FINNISH EXPERIMENTS ON LEVEL 3 PRA

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Level 3 probabilistic risk analysis (PRA) analyses the consequences that radioactive release from a nuclear power plant can have on population and environment. Two level 3 case studies are presented in the paper. The first study experimented with event tree modelling on level 3 PRA using Fukushima accident as the case. This study alternated history so that it was assumed that there was no tsunami, i.e. people near Fukushima had not died or been evacuated. Weather was treated probabilistically instead of using the actual weather from the time of the accident. Atmospheric dispersion and dose calculations were performed using ARANO software, and the calculated population doses were incorporated into the event tree model. The event tree was constructed using FinPSA level 2 software, which enables uncertainty analysis and parametric modelling. The second case study examined the integration of PRA levels 2 and 3 using the results from a level 2 dynamic containment event tree model as a basis. It is not clear what numbers from level 2 should be used in level 3 because uncertainty distributions in level 2 results are wide. Therefore, a moderately large number of source term scenarios were analysed.

I. INTRODUCTION

Level 3 probabilistic risk analysis (PRA) analyses the consequences that radioactive release from a nuclear power plant can have on population and environment (Ref. 1). The consequences can be e.g. doses, health effects, such as cancer deaths due to radiation dose, or economic effects due to contaminated land and food products. Health effects are usually considered most important. The effects occur when wind or water flow carries the release to the population, and the population is exposed to ionizing radiation.

This paper presents two experimental case studies on level 3 PRA. In the first study (Refs. 2-3), a level 3 event tree model was constructed for a modified version of Fukushima Daiichi accident. In the second study (Ref. 4), level 3 analyses were performed for a moderately large number of source term scenarios to study the integration of PRA levels 2 and 3.

Atmospheric dispersion and dose calculations were performed using ARANO software (Ref. 5), which is a simple and fast straight line dispersion model. Event tree modelling and level 2 calculations were performed using FinPSA software (Ref. 6).

II. LEVEL 3 EVENT TREE MODEL

II.A. Modified Fukushima Case

This case study alternated history so that the source term from Fukushima Daiichi accident was used but it was assumed that there was no tsunami. Population near Fukushima were assumed to be in their normal places, instead of being dislocated by tsunami.

The motivation for the case study came from the fact that the Fukushima Daiichi accident had very small radiological consequences: it has been estimated that the radioactive release will likely not produce any extra deaths in the general public (Ref. 7), and probably none even in plant and rescue workers. On the other hand, in the first few days of the release, wind blew dominantly to the Pacific Ocean, thus saving the population from exposure. Therefore, it is of interest to find out whether the near non-existence of radiological consequences were due to good luck and the removal of the people from the nearby areas after the tsunami, or was it to be expected given the weather conditions in Japan.

The source term was also modified so that a constant release of three hours was assumed, while in reality, there were multiple releases over several months. The total amounts of the radionuclides were however assumed to be same as in the real accident and were taken from Ref. 7.

The actual weather from the time of the accident was not used. Instead, weather conditions were treated probabilistically and were assumed to be as they are in March in Fukushima area. The weather statistics (Ref. 8) were from Onahama, which is in the Fukushima prefecture, some 60 kilometres to the south of the Fukushima Daiichi nuclear power plant site.

Five cities presented in TABLE I were considered in the calculations. Population outside these cities were not taken into account.

TABLE I. Cities near Fukushima Daiichi

Name	Point of compass from Fukushima Daiichi	Distance from Fukushima Daiichi, kilometers	Population
Minamisoma	north	27	71 000
Kakuda	north	58	31 000
Fukushima	northwest	64	294 000
Koriyama	west	56	338 000
Iwaki	south southwest	48	345 000

II.B. Event Tree

An event tree model for the consequence analysis of the Fukushima release was constructed using FinPSA software (Ref. 6). In the FinPSA level 2 tool, the probabilities of event tree branches are calculated using functions that are programmed by the user. This offers flexibility and enables parametric modelling to account dynamic dependencies and calculate the amounts of consequences. The model is analysed by Monte Carlo simulations.

The event tree is presented in Fig. 1. The tree includes five sections: wind direction, precipitation, wind speed, population sheltering and evacuation.

There are five wind directions modelled by event tree branches: the directions of the cities and “other directions” where population dose is 0. For precipitation, it is assumed that there is either no rain or the rain intensity is 5 mm/hour. Wind speed is not treated with branches. Instead, wind speed is drawn from a Weibull distribution on each simulation round. The parameters of the Weibull distribution were estimated based on the knowledge that the average wind speed is 4.116 m/s and the probability of wind speed exceeding 4 Beaufort (5.556 m/s) in March is 0.19 (Ref 8). More detailed data on the distribution was not available, but Weibull distribution is known to be the most widely used distribution for wind speed.

Sheltering was simply modelled by a probability for successful sheltering and a factor for the reduction of population dose. Evacuation was modelled as dependent on the time of the arrival of the plume, which was calculated based on the wind speed and the distance for each city. If the plume arrived after the evacuation time, the population dose was 0. If not, the population dose was scaled with the factor $(T_e – T) / T_e$, where T_e is the evacuation time and T is the time that the plume arrived in the city. The evacuation time was assumed to be normally distributed with the mean value of 72 hours.

II.C. Consequence Calculations

Population doses in the cities of TABLE I were calculated using various wind speeds, from 0.5 m/s to 40 m/s, in ARANO. The result was a vector of population doses for each city in both rain and no rain conditions. The population dose curves of the no rain case are presented in Fig. 2. In event tree simulation, when a wind speed was drawn from the distribution, the corresponding population doses were interpolated from these vectors.

