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SITRON

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Published: 18/01/2019

Document Version
Publisher's final version

Link to publication

Please cite the original version:
Tyrväinen, T., & Björkman, K. (2019). *SITRON: Site PSA model management*. VTT Technical Research Centre of Finland. VTT Research Report, No. VTT-R-06885-19
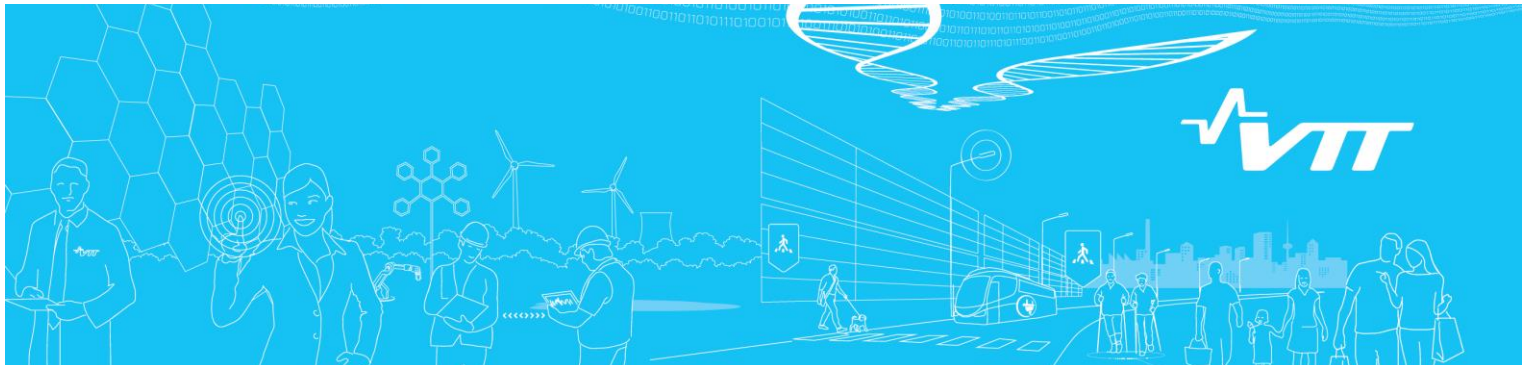
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RESEARCH REPORT

SITRON - Site PSA model management

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Confidentiality:	Public

Report's title	
SITRON - Site PSA model management	
Customer, contact person, address	**Order reference**
VYR, NKS, FKA, RAB, SSM	SAFIR 4/2018
Project name	**Project number/Short name**
Probabilistic risk assessment method development and applications	110223/PRAMEA
Author(s)	**Pages**
Tero Tyrväinen, Kim Björkman	25/
Keywords	**Report identification code**
Site probabilistic safety assessment, model management	VTT-R-06885-18

Summary

In site probabilistic safety assessment (PSA), a nuclear power plant site is analysed as a whole considering all reactor units and other facilities with radionuclide sources. Site PSA especially focuses on dependencies between different units and locations of the radionuclide sources. Most PSAs are unit specific and there are no well-established methods for site PSA.

Besides general method development, procedures are needed for documenting the site PSA, managing possible modifications made to the single-unit PSA models, and managing the data and computation. This report provides guidance for site PSA model management and discusses the needs for a site PSA database. This report is closely connected to a site PSA method described in a separate report and it considers the same analysis phases.

The report discusses single-unit PSA models from site PSA perspective, site PSA documentation and the database for site PSA. Guidelines for site PSA documentation and model management tasks in different analysis phases and in the maintenance phase are given. The focus of the report is on level 1 issues, but also level 2 aspects are covered.

Confidentiality	Public

Espoo 18.1.2019

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Distribution (customer and VTT)
SAFIR reference group 2, FKA, RAB, SSM, Lloyds Register, Risk Pilot AB, VTT archives

Contents

Abbreviations

Acronym	Description
CCDP	Conditional Core Damage Probability
CSTP	Conditional Source Term category Probability
CCF	Common Cause Failure
MCS	Minimal Cut Set
MUCDF	Multi-Unit Core Damage Frequency
MUIE	Multi-Unit Initiating Event
MUSTF	Multi-unit Source Term category combination Frequency
POS	Plant Operating State
PSA	Probabilistic Safety Assessment
SCDF	Site Core Damage Frequency
SSC	Systems, Structures and Components

1. Introduction

In site probabilistic safety assessment (PSA), a nuclear power plant site is analysed as a whole considering all reactor units and other facilities with radioactive sources. Site PSA especially focuses on dependencies between different units and locations of the radioactive sources. For example, an external hazard can affect multiple reactor units or facilities at the same time, and then resources shared between the units might not be available for all units to manage the accident. Most PSAs are unit specific, and there are no well-established methods for site PSA.

Site PSA methods have been studied in separate research reports [1-2]. In addition to methods, procedures are needed for documenting the analysis, managing possible modifications made to the PSA models, and managing the data and computation. This report provides guidance for site PSA model management and discusses the needs for site PSA database. The work is partly based on the requirements presented in [3]. The report is closely connected to the method report [1] and it considers the same analysis phases.

