UNCERTAINTY AND SENSITIVITY STUDIES WITH THE PROBABILISTIC ACCIDENT CONSEQUENCE ASSESSMENT CODE OSCAAR

TOSHIMITSU HOMMA*, KENICHI TOMITA† and SHINJI HATO
Japan Atomic Energy Research Institute
Department of Reactor Safety Research
2-4 Shirakata shirane, Tokai-mura, Ibaraki 319-1195, Japan
*Corresponding author. E-mail : homma@popsvr.tokai.jaeri.go.jp
†Present address :Visible Information Center, Inc. 440 Muramatsu, Tokai-mura, Ibaraki 319-1112, Japan

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This paper addresses two types of uncertainty: stochastic uncertainty and subjective uncertainty in probabilistic accident consequence assessments. The off-site consequence assessment code OSCAAR has been applied to uncertainty and sensitivity analyses on the individual risks of early fatality and latent cancer fatality in the population outside the plant boundary due to a severe accident. A new stratified meteorological sampling scheme was successfully implemented into the trajectory model for atmospheric dispersion and the statistical variability of the probability distributions of the consequence was examined. A total of 65 uncertain input parameters was considered and 128 runs of OSCAAR with 144 meteorological sequences were performed in the parameter uncertainty analysis. The study provided the range of uncertainty for the expected values of individual risks of early and latent cancer fatality close to the site. In the sensitivity analyses, the correlation/regression measures were useful for identifying those input parameters whose uncertainty makes an important contribution to the overall uncertainty for the consequence. This could provide valuable insights into areas for further research aiming at reducing the uncertainties.

KEYWORDS : Stochastic Uncertainty, Subjective Uncertainty, Uncertainty Analysis, Sensitivity, OSCAAR, Probabilistic Accident Consequence, Level 3 PSA

1. INTRODUCTION

Probabilistic accident consequence assessment (PCA) models and computer codes are an integral part of Level 3 Probabilistic Safety Assessment (PSA) of nuclear installations. They assess the consequences of potential accidental releases to the atmosphere, taking into account the range of environmental conditions at the time of the accident and the probability associated with these conditions. These methods describe the behavior of radioactive material through the environment following a release to the atmosphere and calculate the subsequent dose distributions and health effects in the population. The methodology can further evaluate the economic consequences of land contamination and restrictions on land utilization as a result of the introduction of countermeasures.

A number of PCA codes have been developed throughout the world and they have been widely used in many countries. Level 3 PSA results provide a quantitative basis for discussing the risk from potential accidents at a nuclear installation. They may also be used as an input into various matters in decision making and regulatory process such as siting and design criteria, emergency planning and preparedness, and safety goal. With the increasing use of PCA codes, greater attention has been given to the reliability of the methods used and the inherent uncertainty associated with their predictions. In this context, an international comparison exercise on ACA codes has been performed co-sponsored by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) and the Commission of the European Communities (CEC) [1,2]. The main objectives of this study were to compare the predictions of participating codes for a range of postulated accidental releases, to contribute to the quality assurance of the codes, and to guide future research and development. The findings of this international study are presented in two reports [1,2] published by the NEA and CEC. It has to be noted, however, that the study concluded that the observed spread or variation between the predictions of the participating codes was small but it provided little insight into the magnitude of the inherent uncertainties associated with the code predictions.

Another important international activity in this area was a joint project co-sponsored by the United States Nuclear Regulatory Commission (USNRC) and the European Commission (EC) [3]. The main objectives of this joint effort were to develop credible and traceable uncertainty distributions for the respective code input parameters using formal expert judgment elicitation techniques and then to apply them to estimate the uncertainties associated with the predictions of their PCA codes, COSYMA [4] and MACCS [5].

In Japan, an accident consequence assessment code system, OSCAAR [6] was developed by the Japan Atomic Energy Research Institute for use in PSAs of nuclear reactors. OSCAAR participated in the second international exercise and the results indicated that OSCAAR performed almost well, giving predictions in good agreement with the other codes such as COSYMA and MACCS and some improvements would be required for the health effects models. After the international exercise, our efforts were mainly made upon the validation of the individual modules and the verification of the whole OSCAAR system. As part of the Level 3 PSA for a 1,100MWe BWR-5 with a Mark-II containment at a reference site by JAERI, the radiological consequence assessments for various accident scenarios have been performed [7] to find needs for further improvement of risk assessment methodology and to obtain a better understanding of the controlling factors of public risk. Recently the Nuclear Safety Commission in Japan is in the process of developing safety goal for the operation of nuclear installations. At present, two quantitative safety goals for individual fatality are emerging in the interim report [8]:

- Individual early fatality risk: the average (expected) value for individual early fatality risk near the site boundary due to nuclear accidents will be less than about 10^{-6} year^{-1}
- Individual latent cancer fatality risk: the average (expected) value for individual latent cancer fatality risk in a specified region from the site boundary due to nuclear accidents will be less than about 10^{-6} year^{-1}.

It has to be noted that each safety goal involves a requirement that the average value be less than a specific criterion. This interim report also indicates this average value is to be with uncertainty evaluation required in the calculation of the goals. In this regard, our attention is mainly focused to address the uncertainty in predicted individual fatality risk in the population around the nuclear power plant. The primary purpose of this paper is to present the results of uncertainties in individual risk made by the OSCAAR code.

2. UNCERTAINTIES IN ACCIDENT CONSEQUENCE ASSESSMENTS

The predictions of PSA codes are uncertain for a variety of reasons, which were categorized in the PSA Procedure Guide [9] as completeness uncertainties, modeling uncertainties and parameter uncertainties. In probabilistic consequence assessments the complete uncertainties may result from the omission of processes that contribute to risk under study. This can be done deliberately when the contribution to risk is expected to be small relative to other process. The modeling uncertainties may exist due to inadequate mathematical formulation of environmental processes due to a lack of knowledge. There are currently no formal techniques available to quantify the effects of modeling uncertainty. Model validation is one of the best methods for ensuring an acceptable level of model accuracy and for analyzing uncertainties associated with model predictions. After the Chernobyl accident, there have been good opportunities to test models for the environmental transfer of radionuclides through different pathways against measured data. A lot of work has been performed to test a specific part of the accident consequence assessment models in the international model validation studies, such as BIOMOVS [10], VAMP [11] and BIOMASS [12, 13]. It is, however, quite difficult to perform a model validation over the entire set of conditions to which accident consequence assessment models may be applied, because a Level 3 study considers a number of processes and has to take account of the full range of meteorological conditions that might occur.