The uncertainties of the source term were also incorporated in the analysis. It was assumed that if a source term is scaled with a particular factor, the population dose can be scaled with the same factor due to linear correlation. On each simulation cycle, a weight of each radionuclide was drawn from distribution, and the weights were summed up to obtain a scaling factor of the source term uncertainty. The baseline population doses were multiplied with the scaling factor. The scaling factor ranged typically between 0.5 and 1.5 roughly speaking.

The weights of radionuclides were based on ARANO computations performed for different radionuclides separately. It was found out that almost the whole population dose comes from xenon if it rains because the rainfall washes the other aerosols from the plume early. In the case of no rain, different nuclides’ fractions of the population dose also depended slightly on the wind speed and the distance. These dependencies were modelled quite roughly. Correlation between the amounts of different radionuclides was also taken into account with a simple correlation factor common to all nuclides except xenon.

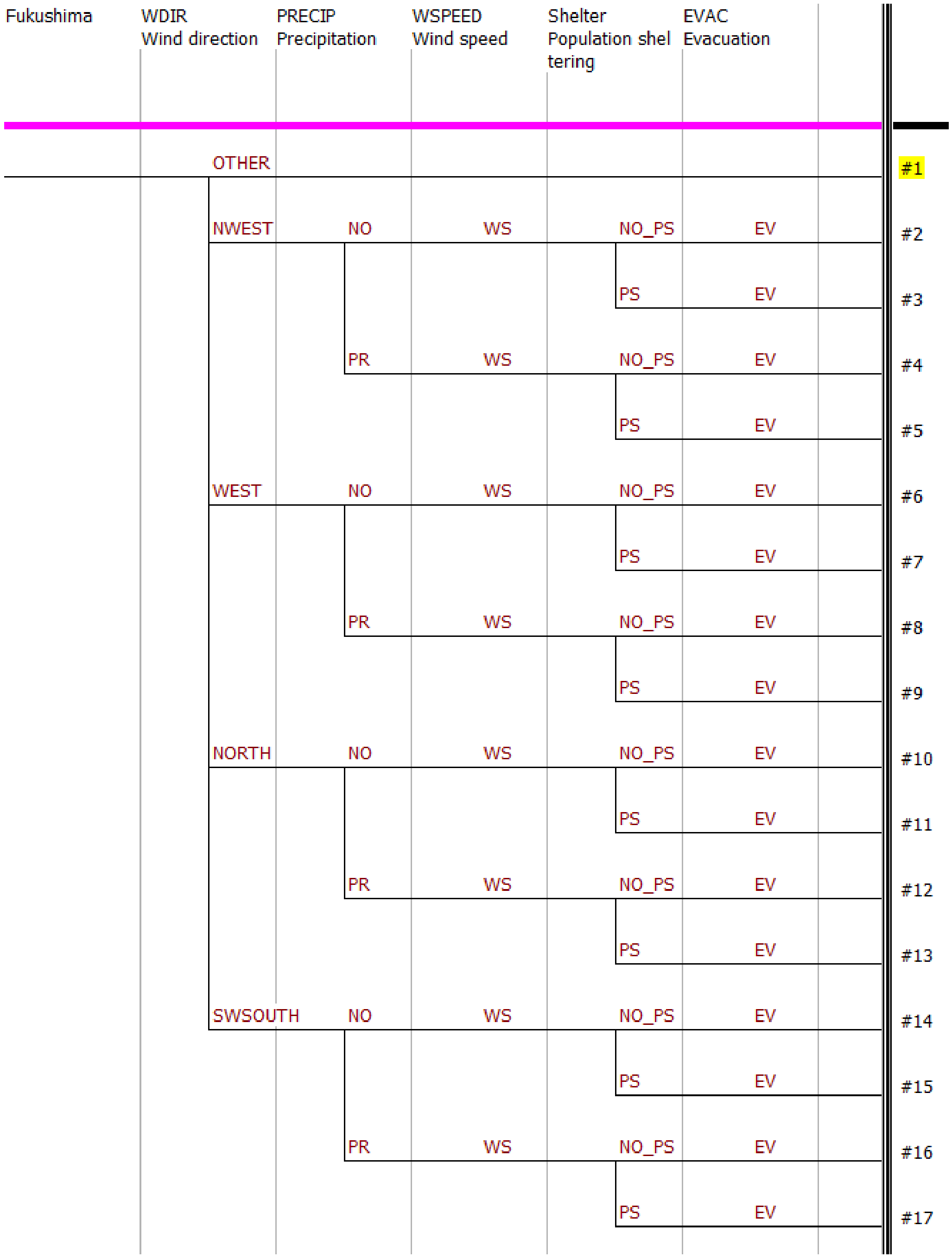

Fig. 1. Event tree model for the consequence analysis of the modified Fukushima accident.

The health hazard considered was the number of cancer deaths, because the maximal individual doses in the five cities considered were too low to cause acute radiation sickness. The linear no-threshold model was used, with the number of cancer deaths equalling 0.05 times the total population dose in manSv. In the uncertainty analyses, the number of cancer deaths was calculated from population dose by multiplying it with a “cancer factor”, which was uniformly distributed between 0.03 and 0.07.