The selection of the risk metrics to be calculated is the starting point for the site PSA. Risk metrics for site PSA have been outlined in [4]. The main site risk metrics for level 1 PSA are the site core damage frequency (SCDF) and the multi-unit core damage frequency (MUCDF). The SCDF is the frequency for any core damage to occur at the site per site-year. The MUCDF is the frequency of core damage occurring in multiple units nearly simultaneously. The MUCDF can be calculated for a specific combination of units, and also the total MUCDF can be calculated as the frequency of core damage occurring in at least two units taking into account all the units at the site. Computation of risk importance measures with regard to different risk metrics is also an important part of site PSA. MUCDF and SCDF can be generalised to concern fuel damage instead of core damage when radioactive sources other than reactor cores are included in the analysis. The main risk metrics for level 2 PSA are the frequencies of site release categories.

Section 2 summarises the method developed in [1] and introduces some basic concepts. Section 3 discusses the challenges related to site PSA analysis and model management. Single-unit models are discussed in Section 4, site PSA document is outlined in Section 5, and database for site PSA is discussed in Section 6. Section 7 goes through the whole site PSA analysis process from the model management point of view. Maintenance of site PSA is briefly discussed in Section 8. The conclusions of the report are presented in Section 9.

2. Method description

Method for evaluating the site risk for nuclear installations using already existing single-unit PSA models is presented in [1]. This section summarizes the method in order to provide basic information as a link to the site PSA model management.

Site PSA mainly concerns three types of analysis elements:

- plant operating states

- multi-unit initiators

- multi-unit dependencies.

A multi-unit initiator is an event that can initiate an accident in multiple units. A multi-unit dependency is a dependency that can cause an event to affect multiple units or dependent events in multiple units. Dependencies related to multi-unit initiators are not included in the category "multi-unit dependencies" here, because they are considered separately.

Based on [1], the following analysis steps can be identified:

1. **Selection of analysis scope and risk metrics:** In this step, the scope of the site PSA is selected. The following issues should be considered in the selection: different radioactive sources, possible operating states, initiators, and PSA end states. The scope of the site PSA needs to be consistent with the scope of the single-unit PSA.

2. **Analysis of POS impact:** Site PSA needs to account for the units' various combinations of possible plant operating states (POSs). The POSs come directly from single-unit PSAs and they concern only one unit. POS groups are created based on individual POSs that are sufficiently similar. POS groups also concern only one unit. Then, POS groups of different units are combined to create POS group combinations that include one POS group from each unit included in the analysis. POS groups and POS group combinations are screened so that only the most relevant POS group combinations are included in the quantification.

   Figure 1 illustrates the creation of POS group combination with four POSs and two units. The POS groups with POS D are screened out, as well as the POS group combination with POSs B and C coming from both of the units.
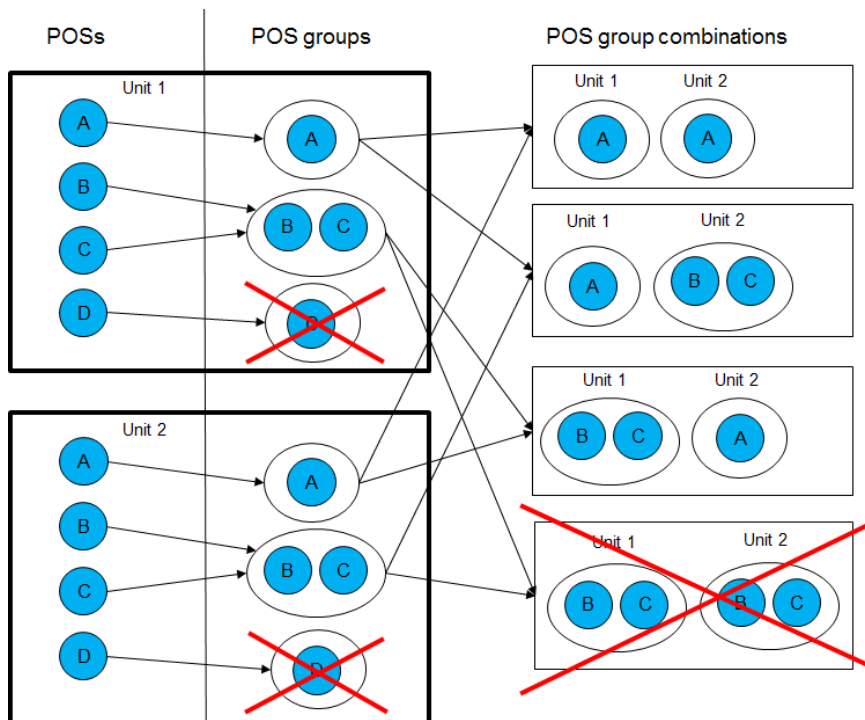
Figure 1: Illustration of the creation of POS group combinations.

3. **Identification of multi-unit initiators:** There are three types of multi-unit initiators:

   - Multi-unit initiating events (MUIEs, that affect always multiple units)

   - Partial multi-unit initiating events (that may affect one or multiple units)

   - Propagating events: Accident starts in one unit and propagates later to another unit.

   Partial multi-unit initiating events are divided into multi-unit initiating events and single-unit initiating events, and the multi-unit initiating events are included in the further analysis.

The multi-unit initiators are screened, and the most relevant ones are selected for quantification. Relevant combinations of multi-unit initiators and POS group combinations are identified for the analysis. Let a pair of a multi-unit initiator and POS group combination be called a *multi-unit analysis case*.