There are two types of parameter uncertainties in probabilistic accident consequence assessments [14]. The first type of uncertainty (stochastic uncertainty) includes those parameters for which there is no single value but for which a probability distribution of values can be specified. The weather condition at the time of an accident is an example of this type of uncertainty and this is usually summarized in the form of complementary cumulative distribution function (CCDF) in probabilistic consequence assessments. Another source of this uncertainty is the stochastic variability of life and dietary habits, as well as the metabolic and anatomical properties with respect to individual. The second type of uncertainty (subjective uncertainty) indicates that there is a correct value but it is not known because of a lack of information about a deterministic process. This type of uncertainty is in general expressed by confidence interval for the CCDFs. Several authors [14, 30] have emphasized the importance of maintaining a distinction between these two types of uncertainty.

In the following sections, we investigated three questions below:

- How do we deal with the stochastic uncertainty (weather conditions) in accident consequence assessments and how much is the statistical variability?
- How much is the uncertainty with respect to imprecisely known variables in the model and what are the main contributors to the uncertainty in individual risks of

early and latent cancer fatality?

- How much of the overall uncertainty about individual risks is attributable to stochastic uncertainty and how much to subjective (parameter) uncertainty?

3. OSCAAR MODELS

Before presenting the results of the uncertainty analyses, the brief summary of the OSCAAR system are described in this section. OSCAAR consists of a series of interlinked modules and data files, which are used to calculate the atmospheric dispersion and deposition of selected radionuclides for all sampled weather conditions, and the subsequent dose distributions and health effects in the exposed population. OSCAAR can consider countermeasures which might be taken to reduce the dose received by the exposed population. Several stand-alone computer codes and databases can also be used to prepare, in advance, necessary input data files for OSCAAR such as dose conversion factors, population and agricultural product distributions, and lifetime risks for exposed population. The principal endpoints of OSCAAR can be roughly divided into health effects, effects of countermeasures and economic impacts.

The atmospheric dispersion and deposition module in OSCAAR has a multi-puff trajectory model that can take account of changes in wind direction and variable long-duration releases. The trajectory and dispersion of each released puff are calculated using two kinds of grid inputs of meteorological data. The hourly surface wind and atmospheric stability fields on the meso scale system are constructed by using Grid Point Value (GPV) provided by the Japan Meteorological Agency. The grid size of the system is 20 km at 30 N and 60 N. A preprocessor program is utilized to estimate stability classes with wind speed, time of day and cloud information based on Turner's method [15]. The meteorological data on the synoptic scale system is also available from GPV data every three hours at three standard pressure levels of 925, 850 and 700 hPa. Surface wind data on the meso scale system and horizontal wind data on the synoptic scale system are applied to define the vertically averaged wind for puff advection calculations. The wind data at the release point are also used at the first step of the trajectory calculations. OSCAAR can handle the spatial and temporal distribution of rainfall to predict wet deposition. The hourly rainfall rates are prepared at each receptor point by averaging GPV data within the corresponding annular receptor grid element. The rainfall rate at the release site, however, is applied to all the receptor points within the 10 km circle from the site of interest.

The two kinds of modules are used to convert the predicted spatial and temporal distributions of activity in the atmosphere and on the ground to distributions of dose in population. The first module calculates early exposure which occurs during and shortly after plume passage. External irradiation from material in the passing cloud (cloudshine), internal irradiation following inhalation of the material and external irradiation from the deposited material (groundshine) are taken into account within several hours to several weeks since the accident occurs. The second module calculates the long-term groundshine doses, internal doses via inhalation of radionuclides resuspended from the ground, and internal doses via ingestion of contaminated foodstuffs. The migration of deposited material into soil as well as the radioactive decay is taken into account for the calculation of the long-term groundshine doses. The food chain model uses analytical solutions of the dynamic compartment model for radionuclide transfer in the environment and is available for important Japanese crops. It can reflect their seasonal dependence in probabilistic assessments. OSCAAR has been recently applied to the dose reconstruction scenarios of the BIOMASS organized by IAEA for the validation of the atmospheric dispersion and deposition, and food chain transport modules [12, 13, 16, 17].

OSCAAR considers both early and late health effects in the population using method recommended by USNRC [18]. The risk of early health effects is calculated using hazard function approach in which cumulative hazard is given by a two parameter Weibull function. The early fatal effects comprise the potentially hematopoietic, pulmonary, and gastrointestinal syndromes. The dose rate dependent models proposed by the revision to the USNRC health effects model [19] are now implemented into OSCAAR. The risk of late health effects is given by linear dose response function for each cancer type. For estimating the lifetime risk in the population, the absolute or relative risk projection models are available for each cancer type. The revisions of the supported stand-alone program calculating the lifetime risk has been performed by reviewing the recent changes in cancer risk factors that come from longer follow-up and revised dosimetry in major studies on the Japanese A-bomb survivors [20].

4. METEOROLOGICAL SAMPLING UNCERTAINTY

One of the important parameters, which influence the magnitude of the consequences following an accidental release of radionuclides to the air, is the sequence of weather conditions that is encountered by the dispersing plume. The stochastic uncertainty associated with weather variability is usually summarized in consequence probability distributions in a probabilistic risk assessment. Theoretically, the complete spectrum of the consequences might be acquired by performing consequence assessment for every possible meteorological sequence that would be encountered by the released radioactive materials. However, the number of possible, different meteorological sequences is extremely large and some sequences may have similar off-site consequences. It is neither practicable nor necessary to consider each of the sequences. In fact, a set of meteorological sequences with suitable size is sampled from one or more years' worth of meteorological data. Therefore, to predict the consequence probability distributions of such an accident, it is necessary to select a representative sample of meteorological sequences for analysis, to perform the accident consequence calculations for these sequences and to determine the probability of occurrence associated with each of these sequences.