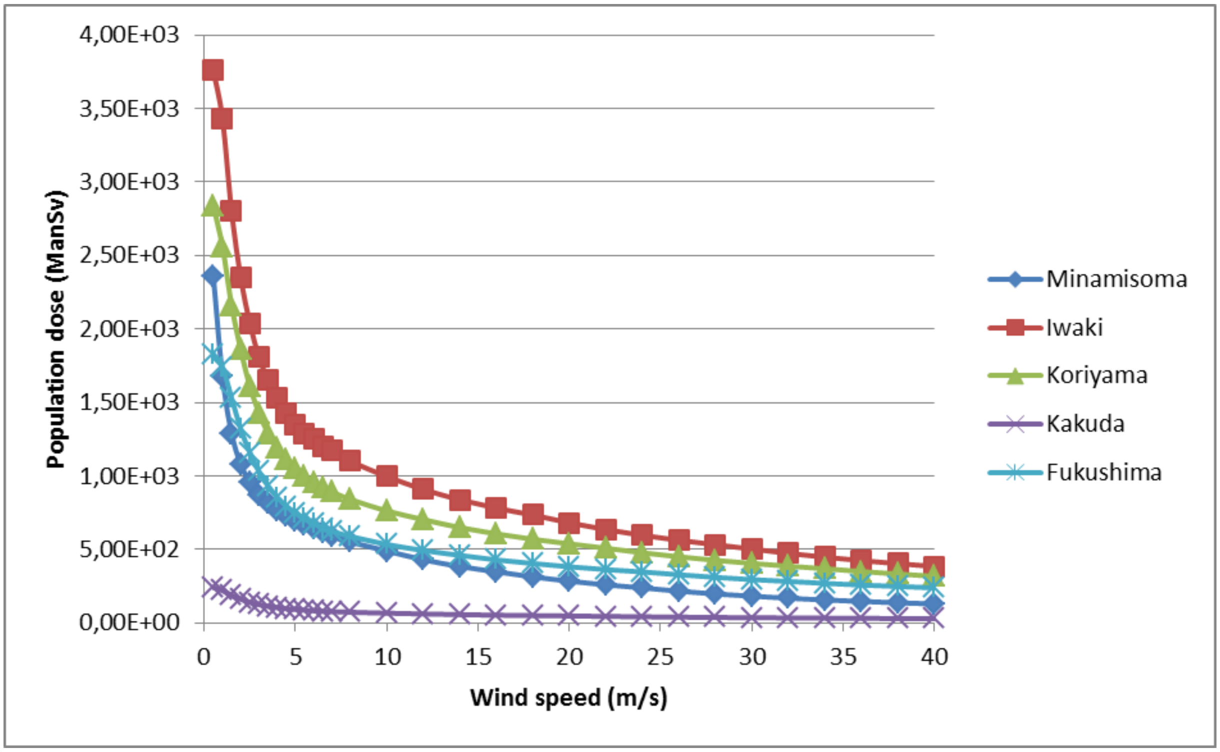

Fig. 2. The population doses calculated in ARANO as functions of wind speed in the case of no rain.

II.D. Results

The expected number of cancer deaths in the cities of TABLE I was 3.6. This is a very small number since approximately 20% of the population will die of cancer due to reasons not related to the radioactive release. The mean value of the probability of more than 0.1 cancer deaths was 0.16. The maximum of this probability was 0.22. Fig. 3 presents complementary cumulative distribution of the number of cancer deaths. The probability for over 20 cancer deaths is around 0.1. The probability for over 60 cancer deaths is around 0.01, while the probability for over 100 cancer deaths is less than 0.001.

Rain was a major factor affecting the population doses. Without rain, the population doses were around 10 times larger. One reason for this was the assumption that the rain continues all the time during the dispersion. Additional analyses showed that if the rain starts just before the town, the dose will increase significantly. Wind speed also had significant effects. The largest cancer death numbers were obtained with wind speeds from 1 to 10 m/s and especially from 1 to 2.5 m/s as can be seen from Fig. 4.

III. INTEGRATION OF LEVELS 2 AND 3

III.A. Level 2 Results

In the second case study, level 2 calculations were performed using FinPSA level 2 tool (Ref. 6). Some capabilities of the tool were already summarised in the previous chapter. The result from FinPSA level 2 analyses is a large number of simulation data and estimated statistical parameters and distributions. Level 3 analyses cannot be performed for each simulation point from level 2. Therefore, it is not clear what numbers from level 2 should be used in level 3. Mean values and 95th percentile values are considerable candidates, but knowledge on uncertainties would be missed.

A simplified containment event tree (CET) representing low pressure transient in a boiling water reactor plant was used in the study (Fig. 5). The CET contains eight accident sequences, which are binned into four release categories: no release (OK), very early release (VEF), early release (EF) and filtered venting (FV).