Figure 2 illustrates how multi-unit analysis cases are constructed based on multi-unit initiators and the POS group combinations which were screened in previously. Propagating event PE (the orange block) is screened out. Based on partial multi-unit initiating event, new multi-unit initiating event MUIE3 is created. Multi-unit initiating event MUIE2 is not relevant for POSs B and C, and the corresponding analysis cases are thus not created. Analysis cases with MUIE1 and POS group combinations A-BC and BC-A are also screened out. Five multi-unit analysis cases are left for further analysis.
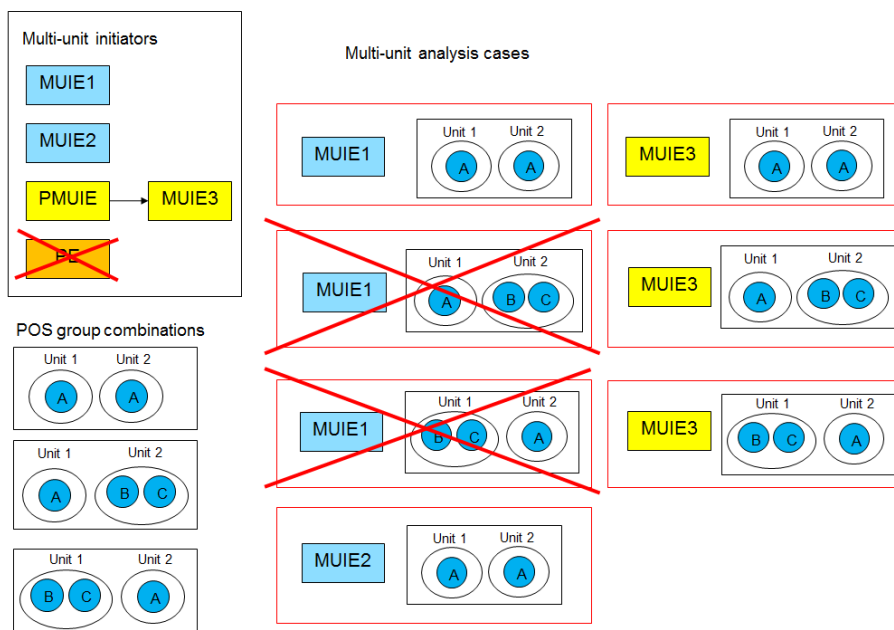
Figure 2: Illustration of the creation of multi-unit analysis cases.

4. **Identification and selection of dependencies:** Different types of multi-unit dependencies include

   - shared systems, structures, and components (SSC)

   - identical components

   - spatial dependencies

   - human and organizational dependencies

   - containment and vessel design

   - simultaneous maintenance

   - phenomenological uncertainty (e.g. epistemic uncertainty related to severe accident phenomena can be common for two units).

Identified multi-unit dependencies are screened qualitatively. Single-unit basic events associated with the screened in multi-unit dependencies are identified. Multi-unit

dependencies are screened quantitatively based on the single-unit basic events. For each multi-unit analysis case, the relevant multi-unit dependencies are identified.

Figure 3 illustrates the screening process of multi-unit dependencies. One dependency is screened out qualitatively, and one dependency is screened out quantitatively. Then, relevant multi-unit dependencies are identified for each multi-unit analysis case.
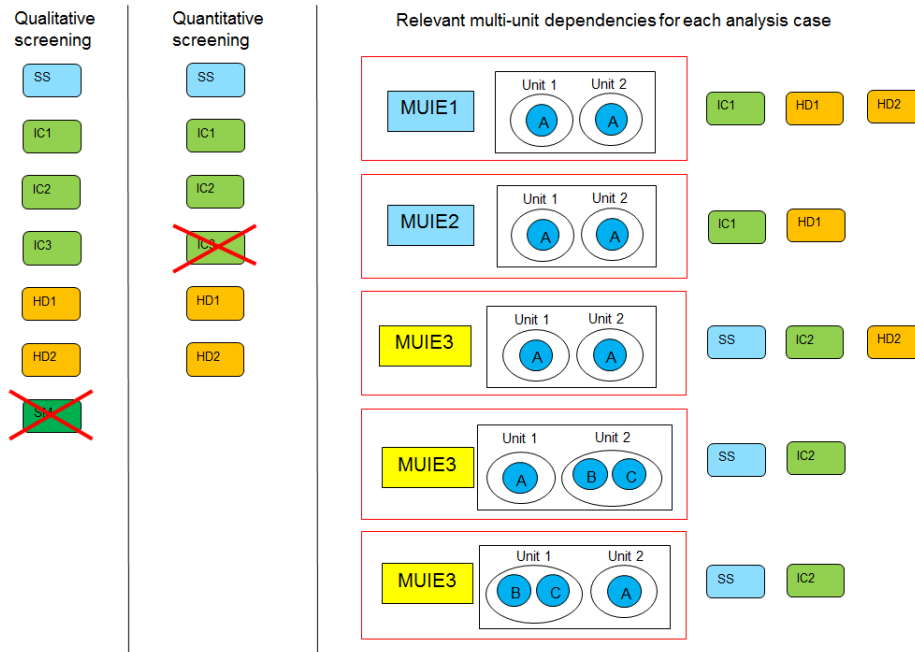
Figure 3: Screening of multi-unit dependencies.

From the screened in multi-unit dependencies, multi-unit basic events are selected. A multi-unit basic event is a set of dependent events in multiple units or an event affecting multiple units. One or multiple multi-unit basic events can be selected based on a multi-unit dependency. For each multi-unit analysis case, the relevant multi-unit basic events are identified.

