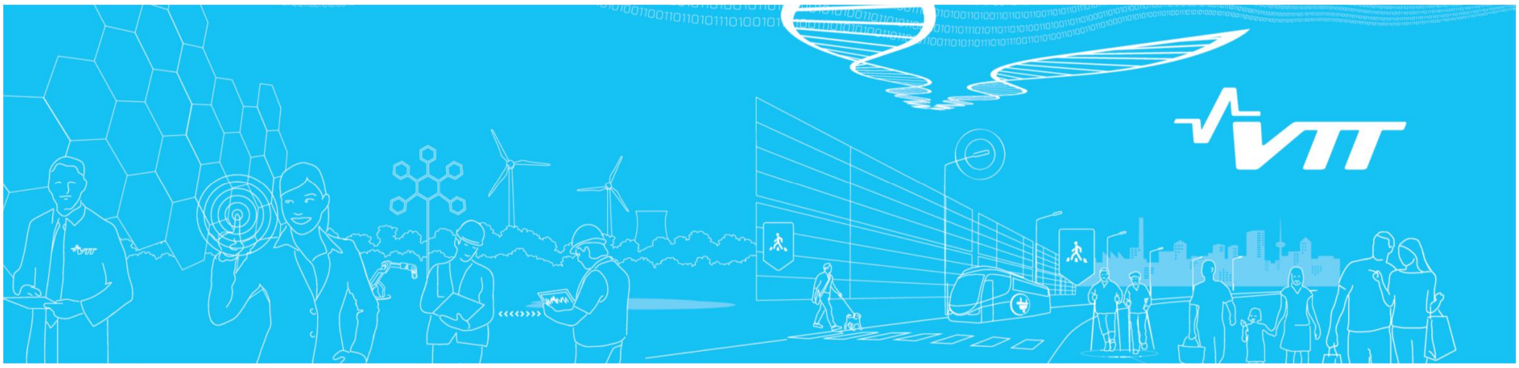

RESEARCH REPORT

VTT-R-00559-14

A plan for a pilot study of level 3 PSA using IDPSA

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Confidentiality: Public

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A plan for a pilot study of level 3 PSA using IDPSA

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Summary

A plan has been created on a level 3 PSA pilot study. The plan covers objectives of the pilot, intended analysis methods, and data needs and how to satisfy them.

The goals of the pilot are

- to gain experience in applying and evaluate the usefulness of integrated deterministic and probabilistic safety assessment (IDPSA), originally developed for PSA level 2
- to gain experience in applying and assessing the properties of various consequence metrics proposed for level 3
- to develop methods for taking multiple source terms in an NPP accident into account
- enable comparison with the Swedish pilot, developed simultaneously in the project
- gain knowledge about issues related to shutdown conditions and fuel pool accidents

The main intended analysis method is IDPSA. It will be applied in the way that atmospheric dispersion of a radioactive release is treated deterministically, and some of its outputs – e.g. concerning the timing of different events – will be forwarded to the stochastic model, here an event tree.

There will be one or more event trees, potentially one per level 3 consequence class. An event tree will be developed at least for population doses. The variables of the event tree(s) are concerned with, e.g., weather factors, countermeasures (sheltering etc.) and their timing, and population behaviour.

The pilot will concentrate on analysing the Fukushima Daiichi NPP disaster in March, 2011. Data will be obtained from various public sources. An issue is the population and topography following the tsunami but before the NPP disaster.

Confidentiality	Public

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Preface

This is a plan for a pilot study to be conducted in 2014. The study has connections to both the Finnish and the Nordic research on nuclear safety. On the Finnish side, it is a part of the PRA Development and Application (PRADA) project which, in turn, is a part of the The Finnish Research Programme on Nuclear Power Plant Safety 2011 - 2014 (SAFIR 2014). On the Nordic side, it is a cooperation between VTT and Swedish partners (Scandpower Ab, RiskPilot Ab, ES-konsult Ab) in the research project “Addressing Off site Consequence Criteria Using PSA Level 3”, funded by NKS and NPSAG. The authors thank Roy Pöllänen and Pia Vesterbacka (STUK) for valuable comments on the manuscript.

Espoo 13.5.2014

Authors

Contents

1. Introduction

In this document, a proposal for the limited PSA level 3 pilot case is illustrated. For this purpose the requirements of a probable pilot case are discussed and finally the specification for a pilot case is represented. The main target is to present the methodology and how to verify the functionality of the calculation process in 2014.

The renewed YVL Guide [STUK 2013] A.7 concerns this issue, but does not actually require PSA level 3 studies. Requirements of Guide A.7 are aligned only to the PSA level 1 and 2 in the case of severe accidents. On the other hand, the YVL Guide C.3 gives deterministic specification that in the case of a severe accident resulting in radioactive release, there shall not be need for evacuation outside the protective zone (< 5 km) and no need for sheltering outside the preparedness zone (< 20 km) and in addition that the release of Cs-137 remains under the release limit of 100 TBq.

In the long-term target this answers the question what are the possible risks in the environment from the severe accident at the nuclear power plant. The procedure presented here contributes to the quantification of risk to the society (Knochenhauer, Holmberg 2009).

The pilot will be a part of the Nordic NKS-funded project “Addressing off-site consequence criteria using Level 3 PSA”. Within this project, various risk metrics will be evaluated in this pilot and in the pilot to be built by the project’s Swedish partners.

2. Goals

The goals of the pilot study are

- to gain experience in the application of the IDPSA methodology (originally developed for level 2) to level 3 studies, and to evaluate its usefulness on level 3
- to apply and evaluate risk measures identified in the NKS project in a case study
- to develop methods for taking into account multiple source terms at different times and from different sources (as was the case in Fukushima)
- to gain experience in conducting level 3 analysis for the development of a new level 3 code
- to study how uncertainties proliferate through level 3 analysis

The pilot allows also other uses. For example, comparisons between the IDPSA approach and the current Swedish approach might be made. The pilot will also give perspective on what input should be expected from PSA level 2 analyses. Such uses may be implemented in later years.