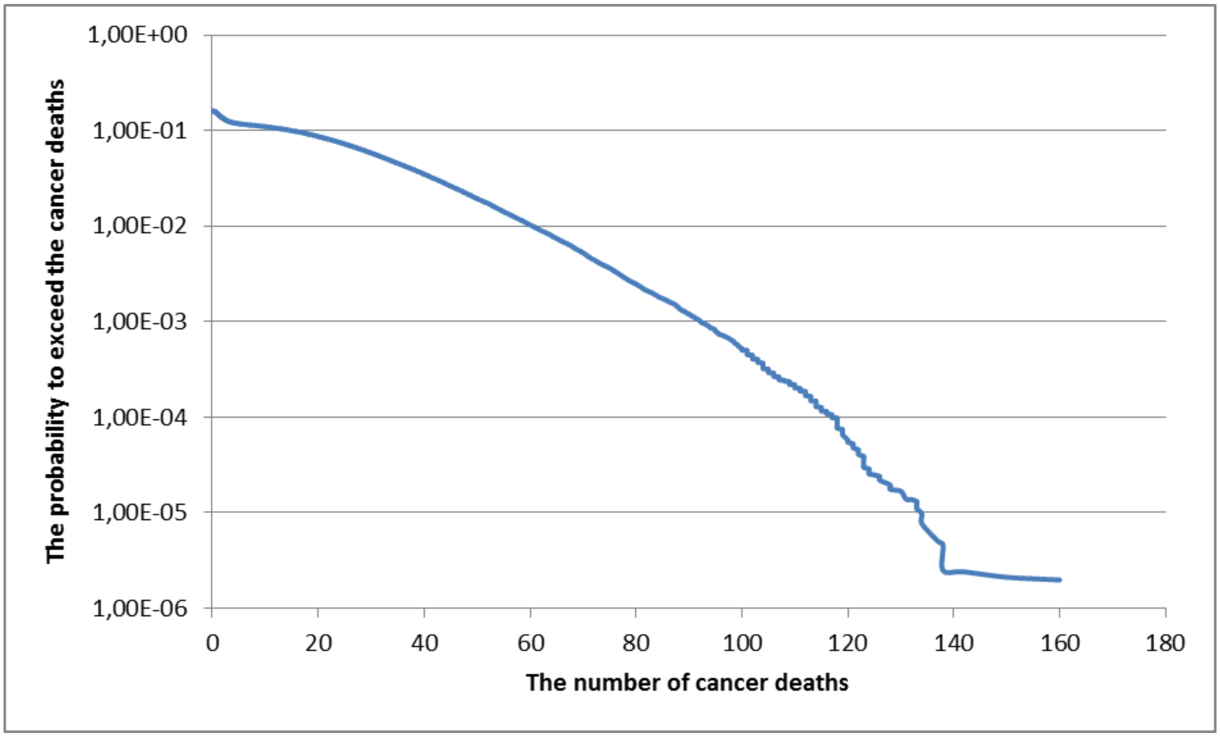

Fig. 3. Complementary cumulative distribution of the number of cancer deaths.

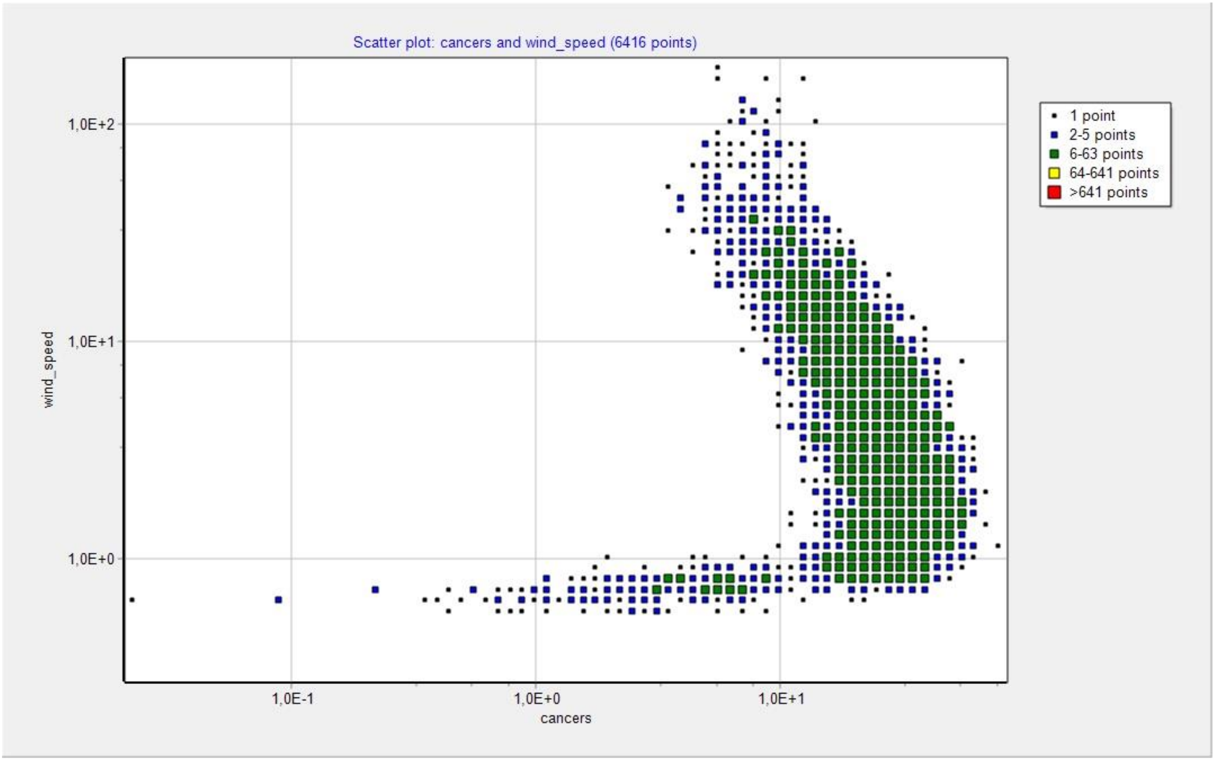

Fig. 4. Scatter plot between the number of cancers and the wind speed.