5. **Analysis of source terms:** This step is relevant only when level 2 analysis is considered. Source term categories are analyzed to determine which of them are relevant for the screened in MUIEs. Screening of source terms can be performed based on single-unit PSA results. Then combined source terms are studied to examine how the source term combinations are mapped into site release categories. Finally, the relevance of source term combinations for multi-unit analysis is assessed. Relevance of a source term combination is dependent on the applied risk metrics. Final selection of release categories to be analyzed can also be made at this point.

6. **Data analysis**: The frequencies of multi-unit initiators and the probabilities of multi-unit basic events are estimated in each multi-unit analysis case.

7. **Quantification of multi-unit risks:** The analyst can select one of the two following approaches:

   a. **Multi-unit event combinations approach:**

      A multi-unit scenario is defined as a combination including

      - a POS group combination

      - a multi-unit initiator

- zero, one or multiple multi-unit basic events.

Multi-unit scenarios are created for the quantification based on the multi-unit analysis cases and multi-unit basic events relevant for each analysis case. In an analysis case, all possible combinations of relevant multi-unit basic events, i.e. all possible multi-unit scenarios, are considered.

The frequency of each multi-unit scenario is calculated as the frequency of the initiator multiplied by the probabilities of multi-unit basic events. The conditional core damage probability (CCDP) or conditional source term category probabilities (CSTPs) of each multi-unit scenario are also calculated. The MUCDF of a multi-unit scenario is then the frequency of the multi-unit scenario multiplied by the CCDP values. Similarly, the multi-unit source term category combination frequency (MUSTF) is the frequency of the multi-unit scenario multiplied by the CSTP values corresponding to source term category combination. The risk metrics and risk importance values are calculated based on the MUCDF or MUSTF values of the multi-unit scenarios.

b. **Minimal cut set list approach:**

The minimal cut set (MCS) lists of different units are combined, and the risk metrics and risk importance values are calculated based on the combined MCS list(s). The quantification is in principle similar to single-unit PSA quantification.

3. Challenges

Site PSA introduces new challenges for documentation, PSA model management and computation tools. Site PSA involves information and data from many different sources, use of multiple PSA models, and several analysis steps, which are potentially applied to a large set of dependencies between units. Systematic data management and documentation procedures are therefore needed to manage the site level analysis process as a whole.

Single-unit PSA models need to be extended to include significant multi-unit dependencies if they have not been modelled before. In addition to documentation, this can be a challenge for PSA model configuration management and change tracking point of view. In addition, some specific scenarios may require special calculations with a single-unit PSA model, e.g. to determine the probability that a shared system is used. This may require creation of new special versions of single-unit PSA models.

Multi-unit risk is estimated based on the information from the different units, which means that risk metrics and risk importance measures are not obtained directly from a single PSA model like in single-unit analyses. Total site calculations need to combine somehow the results from different PSA models.

The maintenance of a site PSA is also more challenging than the maintenance of a single-unit PSA. When a modification is made to one unit, site results need to also be updated. PSAs should also be updated in parallel for site PSA, not one by one. Site PSA could even be maintained as living PSA.

4. Single-unit PSA models

4.1 Requirements for single-unit PSA models

In the site PSA method [1], it is assumed that single-unit PSA covers all scenarios and events that can significantly affect single-unit risk, including multi-unit accident scenarios. It has to be possible to calculate the conditional core damage probability of a multi-unit scenario (defined in Section 2) correctly using a single-unit model. In other words, the consequences of multi-unit events have to be modelled correctly in single-unit PSAs.

Risk-significant shared systems need to be taken correctly into account in the site level quantification. The unavailability of a shared system due to its use in another unit has to be included in the single-unit models as discussed in Section 4.2.

When the analysis includes level 2, it needs to be possible to calculate the conditional source term category probabilities of multi-unit accident scenarios. If release categorisation is changed/simplified compared to the single-unit PSA (e.g. one release category for unacceptable release is used instead of splitting it into multiple release categories), there might be a need to change the release categorisation in the versions of the single-unit models used in site PSA.

If spent fuel pool belonging to a reactor unit is included in the scope of the analysis, the single-unit PSA should cover both the reactor risks and the spent fuel pool risks. It is not necessary to include them in the same PSA model as long as conditional fuel damage probabilities and conditional source term category probabilities of multi-unit scenarios can be calculated.

4.2 Modelling multi-unit aspects in single-unit models

Some multi-unit scenarios may need to be modelled in single-unit models, particularly scenarios involving a shared system or human actions. Separating multi-unit events, particularly multi-unit initiating events, from single-unit events in single-unit models can make modelling of site dependencies easier, since human error probabilities or unavailabilities of shared systems can be different in different scenarios. Easy identification of multi-unit events would also be useful. An identifier could e.g. appear in the name or comment of a multi-unit event.

The probability that a shared system is needed in another unit needs to be considered in single-unit PSA. The probability may need to be calculated using the PSA model of the other unit. The probability can be assumed to be multi-unit initiator specific. A special version of the corresponding event tree can be created so that the end points of the event tree represent conditions where the shared system is needed. The initiating event frequency can be set to 1, and then the probability that the shared system is used can be calculated directly from the event tree. Some probabilities related to multi-unit dependencies, such as identical components, may also need to be adjusted. The event tree does not need to be used, if the unavailability of the shared system can be determined without it, e.g. if the case is very simple. The basic event can then be added to the other single-unit model. There can be basic events representing the same shared system with different probabilities for different multi-unit initiators. A house event or an attribute can be used to select the correct basic event for each multi-unit initiator.