3. Scope

The scope of the pilot is to estimate population doses and related health effects caused by atmospheric dispersion of the radioactive release in the selected case. Emphasis will be on short-term health effects. A metric that will be studied is the averted dose, that is, the dose averted by the population due to countermeasure(s); this metric is useful in the analysis of countermeasure effectiveness. This averted dose will be compared with the dose that the population would have been subjected to without countermeasures. Also the number of persons whose received dose exceeds a certain limit will be examined as a metric. Other consequences, such as land contamination through radioactive fall-out, may be considered.

The methodology used belongs to the IDPSA (Integrated Deterministic and Probabilistic Safety Analysis) family of methodologies. The applicable software available at VTT consists of two programs: SPSA and ARANO [Ilvonen 1994, Savolainen et al. 1977]. According to the IDPSA principle, ARANO and SPSA programs are planned to be used together in such a way that ARANO calculates consequences (the deterministic safety analysis part of IDPSA) and provides some essential data to SPSA which uses these results and produces risk estimates (the probabilistic safety analysis part of IDPSA). Also other programs may be used for atmospheric dispersion calculations.

SPSA (STUK PSA) is essentially a PSA level 2 program that supports event tree analysis, and fault tree analysis related to it. This program is normally used to calculate the source terms and their probabilities on level 2. In this pilot, SPSA is also used to support level 3 analysis by handling and assessment of uncertainty. Modeling with SPSA is based on graphical event tree approach common in PSA applications. The purpose of ARANO (Assessment of Risks of Accidents and Normal Operation) is to calculate health and economic risks from radioactive releases to the atmosphere in deterministic and probabilistic sense.

The case to be analysed this year will be the Fukushima Daiichi nuclear power plant disaster in 2011. We will examine not only the disaster as it unfolded, but also from a more general probabilistic viewpoint; this allows, among other things, a comparison between the implemented countermeasures and the imaginary situation where they hadn't been implemented. Other potential case study targets, such as Sosnovyj Bor and Olkiluoto, will also be examined in this document because they might be used in pilot studies in the coming years.

Here only elements essential and necessary for the level 3 are considered, the more detailed description of the IDPSA and its functions at level 2 are presented in (Silvonen 2013). In the next chapters the data needed in ARANO is described.

4. ARANO

ARANO is a straight line dispersion model, weather remains the same until the plume exits the computation area. Spreading of an emission in the air is calculated on the basis of the application of the diffusion model using the Kz theory where a vertical dispersion and the impact of dry fallout as boundary condition on the deterioration of the cloud are taken into account [Nordlund et al. 1979]. Rain intensity is considered by exponential depletion employing washout coefficient. Annual weather data from one meteorological mast is converted into joint frequency matrix of annual weather statistics.

The exposure pathways are: external radiation from the cloud and fallout, internal exposure from inhalation and ingestion. In ingestion dose seasonal variation due to summer and winter conditions are taken into account. Short-term countermeasures include sheltering, evacuation and iodine tablets. Long-term countermeasures include relocation, land decontamination and food ban.

Economic costs are based on the contamination criterion, which may be based on the dose or ground concentration. Costs of evacuation, relocation, decontamination and food bans can be calculated.

The flow chart of the ARANO computer code is shown in figure 1.

