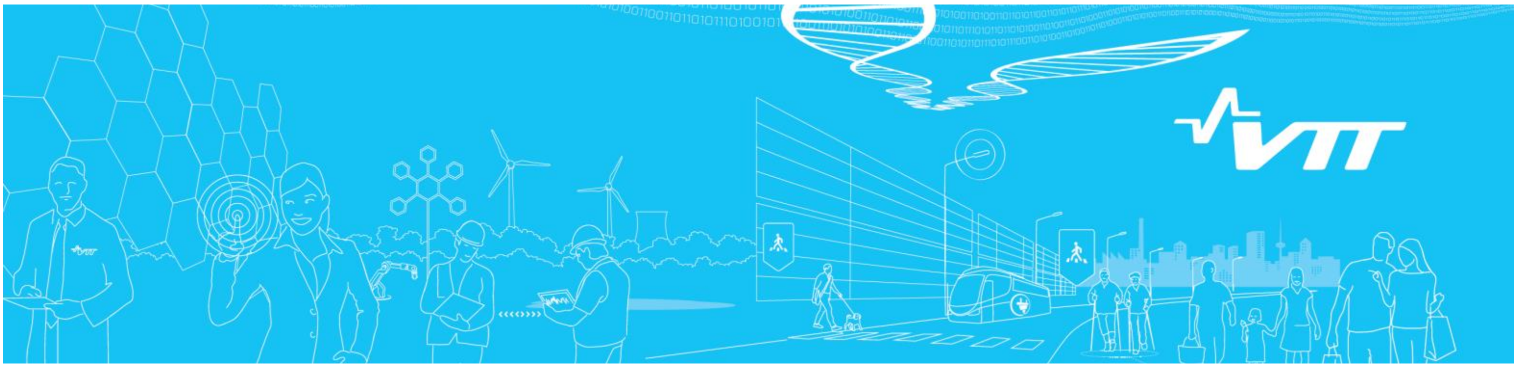
Title	Level 3 PRA computation and its integration to level 2
Author(s)	Tyrväinen, Tero; Rossi, Jukka
Citation	Research Report : VTT-R-00115-16 VTT, 2016
Date	2016
Rights	This report may be downloaded for personal use only.



RESEARCH REPORT

VTT-R-00115-16

Level 3 PRA computation and its integration to level 2

Authors: Tero Tyrväinen, Jukka Rossi

Confidentiality: Public

Report's title	
Level 3 PRA computation and its integration to level 2	
Customer, contact person, address	**Order reference**
Project name YEKEHITYS	**Project number/Short name** 106089/YEKEHITYS
Author(s) Tero Tyrväinen, Jukka Rossi	**Pages** 12/
Keywords probabilistic safety analysis, consequence analysis	**Report identification code** VTT-R-00115-16

Summary

This report studies level 3 probabilistic risk analysis (PRA) and the integration of PRA levels 2 and 3. Level 3 PRA analyses the consequences that radioactive release from a nuclear power plant can have on population and environment. The major parts of level 3 evaluations are the atmospheric dispersion computation of the releases and prediction of various consequences caused by radiation. Here the focus was to assess collective dose. Calculations are performed using ARANO software, which is a simple and fast straight line dispersion model.

Level 2 PRA analyses the magnitude and likelihood of a release. FinPSA level 2 software is used for level 2 calculations in this report. Level 2 results are used as an input for level 3. However, they consist of large number of simulation data and estimated statistical parameters. It is not clear what numbers from level 2 should be used in level 3. In this report, a moderately large number of level 3 calculations are presented to study the integration of the levels 2 and 3.

It was found out that the release categorisation used in the analysed containment event tree of level 2 does correspond to level 3 results quite well, but not perfectly. It is recommended to consider release categorisation from level 3 point of view when performing new level 3 analyses. Uncertainties were also propagated from level 2 to level 3. Uncertainties are so high that at least limited uncertainty analyses should be performed on level 3. The results also indicate that the magnitude of the collective dose is mainly determined by the amounts of radionuclides, and other parameters of the source term have quite small effect.