If there is no priority logic for the use of a system shared between two units, it could be reasonable to divide the calculated probabilities by 2, because the system could be used in either of the units. For example, if probability p_1 is calculated for the scenario that the shared system is also needed in the other unit, probability $p_1/2$ can be used in the PSA model. In

addition, the system has a failure probability p_2. It needs to also be scaled by $1 - p_1/2$. The failure can be modelled as a separate basic event.

It can be stated with some justification that human error probabilities are higher in some multi-unit scenarios. Detailed considerations of human error probabilities in multi-unit scenarios can be found in [1]. The modelling is straightforward, if multi-unit scenarios can be separated from single-unit scenarios in the model, e.g. as separate accident sequences or in the post-processing of minimal cut sets.

Initiating events induced by an accident in another unit need to be taken into account. If such event is found significant, it can be modelled as a separate initiating event or included in the frequency of the corresponding single-unit initiating event. The model of the originating unit may need to be used in the computation of frequency. In addition, the probability of the propagation between units needs to be estimated.

4.3 Updating single-unit models based on multi-unit analysis

It is possible that a need to update single-unit models is noticed when performing multi-unit analysis. It is important to keep the single-unit models up-to-date both from the single-unit and multi-unit analysis point of view. The best option is to perform the correction right away when a need to update (e.g. due to a defect or improvement with regard to increase in realism) is noticed. It also needs to be judged if the analyses performed before the observation need to be revised, e.g. quantitative screening.

It is very case specific what may need to be updated. The update can e.g. be the addition of a new basic event, or the change of a probability or frequency. Modelling of shared systems and human error events are the areas that could most likely require updates from the multi-unit perspective.

5. Site PSA documentation

Site PSA needs to be documented comprehensively. The following chapter titles are recommended to be used in the document:

- o   Selection of analysis scope and risk metrics

- o   Data sources and models

- o   Analysis of POS impact

- o   Identification of multi-unit initiators

- o   Identification and selection of dependencies

- o   Analysis of source terms (level 2 only)

- o   Data analysis

- o   Quantification of multi-unit risks

- o   Documents and files used in the analysis

Section 7 of this document specifies what information should be documented under these chapters.

6. Database for site PSA

A database system is needed to manage the analysis process. It can be just a set of Excel sheets, but since many of the analysis elements are interrelated, a more advanced database system could be considered, e.g. Microsoft Access.

Analysis elements that could be included in the database are presented in Table 1, along with possible data fields. Section 2 contains information on how different analysis elements are linked to the analysis phases. For some data fields, Section 7 provides some further explanation.

Table 1: Site PSA elements.

Element	Description	Possible data fields
Plant operating state	Plant operating state as defined in single-unit PSA	Identifier, description, time share, status of primary circuit, status of the core cooling system, status of the residual heat removal system, status of spent fuel pool, multi-unit initiators
POS group	Group of sufficiently similar POSs for site PSA purposes concerning a single unit	Identifier, POSs belonging to the group, justification for the grouping, time share, time window for core/fuel damage in case of loss of residual heat removal, screening decision, justification for the screening decision, multi-unit initiators
POS group combination	Combination of POS groups (including one group from each unit)	Identifier, the POS groups included in the combination (with correspondence to units), time share, screening decision, justification for the screening decision, multi-unit initiators
Multi-unit initiator	Initiating event that can potentially cause accident in multiple units (including accident propagation to another unit)	Identifier, category, description, frequency, screening decision, justification for the screening decision, source documents, the corresponding initiating events in the single-unit models, relevant POSs, POS dependency, season dependency, POS group combinations to be included in the analysis, justification for the selection of POS group combinations, affected unit combination, data sources, frequency estimation method, frequencies in different POS group combinations
Partial multi-unit initiating event	Initiating event that may affect one or multiple units	Multi-unit initiating events created based on this partial multi-unit initiating event, data sources, frequency estimation method used in single-unit PSA, frequencies in single-unit models, summary of operating data, qualitative analysis, frequency estimation methods for site PSA, new frequencies

Element	Description	Possible data fields
Multi-unit analysis case	A pair of a multi-unit initiator and POS group combination	Identifier, multi-unit initiator, POS group combination, relevant multi-unit dependencies, relevant multi-unit basic events, frequency of the multi-unit initiator in the POS group combination
Multi-unit dependency	A dependency that can cause an event to affect multiple units or dependent events in multiple units (initiating event dependencies excluded)	Identifier, category, description, qualitative ranking, justification for the qualitative ranking, source documents, related units, related basic events in the single-unit models, Fussell-Vesely in each multi-unit initiating event in each unit, maximum contribution from potential multi-unit sequences in each unit, screening decision
Multi-unit basic event	A set of dependent events in multiple units or an event affecting multiple units	Identifier, description, related multi-unit dependency, source documents, related units, related basic events in the single-unit models, relevant multi-unit analysis cases, probability in each relevant multi-unit analysis case
Inter-unit CCF	A CCF where components fail in multiple units (subcategory of multi-unit basic event)	Identifier, component type, failure mode, units, group size, CCF combination, data sources, probability of the corresponding single-unit CCF in each unit, summary of operating data, model used in estimation, parameters used in estimation, probability of the inter-unit CCF
Multi-unit human error event	A human error event affecting multiple units or dependent human error events in multiple units (subcategory of multi-unit basic event)	Identifier, description, related basic events in the single-unit models, probabilities of the basic events in single-unit models, qualitative assessment from multi-unit point of view, probability estimation procedure, penalty factor/dependency category in each relevant multi-unit analysis case, probability in each relevant multi-unit analysis case
Source term	Source term as defined in single-unit PSA	Identifier, description, release size, release timing, other release characteristics, screening decision and justification
Source term combination	Combination of single-unit source terms (including one source term from each considered unit)	Identifier, the source terms included in the combination, associated release category, screening decision, justification for screening and how the combined source terms are associated in the release category
Release category	Group of accident sequences with a similar source term at the site level	Identifier, description, source term combinations