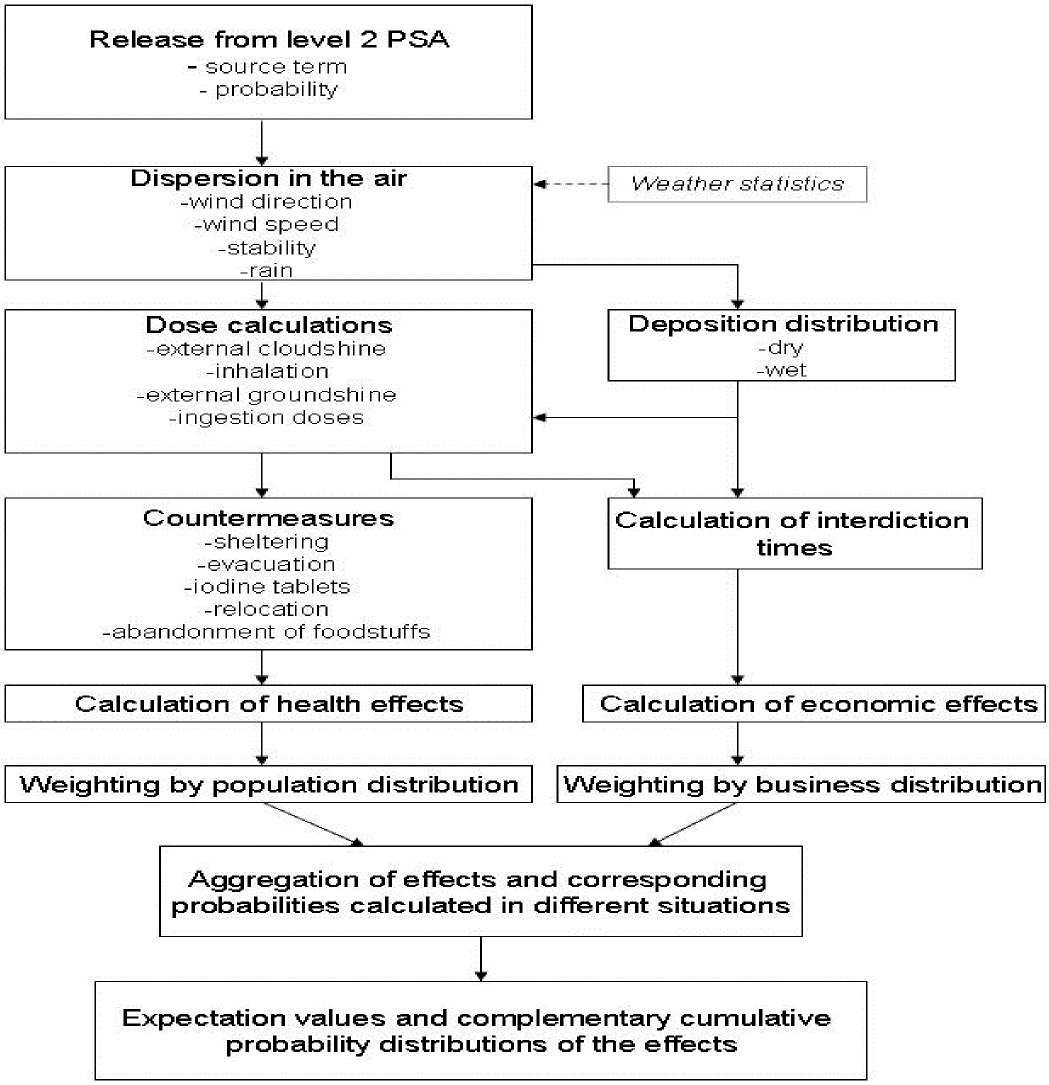

Figure 1. The flow chart of the ARANO computer code

This specification relates to the original version of ARANO. It is possible to calculate consequences in one single dispersion case or dispersion can be calculated in different conditions generally covering the whole year. Then the results are weighted with the frequency of each weather condition.

The main restriction relates to long duration releases i.e. weather cannot change during the release or dispersion. There exists also a renewed version of ARANO which allows weather to change during the release. In that case calculation goes forward using the weather data in one hour step. However this new version is not yet completed and therefore it is not used in this work.

4.1 Site specific data

In the following subsections the data required in ARANO is described.

4.1.1 Weather data

Meteorological data measured at the weather mast of the site covering at least one year can be used. Longer time periods give more reliable data. Data should originally be given in one hour interval, from which it is converted to distributional form for ARANO. Dispersion direction and wind speed are from the altitudes of 20…100 m, as also the atmospheric stability. Occurrence of rain shall also be reported.

The weather distribution in ARANO consist of dispersion direction frequencies in 30 degree's sectors, frequencies of the stability classes in the dispersion sectors, wind speed frequencies in the Pasquill stability categories A…F in 12 sectors and rain occurrence frequency in the stability categories. Recommended washout coefficient in stability categories A, B and C is 10-5 s-1 and in the categories D, E and F 0.7·10-4 s-1. The value of 0.01 m/s is used as dry deposition value for aerosols; the corresponding value for noble gases is 0.

4.1.2 Source term

The ARANO radionuclide package operates on the basis of material classes, which are groups of elements that have similar chemical properties. The default number of classes is 8. Table 1 shows an example on the grouping of the elements into the classes.

Table 1. Grouping of the elements into classes used in ARANO.

Element group	Nuclides
1. Noble gases	Kr, Xe
2. Halogens	I
3. Alkali Metals	Cs, Rb
4. Chalcogens	Te, Sb
6. Platinoids	Ru, Rh, Pd, Mo, Tc, Co
7. Lantanides	La, Zr, Nd, Nb, Pm, Pu, Pr, Y, Cm, Am
8. Others	H, N, C, Ar, Cr, Mn, Fe, Zn, Ag

There are two ways to give the amount of the radioactive release:

1. Define the release of the isotopes in Bqs,
2. Give the reactor inventory in Bqs and the release fraction for each element group.

Radioactive releases are described with a discrete probability spectrum. In addition to the release magnitude the following parameters shall be given:

- start and end time of the release
- warning time
- release altitude

There can be only one release and one release height in one run. The start and end times are given relative to shut down. Warning time means the time to start countermeasures before the release starts.

Release altitude means effective release altitude (the release altitude where e.g. the effects of high temperature have been taken into account). If there is energy release or moment, the final release altitude shall be estimated separately. In the release of radioactive material into the atmosphere account has been taken of the possible mixing effect of plant buildings.

4.1.3 Demographic data

When risks to the society are calculated it is necessary to know demographic data in the environment of the power plant. The most important of these is population distribution. In ARANO population data is given in polar coordinates (segmented by radial lines - r,ϴ). In this annular grid the angle size is 30 degrees which means that data is given in 12 sectors for distance intervals defined by the user.

Agricultural production is given in the same format. The nutrition exposure pathways and the corresponding foodstuffs in ARANO are: cow milk, cattle meat, green and root vegetables and grain products. In general availability of agricultural production data is less obvious. Production data from farms is usually not more precise than municipality-specific, therefore accurate distributions are not easily available. Moreover local inhabitants may produce foodstuffs which are not included in any register.

Economic data distribution is based on the population and job distribution data and the fixed capital property. It is assumed that all the capital property can be divided based on the population and job distribution and the result is property value/person.

For example in Finland capital property data, as well as population and job distributions, is provided by the Statistical Centre of Finland. The capital types needed here are: housing, primary production, processing and service. These types may include several subtypes of capital properties. It is assumed that capital losses of housing relate to the impact of population distribution, but the other types of capital losses are dependent on the impact to the job distribution.

There are also other costs, which follow directly from different countermeasures. Evacuation and relocation creates additional cost due to movement. Purification of residential areas and agricultural land cause extra costs. Assessment of these costs is depicted in the context of countermeasures.