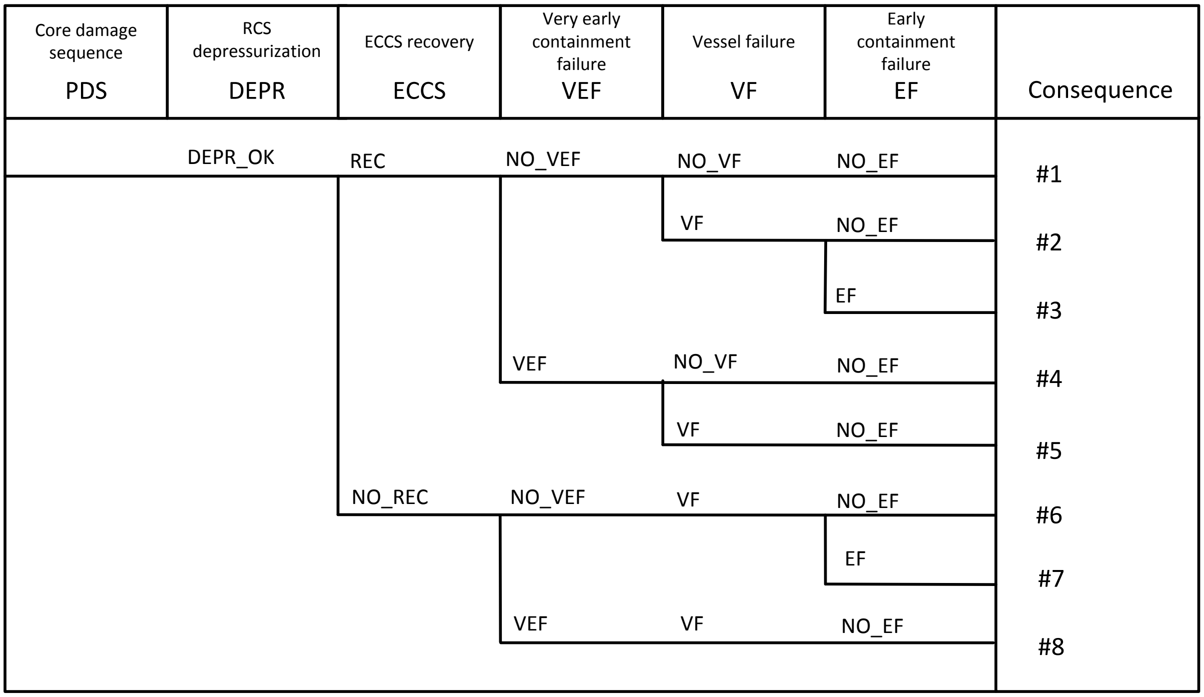

Fig. 5. The containment event tree.

Simulations were performed with 10000 rounds. A simulation result of a sequence from a single round consisted of conditional probability (given core damage), release fractions of radionuclides xenon (Xe), cesium (Cs) and ruthenium (Ru) (of the total core inventory), start time of the release and length of the release interval. For each variable, minimum, 5th percentile, 50th percentile, mean, 95th percentile and maximum were calculated in each sequence and release category.

For each sequence and release category, six level 2 results were prepared based on minimum, 5th percentile, 50th percentile, mean, 95th percentile and maximum values. The results of sequence 7 are presented as an example in TABLE II. For the length of the release, the values were inverted because a shorter release is more dangerous than a longer release. The start time was always 3000 seconds. By computing these cases on level 3, quite good picture on the uncertainties should be obtained. However, it must be noticed that these cases do not represent actual simulation results because the results from different simulation cycles were combined, e.g. all variables did not reach their maximum value in the same simulation cycle. Anyway, the cases are conservative with regard to uncertainty and they are assumed to be realistic enough.

TABLE II. Level 2 results of sequence 7

Case	Xe	Cs	Ru	Start time (s)	Length (s)
Minimum	7.78E-2	4.66E-3	0.00	3000	3980
5th percentile	0.230	3.21E-2	6.61E-9	3000	3950
50th percentile	1.00	0.330	2.35E-3	3000	3560
Mean	0.902	0.347	1.10E-2	3000	3526
95th percentile	1.00	0.891	6.70E-2	3000	3030
Maximum	1.00	0.946	9.88E-2	3000	3000

The produced results were expanded for the level 3 analyses so that iodine (I), tellurium (Te) and release altitude terms were added. Iodine values were derived from cesium results by multiplying them by 1.1, and tellurium values were derived from cesium results by multiplying them by 0.5. These factors were based on expert's knowledge on typical level 2 results, but the numbers are surely very rough. The altitude of the release was assumed to be 108.5 meters added by the buoyant rise due to hot discharge (100 °C) when filtered venting occurs (radionuclides are directed to the stack) and 50 meters otherwise because the height of the containment is around 60 meters.

III.B. Level 3 Calculations

Level 3 calculations were performed using ARANO software (Ref. 5) and weather data of an entire year. Core inventory, population and geographical data were formed exclusively for this case. ARANO divides weather data into weather categories with regard to dispersion directions in sectors of 30 degrees, stability categories, wind speed categories and the appearance of rain. For each category, a probability is derived from the data. Finally, the collective doses are calculated in different weather conditions and the results of different categories are merged to form a complementary cumulative distribution and calculate mean collective dose.

The area that was analysed was a circle with radius of 100 km. The doses were calculated based on the external dose coming from cloudshine and groundshine, and internal dose coming from inhalation. The integration time of the external dose from the fallout was one year. The population distribution was assumed to be uneven in the environment of a NPP. The total population in the analysis area was about 460,000.