Several analysis elements are connected. A POS group combination consists of POS groups, and a POS group consists of POSs. Inter-unit CCFs and multi-unit human error events are multi-unit basic events with specific properties. Multi-unit basic events originate from multi-unit dependencies. A partial multi-unit initiating event is a multi-unit initiator with special properties. Some new multi-unit initiators are also created based on a partial multi-unit initiating event.

Multi-unit initiators are also associated with specific POSs, POS groups and POS group combinations. Practically, POS groups and POS group combinations inherit the relevant multi-unit initiators from individual POSs. A multi-unit analysis case consists of a multi-unit initiator and a POS group combination.

In a database these connections can be presented as relationships (i.e. one table has a foreign key that references the primary key of another table). For example, the POS data field (foreign key) of a POS group is linked to the respective POS table based on the POS element identifier (primary key).

The database should include one or more tables for each analysis element type. Some functionality that could be useful includes:

- Data could be inherited from an analysis element to another one. E.g. a POS group combination could automatically inherit multi-unit initiators from the POS groups participating in the combination.

- It would be useful to sort tables according to different attributes.

- It could be useful to customize tables, because some of analysis elements include many data fields and the user may be interested only on specific fields at a time. In addition, some analysis elements, like multi-unit dependencies and multi-unit initiators, go through multiple analysis phases and only some of the data fields are relevant for a single analysis phase. It could be useful to have different header sets or tables for different analysis phases.

- Filtering of data could be useful. For example, the user could want to view only those multi-unit dependencies that are screened in for further analysis.

- Since several analysis elements are connected, data links could be used so that it would be possible to e.g. jump from the data of multi-unit initiator to the data of an associated POS group combination.

- Convenient ways for viewing data need to be considered. For example, it might be useful to view data only related to a single multi-unit analysis case because there are a lot of data connected to an analysis case (considering also the data of the multi-unit initiator and POS group combination of the analysis case).

- Search functions would be useful (available in normal Excel application).

- It should be possible to export selected tables to the site PSA document.

- Since some computations need to be performed with the data, the computation formulas could be built in into the database system. For example, some inter-unit CCF probability estimation formulas could be useful.

- Some data, like some initiating event frequencies and single-unit CCF probabilities, come from the databases of single-unit PSAs. Functionality to facilitate such data imports can be considered.

It can be useful to extend the database with a new analysis element: multi-unit scenario, which has been defined in Section 2. It is needed if the multi-unit event combinations approach (see Section 2) is used in quantification, and could be of interest also otherwise. A multi-unit scenario could have the following data fields:

- Identifier

- POS group combination

- Multi-unit initiator

- Multi-unit basic events

- Frequency

- The related initiating/basic events in the single-unit PSA models

- The CCDP in each unit (given the multi-unit initiator, POS group combination and multi-unit basic events)

- The MUCDF of the scenario (for each combination of units if there are more than two units)

The multi-unit scenarios could be created automatically based on the multi-unit analysis cases. An event tree presentation of a multi-unit analysis case could also be created. The multi-unit basic events would be the nodal questions in such event tree, and each sequence would represent a multi-unit scenario.

If the minimal cut set list approach (see Section 2) is used in the computation, the combined minimal cut set list needs to be treated with a set of rules to ensure correct quantification. The database could support the practical implementation of such rules. For example, rules could be created automatically based on the multi-unit initiators and multi-unit basic events in the database or the database could directly serve as a set of rules if it was integrated with the computation tool. A typical example of a rule would be that two single-unit basic events related to the same multi-unit basic event are identified in the same minimal cut set, and the frequency of the minimal cut set is increased according to the probability of the multi-unit basic event.

If minimal cut set lists are combined in the site PSA, different units cannot contain single-unit events with the same names. If there are same names, the names need to be changed to unit specific at some point. The change of names can take place when the minimal cut sets are pre-processed for the combination in site PSA. The database needs to contain information on the correspondence between the names used in the single-unit PSA and site PSA.

The quantification of the minimal cut sets could also utilise the site PSA database. Alternatively, relevant initiating event and basic event data from the site PSA database could be imported to the software tool used. In this latter case, an interface between the database system and the software tool would need to be developed.

7. Guidelines for site PSA model management

Table 2 presents the main documentation and model management tasks in different analysis phases and in the maintenance phase. In this section, the whole analysis process is gone through from the documentation and model management point of view.

Table 2: Documentation and management tasks in different analysis phases.

