Expert judgement elicitation on probabilistic accident consequence codes

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ABSTRACT: The development of two probabilistic accident consequence codes sponsored by the European Commission and the United States Nuclear Regulatory Commission, COSYMA and MACCS respectively, was completed in 1990. These codes estimate the risks and other endpoints associated with accidents from hypothesised nuclear installations. In 1991, both Commissions sponsored a joint project for an uncertainty analysis of these two codes. The main objective of this joint project was to systematically derive credible and traceable probability distributions for the respective code input variables. These input distributions will subsequently be used in two uncertainty analyses for each code separately. A formal expert judgement elicitation and evaluation process was used as the best available technique to accomplish that objective. This paper describes the process and some of the findings of the eight expert judgement exercises performed under the joint study. Reference is made to a Special Issue of *Radiation Protection Dosimetry* (Goossens and Kelly 2000).

1 INTRODUCTION

1.1 *Expert judgement study*

The U.S. Nuclear Regulatory Commission (USNRC) and the Commission (EC) began formulating a joint uncertainty analysis on their respective codes, MACCS (Chanin *et al* 1990) and COSYMA (Kelly 1991), in 1991. Although consequence uncertainty analyses have been performed in the past for the predecessors of both codes, the probability distributions utilised were assembled primarily by the consequence code developers rather than by phenomenological experts in the many different scientific disciplines that comprise a radiobiological consequence analysis.

Both commissions were aware of the key role of uncertainty in decisions involving prioritisation of activities and research. They initiated a comprehensive assessment of the uncertainty in consequence code predictions used for risk assessments and regulatory purposes. Identifying benefits, such as gaining access to a greater pool of experts, combining experience and knowledge in the areas of uncertainty analysis, formal expert judgement elicitation and consequence analysis, and the potentially greater technical and political acceptability of a joint project, the two commissions decided to enter this collaborative effort.

The main objective of this effort was to systematically obtain much of the quantitative information necessary for performing uncertainty analyses for their respective consequence codes from the phenomenological experts by using a state-of-the-art formal expert judgement elicitation and evaluation process. Therefore eight different panels were established to cover the different areas of expertise involved (Tables 1 and 2). The physical processes were sufficiently similar for MACCS and COSYMA, so that the required input distributions could be developed jointly in a collaborative effort. The countermeasures inputs were recognised to be different for both codes. Therefore both commissions decided to address the countermeasures assessments separately, but with the same formal expert judgement process. The expert judgement study has been summarised in Goossens and Harper (1998).

This paper describes the project (the expert judgement study and the selection of parameters for the uncertainty analysis of the COSYMA code). Section 2 explains the formal expert judgement approach with the various procedures to be taken to achieve robust assessments from experts. Section 3

provides an overview of the elicitation variables and the questions posed to the experts. In total, 1920 questions were posed to the experts. For further details the authors refer to the relevant report mentioned in Table 2. Section 4 describes the selection process of the experts for each field of interest and provides a flavour of the results. Section 5 highlights the selection of important parameters for the uncertainty analysis of the COSYMA code. Finally, section 6 draws the main conclusions on the project as a whole. Currently also the USNRC is undertaking an uncertainty analysis for their accident consequence code MACCS, in which the expert assessments are being used.

Table 1. Overview of expert judgement panels

Panel number	Panel name
1	Atmospheric dispersion
2	Deposition (dry and wet)
3	Behaviour of deposited material and its related doses
4	Foodchain on animal transfer and behaviour
5	Foodchain on plant/soil transfer and processes
6	Internal dosimetry
7	Early health effects
8	Late health effects

Table 2. Overview of expert judgement reports

Panel number	NUREG/CR	EUR	Year
1	6244	15855	1995
1	-	15856	1995
2	6244	15855	1995
2	-	15856	1995
3	6526	16772	1997
4	6523	16771	1997
5	6523	16771	1997
6	6571	16773	1998
7	6545	16775	1997
8	6555	16774	1997

1.2 *Uncertainty analysis of the COSYMA code*

The distributions on the input parameter values were obtained from the expert judgement elicitations. The overall uncertainty analysis of the COSYMA code was preceded by analyses of the uncertainty in the main modules of the code. One of the main aims of these submodule analyses was to identify those model parameters contributing most to the uncertainties of the code endpoints. This was of particular interest for two reasons:

- the ranking of model parameters according to their contribution to uncertainties gives insight and guidance for further data and model improvements;
- computational limitations of storage and CPU times mean that the overall uncertainty analysis considering the 376 model parameters considered in the submodule analyses would be impractical.

In this way, 186 model parameters (out of the 1920 variables posed to the experts) were identified as relevant for the overall uncertainty and sensitivity analyses. The results are published in EUR reports (Table 3).

Three different source terms (UK1, CB2 and DBA), taken from PRA level 3 analyses of the Hinkley Point PWR, were considered in the analyses. They encompass a wide range of characteristics as can be seen from Table 4, which gives the release fractions of the key nuclide groups. The whole study has been published in a Special Issue of the journal *Radiation Protection Dosimetry* (Goossens and Kelly, 2000).

Table 3. Overview of the COSYMA code uncertainty analysis

EUR number	Report name
18822	Uncertainty from the atmospheric dispersion and deposition module
18823	Uncertainty from the food chain module
18824	Uncertainty from the health effects module
18825	Uncertainty from the dose module
18826	Overall uncertainty analysis
18827	Methodology and processing techniques

Table 4. Main characteristics of the source terms considered in the uncertainty analysis.