Confidentiality	Public

Espoo 12.1.2016

Written by	**Reviewed by**	**Accepted by**
Tero Tyrväinen, Research Scientist	Ilkka Karanta, Senior Scientist	Eila Lehmus, Head of Research Area

VTT's contact address

Tero Tyrväinen, Box 1000, FI-02044 VTT, Finland, tero.tyrvainen@vtt.fi

Distribution (customer and VTT)

VTT

Contents

1. Introduction

This report studies level 3 probabilistic risk analysis (PRA) (Lee and McCormick 2011) and the integration of PRA levels 2 and 3. Level 3 PRA analyses the consequences that radioactive release from a nuclear power plant can have on population and environment. The effects can be e.g. doses, health effects, such as cancer deaths, 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.

The population dose caused by radionuclides carried by wind can be analysed using atmospheric dispersion computation. Calculations are performed using ARANO software (Savolainen and Vuori 1977), which is a simple and fast straight line dispersion model. The results of atmospheric dispersion depend substantially on the prevailing weather conditions. Here, calculations are performed using weather data of an entire year.

Level 2 PRA analyses the magnitude and likelihood of a release (IAEA 2010). FinPSA software (Mätäsniemi et al. 2015) is used for level 2 calculations in this report. Level 2 results are used as an input for level 3. They include the amounts of radionuclides, the probability/frequency of the release and timings of the release. They usually do not include the altitude and temperature of the release even though such information is needed in level 3.

FinPSA produces a large number of simulation data and estimated statistical parameters and uncertainty distributions as level 2 results. It is not clear what numbers from level 2 should be used in level 3 because analyses cannot be performed for each simulation point. Level 2 model is also divided into accident sequences that usually have different results. The sequences need to be categorised for level 3 because it would not be sensible to perform analyses for each sequence. Therefore, it is studied how much the results of different sequences differ. A moderately large number of level 3 computation scenarios are prepared based on level 2 results to propagate uncertainties to level 3 and study the sensitivity with regard to some parameters, such as the altitude and timing of the release.

2. Computation methods

2.1 Level 2 PRA

Level 2 PRA analyses the progression of a severe nuclear power plant accident after a core damage has occurred (IAEA 2010). The main goal is to calculate the magnitude and likelihood of a release in each accident scenario. Methods used on level 2 have varied a lot even though they are mostly based on event trees. In this report, level 2 calculations are performed using FinPSA software (Mätäsniemi et al. 2015) which uses dynamic containment event trees (CET).

In FinPSA level 2, the probabilities of containment event tree branches are calculated using functions which are programmed in containment event tree programming language (CETL). Script files containing CETL codes are linked to CET sections. In addition to probabilities, the CETL functions can calculate other variable values, such as release fractions of radionuclides and timings of events. The model is solved by Monte Carlo simulation, and FinPSA produces simulation results for each accident sequence. Based on simulation results, FinPSA calculates statistical parameters and uncertainty distributions of the releases.

2.2 Level 3 PRA

In Level 3 PRA, radiation doses, public health and other societal consequences are estimated, such as the contamination of land or food from the accident sequences that lead to a release of radioactivity to the environment at level 2. In addition, Level 3 PRA provides insights into the relative effectiveness of aspects of accident management relating to emergency preparedness and response. A variety of possible countermeasures or protective actions may be taken following an accidental release to reduce the impact of the accident on the environment and the public. In principle, the radionuclide release can be either to the atmosphere or to the aquatic environment. In practice, accidental releases to the aquatic environment make a comparatively small contribution to the overall risk from nuclear power plants. For this reason, historically the assessment of releases to the atmosphere has been the principal concern.

Probabilistic consequence assessment models describe the dispersion of released radioactive materials and predict the resulting interaction with the environment and man. Predicted consequences may consist of individual and collective doses, early and late health effects, the effects of countermeasures on people and agriculture and the magnitude of economic impacts (IAEA 1996). Here the atmospheric dispersion and dose model ARANO (Savolainen and Vuori 1977) is used for the probabilistic calculations.

3. Level 2 calculations

In this study, level 2 calculations are performed using a simplified containment event tree representing low pressure transient in a boiling water reactor plant (Figure 1). The CET contains eight accident sequences (numbered from 1 to 8 in Figure 1), which are binned into four release categories: no release (OK), very early release (VEF), early release (EF) and filtered venting (FV). Binning is performed so that an accident sequence can have different release categories in different simulation rounds depending on some variable values.