4.2 Countermeasures

4.2.1 Short-term countermeasures

In the acute phase of an accident short-term countermeasures are: sheltering, evacuation and iodine tablets. These measures shall be performed mostly based on limited and perhaps uncertain information. Local sheltering with doors and windows closed and turning off ventilation or air conditioning is meant to decrease exposure to external radiation from the cloud and fallout, and even more importantly decrease exposure to internal radiation (especially iodine) through breathing [STUK 2012a]. Effectiveness of sheltering depends also on the construction material of the shelters. In general wooden houses are less sheltering than concrete houses.

In ARANO sheltering is taken into account by using sheltering factor for external radiation from the cloud and from the fallout. Population can be divided into two shielding factor groups, of which the first one is assumed to be out of doors and the second one indoors when the plume is passing over. Later both groups spend e.g. 10% of time outdoors and the rest of time indoors.

Evacuation is especially useful if it is carried out before the plume reaches the evacuation point. If evacuation is going on when the plume is already overpassing the area, the evacuees expose to direct radiation from the plume.

In ARANO there are two parameters affecting the evacuation: distance and evacuation time. The distance means that all the inhabitants are evacuated up to that range instantly after the time given for the evacuation. The time is calculated since the plume has reached the point. If the time value is 0, the population has been evacuated before the plume is spread to the point and dose to the population is 0. Actually there are two distance and time parameters. For example it is possible to define that groundshine dose is integrated until the planned evacuation time point at 4 hours up to 5 km and 24 hours at longer distances.

Also warning time parameter affects evacuation. If there is a sure knowledge that the release will start after a certain time period, there is a period of warning time available for the initiation of evacuation before the release to the environment begins.

Stable iodine tablets can be used for thyroid blocking. This prevents radioiodine to be taken up from the blood.

In ARANO there is no direct input for iodine tablets, but it can be taken into account in calculation by reducing internal dose from iodine isotopes.

4.2.2 Long-term countermeasures

Long-term countermeasures include relocation, land decontamination and food ban. It can be assumed that after the acute phase of an accident there is now sufficiently time to consider and evaluate different countermeasures and their combinations. Relocation refers to moving people away from the contaminated area for a longer time period (weeks, months, years). Decontamination of land means cleaning and removal of radioactive substances. Food prohibition is based on ingestion dose levels or ground concentrations.

If external radiation dose exceeds a limit value the first protection measure could be decontamination. If the cleaned area after decontamination is still too contaminated, staying there shall be reduced or denied. Criterion for the contaminated area can be based on the external radiation dose from fallout during 30 years. As reference it can be mentioned that 0.1 Sv/30a approximately corresponds to the dose from normal background radiation.

4.3 Health effects

If the radioactive release is large and exposure to radiation is remarkable, early health effects can occur during a short time period (days, weeks). Late effects appear later in subsequent years. Early effects require that acute radiation dose is sufficiently high and often there is a threshold value for a health effect. Below the threshold dose no early effects can be observed. The late effects are mainly cancers in exposed persons and hereditary diseases in their descendants. The amount of these stochastic effects is based on the collective dose of the population and a conversion factor for a cancer appearance.

In ARANO early health effects base on the acute or step function type, late effects on the linear function type. The effective dose threshold of 1 Sv may be employed for assessment of number of radiation illness cases. The number of early fatalities can be calculated using a dose response relationship in which the effective dose of 2 to 5 Sv causes the probability of early fatalities to increase from 0 to 1. Concerning late effects a linear dose-response function can be used. The number of fatal cancers is calculated by multiplying the total collective dose with a risk factor of 0.05 cancers/manSv.

4.4 Economic costs

The estimation of economic losses in accidents can be formulated similar to the estimation of health effects. Instead of dose-response relationships various contamination criteria can be used. These are either limits for activity concentration on the ground or limits for the integrated effective dose (the dose of whole body, calculated as a weighted sum of the doses of individual organs) over 30 years. Economic losses can be divided based on the macro-economic indicators into losses of investments, losses of production, relocation costs and losses due to costs of health effects.

The investments are divided into four main groups: 1) primary production (agriculture and forestry), 2) manufacturing and construction, 3) service and 4) housing. The spatial distributions of investments (1-3) are assumed to be the same as the numbers of workers in the same fields. The housing investments are distributed according to the population. The investments are assumed to be lost as long as the effective dose within 30 years from the end of the interdiction period exceeds the predefined value. The lost fraction of investments is assumed to increase linearly with the interdiction time until 10 years, when the whole value is lost.

4.5 Results

The consequences of a given source term vary with the meteorological conditions. Each meteorological condition has a probability of occurrence and the consequence value is calculated by ARANO. At each (r,Ɵ) grid element around the release location the following quantities can be evaluated:

- radiation dose
- number of health effects
- areas, persons and amounts of agricultural produce affected by countermeasures
- economic costs

The consequences of a radioactive release are calculated for a large number of atmospheric dispersion conditions and the consequences are then combined with their probabilities of occurrence into forms of expectation values and e.g. complementary cumulative distribution functions (CCDF's) which express the probability of exceeding a given consequence magnitude. It is a standard practice to produce the expectation and various percentile values for the CCDF. There will be guidance on the required confidence level (fraction in cumulative probability distribution) in STUK YVL guidelines C.4 (in draft stage at the moment of writing).

5. Pilot application

First the requirements of the pilot case for a limited PSA level 3 study are defined. The ARANO input is dependent on the desired results to be obtained. Concerning potential consequences in pilot case it may be reasonable to start with radiation doses to population and subsequently proceed to health effects. Economic consequences may be studied afterwards depending on the extent of the study in the later phase. Radiation doses can be caused in two phases – early in the beginning of the accident and later after the fallout has taken place. Countermeasures can be taken into account in both early and late phase.

If the collective dose to the population in a spatial grid is obtained it is also possible to determine the societal risk.

As noted in section 3, the Fukushima Daiichi disaster of March 2011 is the object of the pilot. However, Sosnovyj Bor or Olkiluoto are also considered here, because they might be chosen for pilot applications in the future. In the following paragraphs the site specific data necessary in the pilot case is estimated for each of these sites. The existing input data for a power plant is mentioned, but missing essential input data is also discussed.