Source term	Fraction of core inventory released			
	Xe-Kr	I	Cs-Rb	Te-Sb
UK1	9E-01	7E-01	5E-01	3E-01
CB2	1E-02	2E-03	8E-03	8E-06
DBA	1E-07	1E-06	1E-06	1E-08

2 EXPERT JUDGEMENT APPROACH

2.1 *Principles*

Two important principles with respect to the application of expert judgement were established for this joint project:

- the elicitation questions (i.e., the questions on variables for which the experts provided uncertainty distribution data) would be based on the existing models already used in COSYMA and MACCS because both the EC and the USNRC were primarily interested in

the uncertainties in the predictions of these codes, and

- the experts would only be asked to assess physical quantities which could be hypothetically measured in experiments.

Since many code inputs are mathematical constructs resulting from fitting a particular function (model) to the available experimental data, eliciting assessments on physical quantities rather than these mathematical constructs (code inputs) avoids ambiguity and disagreements in variable definitions. In addition, assessments that are formulated for physical quantities are deemed to have a much wider application beyond the joint study.

Formal expert judgement elicitations were used to develop distributions for important consequence analysis input variables for which the experimental database did not provide all the necessary information, and the analytical models used for extrapolation were not indisputably correct. To ensure the quality of the elicited information, a formal expert judgement elicitation process, built on the process developed for and used in the NUREG-1150 study (USNRC 1990), was followed. Refinements were implemented based on experience and knowledge (Cooke 1991) gained from several formal expert judgement elicitation exercises performed in Europe by Delft University of Technology as well as in the U.S. (Hora and Iman, 1989). This latter paper provides an overview of the method used in NUREG-1150. This expert judgement method emphasises the discussions with individual experts on the phenomena to be elicited.

The formal expert judgement elicitation process that was implemented in the joint project is briefly explained in section 2.3. It formed a base for the Procedures Guide for Structured Expert Judgement published as EUR 18820 (Cooke and Goossens, 2000).

2.2 *Objectives of the study*

The objectives of the project were:

(1) to formulate a generic, state-of-the-art methodology for uncertainty estimation which is capable of finding broad acceptance;

(2) to apply the methodology to estimate uncertainties associated with the predictions of probabilistic accident consequence codes (COSYMA and MACCS) designed for assessing the consequences of commercial nuclear power plant accidents;

(3) to better quantify and obtain more valid estimates of the uncertainties associated with probabilistic accident consequence codes, thus enabling more informed judgements to be made in the areas of risk comparison and acceptability and therefore to help set priorities for future research.

Since the elicitation process is very resource intensive, the importance of clear understanding of the objectives, scope and constraints of each individual expert panel were fully recognised. Although the project focussed on the COSYMA and MACCS codes, application to other probabilistic accident consequence codes should be possible as well.

2.3 *Formal steps in expert judgement*

Defining elicitation variables and developing elicitation questions. Elicitation variables are the variables presented to the experts for assessments. Based on past sensitivity analyses (Ritchie *et al* 1984, Fischer *et al* 1990, Jones *et al* 1995), important code inputs that had significant contributions to the endpoints' uncertainties were identified. Endpoints are, among others, individual and collective risks and number of deaths and incidence of early and late health effects. When the important code inputs were not physical quantities, other variables, physical code output variables, were selected as elicitation variables. Elicitation questions were then developed for the elicitation variables, applying post-processing methods to generate the needed code input distributions from the assessed elicitation variables. The initial conditions to match the level of detail considered in MACCS and COSYMA were specified, as also the boundary conditions specifying which phenomena should or should not be considered in the uncertainties to be assessed. Examples of elicitation variables, questions and conditions for the various panels are provided in section 3.

Dry run exercise. Dry runs were conducted with experts in the various fields of interest to test the clarity ("clairvoyance test") of the elicitation questions, and the reasonableness of the exercise ("is the number of questions doable?"). Feedback from the dry run experts was factored into the modified questionnaires.

Selecting experts. The objective for each panel was to engage the best experts from various viewpoints in the phenomenological areas of interest. A large list of experts was compiled from the literature, and by requesting nominations from experts and organisations. The experts were contacted and sent in curricula vitae (CVs). Impartial selection panels both in the U.S and Europe were formed. The CVs were evaluated and experts were chosen on the same set of established criteria: reputation in the relevant fields, number and quality of publications, familiarity with the uncertainty concepts, diversity in background,

balance of viewpoints, interest in the project, and availability to undertake the task in the prescribed time-scale. The selection of the expert panels is descibed in section 4.

Selecting normative specialists. The main responsibility of a normative specialist is to conduct the expert elicitation sessions. It is imperative that the normative specialist is able to assist the experts in encoding subjective assessments into coherent probability distributions during the elicitation sessions. The normative specialists were selected for the project based on their experience with other expert judgement exercises in the past. They were part of the project staff and they assisted in drafting the elicitation questions for the panels.

First expert meeting. The experts were convened for a first meeting where they were briefed on the purposes of the study, introduced to the relevant material on the consequence codes, and provided training in probabilistic assessments. In addition, the complete set of elicitation variables and questions were reviewed by and discussed among the experts and project staff, and, if needed, further modifications were added. That was to ensure that the experts felt comfortable with and would respond to the same questions. The initial and boundary conditions were also discussed at the first meeting.

Performing assessments. After the first meeting, the experts prepared their responses to the elicitation questions (during a period of 6 to 10 weeks). They were free to use any modelling techniques they believed were appropriate to assess the problems. For each elicitation variable, the experts provided three quantile points (5%, 50%, 95%) representing their uncertainty. No distribution shapes were required. In addition to the quantitative judgements, each expert also provided a written rationale to document the sources and explain the approaches used in arriving at the assessments. All data and rationales are (anonymously) reported in the references mentioned in table 2.