Analysis phase	Documentation	Model and database management
Selection of analysis scope and risk metrics	Documentation of the scope and risk metrics	
Preparations before analysis	Documentation of references and PSA model versions	
Analysis of POS impact	Documentation of the POS analysis process and results	Insertion of POSs, POS groups and POS group combinations to the database
Identification of multi-unit initiators	Documentation of the initiator screening process and results	Insertion of multi-unit initiators to the database
Identification and selection of dependencies	Documentation of the dependency screening process and results	Insertion of dependencies to the database, screening of dependencies with the single-unit models, insertion of multi-unit basic events to the database
Analysis of source terms (level 2 only)	Documentation of the source term analysis process and results	Insertion of source terms, source term combinations and release categories to the database
Data analysis	Documentation of the data analysis process and results	Systematic analysis of those multi-unit initiators and basic events that were screened in using the database, insertion of frequencies of initiating events and probability parameters related to multi-unit basic events to the database
Quantification of multi-unit risks	Documentation of the results	Computation based on the single-unit models and database
Maintenance of site PSA	Update of relevant parts of the documentation when needed, documentation of changes	Process for updating site PSA, model configuration management, version control, verification and validation of model changes

Besides the above listed analysis phases, for level 2 purposes, it might be necessary to dedicate a step for the assessment of multi-unit plant damage states.

7.1 Selection of analysis scope and risk metrics

The analysis starts with the selection of scope and risk metrics. Recommended risk metrics have been documented in [4]. In the selection of the scope at least the following issues should be considered:

- Radionuclide sources that are considered

- PSA levels and end states included in the analysis

  - Release categories need to be selected if the analysis covers level 2. The release categories can be the same as in single-unit PSAs, but the analysis can also be simplified by creating larger release categories and not considering release timings in the release categorisation. It is possible to consider only one release category of large or unacceptable release, which is considerably simpler than the analysis of multiple

smaller release categories. Release categorisation may also be decided later after the analysis of source term combinations.

- Types of initiators considered

- Operating states considered

- The scope of SSCs considered including the fixed date for the plant (site) configuration being analysed.

These selections are documented in the chapter Selection of analysis scope and risk metrics in the site PSA document.

7.2 Preparations before the analysis

PSA model versions that are used in the analysis are selected and documented. It is possible to make some adjustments to the model versions before the analysis, e.g. concerning release categorisation or modelling of multi-unit aspects as discussed in Section 4.2.

The main source documents are listed in the site PSA document.

7.3 Analysis of POS impact

Analysis of POS impact is performed in the following steps:

1. Review POSs to obtain basic information on their differences. Pay particularly attention to the status of the primary circuit and available core cooling and residual heat removal systems.

   Steps 2-5 concern an individual unit. If the units are similar with regard to POSs, the procedure can be performed only for one unit, but otherwise it needs to be performed for each unit separately.

2. Make a table of POSs e.g. with the following headers: POS identifier, description, time share, status of primary circuit, status of the core cooling system, status of the residual heat removal system and status of the spent fuel pool. The relevant systems to be included here are plant specific and more headers should be included if there are more systems.

3. Merge together those POSs that are sufficiently similar to form POS groups. The grouping can be based on the configuration of residual heat removal systems as discussed in Section 4.2 of [1].

4. Make a table of the **individual** POS groups with the following headers:

   a. POS group identifier

   b. Specific POSs belonging to the group

   c. Justification for the grouping

   d. Estimated time share

   e. Time window for core/fuel damage in case of loss of residual heat removal

   f. Screening decision and justification

Add the POS group table to the site PSA document.

5. Estimate the time shares of POS group **combinations**. Consider only the POS groups that have been screened in.

6. Make a table of POS group combinations with the following headers:

    a. POS group combination identifier

    b. For each unit, the POS group included in the combination

    c. Estimated time share

    d. Screening decision and justification

Add the POS group combinations table to the site PSA document.

7.4 Identification of multi-unit initiators

1. Go through the initiating events in the single-unit PSA models and categorize them in the following groups:

- single-unit initiating event

- multi-unit initiating event

- partial multi-unit initiating event

2. Analyse the possibility that a single-unit accident introduces an initiating event in another unit (or that a multi-unit accident of two units introduces an initiating event in third unit, etc.). Make a list of potential cases.

3. Make a table of multi-unit initiators (including partial multi-unit initiating events and propagating accidents) e.g. with the following headers:

    a. Identifier

    b. Category (multi-unit initiating event, partial multi-unit initiating event or single-unit event that propagates to another unit)

    c. Description

    d. Frequency (may not be available at this point for all events)

    e. Screening decision and justification

    f. Source documents

    g. The corresponding initiating events in the PSA models

    h. Relevant POSs

    i. POS dependency

    j. Season dependency

    k. POS group combinations to be included in the analysis and justification

4. Divide each partial multi-unit initiating event into multi-unit initiating events corresponding to different unit combinations and into single-unit initiating events. Add the information on this process to the database and site PSA document. Add the new multi-unit initiating events to the previous table. The category for these events is a 'multi-unit initiating event that originates from a partial multi-unit initiating event.' The other data, except the frequency, can be inherited from the original partial multi-unit initiating events.

   Add the multi-unit initiator table to the site PSA document.

5. Make a table of the multi-unit analysis cases. For each analysis case, at least the following information needs to be included (possible to complement with information related to the initiator or POS group combination):

   a. Identifier

   b. Multi-unit initiator

   c. POS group combination

   List the multi-unit analysis cases in the site PSA document.

7.5 Identification and selection of dependencies

7.5.1 Qualitative analysis

1. Identify all multi-unit dependencies. Some guidance can be found in Sections 5.2 and 6 of [1]. The identification of human action dependencies is specifically discussed in Sections 8.2-3 of [1].