Collective dose distributions were calculated for each level 2 result. Mean collective doses of sequence cases are presented in Fig. 6. Sequence 6 is left out because it has no releases. Sequences 1 and 2 lead to release categories FV and OK. Sequences 3 and 7 lead to release category EF, and sequences 4, 5 and 8 lead to release category VEF. This categorisation does support level 3 analyses to some extent. It might however be useful to divide release category VEF into two parts.

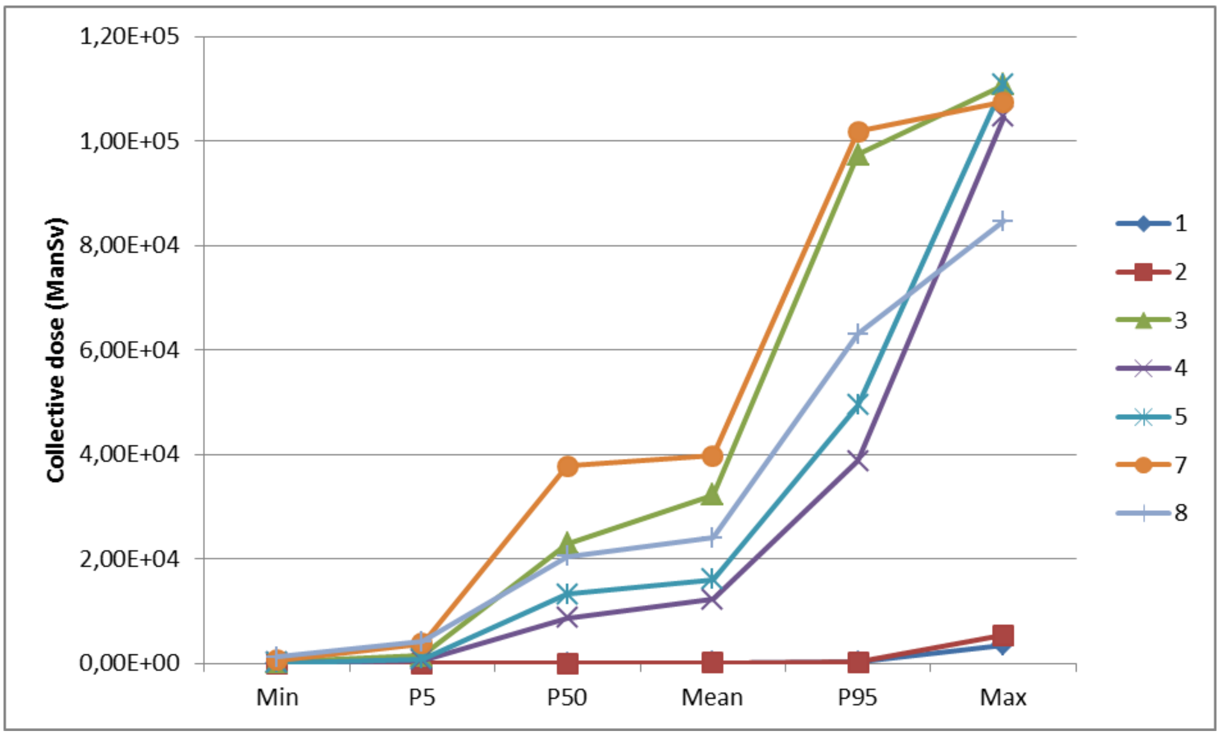

Fig. 6. Mean collective doses of the sequences.

The complete mean collective dose uncertainty distribution of sequence 7 was also calculated and is presented in Fig. 7.