A number of sampling methods or procedures have been developed for choosing representative set of meteorological sequences so as to conduct probabilistic consequence assessment [4, 21]. Cyclic, simple random and stratified sampling techniques are widely utilized in the PCA codes. The original emphasis in this area was on stratified sampling (for example, the sampling method incorporated in the MACCS code system) since it was thought to be able to yield better results than cyclic and simple random sampling. Stratified sampling would have better results if the classification of meteorological sequences had met the objectives of the scheme that members in each group should be similar and the groups themselves should be distinctly different from each other. An ideal stratified sampling scheme may identify rare cases that are associated with the most adverse off-site consequences. Cyclic and simple random sampling schemes tend to sample the more common sequences frequently, whilst overlooking the rare cases. They can only be used for predicting the higher percentiles of the distributions of consequences if a large number of sequences are considered for analysis [4]. The procedures generally adopted with straight-line dispersion models are to calculate the pattern of consequences with distance from the source and to assume that this consequence pattern could be applied in different wind directions. However, the pattern of consequences calculated using a trajectory model could not be applied in directions other than the one of the wind at the start of a sequence. Therefore, the sampling procedure must be tailored to particular aspects of the atmospheric dispersion model used. The different sampling schemes were compared in an international comparison of PCA codes. This comparison suggested that the spread of predictions within a single sampling scheme was greater than the spread between the schemes [22]. These results suggest that further work on meteorological sampling, especially when calculating consequences at a single point with a trajectory model of atmospheric dispersion, would be justified. Two options for improving the existing sampling schemes have been proposed in: (1) selecting more than one sequence from each of the groups included in the current schemes, (2) defining a larger number of groups of conditions and selecting one sequence from each group [23].

The primary purpose of this study [24] was to design an appropriate meteorological sampling scheme for use with the puff trajectory dispersion model used in OSCAAR. The secondary purpose was to find the statistical variability in the probability distribution of the consequences, resulting from the adoption of different meteorological sampling schemes.

4.1 General Considerations

In developing the new scheme of meteorological sampling for the OSCAAR code, the following issues were contemplated [25].

A. COMPLETENESS : Because the objective of Level 3 PSA is to describe the complete distribution of off-site consequences due to postulated nuclear accidents, the sampled meteorological sequences should cover the rare cases that lead to the most severe consequences. Hence, the sequences chosen should represent the complete range of all possible sequences and yield the full spectrum of the consequences related to the postulated accident under investigation.

B. CONSISTENCY : The parameters selected for classification of meteorological sequences and the sampling scheme itself should be seamlessly associated with the models, parameters and methods used in the code system. In the OSCAAR code system, trajectory puff model is utilized to predict the transport and dispersion of released radioactive materials, so traveling information of a puff has to be accounted for. This is expected to ensure meteorological sequences be specially chosen for the dispersion model used in the code system.

C. OPTIMUM STRATIFICATION : The sampling scheme could divide the entire set of meteorological sequences in such a manner that the members in each single stratum or group would be very similar and the strata be quite dissimilar. This is the guarantee of reasonable results from a stratified sampling scheme.

D. PRACTICABILITY : A full scale of Level 3 PSA consists of assessment of a series of postulated nuclear accidents and the corresponding uncertainty and sensitivity analyses. The computation time consumption will definitely be intolerable if the number of samples is too large. A practicable number of samples should be predetermined according the models used in the consequence assessment code system.

E. OPTICAL ALLOCATION : In some of the existing sampling schemes, sample number for each group is equal or proportional to the size of each group. These procedures may obtain a satisfactory solution when the sizes are equal for all the groups or all the groups are equally important for prediction of the consequences. A fixed number of samples need to be optically allocated among the groups in order to "maximize" the precision of consequence assessment. Therefore, more sequences should be sampled from a particular group if (1) the group size is larger, (2) the variance of consequences is larger, or (3) the members are of higher interest. Additionally, a lower number of sequences to be sampled from each group should be determined in such a way that the consequence variability within a single group can be reflected.

Obviously, the detailed criteria or quantitative description of these principles depend on the model used in the Level 3 PSA code system, the computer performance and the purposes of the assessment undertaken. For example, if the rare cases of catastrophic health effects are to be emphasized, more samples should be allocated in the group that may likely lead the highest health consequences. The number of samples should be decided on a case-by-case basis.

4.2 New Sampling Scheme and its Variability

This study focused on the sensitivity of the major consequences to certain meteorological conditions to improve a method of meteorological sampling scheme for the trajectory model. Hence, all possible sequences of weather conditions from one year of hourly meteorological data, in other words, 8760 starting times for the sequences were taken into account to produce the possible probability distribution of the consequences. Since the details of the meteorological sampling scheme are more important when large releases and effects involving dose thresholds are considered, the source term with a relatively large release was used for the study. The release characteristics of the source term, called ST2, which was provided to participants in the international comparison [1]. The source terms used for that study were based on those contained in NUREG-1150 [26].

As all of the nuclear power plants in Japan are located in coastal regions, population distributions around the sites have clear non-uniform features. To clarify the interaction of the atmospheric dispersion with the population distribution which varies with distance and direction from the site, it was assumed that the reactor is located at a semi-urban site facing to the Pacific Ocean. The population and agricultural product distributions in thirty-two sectors (i.e. 11.25° sectors) and twenty-five distance bands around the site were used for the calculation. The population distribution was compiled from 1990 census in Japan on a 1km x 1 km grid.