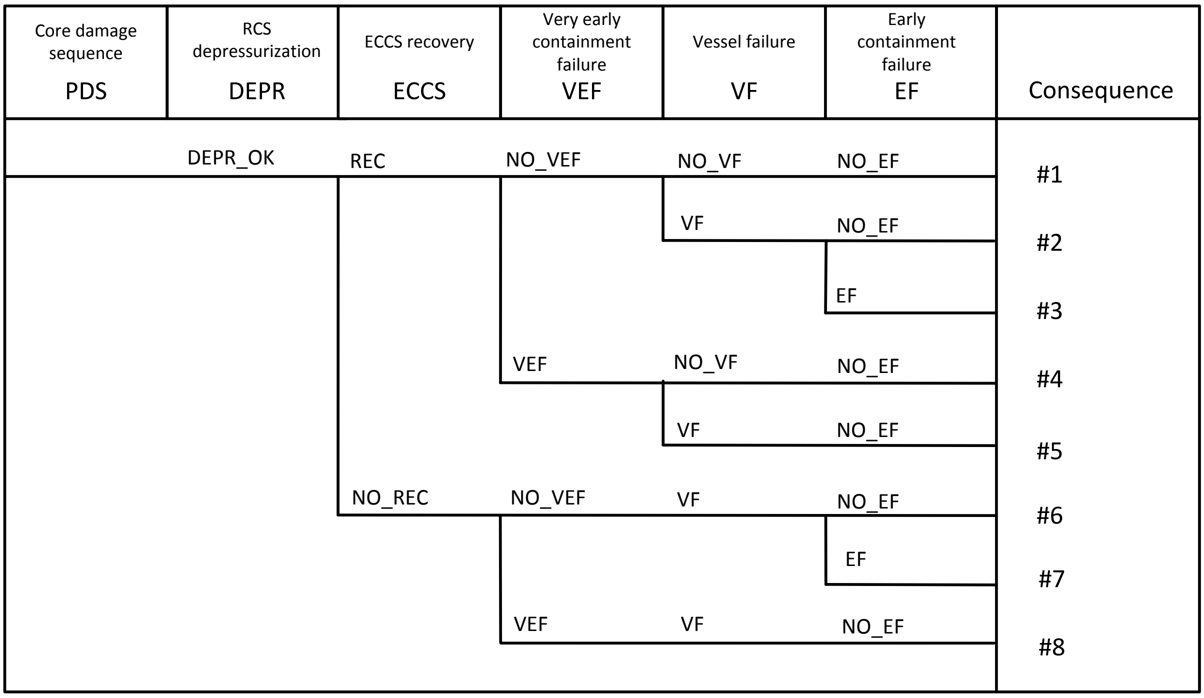


Figure 1: The containment event tree.

Simulations were performed with 10000 rounds. A simulation result of a sequence from a single round consisted of conditional probability (assuming 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, except the probability, minimum, 5th percentile, 50th percentile, mean, 95th percentile and maximum were calculated in each sequence and release category. They were not calculated for the probability because the uncertainty analysis was not performed with regard to probabilities and atmospheric dispersion calculation does not need the probability anyway (though ARANO could take the probability into account, but does not in this study).

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 1. For the length of the release the values were inverted (maximum used as minimum, 95th percentile used as 5th percentile, etc.) 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 rounds were combined, e.g. all variables did not reach their maximum value in the same simulation round. Anyway, the cases are conservative with regard to uncertainty and they are assumed to be realistic enough. For sequence 6 and release category OK, releases were close to 0, and hence, they were not evaluated further.

Table 1: Level 2 results of sequence 7. The amounts of radionuclides are presented as fractions of the total core inventory.

Case	Xe	Cs	Ru	Start time (s)	Length (s)
Minimum	7.78E-2	4.66E-3	0	3000	3980
5th percentile	0.23	3.21E-2	6.61E-9	3000	3950
50th percentile	1	0.33	2.35E-3	3000	3560
Mean	0.902	0.347	1.10E-2	3000	3526
95th percentile	1	0.891	6.70E-2	3000	3030
Maximum	1	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 chimney) and 50 meters otherwise because the height of the containment is around 60 meters.

The simulation results of this model included many unnecessary/incorrect points with small probabilities due to modelling decisions. Such points were filtered out before calculating final level 2 results. For sequence 7, only 89 valid points were left. It was decided that level 3 analyses would be performed for each simulation point to calculate the full uncertainty distribution in level 3 in this case.