5.1 Weather data

For the Olkiluoto site there exist the long-term annual weather data since 1990 until recent years. This data has been initially measured every 10 minutes at the meteorological mast of the site and afterwards it has been converted to represent average hourly values. This data covers the altitudes of 20 m and 100 m. This data is the most extensive available for the pilot case.

For the Fukusima Daichi site, weather data of a two month period from March 11th to May 11th in 2011 exists and is provided by the Finnish Meteorological Institute (FMI). This data covers only a part of one year data, but the missing data may be possible to calculate by the FMI which may incur costs.

In the case of Sosnovyj Bor there is no meteorological site specific data and it should be bought from the FMI.

5.2 Source term

In the case of Olkiluoto there are various source terms covering also PSA level 2. Those data include both release magnitudes and probabilities of release occurrence.

In the PSA level 2 results the release magnitude is given by the release fraction of the core inventory. Besides the times for the release starting and ending are given. Energy releases or release altitudes are not reported. Effective release altitude of each release period should be estimated separately.

Concerning the Fukusima Daichi accident in March 2011 there are several estimates about the radioactive releases occurred at the reactors [Ikäheimonen 2011, Kobayashi 2013, Saunier 2013]. Variation between the estimates is remarkable. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has released a report [UNSCEAR 2014] with source term estimates which will be used in the pilot. Characteristic of the release was that there were releases simultaneously from the three reactors with varying intensity. The releases to the atmosphere took place notably for a week and afterwards the release intensity decreased substantially.

One of the Chernobyl type RBMK reactors is in operation in Sosnovyj Bor. There are several estimates of the source term of the release in Chernobyl 1986; however, the disaster of Chernobyl was due to the explosion of the reactor, and may therefore be of limited applicability in the present context. UNSCEAR has released a report with source term estimates [UNSCEAR 2000], which can be used in the pilot.

5.3 Topographic and terrain data

In the case of Olkiluoto, topographic information is available.

In the case of Fukushima, the topography and vegetation information can roughly be estimated from ordinary maps of the area, and aerial photographs in Google Maps. However, it must be taken into account that the local conditions changed following the tsunami, as a large number of houses and much of vegetation were destroyed.

5.4 Demographic data

In Olkiluoto there are population data available around the site up to the distance of 100 km; however, the data currently at the possession of VTT is old, and may need updating. At larger distances population can be estimated based on the population density in the ambient provinces. Agricultural production distributions are not available. Doubtless it is only possible to make rough estimates of this kind of data based on the foodstuffs production in the ambient counties. There are some economic data for Olkiluoto specified by the Statistical Centre of Finland, but also this data currently available at VTT is several years old.

In Fukushima and its surroundings, the population distribution could be roughly estimated e.g. based on the NRC's estimates (NRC 2011). In that estimate there is a map including the number of occupants of the largest towns and the total population inside the circle with the radius of 50 miles. Based on that information it could be possible to prepare a rough population peripheral distribution for the Daichi site. In the estimates, it has to be taken into account that by the time of the nuclear disaster, the population of many districts were fully or partially depopulated due to the earlier tsunami and evacuations carried out because of that. Agricultural and economic data of Daichi are unknown.

The authors are unaware of any demographic data for Sosnovyj Bor. Some data may be available from STUK.

5.5 Countermeasures

In the pilot study countermeasures depend on the site. Countermeasures in Olkiluoto can be determined based on the STUK guidelines [STUK 2012a] and [STUK 2012b]. However, e.g. timing of the release may affect the measures. In Fukusima there were reported countermeasures which may be adopted in the calculations [Ikäheimonen 2011][UNSCEAR 2014]. If countermeasures in Sosnovyj Bor are to be estimated, rather few data is available and it is necessary to adapt some conventional measures.

5.5.1 Short-term countermeasures

In Olkiluoto the protective zone ranges from the site up to 5 km and the countermeasures planned for that area are sheltering, evacuation and iodine tablets. In basic case it can be supposed that iodine tablets are ingested before the exposure starts. Also sheltering is assumed to be done before the plume reaches the distance which is under review. Evacuation can be done before the exposure starts or in the less recommended case during or after exposure.

As a reference case it can be assumed that no countermeasures are carried out. This case shows, what the consequences are if dose reducing measures are not implemented. Then sheltering, evacuation and iodine tablet can be applied together or separately. Evacuation can be done first of all up to the distance of 5 km, but sheltering as well as iodine tablet delivery to the population up to the distance of 20 km.

Integration time of groundshine may vary from few hours to one week. Table 2 shows different combinations of short-term countermeasures. There could be also other combinations of the countermeasures, but Table 2 corresponds to a large extent the idea of the YVL guidelines. Evacuation times are given only as options. Maximum exposure duration is 1 week.

Table 2. Short-term countermeasures in Olkiluoto.

	Iodine tablet	**Evacuation**	**Sheltering**
1(Reference case)	No	No	No

2	No	No	20 km
3	20 km	No	No
4	20 km	No	20 km
5	20 km	3 km (4,12,24,48,168h)	20 km
6	20 km	4 km (4,12,24,48,168h)	20 km
7	20 km	5 km (4,12,24,48,168h)	20 km

It is assumed that iodine tablet is taken as a basic countermeasure and evacuation cannot be done without sheltering. There are five different evacuation times in Table 2. This results in 19 calculation cases.

In the case of Fukusima there is some information available of the real countermeasures done in the environment of the Daichi site. The most important measure to be done here is evacuation. Damage on the coastline after tsunami was extensive and complicated implementation of evacuation. According to NRC about 2 million people live within 80 kilometres of the plant [NRC 2011]. Soon after the accident NRC recommended that all the Americans should be evacuated from that area. Japanese government recommended two evacuation zones. The inner zone of 77000 residents in the 19 km zone should be evacuated immediately and the zone of 19-30 km with 62000 residents should be evacuated after two weeks. Based on Figure 2 it is possible to approximately divide population into the calculation grid.