To investigate the sensitivity of the major consequences to certain meteorological conditions, the computer code SPOP [27] developed at the Joint Research Centre of the European Commission was used. Among a number of the sensitivity analysis techniques that users can select in SPOP, two kinds of the statistics, namely the Spearman rank correlation coefficient (SPEA) and the Smirnov test (SMIR) were applied to the analysis. The Smirnov test is a two-sample test designed to check the hypothesis that two samples belong to the same population. It is used in sensitivity analysis by partitioning the sample of the parameter X_i under consideration into two sub-samples according to the quantiles of the output variable (Y) distribution. In the application one sub-sample collects all the parameter values for the selected X_i which corresponds to the 10% highest output values. The second sub-sample collects the remaining values. The test is based on differences in the cumulative distributions of the two sub-samples. If the two distributions are different, it can be said that the X_i influences the output [28].

SPEA and SMIR values for early health effects were calculated for several selected meteorological conditions. SPEA values indicated that those conditions which might influence the numbers of early health effects were the initial wind speed, the initial stability at the release, and the travel time of a puff and the average stability during the travel of the puff to specified distances. Although SPEA failed to identify the sensitivity of early health effects to the rain conditions, SMIR values could find that the total amount and duration of rain within specified distances influenced the high consequence part.

From the sensitivity analysis discussed above, the new stratified sampling scheme was designed to contain a set of options for identifying "wet" and "dry" sequences. The scheme designed included the nine groups of initial wind direction with two groups for wet conditions and nine groups for dry conditions. The wet sequences were specified in terms of the total amount of rain within the distance of interest. The dry sequences were described in terms of the mean stability category and the travel time to a selected distance. The scheme used in this analysis is summarized in Table 1. From a total of 99 groups, the representative sample of 144 sequences was selected for this analysis by choosing at least one sequence per 100 sequences at random from each group.

In order to verify the performance of the new stratified sampling scheme, 1000 different sets of CCDF of early health effects with 144 meteorological sequences were produced by selecting different sets of meteorological sequences from the stratified sampling groups. The percentile values from the stratified sampling scheme show rather better agreement with the real case and are less scattered than those from both random and cyclic sampling schemes. As shown in Fig. 1, the statistical variability defined by the ratio of 95% bound to the mean

Table 1. Meteorological Sampling Scheme Used by OSCAAR

Wind direction		9 groups		
Wet (to 10km)	Rain < 5 mm	G1		
	Rain ≥ 5 mm	G2		
Dry (to 10 km)	Travel time (to 20 km)	Unstable	Neutral	Stable
	< 2.5 hr	G3	G6	G9
	2.5 – 5 hr	G4	G7	G10
	5 hr ≤	G5	G8	G11

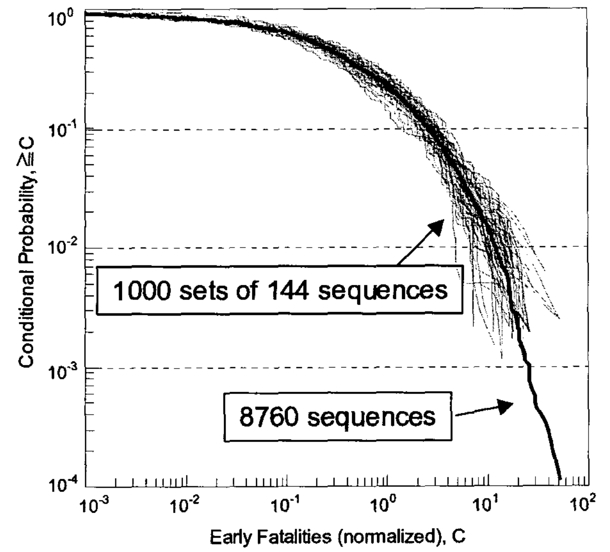

Fig. 1. Statistical Variability of a Set of Meteorological Sequences Obtained from a New Sampling Scheme

value at the 99th percentile was calculated by about 1.6 from these CCDF.

The following conclusions were given in this study [24]. The stratified sampling scheme appropriate for the trajectory dispersion model has been developed for identifying a representative sample of weather conditions from a meteorological database, for use in accident consequence assessments. The statistical variability of the probability distribution of the early health effects from the stratified sampling was small and the performance of this scheme was better than that of conventional random and cyclic sampling schemes. Comparing with the other schemes, the method of stratified sampling is suitable because it enables the probabilities of occurrence of the sampled meteorological sequences be determined directly. However, the performance of this method depends on the criteria used in grouping similar sequences of weather conditions. Further work is still required to find better criteria in grouping similar sequences for the particular application of the scheme.

5. INPUT PARAMETER UNCERTAINTY

Uncertainty analysis aims to quantify the uncertainty in the predictions of a model caused by the uncertainty in the model input parameters. Sensitivity analysis of a model output aims to quantify the relative importance of each input model parameter in determining the value of an assigned output variable. A number of sensitivity analyses have been performed over the years in accident consequence assessments. Most of the sensitivity analyses use a one-at-the-time method in which a parameter value is changed at a specific amount and the influence of the change is determined on the predicted output itself. Some studies have been undertaken using Monte Carlo methods which focus on the output uncertainty over the entire range of values of the input parameters [29, 30, 31]. These studies quantified the uncertainties in the model predictions and the global sensitivity analysis methods can identify key parameters whose uncertainty affect most the output uncertainty. This in turn can be used to establish research priorities, leading to a better definition of the unknown parameter and hence to a reduction of its uncertainty. One feature of these studies was that the uncertainty distributions on the model input parameter were specified mainly by the code developers.

In JAERI, the preliminary analysis has been carried out on the prediction of the OSCAAR code by uncertainty in the values of the input parameters [32]. The primary objective of this analysis was to establish the systematic methodology of implementing the uncertainty and sensitivity analysis using OSCAAR. The joint distributions of uncertainty on the model input parameter were also specified by the code developers. This section describes the subsequent uncertainty and sensitivity analysis using the distributions on the input parameter values obtained from a joint EC/USNRC project [3]. The objective was to estimate the uncertainties associated with the individual risks of early and latent cancer fatality in the population predicted by OSCAAR and to identify the important parameters that contribute most to the uncertainty of the predicted risks of early and latent cancer fatality.