4. Level 3 calculations

In the analysis, modified core inventory, population and geographical data from a nuclear power plant was used. Atmospheric dispersion and dose calculations were performed for seven accident sequences and three release categories from level 2. Weather data of an entire year was used. This means that the dose has been calculated in all various dispersion situations to which a specific probability is associated. The dispersion material used is the dispersion data measured at a meteorological mast, divided into dispersion directions in sectors of 30 degrees, stability categories, wind speed categories and the appearance of rain. When the radiation doses caused in various annual dispersion situations, where the occurrence frequency is known on the basis of the measurement material, are organised according to their magnitude, the corresponding complementary cumulative distributions can be formed and mean values can be calculated.

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 the dose coming from inhalation. The integration time of the external dose from the fallout was one year. In the case of one countermeasure evaluated here, evacuation, the population up to the distance of 5 km was assumed to be evacuated before the plume arrives to this area. In that case evacuation was assumed to be an instantaneous event. The evacuation relates to about 350 inhabitants living in the area. The total population in the circle with the radius of 100 km is about 460000.

For filtered venting releases, the buoyant rise of the release was added to the actual release height. The buoyant rise was determined to be 200 meters in the Pasquill classes A, B and C with the low wind speed, but 80 meters with the high wind speed, assuming linear behaviour with other wind speeds. Also, the buoyant rise was determined to be 100 meters in the Pasquill classes D, E and F with the low wind speed, but 40 meters with the high wind speed, assuming linear behaviour with other wind speeds. When the release occurs under the level of 60 m, the building wake is taken into account by adopting a virtual transfer of the plume. Here the value of 80 m in the Pasquill class A and 800 m the Pasquill class F were used assuming linear behaviour in other stability classes.

Collective dose distributions were calculated for each case. Mean collective doses of different cases are presented in Tables 2 and 3. The sequence results are presented also in graph form in Figure 2.

Table 2: Mean collective doses (manSv) of sequence cases.

Sequence	1	2	3	4	5	7	8
Maximum	3460	5410	111000	105000	111000	107000	84700
95th percentile	205	205	97400	38700	49500	102000	63100
Mean	66.9	79.9	32200	12200	16000	39700	24000
50th percentile	1.44E-08	1.44E-08	22900	8620	13200	37700	20500
5th percentile	2.55E-09	3.72E-09	1470	519	864	3700	4070
Minimum	6.77E-10	6.55E-10	154	20.6	29.9	549	1180

Table 3: Mean collective doses (manSv) of release category cases.

Release category	VEF	EF	FV
Maximum	106000	111000	5840
95th percentile	42700	97500	403
Mean	15400	32500	176
50th percentile	12300	22600	149
5th percentile	720	1160	21.9
Minimum	17.2	39.0	6.66