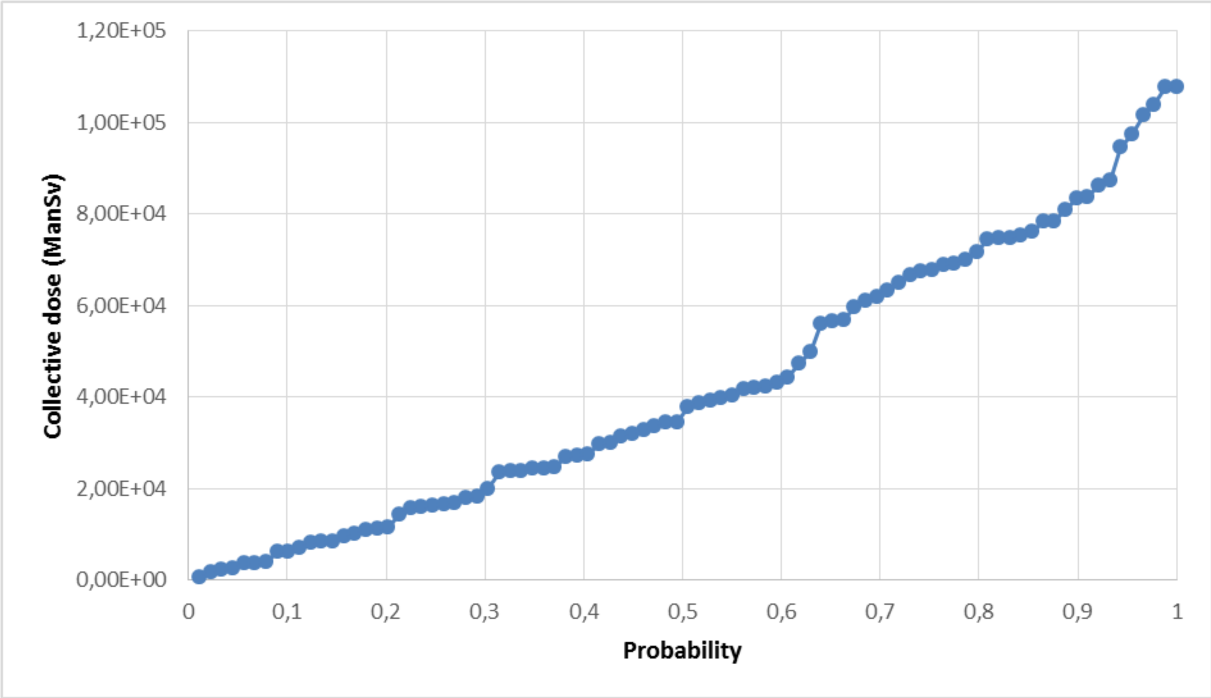

Fig. 7. Cumulative distribution of the mean collective dose from sequence 7.

Based on the mean collective dose results and release distributions of level 2 results, rough estimates of collective dose distributions of the sequences were constructed (by determining 13 percentile values by rough interpolation and assuming linear distribution between the percentiles). Then based on those distributions and conditional probabilities of the sequences, 50000 simulations were performed to calculate a rough estimate of the overall mean collective dose distribution (collective dose distribution with a condition that core damage occurs) presented in Fig. 8. The probability of a significant collective dose is between 0.5 and 0.6 (50^{th} percentile is 56.8 manSv). The division to two clusters originates from simplifications in the level 2 model. This distribution is however just indicative, not accurate. More accurate distribution would require more dispersion and dose calculations.

The previous results were produced based on mean values of level 3 calculations that used the weather data of an entire year. Uncertainties with regard to the weather were also obtained as results. Fig. 9 presents the complementary cumulative distribution of the collective dose assuming release of sequence 7 including minimum, 5^{th} percentile, 50^{th} percentile, mean, 95^{th} percentile and maximum curves.

Few sensitivity studies were performed with regard to the length, altitude and starting time of the release. The results changed very little when these parameters were changed. The altitude had the biggest effect. When the altitude was 70 meters instead of 50 meters, the collective dose decreased 11%, which is quite little too. It seems that the collective dose is not very sensitive to these parameters.

IV. CONCLUSIONS

This paper presented two case studies on level 3 PRA. The first studied the use of event tree modelling on level 3, and the second studied the integration of PRA levels 2 and 3. The studies were experimental in nature and provided some ideas that may be considered when performing real nuclear power plant level 3 PRA analyses.

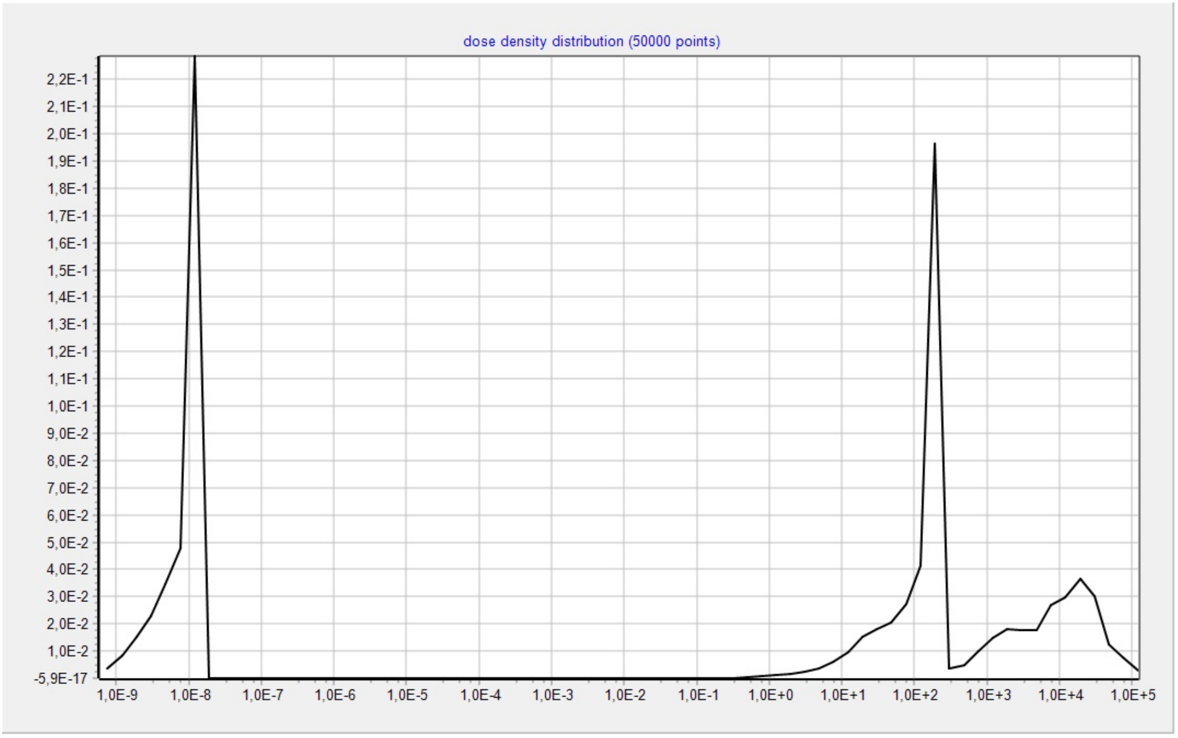

Fig. 8. The overall mean collective dose distribution.