Second expert meeting. The experts were reconvened for a second session (except the food chain and external dose panels) where they shared approaches without giving their quantitative assessments during a common session. Individual elicitation sessions were held thereafter. During these individual sessions, each expert worked with a normative specialist and a project specialist on the particular field of interest, to arrive at quantitative assessments. The dependence among the various elicitation variables was elicited to facilitate the future uncertainty analyses for the codes, when all distributions will be linked and propagated through the codes.

Processing the judgements. The set of multiple elicited quantile points was aggregated to form a single set of quantile points for the corresponding elicitation variables. The processing tool for aggregating the individual assessments was the computer code EXCALIBR (Cooke and Solomatine 1992). Throughout the study, the term "range factor" is used to express the ratio between the 95th and the 5th quantile point of the distribution, which is used as a measure of uncertainty.

For each variable, non-negative weights summing to one were assigned to the cumulative distribution function (CDF) developed for each individual expert assessment, and the aggregation was accomplished by taking the weighted sums of the cumulative probabilities for each variable with an equal weighting scheme. EXCALIBR output the three quantile points (5%, 50%, 95%) from the combined assessment (combined CDF) for each variable.

In an equal weighting aggregation scheme, an equal weight is assigned to each expert. If N experts have assessed a given set of variables, the weights for each density are $1/N$; hence for variable i in this set the decision maker's CDF is given by:

$$F_{ewdm,i} = (1/N) \sum_{j=1}^{N} f_{j,i}$$

where $f_{j,i}$ is the cumulative probability associated with expert j's assessment for variable i.

EXCALIBR contains three different weighting schemes for aggregating the distributions elicited from the experts. These weighting schemes are equal weighting, global weighting, and item weighting. Global and item based weighting techniques are termed performance-based weighting techniques because weights are developed based on an expert's performance on elicitation variables, for which the values measured in existing (experimental) data are known by the project staff, but not by the experts. This results in non-equal weights for the individual expert's assessments in the aggregation process (Cooke 1991, Goossens *et al* 1996).

Investigating the different weighting schemes was not the objective of this joint effort. A programmatic decision was therefore made to assign all experts equal weight, i.e., all experts on each respective panel were treated as being equally credible. One of the primary reasons the equal weighting aggregation method was chosen for this study was to insure the inclusion of different modelling perspectives in the aggregated uncertainty distributions. However, additional information was elicited from the experts to allow the application of performance based weighting

schemes to the elicited distributions. For the dispersion and deposition panels the results are reported in EUR 15856 (see Table 2).

3 ELICITATION VARIABLES AND QUESTIONS

3.1 *In general*

For all fields of interest listed in table 1, it was impossible for the experts to provide quantitative assessments over the complete range of interest for each individual variable. That would require an unfeasibly large consequence uncertainty study. It was therefore necessary to design a case structure that would cover the variable space so that the project could interpolate and extrapolate to all areas necessary to perform consequence uncertainty studies. Each following subsection describes the scope of the case structure for each expert panel. Examples of elicitation variables and questions are provided for each field of interest.

3.2 *Atmospheric dispersion*

For the dispersion questions, the case structure consisted of many perturbations of downwind distances and the synoptic weather conditions at the source. After several iterations, a condensed version of the case structure was developed. Elicitation variables were downwind concentration ratios and horizontal plume spread. Basically, each case represented a single accident with the wind blowing from one direction during the whole dispersion provess.

In total, 77 questions were asked, of which

- 20 questions on plume centerline concentration ratios,
- 34 questions on plume off center concentration ratios,
- 20 questions on plume spread,
- 3 questions on far field characteritics.

An example of a question is:

Given a temperature lapse rate, wind speed and standard deviation of wind direction, surface roughness, release height and sampling time, what is the centerline concentration ratio at five distances from the source in the direction of the wind, units [s m^{-3}]?

3.3 *Deposition*

For the deposition questions, the case structure consisted of many permutations of different surface types, particle sizes, chemical types, rain intensities (for wet deposition) and rain duration (for wet deposition).

For dry deposition four surface types were considered: urban, meadow, forest, and skin. The particulate forms for which data were elicited were: aerosols (ranging over 5 spherical particle sizes of 0.1 to 10 μ diameter AMAD), elemental iodine and methyl iodide. The experts were instructed to include any effects not specified in their uncertainty distributions, such as humidity, ambient air temperature, chemical reactions, vapour-to-particle conversion, and variations within surface types.

For wet deposition, the particulate forms were similar. Two rain intensities cases were considered: average rain intensities over one hour, and average continuous rain intensities over ten minutes. Here too, experts were asked to include effects such as chemical reactions, electrostatic effects, vertical profiles and rain rate. Rain was assumed to be present over the entire area, a factor which the experts needed not to take into account.

In total, 87 questions were asked, of which

- 56 questions on dry deposition velocities for aerosols (5 diameters), elemental iodine and organic iodide,
- 20 questions on fractions washed out for wet deposition for aerosols (5 diameters), elemental iodine and organic iodide.

Two examples of questions are:

[1] Given a wind speed of 2 m s^{-1} (5 m s^{-1}), what is the dry deposition velocity for elemental iodine on an urban surface (meadow, forest, skin), units [cm s^{-1}]?