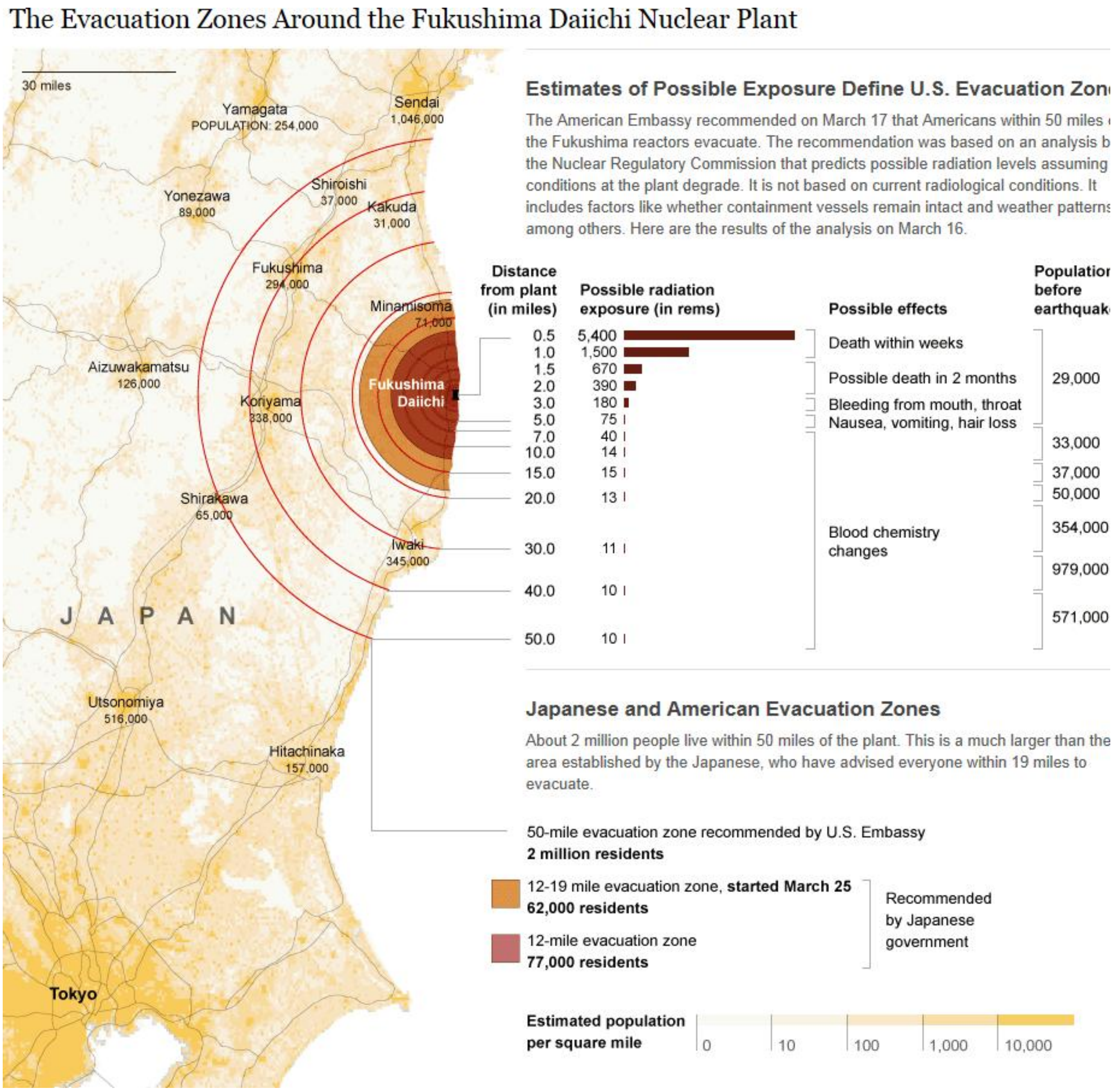

Figure 2. Evacuation plans in Fukusima according to NRC (NRC 2011).

Additional and more precise information is published in (Ikäheimonen 2011). This reference reports that residents were actually evacuated on March 11 first up to the distance of 3 km and then soon up to 5 km even before the releases started on March 12. On that day evacuation was extended to the distance of 20 km. Then some extra evacuation was carried out not until in April, probably based on the local radiation measurements.

In (Ikäheimonen 2011) it is also said that iodine tablets were reserved for residents within 50 kilometres, but those tablets were never eaten. There is no clear information about how sheltering was conducted.

There is no data about countermeasure strategies for Sosnovyj Bor. In calculations it would be possible to assume some general mitigation activities.

5.5.2 Long-term countermeasures

In Olkiluoto the preparedness zone ranges up to 20 km and the long-term countermeasures planned for that area are relocation, land decontamination and food ban. Also iodine tablets and sheltering are relevant up to this distance but these actions are planned to take place in the short-term phase.

Relocation criterion is based on the external dose from the ground (groundshine) during e.g. 1 or 30 years. Food ban is based on the ingestion dose from different foodstuffs, when eating lasts either one year or 30 years.

Table 3 includes different alternatives for the long-term countermeasures. Long-term exposure starts when the short-term exposure terminates.

Table 3. Long-term countermeasures in Olkiluoto up to the distance of 20 km.

	Land decontamination	Relocation	Food ban
1(Reference case)	No	No	No
2	No	No	Yes
3	No	Yes	Yes
4	Yes	Yes	Yes

In Olkiluoto the land decontamination factor could be 3. Relocation criterion could be 0.1, 0.3 or 1.0 Sv/one year. Food ban could correspond to the relocation criterion. When the dose is calculated the criterion indicates to what value the individual dose is reduced.