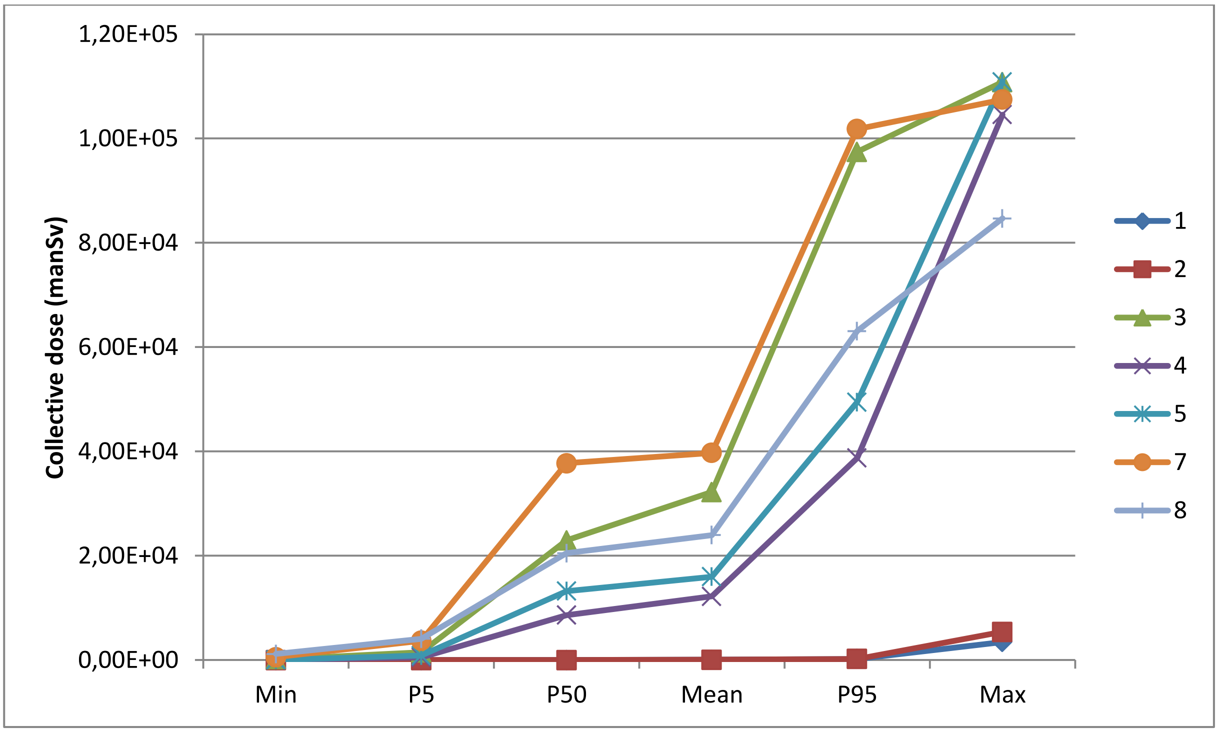


Figure 2: Mean collective doses of the sequences.

Sequence pairs 1 and 2, and 4 and 5 have quite similar results, and they could be merged together for level 3 analyses. The results of sequences 3 and 7 are also close for some parts (maximum, 95th percentile and mean). The results of sequence 8 do not match very accurately with any other sequence, but they are not very far from the results of sequences 3-7 either.

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.

Based on the mean collective dose results (Table 2) and release distributions of level 2 results, rough estimates of collective dose distributions of the sequences were constructed (by determining 13 different percentile values for each distribution by rough interpolation and assuming linear distribution between the percentiles). Then based on those distributions and conditional probabilities of 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 Figure 3. The probability of a significant collective dose is between 0.5 and 0.6 (50th 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.