[2] What is the fraction of elemental iodine removed by rain given rainfall and period (0.3 and 2.0 mm during 1 hour, 0.05 mm and 0.33 mm and 1.67 mm during 10 minutes continuously)?

3.4 *Behaviour of deposited material and its related doses*

The case structure is designed to elicit external dose variables, which predict the doses to individuals in the population from radioactive material deposited onto the ground. As the models are based on adults who are outdoors in an open area, the elicitation questions were formulated likewise. To account for the scaling factors used in the consequence codes for people living in urban and suburban areas, additional questions were incorporated. The results of these outdoor dose models are commonly known as "dose conversion factors" (IAEA 1994) and they relate the initial deposited activity on the ground to the dose as a function of time following initial deposition. Gamma dose rates and effective dose rates as well as integrated effective doses to adults were elicited over time following initial deposition. The results are applied to predict outdoor doses.

The dose indoors is predicted by reducing the outdoor dose using a location or shielding factor (for buildings, basements and cars and buses). For the inhalation dose delivered to individuals indoors relative to that outdoors, a reduction in the time-integrated air concentration indoors relative to that outdoors was elicited. Furthermore, questions were asked on the fraction of time that the average adult spends in each location under consideration.

In total, 505 questions were asked, of which

- 69 questions on γ dose rates above a uniform, flat and open lawned area (Gy/sec),
- 90 questions on effective dose rates to an adult outdoors (Sv/sec),
- 75 questions on integrated adult effective doses (Sv),
- 14 questions on similarity between nuclides wrt external dose,
- 175 questions on location factors for shielding in an open lawned area shortly after an initial uniform deposit,
- 8 questions on time-integrated air concentration ratios indoors to outdoors,
- 7 questions on similarity between nuclides wrt inhalation dose,
- 67 questions on fractions of average population (in own country.

Examples of questions are:

[1] What is the γ dose rate in air at 1 meter above a uniform, flat and open lawned area at the time of deposit and at several times following the initial dry (wet, average) deposition of 1 Bq/m^2 of ^{95}Zr/^{95}Nb (^{106}Ru/^{106}Rh-, ^{131}I, ^{137}Cs/^{137m}Ba) to the ground?

[2] What is the ratio of the effective dose in Sv received by an adult indoors to that received outdoors in an open lawned area shortly after an initial deposit of 1 Bq/m^2 of ^{95}Zr (^{106}Ru, ^{131}I, ^{137}Cs, ^{144}Ce) to the ground (lawn)?

Indoors means:

** inside a low (medium, high) shielding building*

** inside the basement of a single family house (multi-storey building)*

** in a typical car (bus) on a suburban street.*

3.5 *Foodchain: animal transfer and behaviour*

The transfer of radionuclides to animals can be considered in two stages: (1) the intake of radionuclides by ingestion and inhalation, and (2) the subsequent metabolism of these radionuclides and in particular their transfer to animal tissues and animal products that are consumed by man. Since ingestion is the most important route of intake for animal uptake, inhalation by animals was not considered for expert elicitation (only caesium, strontium and iodine).

The rate of intake for ingestion is a very important parameter. Ingestion rates depend on the grazing habits of the animal and whether they are free-grazing or provided with feedstuffs. The metabolism of animals was represented by three physiological mechanisms: (1) the absorption of the nuclide into the bloodstream and body fluids from the gastrointestinal tract; (2) the distribution and recycling of the nuclide between the circulating fluids and the body organs and tissues; and (3) the excretion of the nuclide from the body, including secretion into milk, and for chickens, transfer to eggs.

Elicitation variables were animals' consumption rates, soil consumption rates, availability of ingested feed, transfer to meat, eggs and milk, and biological half-lifes in animals.

In total, 115 questions were asked, of which

- 30 questions on animals' consumption rates
- 4 questions on animals' soil consumption rates
- 9 questions on availability of ingested feed
- 10 questions on transfer to meat
- 3 questions on transfer to eggs
- 9 questions on transfer to milk
- 15 questions on biological half-life in animals.

An example of a question is:

Consider an animal (dairy cows, beef cattle, sheep, pigs, poultry) which is continuously fed Sr or Cs at a constant daily rate under field conditions. What is the observed equilibrium transfer of activity, F_f to the meat of the animal for each element? The quantity should be expressed as the fraction of the daily intake which is in kg of animal's meat, once an equilibrium situation is reached, units [d kg^{-1}].

3.6 *Foodchain: plant/soil transfer and processes*

The main transfer mechanisms included in a food chain model are: (1) migration of radionuclides in soil; (2) root absorption into plants from soil; (3) surface contamination of plants; and (4) loss from the surface and subsequent translocation to the edible part of the plant.

Elicitation variables were soil migration times at fixed depths, fixation to soil with time after deposition (fraction unavailable for uptake), root uptake concentration factors, interception factors, resuspension factor, retention times on surfaces, and concentration in grain at harvest and crops. Since the consequence codes do not specify the type of soil in the calculations and warrant a generic application for all relevant circumstances, the concept of generic soil was introduced. Experts had to consider all types of soil where crops could grow with the exeption of soils above the arctic circle and mediterranean soils, and had to take the consequent variation into account

in their assessments. Apart from that, experts were expected to assess their uncertainty on the average value of the elicitation variable, and not to take account of the spread of the variable in their uncertainty distribution.

In total, 244 questions were asked, of which

- 32 questions on soil migration
- 32 questions on fixation of Cs and Sr in soil
- 160 questions on root uptake concentration factors
- 5 questions on interception factors
- 2 questions on resuspension factors
- 5 questions on retention times
- 4 questions on concentrations in grain at harvest
- 4 questions on concentration in root crops.

