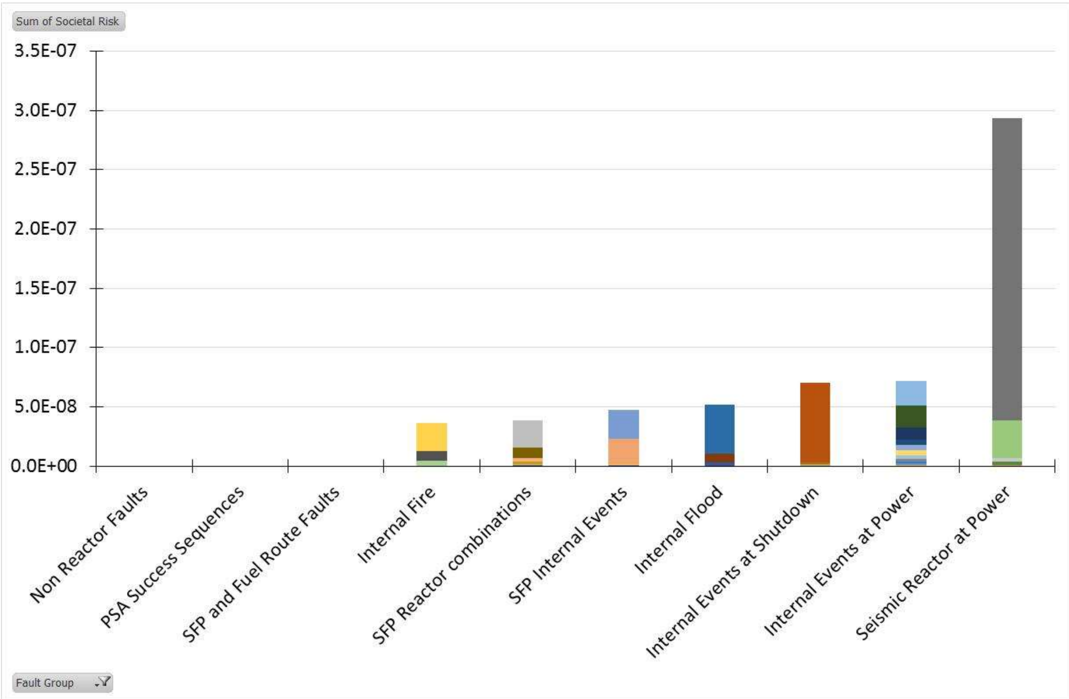

FIG. X–16. Fabricated Target 9 Assessment Results for Illustrative Purposes

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ABBREVIATIONS

BDBA	beyond design basis accident
CCDF	complementary cumulative distribution functions
DBA	design basis accident
LER	limiting emergency release
LWR	light water reactor
MMD	Mass Median Diameter
NES	nuclear energy system
NPP	nuclear power plant
PSA	probabilistic safety analysis
PWR	pressurized water reactor
SDRC	significant degradation of the reactor core
SOARCA	state-of-the-art reactor consequence analysis

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