5.1 Source Term and Countermeasure Scenarios

The source term was taken from Level 3 PSA results of a 1,100MWe BWR-5 with a Mark-II containment for a reference site in Japan. The release considered is a relatively large early release, which has been found to dominate the predicted risk of early health effects and to be a major contributor to the overall risk of late health effects from all accident sequences considered in the analyses. The release characteristics of the source term adopted for the calculation are given in Table 2. This was estimated using the THALES-2 code, which is an integrated severe accident analysis code developed at JAERI, with the simplified models partly based on the expert judgments in NUREG-1150 for steam explosion cases [33]. The release fractions of non-volatile radionuclide groups such as Sr, Ru, La to the environment are about 1 % of core inventory.

The analysis was carried out for the same reference site described in Section 4.2. The countermeasures considered for the population are sheltering in their home, sheltering in the specified concrete building followed by evacuation, and relocation. The criteria and the scenario adopted in this analysis are given in Table 3. The criteria, which might be adopted for initiating and withdrawing countermeasures and timings of the emergency actions, are not considered to be uncertain. The results of this

Table 2. Characteristics of the Source Term Used

Item	Value
Time before release	3.0 h
Duration of release	1.0 h
Warning time	2.0 h
Release height	40 m
Energy content of release	0 MW
Reference inventory	1100 MW(e)

ChemicalGroup	Xe-Kr	Organic-I	I	Cs-Rb	Te-Sb	Ba-Sr, Ru	La
Release Fraction	0.56	0.004	0.07	0.01	0.03	0.01	0.01

Table 3. Criteria and Timings Adopted for Countermeasures

Countermeasure	Criteria	Timing
Sheltering followed by evacuation	If the effective dose exceeds 50 mSv within a circle of radius 10 km	· Sheltering for 2 hours after the delay of 2 hours · Evacuation for 7 days after the delay of 2 hours
Sheltering	If the effective dose exceeds 10 mSv within a circle of radius 30 km	· Sheltering for 2 hours after the delay of 1 hour
Relocation	If the effective dose exceeds 140 mSv/a	· Relocation after the delay of 7 days until the effective dose drops below 120 mSv/a

study, therefore, will be specific, to some extent, to the source term and the set of the countermeasure criteria and scenario adopted.

5.2 Uncertain Parameters

In the derivation of a joint distribution on the values of many parameters involved in OSCAAR, a library of information was used from a Join EC/USNRC project on "Probabilistic Accident Consequence Uncertainty Analysis" [34-39]. Two important principles with respect to the application of expert judgment were established for this project [3]:

(1) The elicitation questions would be based on the existing models used in their codes such as COSYMA and MACCS.

(2) The experts would only be asked to assess physical quantities which could be hypothetically measured in experiments.

Although the project focused on the COSYMA and MACCS codes, the project report suggested that a library of information be of use to other models and codes.

According to the methodology and processing techniques used in the uncertainty analysis on the predictions of the accident consequence assessment code COSYMA, the following steps have been undertaken to convert the distributions provided by experts into distributions on the COSYMA input parameters [40]. Uncertainty distributions for physically observable (elicitation) variables were provided by experts and then these uncertainty distributions were combined into a single joint distribution. The joint distributions for the elicitation variables need to be translated into distributions on code input (target) parameters. There are three cases for relation between target variables and elicitation variables. In the first case, the code input parameters correspond to physically measurable quantities, for example, deposition velocities for radionuclides to various surfaces. In this case the experts are questioned directly about the uncertainty with respect to code input parameters. In the second case, the code input parameters has an analytical functional dependence on elicitation variables. For example, the lateral plume spread σ_y, which is physically measurable, is modeled as a power law function of downwind distance x from the release point:

$$\sigma_y(x) = Px^Q \qquad (1)$$

where the dispersion parameters P and Q are the code input parameters. The third case is similar to the second one, but has some numerical relationship between target variables and elicitation variables. For example, the retention of radioactive material in the body is modeled using a set of first-order differential equations with the code input parameters, such as transfer coefficients. In both second and third cases, the distributions on the code input parameters must be specified using the information on the elicitation variables by probabilistic inversion.

In this analysis we directly used the distribution for the input parameter if the OSCAAR input parameter was the same as the COSYMA input parameter [41]. The parameter distributions, which could not be used from a library of information from the project, were determined by probabilistic inversion [40].

For example, OSCAAR uses a set of database on internal dose coefficients obtained from the computer code DSYS, which is based on the ICRP models for evaluating dose coefficients. DSYS calculates the distribution and retention of the radionuclides in the body based on the metabolic models of the specific radionuclide and uses the dosimetric data to obtain dose coefficients for different organs. The input parameters to the metabolic model are the transfer coefficients between the body organs considered. The calculations for the uncertainty on the dose coefficients require information on the uncertainty distributions on these transfer coefficients.

Table 4. Comparison Between Marginal Distributions of Elicitation Variables

Time		Fraction of amount reaching blood retained in whole body	
		Expert Judgment	Prediction
1 day	5%	8.70E-01	8.70E-01
	50%	9.62E-01	9.62E-01
	95%	9.92E-01	9.93E-01
1 week	5%	7.45E-01	7.45E-01
	50%	8.59E-01	8.59E-01
	95%	9.43E-01	9.43E-01
1 month	5%	5.45E-01	5.45E-01
	50%	7.24E-01	7.24E-01
	95%	8.93E-01	8.97E-01
1 year	5%	2.38E-03	2.36E-03
	50%	6.48E-02	6.48E-02
	95%	2.64E-01	2.49E-01
5 years	5%	1.21E-10	1.21E-10
	50%	1.08E-05	1.08E-05
	95%	6.30E-03	4.74E-03