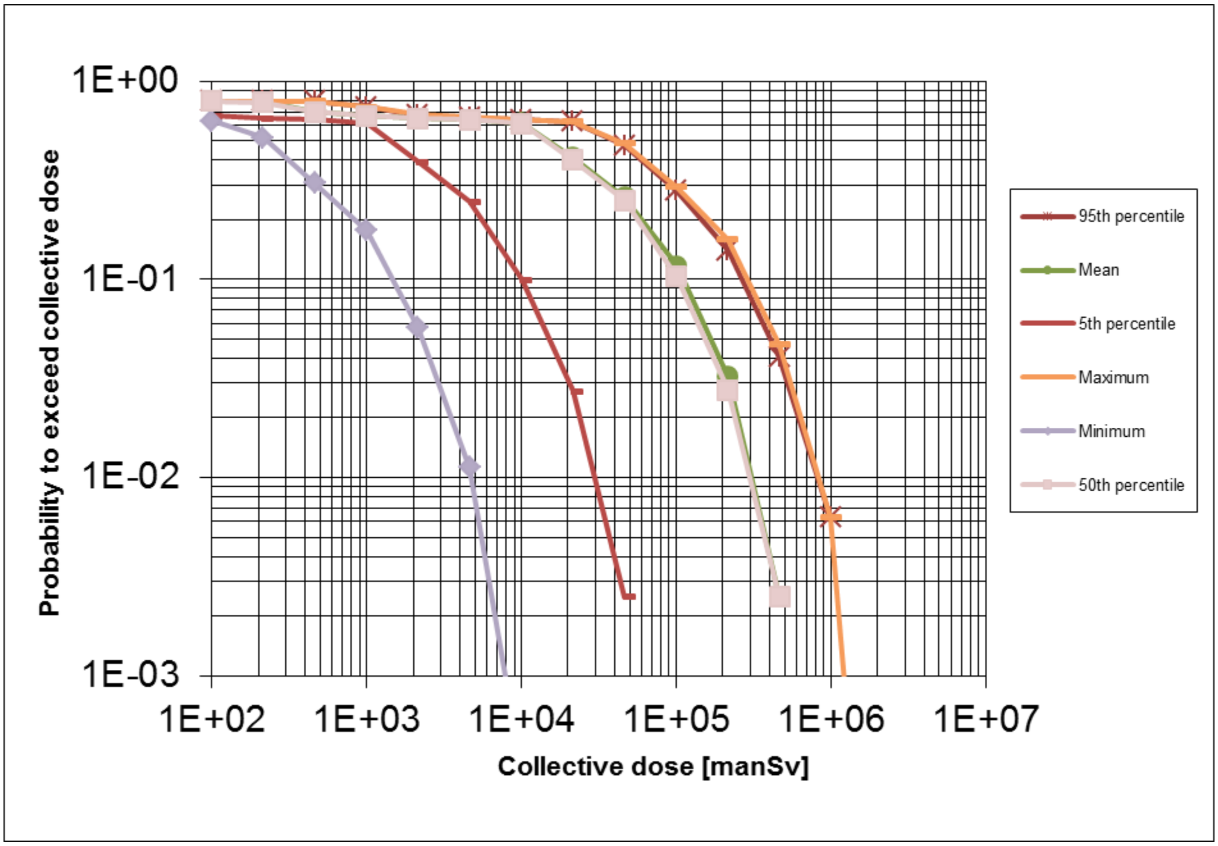

Fig. 9. Complementary cumulative distribution of sequence 7.

The benefits of using event tree on level 3 were the well-structured representation of computation cases and uncertainty handling. An alternative to this approach would have been to use the weather data of sufficiently long time period and to calculate all the appeared weather cases. Such approach would probably have been more accurate in estimating the expected number of cancer deaths. However, it would have been also more demanding computationally, especially if some uncertainty analysis would have been performed. On the other hand, the event tree approach does not suit very complex modelling well, and it is difficult to include any dynamic weather phenomena, such as changes in wind or rain. The used event tree tool did not support the level 3 analysis in the best possible way, and e.g. some produced distributions were difficult to interpret. For further use of the event tree approach, it might be beneficial to develop improved tool support. On the whole, the event tree approach seems to be suitable when some limited questions – in contrast to evaluating all the consequences – need to be answered, and extensive resources are not available for modelling and computing.

A challenge to level 3 analysis is that level 2 results contain typically high uncertainties. Therefore, using only some single point values as an input for level 3 is very restricting. It is also difficult to determine which numbers should be used, e.g. mean values or 95th percentile values, because differences are significant. In this study, uncertainties were propagated from level 2 to level 3 in a limited but sufficiently detailed manner. It can be concluded that performing adequate uncertainty analyses on level 3 is possible with fast software like ARANO. It seems beneficial to choose a set of percentile values from level 2 for level 3 analyses instead of a full uncertainty distribution.

The categorisation of level 2 accident sequences was examined with regard to level 3 results. The release categorisation in the example case corresponded quite well to the level 3 results. Anyhow, it is always important to consider release categorisation when performing new level 3 analyses. With ARANO software, supporting analyses for release categorisation can be performed in a reasonable time.

Sensitivity analyses were performed with regard to the length, altitude and starting time of the release. The collective dose was not very sensitive for these parameters. Instead, the released amounts of radionuclides seem to be the variables that mainly determine the magnitude of the collective dose.

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