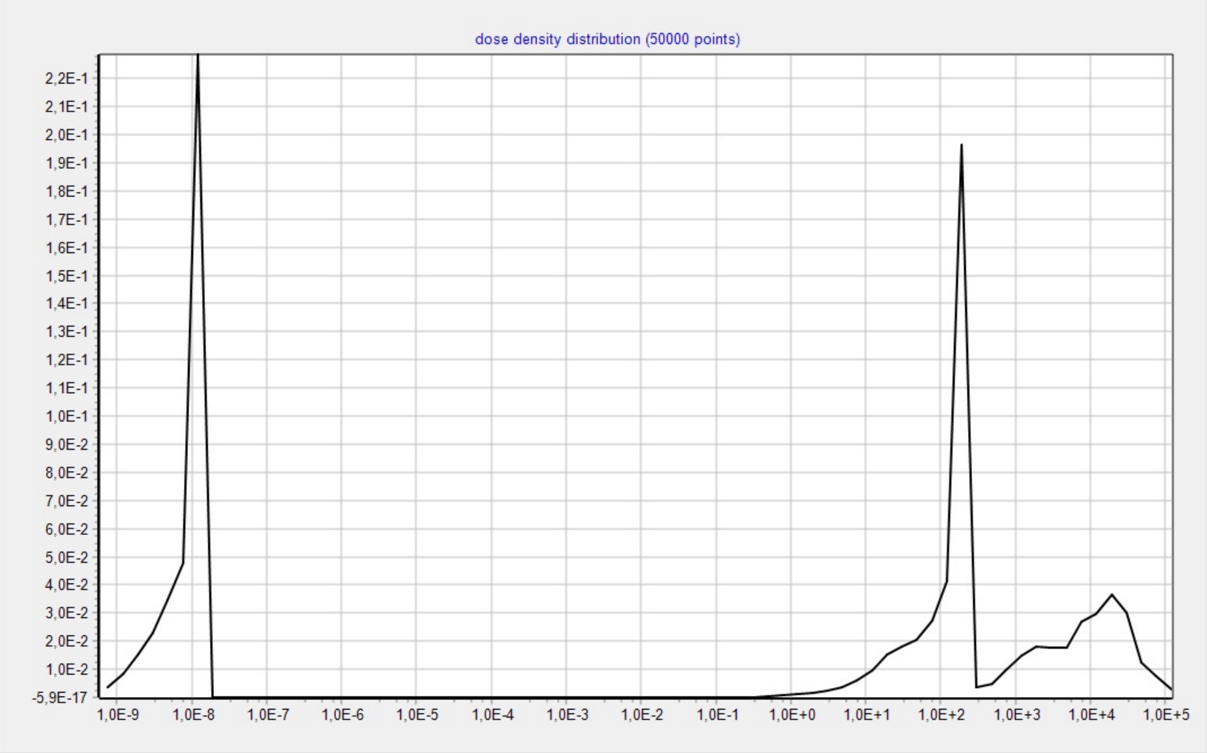


Figure 3: The overall mean collective dose distribution.

The complete mean collective dose uncertainty distribution of sequence 7 was calculated and is presented in Figure 4.

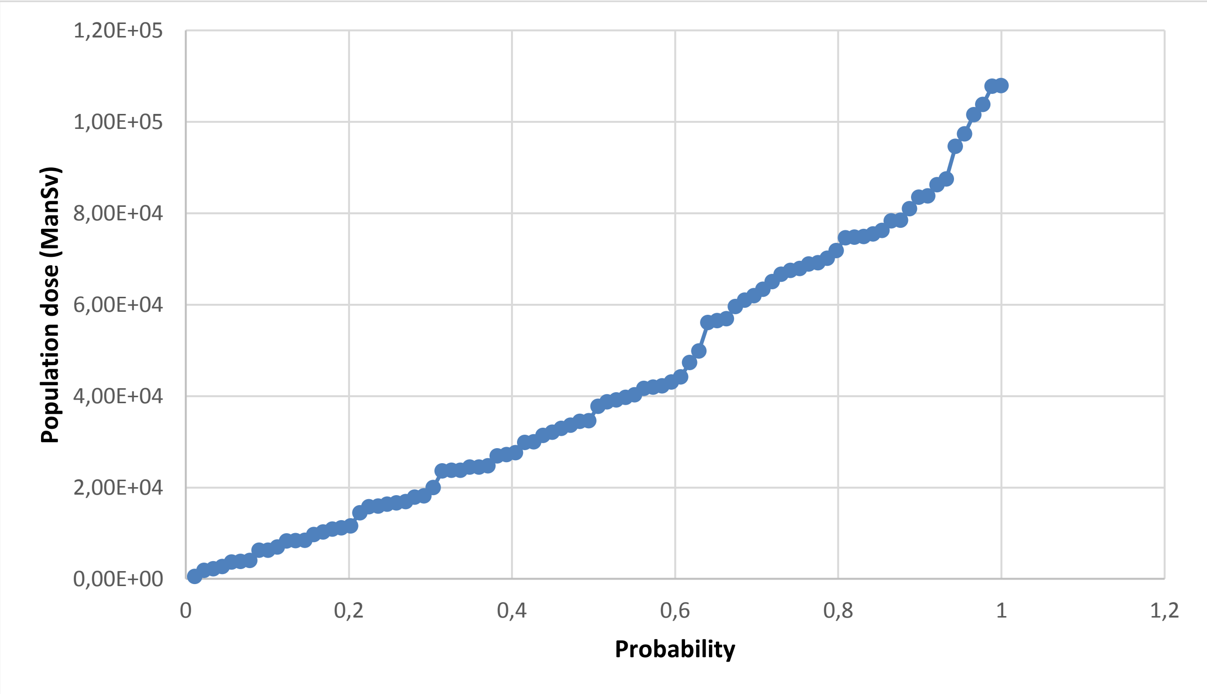


Figure 4: Cumulative distribution of the mean collective dose from sequence 7.

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. Figure 5 presents the complementary cumulative distribution of the collective dose assuming release of sequence 7 including minimum, 5th percentile, 50th percentile, mean, 95th percentile and maximum curves.