An example of a question is:

Following a single deposit, what are the concentrations, units [Bq kg^{-1}], at maturity of Sr and Cs in grain, green vegetables, pasture grass, root crops and potatoes which are grown on (generic [in Europe, in the US], sandy, highly organic) soil that contains 1 Bq kg^{-1} of Sr and Cs as a function of time following deposition?

3.7 *Internal dosimetry*

Doses are calculated within accident consequence codes either for presentation as an end-point of the assessment or for use in further calculations of health effects. Both individual and collective doses can be evaluated and include external exposures and internal exposures due to the inhalation and ingestion of radionuclides.

The main areas in which elicitation questions were framed were: 1) inhalation by persons directly, 2) ingestion, 3) systemic distribution and retention, and 4) organ dose coefficients. While the first three provide information from which dose coefficients can be calculated and are in principle measurable quantities, organ dose coefficients are the required input to the consequence codes and are generally not directly measurable or observable quantities. Although much of the background thinking is driven by ICRP-publications (e.g., ICRP 1993, 1995), the questions were therefore phrased independently of the models used in the ICRP-community.

For inhalation by persons directly the experts were asked to consider exposure to unit air concentration of radioactive aerosols (say 1 Bq m^{-3}) for a short duration (say 1 minute). Questions addressed primarily adult exposures, but with additional information sought for 5 year old children. The parameters elicited were estimates of ventilation rates, total initial deposition in the respiratory tract as a percentage inhaled, assuming a normal daily mix of activities, for various particle sizes, distribution of deposited material, between the extrathoracic, tracheobronchial and pulmonary regions of the respiratory tract, retention of material in the tracheobronchial and pulmonary regions as a percentage of total initial deposition, assuming completely insoluble particles, at times from 10 minutes to 10 years after deposition, and absorption to blood as a percentage of the total initial deposition for several elements at times from 1 hour to 10 years after deposition.

For ingestion the main factors determining radiation dose are the rate of movement of material through the different regions of the gastrointestinal tract and the proportion absorbed and transferred to blood.

For the behaviour of systemic radionuclides reaching blood, the elicitation variables were on quantification of the distribution between tissues and duration of retention. In some cases, distribution within individual tissues was considered to be important. For radionuclides for which the skeleton is a significant site of retention, behaviour within bone was taken into account.

The information elicited on the dose coefficients, was absorbed organ dose per unit intake, and committed dose to 70 years of age (Gy Bq^{-1}). For inhalation, 1 μm AMAD particles were specified except in the case of ^{131}I for which a mixture of 1 μm AMAD particles and vapour was specified and experts were asked to determine the proportions of various parts of the lungs. The radionuclides for which both inhalation and ingestion were considered were ^{90}Sr, ^{131}I, ^{137}Cs and ^{239}Pu. Inhalation only was considered for ^{132}Te and ^{144}Ce. In each case, the most important organ or organs were specified.

In total, 332 questions were asked, of which

<u>For inhalation:</u>

- 2 questions on average ventilation rates
- 12 questions on initial deposition in respiratory tract regions
- 24 questions on retention of insoluble particles in respiratory tract region

<u>for ingestion:</u>

- 84 questions on absorption to blood

<u>for systemic distribution and retention:</u>

- 84 questions on retention in liver + skeleton (and skeleton only)
- 36 questions on retention of Pu in bone surfaces and bone marrow
- 20 questions on retention of Ru/Cs in blood
- 8 questions on retention of iodine in thyroid
- 62 questions on dose coefficients (inhalation and ingestion).

Four examples of questions are:

[1] Initial deposition in the extrathoracic region, what is the percentage of total deposition in the respiratory tract?

[2] What is the fraction absorbed to blood of activity (Sr, I, Cs, PuO_2, Pu biol) ingested?
[3] Considering the total amount reaching blood (as if administered intravenously as a single injection), what is the percentage retained in liver and skeleton (bone + bone marrow), as a function of time after entry of Sr (Pu, Ce, Te) into blood?
[4]What is the absorbed dose to specified organs or tissue (lung, bone marrow, bone surface, thyroid, colon, stomach, liver) per unit activity (Sr, I, Te, Cs, Ce, Pu) inhaled or ingested (committed equivalent dose), Gy Bq^{-1})?

3.8 *Early health effects*

In the accident consequence codes the early health effect risk models have sigmoid dependencies of individual risk on the dose to the target organ in an exposed individual. The hazard function applied in both accident consequence codes is calculated from the ratio between the biologically effective dose (Sv) delivered to the target organ and the D_{50}, the dose that would induce the effect in half of the exposed population. The ratio is adjusted with a shape parameter determining the steepness of the sigmoid curve. The individual risk R is

$$R = 1 - \exp(-H)$$

where is $H = \ln_e[2].(D / D_{50})^{\gamma}$ is the hazard function, which is determined by the dose, D, the D_{50} parameter and shape parameter, γ.

Early health effects in the COSYMA code are determined by these parameters, over which uncertainty distributions are therefore required. In order to comply with the condition of eliciting only on observable quantities, the experts were asked questions on doses at which a defined percentage of the population (10%, 50% and 90%) is functionally impaired by the effect. Also threshold values were elicited below which no effect is supposed to take place.

Since hematopoietic syndrome is the largest contributor to early health effects, but difficult to an observe directly, questions were asked on the effect of whole body radiation, and separately on effects for specific organs, such as gastro-intestinal syndrome, lung mortality and morbidity, and three skin effects. Questions were also asked about combined effects to all relevant organs, taking a decrease of dose rate after one hour into account.