For Fukusima there is no data of decontamination or relocation activities. Food usage bans were implemented. Report (Ikäheimonen 2011) says that the estimated internal dose from controlled food products would be at the level of 3 mSv.

For Sosnovyj Bor there is no data for long-term countermeasures.

5.6 Economic costs

Short-term countermeasures such as iodine tablets and sheltering locally cause probably less economic costs than evacuation or relocation. Therefore costs from evacuation and especially from relocation are planned to be estimated here. In practice interdiction of the contaminated land area results in losses of capitals and long-term investments for the period of the ban. In ARANO this can be taken into account by the method presented in chapter 3.4, which defines that either all the investment or a fraction is lost. By decontamination of land the interdiction time can be reduced.

Because here the main interest is to verify the calculation method for a limited level 3 PSA, economic costs are not calculated in the first phase.

5.7 ARANO results

In first phase the target in ARANO is to calculate:

- radiation dose through immersion, inhalation, ingestion and radiation from the ground
- number of early health effects

The relevant results and corresponding parameter values are used as input for SPSA for further treatment in according to IDPSA principles as described in chapter 6.

5.8 SPSA analysis

To manage the uncertainty in level 3, an event tree model will be constructed. This consists of one or more event trees that collectively constitute a probabilistic model of accident consequences.

In the event tree, several factors have to be considered. Some of these are continuous in nature, so they have to be binned into discrete classes. Information needed for modelling of these events and factors originate principally from ARANO consequence analyses, although source term data stem mainly from level 2 analyses performed with SPSA. In addition, expert judgement and literature are valid sources to support modelling work.

The main factors that affect accident consequence uncertainty are as follows:

- *source term:*
  amount of each radioactive isotope, chemical composition (especially iodine in organic or inorgamic compounds), particle size distribution, release energy (temperature), release height from ground level
- *weather during radioactive plume dispersion:*
  wind direction and speed, atmospheric turbulence (stability class), precipitation (rainfall) and mixing layer altitude
- *counter-measures taken to secure population safety:*
  sheltering at homes, distribution of iodine tablets, evacuation etc. The timing and organization of these may have great impact on the doses that the population receives. Counter-measures can be further divided into those which are executed as soon as possible (e.g. sheltering) and those which have significance mainly in the long term (e.g. relocation of people).
- *population behaviour:*
  a part of the population may panic, and this may result in traffic and other accidents and traffic congestion. The quality of official action, especially counter-measures, contributes greatly to the risk of disorder.

For the purposes of event tree modelling, those quantities – such as wind speed and direction – that are continuous, have to be discretized. Another important design decision concerns the number and naming of variables in the decision tree.

An important feature of level 3 modelling is the high significance of decision making aspects of the problem. On PRA levels 1&2 Severe Accident Management (SAM) guidelines can be followed more rigorously, but level 3 contains e.g. political, economic and societal dimensions which increase the complexity of the analysis. An emergency response plan of some kind for off-site measures usually exists, but in addition to the success of a countermeasure also the decision process behind the implementation of the countermeasure should be modelled.

Each countermeasure can be assigned an implementation criterion e.g. in terms of averted dose, which means the dose that could be averted if the countermeasure was to be applied. In real emergency situations the estimation of averted dose may be impractical and operational measures such as dose rates can be used as surrogates. Modelling should also consider to what extent the situation (plant state, release timing, source term etc.) is uncertain to the decision maker, which may result in decisions that do not always turn out to be optimal due to incomplete information on the prevailing conditions.

Branch probability of a countermeasure in the event tree practically refers to uncertainty of the decision to implement the countermeasure. Although emergency response plans should give unambiguous instructions and intervention criteria, uncertainty arise from incomplete knowledge of the situation. Measurements/calculations on which intervention criteria are founded on can also be inaccurate. Success of a countermeasure can be measured in terms of e.g. evacuation need vs. road/transportation capacity. Only a partial success of a countermeasure is likely if it is for example implemented too late, i.e. the effect of countermeasures can vary and this has to be taken into consideration in the model.

Figure 3 illustrates what an event tree for level 3 might look like. The structure of the tree, binning of variables etc. will be specified during the construction of the pilot.