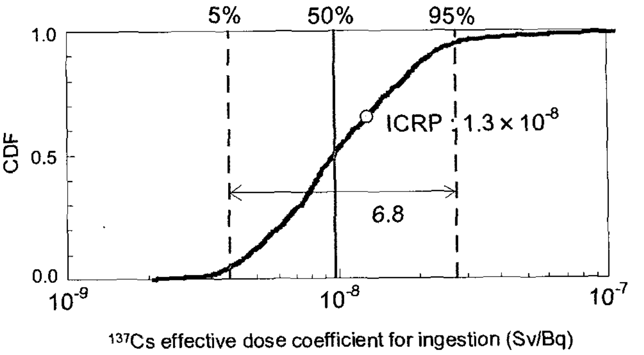

Fig. 2. Probability Distribution Function of a Dose Coefficient of ^{137}Cs

In the internal dosimetry panel, experts were asked about the retention of materials in the human body. They gave information on the uncertainties on the total amount of material reaching blood by a series of times after ingestion, the amount of cesium retained in the body at different times after intake and on the uptake value to blood. The metabolic model for cesium used in DSYS is based on ICRP 56 [42]. The distributions of the target variables, which were four different transfer coefficients, were obtained by probabilistic inversion from the values of elicitation variables. Table 4 shows a comparison of the distributions on the elicitation variables, given by the experts with those obtained using the metabolic model calculations. The distributions obtained using the model input parameters give a good representation of the experts' distributions for most quantities except the 95% value for the amount of material retained in the body after 1 year. Using the uncertainty distributions of the biological half lives for ^{137}Cs obtained from probabilistic inversion, the uncertainty distributions of ^{137}Cs dose coefficient for different organs were calculated. Fig. 2 shows an example distribution for ^{137}Cs effective dose coefficient from ingestion. ICRP recommended value usually used as a default value is almost located at about a median value.

A total of 65 uncertain input parameters was considered in the atmospheric dispersion and deposition module, dose module and health effects module of OSCAAR. As described earlier, the parameters associated with the countermeasure scenarios were not considered to be uncertain. Table 5 shows the range of values adopted for some of the important input parameters in this study.

5.3 Uncertainty and Sensitivity Analysis

In the uncertainty and sensitivity analysis, a parameter uncertainty propagation analysis based on Monte Carlo simulations was performed. The software package PREP/SPOP [27, 43] is linked with OSCAAR to allow for an automatic performance of all necessary steps in the

Table 5. Distributions of Selected Uncertain Input Parameters

Variable	Meaning	5%	95%	95%/5%
· Atmospheric dispersion and deposition: 19 parameters				
VG	Deposition velocity for particulates (m/s)	2.2×10^{-5}	1.3×10^{-2}	570
RA	Washout coefficients (hr/mm/s)	5.1×10^{-3}	4.8	941
PY_D	Horizontal dispersion coefficient Py for stability D	0.17	0.36	2.2
QY_D	Horizontal dispersion coefficient Qy for stability D	0.77	1.03	1.3
PZ_D	Vertical dispersion coefficient Pz for stability D	0.23	3.06	13
QZ_D	Vertical dispersion coefficient Qz for stability D	0.31	0.87	2.8
QZ_AB	Vertical dispersion coefficient Qz for stability AB	0.40	1.08	2.7
· Dose model: 33 parameters				
BRATES	Breathing rate (m^3/s)	1.5×10^{-3}	3.2×10^{-3}	2.3
FFI1	Filtering factor for wood building (-)	0.037	0.96	26
FFI2	Filtering factor for concrete building (-)	0.015	0.39	26
INH_CS	Inhalation effective dose coefficient (Sv/Bq)	4.0×10^{-9}	2.7×10^{-8}	6.8
· Health effects model: 13 parameters				
LD50_PULM	LD50 for pulmonary syndrome (Gy)	7.68	156	20
BETA_PULM	Shape factor for pulmonary syndrome (-)	5.44	10.1	1.9
L_LUNG	Life-time risk for lung cancer (10^4 person-Gy)	0.00020	453	2.3×10^6
L_OTHERS	Life-time risk for other cancer (10^4 person-Gy)	0.0011	947	8.6×10^5

uncertainty and sensitivity analysis. The PREP code generated a series of combinations of input parameters from the uncertainty distributions with correlations between them by Latin hypercube sampling. Then, a total of 128 OSCAAR runs were performed to assess the effect of uncertainties in the 65 input parameters on the output for the source term described above. Each of these runs included an assessment of the consequences of the release for the 144 weather sequences for this site selected by the meteorological sampling scheme developed for OSCAAR [24]. Each of 128 runs in the uncertainty analysis used the same 144 weather sequences. In the third step, the SPOP code quantified the output statistics and identified key parameters whose uncertainties affect most the output uncertainty. SPOP includes several parametric and non-parametric techniques, based on two-sample tests and variance-based methods, as well as correlation/regression measures.

The endpoints of OSCAAR including the health effects in the exposed population and the impacts of countermeasures were described in terms of 128 sets of CCDFs of the consequences. The quantities considered in this analysis were the expected values of the CCDFs for the endpoints. The endpoint of interest here was the population weighted individual risks of early and latent cancer fatality at the different distances from the release point. The expected value of the CCDFs for this endpoint considered in this analysis was defined as:

$$E[R(x)] = \sum_{i=1}^{n} p_i \cdot R_i(x) = \sum p_i \cdot \left(\frac{\sum_{j=1}^{32} P_j(x) \cdot r_{i,j}(x)}{\sum_{j=1}^{32} P_j(x)} \right) \qquad (2)$$

where P_i is the probability of i th meteorological sequence, $r_{i,j}(x)$ is the individual risk of early or latent cancer fatality at the sector j and distance x, and $P_j(x)$ is the population at the sector j and distance x.