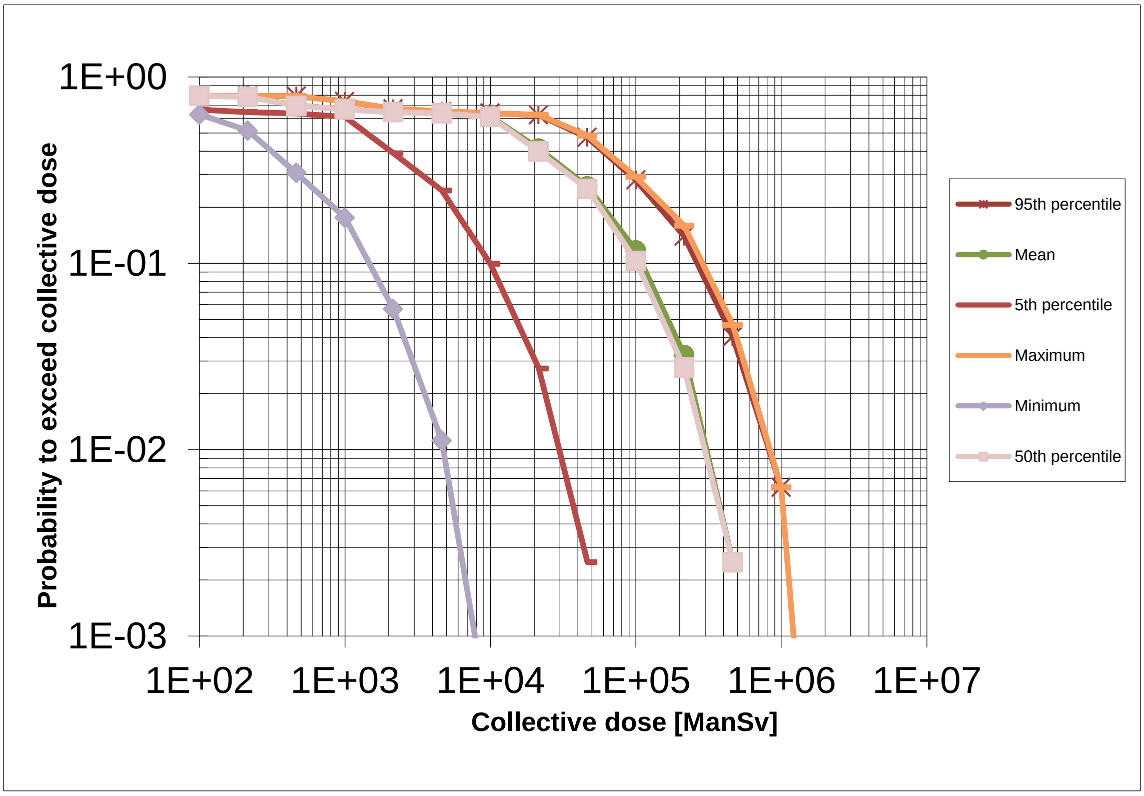


Figure 5: Complementary cumulative distribution of sequence 7.

Complementary cumulative distributions of accident sequences are presented in Figure 6. They are drawn based on 95th percentile values from level 2. This does not provide much additional information compared to the mean values. The curves of sequences 1 and 2 are overlapping.