In total, 489 questions were asked, of which

- 49 questions on early fatalities due to whole body dose
- 49 questions on early fatalities due to gastro-intestinal syndrome
- 48 questions on early fatalities due to beta lung dose
- 40 questions on morbidities due to beta lung dose
- 12 questions on deterministic fatalities due to alpha long dose
- 45 questions on non-fatal skin effects
- 18 questions on fractions to die from skin effects
- 24 questions on early fatalities due to whole body dose (varying dose rates)
- 12 questions on early fatalities due to lung dose (varying dose rates)
- 192 questions on early fatalities, in cases of multiple exposed organs and exposure periods.

Three examples of questions are:
[1] What is the whole body dose that will result in fatalities (threshold, LD10, LD50, LD90) when exposed to a whole body dose rate of 100 (10, 1, 0.2) Gy hr^{-1} for minimal treatment (supportive treatment without/with growth factors) [Gy]?
[2] What is the lung dose that will result in respiratory-functional morbidities (threshold, ED10, ED50, ED90) when exposed to a lung dose rate of 100 (10, 1, 0.2) Gy hr^{-1} for age groups of the population [Gy]?
[3] What is the dose causing acute ulcerations (acute epidermal necrosis, moist desquamation) on the skin in 10% (50%, 90%) of the skin area when 20% (40%, 60%) of the skin is exposed (bare) [Gy]?

3.9 *Late health effects*

Originally all late health effects were to be considered in this panel. The decision was made to not consider hereditary health effects, because the uncertainties in the category of multifactorial disorders are large, and these disorders make up potentially the largest class of radiation-induced hereditary diseases. At the moment there is no adequate way to assess the likely magnitude of this component of hereditary diseases.

The main requirement of the consequence codes is for cancer risks to be evaluable following moderate to low dose-rate exposure, since this characterises the overwhelming majority of exposures following a typical nuclear accident. It was decided, for example, as a result of preliminary discussions among various experts, that one would expect linearity of risk at low dose-rate exposure, so that eliciting risks for one value of administered dose would suffice. Linearity would not however be expected to apply in general e.g. in extrapolating from high dose-rate exposure (e.g. 1 Gy over 1 minute) to low dose-rate exposure (e.g. 1 Gy over 1 year). For that reason assessments were required for at least one additional low dose rate case. DDREF (dose and dose-rate effectiveness factor) values were

not elicited, but could be deduced from the high and low dose-rate assessments. The cancer risks elicited are listed in the examples of late health effects elicitation questions below.

Equally, it was decided that although not strictly required by the initial consequence uncertainty exercise, it would be desirable to obtain expert judgement on the variation of cancer risk by age at exposure (including in utero exposure), as a function of dose and dose-rate (including the possibility of threshold effects), and for certain sorts of high LET and low LET radiation. The experts quite strongly asked to take questions on those late health effetcs into consideration, because they considered the endpoints to be critical and they expected to get useful information for future applications from those.

In total, 106 questions were asked, of which

- 44 questions on numbers of radiation induced cancer deaths after a whole body dose of 1 Gy low LET over 1 minute
- 4 questions on numbers of radiation induced cancer deaths received in utero after a whole body dose of 1 Gy low LET over 1 minute
- 12 questions on numbers of radiation induced cancer cases after a whole body dose of 1 Gy low LET over 1 minute
- 12 questions on numbers of radiation induced cancer deaths after a whole body dose of 1 Gy low LET over 1 year
- 1 question on the number of radiation induced cancer cases after a whole body dose of 1 mGy high LET over 1 year
- 9 questions on numbers of radiation induced cancer deaths after inhaling 10 kBq of radionuclides specified
- 12 questions on expected numbers of lifetime years lost after a whole body dose of 1 Gy over 1 minute
- 12 questions on threshold doses for low LET radiation.

Three examples of questions are:

[1] What is the number of radiation-induced cancer deaths (bone, colon, breast, leukemia,liver, lung, pancreas, skin, stomach, thyroid, all other cancers, all cancers) up to 20 years (40 years, over a lifetime) following exposure in a population of a hundred million persons each receiving a whole body dose of 1 Gy low LET (=γ) radiation at a uniform rate over 1 minute?

[2] What is the number of radiation induced cancer deaths (lung, bone, liver, leukemia, all cancers) up to 40 years following exposure in a population of a hundred million persons each of whom inhales 10 kBq of ^{239}Pu (^{90}Sr), 1 μm AMAD oxide?

[3] Given that radiation induced cancer death due to the specified cause (bone, colon, breast, leukemia,liver, lung, pancreas, skin, stomach, thyroid, all other cancers, all cancers) has occurred as a result of a dose of radiation delivered over 1 minute, what is the average expected length of life lost in years, for a population followed up to extinction after exposure?

4 EXPERT SELECTION AND ASSESSMENTS

Following the criteria mentioned in section 3 (under Selecting experts), 68 experts were selected for all eight panels, of which two experts provided assessments in two panels. The panels mentioned in one table performed their assessments at the same time, having a joint training session.

Table 5 gives an overview of aggregated experts' assessments on some of the elicitation variables. The examples shown indicate large differences in assessed ranges for the 90 percent central confidence bands. The bands vary from a factor of 2 to about three orders of magnitude. In those assessments where the individual experts' assessments deviate, wider bands are derived for the combined experts' judgements. This is partly caused by the procedure of equally weighting all experts. For the dispersion and deposition panels performance-based weighting schemes were also investigated (see EUR 15856 in Table 2), which shows narrower combined judgements.