Figs. 3 and 4 show the resulted distributions of the expected values for the average individual risks of early and latent cancer fatality in the form of box plots. The expected value of the individual risk of early fatality decreases with increasing the distance from the site. The uncertainty factor defined by the ratio of the 95% value to the mean is less than about four close to the site. It increases with increasing distance from the site. This reflects the greater uncertainty where doses are just above or below the threshold for early fatality. The smaller uncertainty factors close to the site could also reflect the higher doses in this case when the doses are further from the threshold. The expected value of the individual risk of latent cancer fatality, on the other hand, is stable over the distance from the site. This reflects the impact of the relocation countermeasure in reducing high doses. The individual risk in the region where the doses exceed the relocation criteria is mainly determined by the return criteria of relocation. The uncertainty factor for cancer fatality risk is quite stable over the distance from the site, at less than about four.

Among a number of the sensitivity indicators in SPOP, the partial rank correlation coefficients (PRCCs) were calculated to provide a measure of the relationship between the input and output values. Figs. 5 and 6 show PRCCs with the coefficients of determination as a distance from the site. The coefficients of determination R^2, which indicate how much of the variation of the output values can be explained by a linear (monotonic) relationship between the output and input values, are

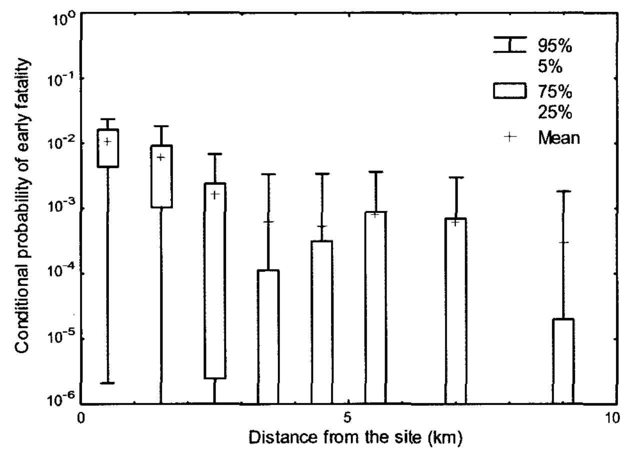

Fig. 3. Uncertainty Distributions of the Expected Values for Individual Risk of Early Fatality

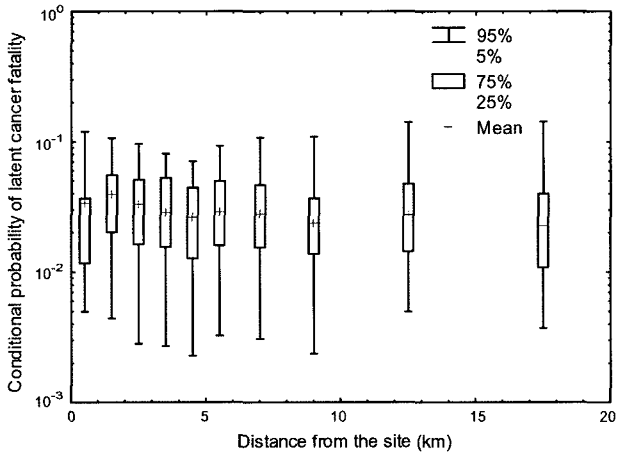

Fig. 4. Uncertainty Distributions of the Expected Values for Individual Risk of Latent Camcer Fatality

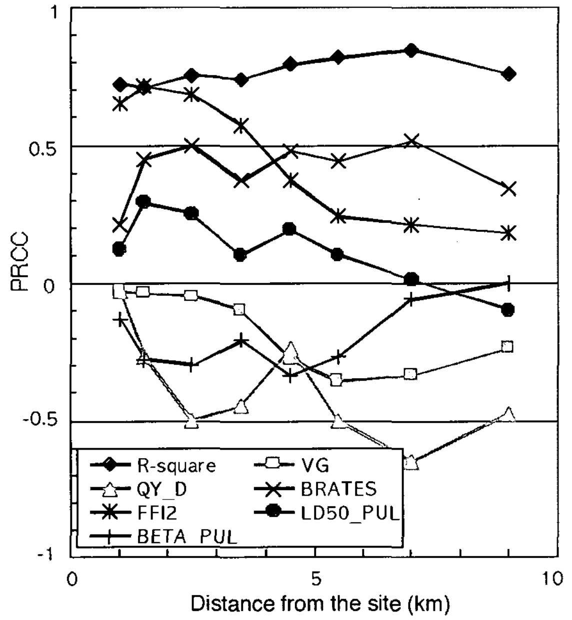

Fig. 5. Partial Rank Correlation Coefficients for Individual Risk of Early Fatality

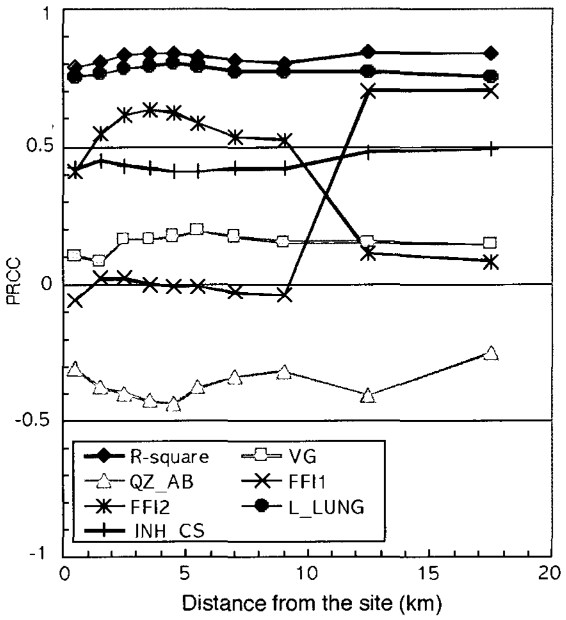

Fig. 6. Partial Rank Correlation Coefficients for Individual Risk of Latent Cancer Fatality

always above 0.70 at all distances in this analysis.