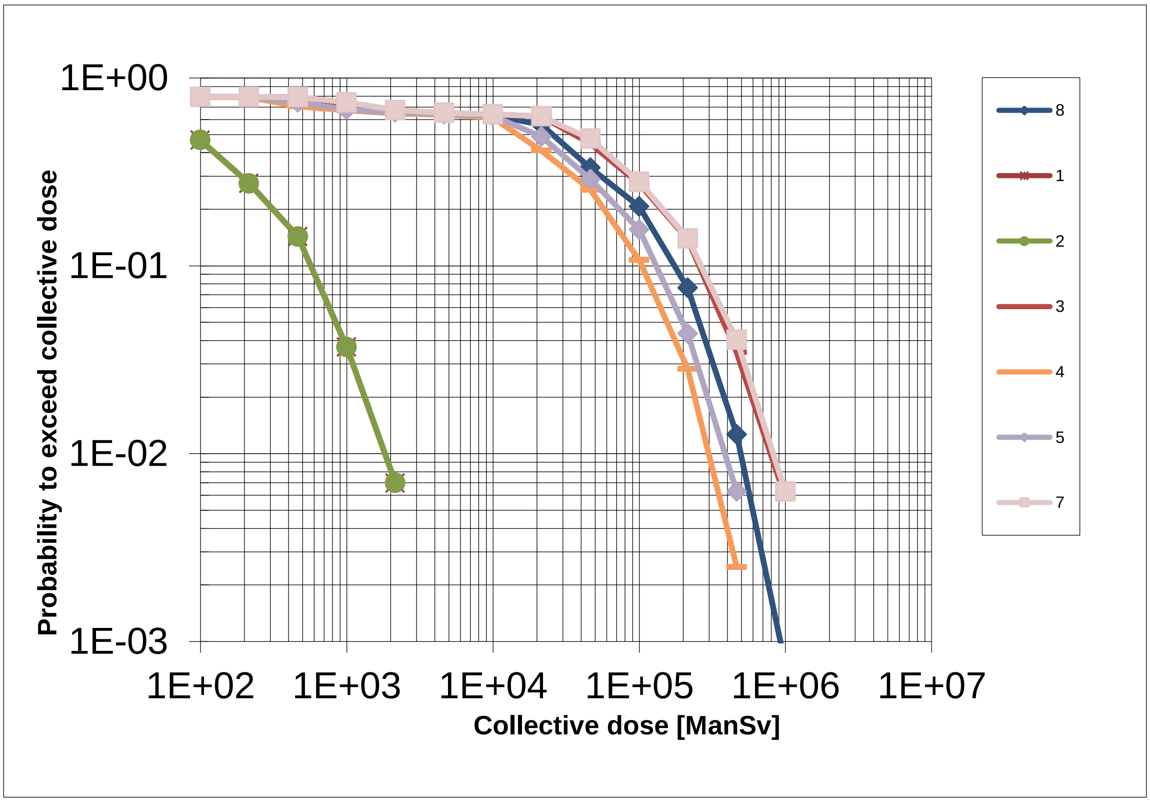


Figure 6: 95th percentile complementary cumulative distributions of accident sequences.

The main computation cases were also calculated using evacuation as countermeasure. However, the effect of evacuation was small. The collective doses decreased less than 5 % in most cases. Probably the reason is that the number of the evacuated people (350) was small compared with the number of people exposed to the radiation (nearly 460000).

Because evacuation is normally planned and aimed against severe early health effects, it probably could reduce more effectively those consequences. However, release fractions were also so large that they could cause severe early health effects beyond 5 km, and therefore, it might be efficient to extend evacuation beyond the presumed evacuation distance.

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 for these parameters.

5. Conclusions

In this report, the integration of PRA levels 2 and 3 was studied so that a moderately large number of source term scenarios were taken from level 2 results for level 3 analysis. The categorisation of level 2 accident sequences was examined with regard to level 3 results, and it was found that the release categorisation used in the containment event tree of level 2 does correspond to level 3 results quite well. On the other hand, more detailed release categorisation could be used for integration of levels 2 and 3. The model was very simplified and has only been used in research purposes. 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.

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 95^{th} percentiles, 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 effect of evacuation was small in the analyses. Probably the reason is that the number of the evacuated people was small compared with the number of people exposed to the radiation. The benefits of evacuation might emerge more if early health effects were analysed.

The level 2 model did not calculate the altitude and temperature of the release even though they are important inputs for level 3. It would be beneficial to expand level 2 models in this area.

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

Finally, this exercise demonstrates that integration of the PRA levels 2 and 3 seems to be possible with the existing tools. However, a full scale study would require much wider approach with site specific data and then supplementary models might be needed.

References

International Atomic Energy Agency, IAEA 2010. Development and application of level 2 probabilistic safety assessment for nuclear power plants: Specific safety guide No: SSG-4. Vienna (Austria).

International Atomic Energy Agency, IAEA 1996. Procedures for conducting probabilistic safety assessments of nuclear power plants (level 3). Safety series No. 50-P-12. Vienna (Austria).

John C. Lee, Norman J. McCormick 2011. Risk and safety analysis of nuclear systems. Hoboken NJ, USA: Wiley. xxi+477 p.

Teemu Mätäsniemi, Tero Tyrväinen, Kim Björkman, Ilkka Niemelä 2015. FinPSA knowledge transfer (FINPSA-TRANSFER). In: SAFIR2014 – The Finnish Research Programme on Nuclear Power Plant Safety 2011-2014, Final Report. VTT Technical Research Centre of Finland, Espoo (Finland).

Ilkka Savolainen, Seppo Vuori 1977. Assessment of risks of accidents and normal operation at nuclear power plants. Valtion Teknillinen Tutkimuskeskus, Otaniemi (Finland). Ydinvoimatekniikan Lab.