Table 5. Examples of quantile points for distributions given by the experts (aggregated data over all panel experts panel)

Elicitation variable	Unit	5th percentile	50th percentile	95th percentile
Centerline concentration ratio (weather class A/B) at 3 km	s m^{-3}	2.24 E-8	3.08 E-7	2.48 E-6
Centerline concentration ratio (weather class E/F) at 3 km	s m^{-3}	1.03 E-6	1.07 E-5	8.47 E-5
Dry deposition velocity at 5 m s^{-1} wind speed for elemental iodine on meadow	cm s^{-1}	0.0095	1.22	20.8
Dry deposition velocity of 1 μ particles on meadow	cm s^{-1}	0.0054	0.11	2.60
Fraction of elemental iodine removed by 0.33 mm of rain during 10 minutes	-	0.0024	0.062	0.40
Fraction of 1 μ particles removed by 0.33 mm of rain during 10 minutes	-	0.0016	0.023	0.64
γ dose rate in air at 1 m above a uniform, flat and open lawn at average deposition of 1 Bq m^{-3} $^{95}Zr/^{95}Nb$ at initial deposition and at 30 days resp.	Gy s^{-1}	4.40 E-16 2.44 E-16	8.37 E-16 7.65 E-16	2.40 E-15 1.45 E-15
Ratio of effective dose for ^{137}Cs in-doors/outdoors in a low, medium and high shielding building respectively	-	0.053 0.021 0.00063	0.36 0.094 0.017	0.89 0.28 0.11
Transfer factor of Cs to cow's meat F_f	d l^{-1}	0.0030	0.039	0.093
Transfer factor of Cs to cow's milk F_m	d l^{-1}	0.0010	0.0055	0.022
Cs root uptake concentration ratio for grain on generic soil after 6 months, 3 years and 10 years resp	Bq kg^{-1} fresh mass plant per Bq kg^{-1} dry mass soil	0.00097 0.00075 0.00043	0.028 0.015 0.012	0.25 0.18 0.089
Interception factor for grain	-	0.023	0.46	0.98
Resuspension factor for surface crop	-	1.16 E-9	3.19 E-8	2.14 E-5
Dose coefficient for inhalation to the lung of Sr, Cs and Pu resp (for adults)	Sv Bq^{-1}	1.54E-10 1.55 E-9 3.62 E-7	1.44 E-7 9.10 E-9 9.00 E-6	8.20 E-7 8.11 E-8 0.00015
Dose coefficient for ingestion to bone marrow of Sr, Cs and Pu resp.	Sv Bq^{-1}	3.35 E-9 6.90 E-9 2.20E-10	1.01 E-7 1.28 E-8 2.73 E-8	8.10 E-7 2.64 E-8 9.48 E-7
LD_{50} for whole body dose at 100 Gy hr^{-1} dose rate for adults	Gy	2.2	3.4	4.5
LD_{50} for lung dose at 100 Gy hr^{-1} dose rate for adults	Gy	7.1	8.8	11
Risk coefficient for thyroid cancer deaths over a lifetime after a high dose of 1 Gy in 1 minute	Gy^{-1}	6.9 E-8	0.00059	0.071
Risk coefficient for leukemia deaths over a lifetime after a high dose of 1 Gy in 1 minute	Gy^{-1}	0.00026	0.0091	0.023
Risk coefficient for all cancer deaths over a lifetime after a high dose of 1 Gy in 1 minute	Gy^{-1}	0.035	0.10	0.28

The dispersion experts tended to rely on the Gaussian model, particularly to estimate the median assessments, and used different approaches to derive the 5% and 95% quantiles. The deposition experts tended to use a wide variety of models for dry deposition and agreed that there is a lot of modelling uncertainty still driving the wider bands of the wet deposition assessments. The deposited material and external dose experts based their assessments mostly on observations from the Chernobyl accident. For all radionuclides the experts gave relatively narrow confidence bands.

The foodchain experts used a variety of models and based their assessments largely on theoretical considerations and experiments. In some cases individual experts provided large uncertainty bands. For instance, the resuspension factors were assessed with an aggregated range factor of more than 10,000, with the 50% quantile relatively close to the 5% quantile. The internal dosimetry experts largely made use of knowledge and experiences gained in the ICRP committees. For instance, the assessments for absorption of radionuclide elements to blood following ingestion were similar, reflecting current ICRP work. Other assessments, such as retention of strontium, caesium and plutonium in tissues after absorption to blood showed a wide diversity in the experts' answers.

5 SELECTION OF PARAMETERS FOR THE UNCERTAINTY ANALYSIS OF THE COSYMA CODE

The uncertainty analysis of the COSYMA code consisted of an overall analysis preceeded by four submodule analyses.

As described in the individual submodule analyses, partial rank correlation coefficients (PRCC) and percentage contributions derived from R^2 values were used to provide an ordered list of model parameters according to their contribution to the uncertainties of code endpoints. The number of parameters considered in these analyses are given in Table 6. The same procedures were used to identify those parameters whose uncertainty makes an important contribution to the uncertainty from the overall analysis.

Restrictions to the available CPU time and disk storage limit what can be undertaken in a single analysis. As a consequence, the number of parameters should not be much larger than in the individual submodule analyses. The following considerations led to the total of 186 model parameters for the overall analysis.