As shown in Fig. 5, the parameters whose uncertainties are identified as making important contributions to the uncertainty for the individual risk of early fatality differ for the different distances. The parameters whose uncertainties make important contributions to the overall uncertainty for individual risk of early fatality are the horizontal dispersion parameter, the filtering factor for inhalation in concrete buildings, and the breathing rate. It is noted that the uncertainties on the parameters which relate to the inhalation doses make larger contributions to the uncertainties for individual early fatality risks than the uncertainties on parameters connected with the dose-response relationship. As shown in Fig. 6, the parameters whose uncertainties make large contributions to the overall uncertainty for individual fatal cancer risks are the lifetime risk of lung cancer, the vertical dispersion parameter, and the inhalation dose coefficient for cesium. The uncertainty on the filtering factor for inhalation in concrete buildings is an important contributor close to the site, but not at the distances beyond 10 km. Instead, the filtering factor in wood buildings is an important parameter at the distances beyond 10 km. This reflects the assumptions on countermeasures described in Table 3.

5.4 Stochastic Uncertainty versus Subjective Uncertainty

We investigated the final question that how much of the overall uncertainty about individual risk was attributable to weather scenario uncertainty and how much to parameter uncertainty. This question is important for decision making because it indicates where parameter uncertainty arising from lack of knowledge can be reduced by gathering information and, on the other hand, where stochastic uncertainty can not be reduced. To answer this question, the following formula for variance decomposition was used to partition the total variance in individual risk into two components, between weather scenarios and within weather scenarios, with y as individual risk, and weather scenario i occurring with probability P_i, and leading to estimated mean and variance across the 128 simulation replications:

$$\begin{aligned}\hat{V}(y) &= V_S\left[\hat{E}(y\mid S)\right]+E_S\left[\hat{V}(y\mid S)\right]=\hat{\sigma}^2 \\ &= \sum_{i=1}^{k} p_i(\hat{\mu}_i-\hat{\mu})^2+\sum_{i=1}^{k} p_i\hat{\sigma}_i^2\end{aligned} \tag{3}$$

where

$$\hat{E}(y)=E_S\left[\hat{E}(y\mid S)\right]=\sum_{i=1}^{k} p_i\hat{\mu}_i=\hat{\mu} \tag{4}$$

In the expression (3), the first term on the right-hand side gives the variance between weather scenarios of the mean of sample individual risks, and the second term gives the mean over the weather scenarios of the variance due to the parameter uncertainty [44].

Table 6 presents the overall mean and variance estimates, with those two terms as a function of distance from the site. It may be seen that the percentage of variance for the individual risks of early fatality arising from weather scenario uncertainty is about 20% of the total variance close to the site and decreases as the distance increase. For the fatal cancer case, it is quite

Table 6. Contributions of Stochastic Uncertainty to Overall Uncertainty as a Distance from the Site

Early Fatality	0.5km	1.5km	2.5km	3.5km	4.5km	5.5km	7km	9km
overall mean individual risk	3.36E-02	3.91E-02	3.28E-02	2.84E-02	2.60E-02	2.87E-02	2.77E-02	2.34E-02
overall variance V(y)	9.62E-03	9.73E-03	8.21E-03	6.11E-03	4.29E-03	4.26E-03	3.82E-03	2.88E-03
Vs[E(y|S)]	1.67E-03	2.27E-03	2.09E-03	1.55E-03	9.01E-04	9.42E-04	8.96E-04	5.98E-04
Es[V(y|S)]	7.96E-03	7.46E-03	6.12E-03	4.56E-03	3.39E-03	3.32E-03	2.92E-03	2.28E-03
% of variance between scenarios	17.3	23.4	25.5	25.3	21.0	22.1	23.5	20.8
Latent Cancer Fatality	0.5km	1.5km	2.5km	3.5km	4.5km	5.5km	7km	9km
overall mean individual risk	1.05E-02	5.92E-03	1.59E-03	6.06E-04	5.04E-04	7.80E-04	5.97E-04	2.93E-04
overall variance V(y)	1.06E-03	6.96E-04	1.81E-04	6.42E-05	6.46E-05	1.04E-04	6.64E-05	3.14E-05
Vs[E(y|S)]	2.44E-04	1.49E-04	1.99E-05	4.12E-06	4.05E-06	1.42E-05	8.18E-06	2.57E-06
Es[V(y|S)]	8.17E-04	5.47E-04	1.62E-04	6.01E-05	6.05E-05	8.95E-05	5.82E-05	2.89E-05
% of variance between scenarios	23.0	21.4	11.0	6.4	6.3	13.7	12.3	8.2

stable at about 20 to 25% of the total variance.

6. SUMMARY

The uncertainty and sensitivity methodology has been successfully implemented for the probabilistic accident consequence assessment code OSCAAR. The study addressed the uncertainty in the predicted individual risks of early fatality and latent cancer fatality in the population near a nuclear power plant, which might be relevant to the safety goal application in Japan. The distinction between the stochastic and subjective uncertainties in the accident consequence assessment is important for decision making because an increased effort in gathering information can improve the quality of decision making by reducing the subjective uncertainties, while it would be ineffective for the stochastic uncertainties.

The stratified sampling scheme appropriate for the trajectory model for atmospheric dispersion has been developed for identifying a representative sample of meteorological sequences for use in accident consequence assessments. It has been found that the 99th percentile of the CCDF for early health effects was uncertain by a factor about two. The parameter uncertainty propagation analyses performed with OSCAAR provide quantitative information on the uncertainties of individual fatality risks of the probabilistic accident consequence assessment. The uncertainty factor defined by the ratio of the 95th percentile value to the mean value of the expected value of the CCDF for individual risks of early and latent cancer fatality were both less than about four close to the site. This result could give valuable insights for the discussion of safety goal. In the sensitivity analyses, the parameters whose uncertainties make important contributions to the overall uncertainty were identified as the parameters which related to the inhalation dose. This result might be relevant to the situation considered. Therefore, further analyses will be needed for different situations. Finally, it was found that the contribution of stochastic uncertainty due to weather scenarios to the overall uncertainty for individual fatality risks was less than about 25% at all distances. This quantitative information could also emphasize further research aiming at reducing the uncertainties due to lack of knowledge about the important parameter values.

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