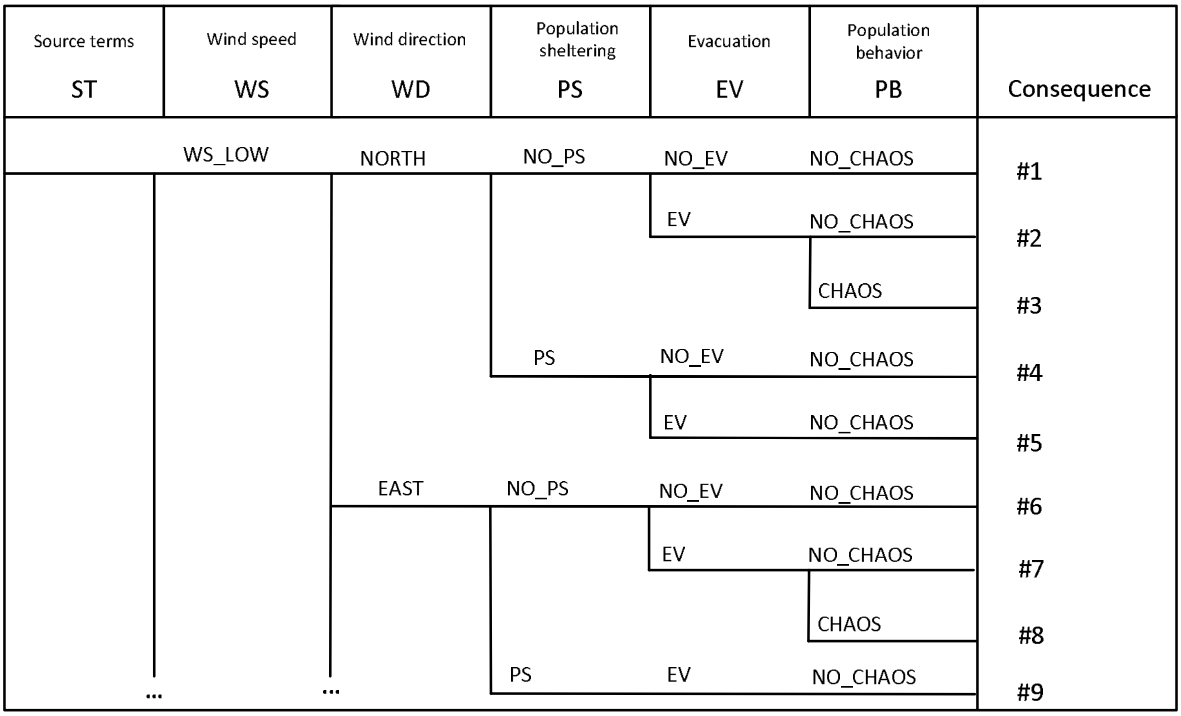

Figure 3. An event tree sketch illustrating what a model for level 3 PSA could look like.

An essential factor affecting consequences is the timing of events and processes during release and plume dispersion. This concerns the time that it takes for the plume to reach inhabited areas, the timing of official and population alert and countermeasure commands, the time it takes the population to evacuate or seek shelter etc. In SPSA, timing logic is built into the handling of events.

The relative timing of events is taken into consideration in the event tree structure. The problem is divided into successive sections which are represented by headings in the event tree. Thus the possible chronology of events can be intuitively depicted. Another benefit of event tree modelling is that interdependency of events and their probabilities is easily accommodated. For individual events whose timings overlap each other, the order in the tree is more or less arbitrary, i.e. the events do not necessarily have to be strictly successive. In that case, however, their interdependence is more difficult to take into account.

Practically arbitrarily many parameters and functions written in SPSA's CET language can be associated with the event tree. Therefore it is possible to define a global timing variable which is updated throughout the calculation of the model. The timings of individual events can also be dedicated own variables, and they can be later used e.g. in the estimation of consequences. Parametric time-step models can be included as well to introduce more detailed modelling. It can be concluded that modelling of timings of events, and modelling in general, is quite flexible in SPSA, and is founded on event tree methodology.

6. Integration with IDPSA

Generally speaking, IDPSA is a set of methodologies that aim to support risk-informed decision making. IDPSA takes both stochastic disturbances and deterministic responses, and especially their mutual interactions, into consideration in safety justifications. Use of IDPSA can reveal unknown scenarios and it can also be used to reduce excessive conservatism in analysis.

In chapter 5 there are descriptions of various site specific data, which shall be specified in the pilot case. Some of these are typically dependent on the case and may be changed a case by case (e.g. source term and countermeasures).

In the IDPSA procedure it is possible to vary those parameters and calculate consequences in each case, and finally integrate an all-inclusive result as a combination of numerous input data alternatives. Thereby uncertainties involved in the analysis can be propagated through the model. In addition to input variations in level 3 it is possible to take into account parameter variations from level 2. The two analysis tools used in this work, ARANO and SPSA, do not communicate with each other which means that the analyst needs act as an interface between the programs. Figure 4 illustrates the procedure of the IDPSA in the pilot case.

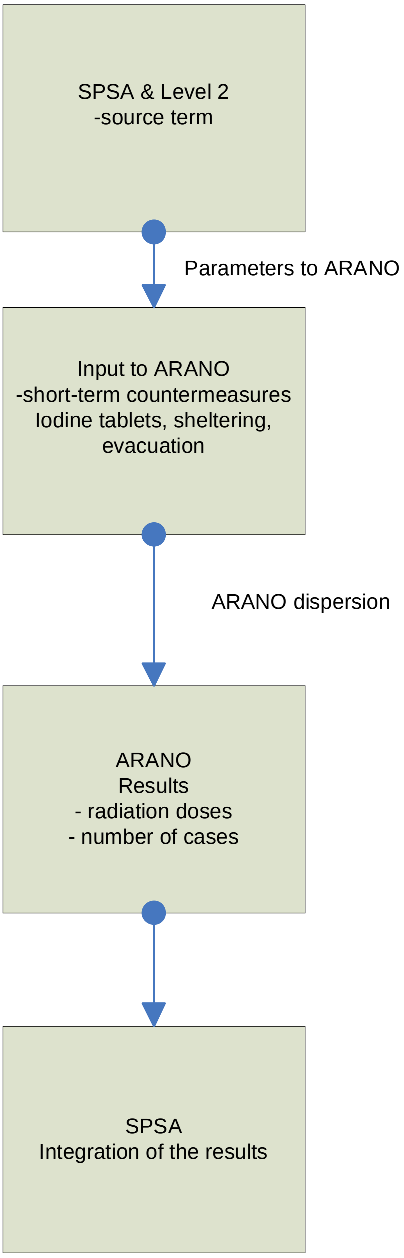

Figure 4. Flowchart of the IDPSA procedure.

7. Conclusions

A proposal for the limited PSA level 3 pilot is represented. Here the method is based on the IDPSA approach, and applies a Monte Carlo type procedure to make consequence calculations by using a level 3 code in conjunction with a level 2 PSA code. Level 2 provides part of the interesting input parameters, but level 3 naturally has some typical parameters to be varied. In principle, numerous consequence calculations are done with varying parameters. The codes relay necessary parameters to each other. In the first phase, short-term radiation doses and health effects are obtained and the main purpose is to verify the functionality of the system consisting of the programs used.

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