Table 6. Overview of the COSYMA code uncertainty analysis

Submodule		Number of parameters considered in	
Abbr.	Name	submodule analysis	overall analysis
ATM	Atmospheric dispersion and deposition module	28	24
FOO	Food chain module	162	35
DCF	Dose conversion factors	159	100
HEM	Health effects module	27	27
OVA	Overall analysis	376	186

The number of parameters used in the ATM and HEM analyses is small compared to those of FOO and DCF. Therefore, only those parameters of ATM were taken out which give no contribution to the uncertainties for physical reasons. As the fraction of organic iodine is only 1% of the total iodine release, the four dry and wet deposition parameters for organic iodine were excluded from the overall analysis (see Table 6). All uncertain parameters contributing to the health effects were identified as important for at least one of the endpoints.

The selection of the most important parameters for FOO and DCF is described in detail elsewhere[6,7]. The procedure ensured that those parameters are included that are assigned first or second rank using PRCC or those that make more than 15% contribution to the overall uncertainty for at least one endpoint and source term. It was applied to the mean values and the 95^{th} and 99^{th} percentiles of endpoints.

The submodules FOO and DCF consist of a number of models. In some cases, the experts gave uncertainty distributions of outputs of such models. They were used to quantify the uncertainties of the parameters of the model. If the OVA were carried out using only some of the parameters from a box model, then the distribution on the outputs of that model would not reflect the distributions specified by the experts. Therefore, where some parameters from a model were identified as important, the remaining parameters for that model were also included in the final analysis. This led to the number of parameters given in Table 6. The food module analysis considered the uncertainty on the food chain transfer of a number of radionuclides, which might be important contributors to the overall uncertainty on the module endpoints. However, it was found that the uncertainty is dominated by only a few nuclides, and so there are few food chain parameters that need to be considered in the final analysis.

Besides the PRCC ranking, the percentage contribution to the uncertainties of endpoints provided by the selected parameters can be used to check whether the selection of the FOO and DCF parameters is appropriate. The general result is that for the majority of endpoints more than 90% of the uncertainties of the 99th percentiles can be explained by those parameters selected for the overall analysis. Only in a few cases smaller percentages are found; these cases generally correspond with rather low R^2 values (typically < 0.4) where the uncertainty cannot be explained by simple linear or monotonic relationships between the input parameter values and the consequences.

6 CONCLUSIONS

Uncertainty distributions were developed which represent state-of-the-art knowledge in the eight areas mentioned in Table 1. The quantile points of the uncertainty distributions assessed by the experts relate to physically measurable quantities, conditional on the case structures provided to them. The experts were not directed to use any particular modelling approach but were free to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were developed by the experts from a variety of information sources. The aggregated distributions therefore include variations resulting from different modelling approaches and perspectives.

The experts were also asked to provide quantitative data on dependencies between the elicted variables, the dependencies are not elaborated further in this paper.

Valuable information has been obtained from this exercise. Thus, the goal of creating a library of uncertainty distributions, which will have many applications outside of the scope of this project, has been fulfilled. In this project, teams from the USNRC and European Commission were able to successfully work together to develop a unified process for the development of uncertainty distributions on consequence code input variables. Use of staff with diverse experience and expertise and from different organisations made possible a synergistic interplay of ideas, which would not have been possible if they had worked in isolation. Potential deficiencies in processes and methodologies were identified and addressed in this study, which might not have received sufficient attention in studies conducted independently. It is believed that the final product of this study carries more weight than either organisation could have produced alone.

Furthermore, in this exercise, formal expert judgement elicitation has proven to be a valuable vehicle to synthesize the best available information by a qualified group. With a well designed elicitation approach addressing issues such as elicitation variable selection, case structure development, probability training, communication between the experts and project staff, and documentation of the results and rationale, followed by an appropriate application of the elicited information, expert judgement elicitation can play an important role. Indeed, it possibly becomes the only alternative technique to assemble the required information when it is impractical to perform experiments or when the available experimental results do not lead to an unambiguous and non-controversial conclusion. The distributions for the code input parameters are available on computer media and can be obtained from the project staff.

The uncertainty analyses performed with the program package COSYMA provide quantitative information on the uncertainties of all endpoints of probabilistic accident consequence analyses, which might be relevant in decision making or other applications. The investigations cover a large spectrum of source terms and provide a large data base together with an extensive documentation. Some guidance is given how to quantify the uncertainties of consequence assessments other than those performed in the analyses. In complementary sensitivity analyses, the contribution of submodules of COSYMA to the uncertainties and the most important parameters responsible for them have been identified. Their evaluation can help identify areas for further R&D work aiming at reducing the uncertainties by model improvements.

7 ACKNOWLEDGMENTS

The results as presented were prepared under the following CEC-contracts:

* contract F13P-CT92-0023 for the European Commission, Directorate-General for Science, Research and Development, XII Radiation Protection Research, and
* contract No. 93-ET-001 for the European Commission, Directorate-general of Environment, Nuclear Safety and Civil Protection, XI-A-1 Radiation Protection
* contract L2294 for the United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Safety Issue Resolution
* contract F14P-CT95-0006 for the European Commission, Directorate-General for Science,

Research and Development, XII Radiation Protection Research.

The authors express their thanks to many others who have contributed largely to what has been established in the joint project so far: EC and USNRC staff, the experts, and the persons who kindly provided us with additional information and data. In particular, they want to mention Dr. G.N. Kelly (EC), Dr. F.T. Harper (Sandia National Laboratory, USA), Prof. Dr. R.M. Cooke (Delft University of Technology, the Netherlands), Dr. J.A. Jones (National Radiological Protection Board, UK) and Dr. J. Ehrhardt (Research Centre Karlsruhe, Germany).

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