2. Make a table of multi-unit dependencies with e.g. the following headers:

   a. Identifier (name)

   b. Dependency category (shared SSC, identical components, spatial dependency, human dependency, simultaneous maintenance or phenomenological uncertainty)

   c. Description (e.g. systems and components involved)

3. Analyse each dependency qualitatively and define the qualitative ranking according to the categories defined in Table 5.1 of [1].

4. Add the following information of each dependency to the dependency table (if applicable):

   a. Qualitative ranking and its justification (reasoning behind it)

   b. Source documents

   c. The units to which the dependency is related, if there are more than two units

   d. Basic events related to the dependency in the single-unit PSA models

   Add the multi-unit dependency table to the site PSA document.

7.5.2 Quantitative screening

1. Screen each previously screened in multi-unit dependency quantitatively based on single-unit basic events as presented in Section 5.2.2 of [1]. For each dependency, add the following information to the database and site PSA documentation:

    a. Fussell-Vesely in each multi-unit initiating event in each unit

    b. The increase factor (defined in [1]) in each multi-unit initiating event in each unit

    c. Maximum contribution from potential multi-unit sequences in each unit

    d. Screening decision

    Note that if the analysis covers level 2, at least the level 2 dependencies need to be screened on the basis of release category frequencies. It is possible to perform the screening for multiple release categories separately.

2. For each screened in dependency, identify the relevant multi-unit initiating events. The previously calculated Fussell-Vesely values can be utilised. Make a table of the multi-unit analysis cases specifying the relevant multi-unit dependencies for each analysis case.

3. Based on each screened in multi-unit dependency, define one or more multi-unit basic events. Make a table of the multi-unit basic events e.g. with the following fields:

    a. Identifier

    b. Description

    c. Related multi-unit dependency

    d. Source documents

    e. Related units (if there are more than two units)

    f. Related basic events in the single-unit models

4. Make a table of the multi-unit analysis cases specifying the relevant multi-unit basic events for each analysis case based on the relevant dependencies.

7.6 Analysis of source terms (level 2 only)

1. Review source terms of individual units. Determine which source terms are relevant for the screened in MUIEs. Make a table of source term categories, with the following headers: Source term category identifier, description, screening decision (based on relevance for selected MUIEs and possibly based on single-unit level 2 PSA results) and justification. The description header can be split into several headers describing specific characteristics of the source term category.

2. Analyse combined source terms from individual units and how they are associated in different release categories. Assess the relevance of source term combinations for multi-unit analysis. Screen out insignificant combinations. Make a table for source term combinations with headers: Group identifier, associated release category, screening decision, and justification for screening and how the combined source terms are associated in the release category.

3. Review selected release categories based on analysis results. Make a table of release categories with headers: identifier, description, source term combinations.

4. Add the source term combinations table to the site PSA document. If release categories have been changed, update the Selection of analysis scope and risk metrics chapter in the site PSA document accordingly.

7.7   Data analysis

7.7.1   Initiating events

1. Go through each partial multi-unit initiating event. If at least one multi-unit initiating event that has been created based on the partial multi-unit initiating event has been screened in, estimate the corresponding frequency/frequencies as discussed in Section 7.2.2 of [1].

   Write the following information of each partial multi-unit event in the site PSA document if applicable:

   - Data sources

   - How the frequencies have previously been estimated for individual units

   - The frequencies used in single-unit PSAs

   - Summary of operating data

   - Qualitative analysis including

     - different causes for the event and how they affect units

   - How the new frequencies are estimated for multi-unit analysis

   - The frequencies of the new multi-unit initiating events.

   A database table with the above information for each partial multi-unit event can also be made.

2. Make a table of all multi-unit initiators that have been screened in. The headers of the table can be e.g.:

   a. Identifier

   b. Affected unit combination (if there are more than two units)

   c. Data sources

   d. How the frequency is estimated

   e. Frequency (total annual frequency)

   Add the table to the site PSA document.

3. Estimate the frequency of each multi-unit initiating event in each POS group combination that is relevant for the initiating event (if not already available). If an initiating event has no POS dependence, the annual event frequency can be multiplied

by the POS group combination time share. If an initiating event depends on POSs, it is expected that POS specific frequencies can be found in the single-unit analyses.

4. Make a table of multi-unit initiating events and POS group combinations. Each cell of the table specifies the frequency of the corresponding initiating event in the corresponding POS group combination. Add the table to the site PSA document.

7.7.2 Multi-unit basic events

1. Estimate the probability of each inter-unit CCF that has been screened in according to formulas presented in Section 7.3 of [1].

2. Make a table for inter-unit CCFs including the following information for each CCF if applicable:

   a. Identifier

   b. Component type

   c. Failure mode

   d. Units (if more than two units are analysed)

   e. Group size

   f. CCF combination (or combinations if multiple combinations are merged)

   g. Data sources

   h. Single-unit CCF probability in each unit

   i. Summary of operating data

   j. Model used in the estimation

   k. Parameters used in the estimation

   l. Probability of the inter-unit CCF

Add the table to the site PSA document.

3. Estimate the probability of each multi-unit human error event. Section 8.4 of [1] provides instructions for two different estimation methods.

4. Make a table of multi-unit human error events e.g. with the following headers:

   a. Identifier

   b. Description

   c. Related basic events in the single-unit models

   d. Probabilities of the basic events in the single-unit models

   e. Qualitative assessment from the multi-unit point of view

   f. Multi-unit probability estimation method

g. Multi-unit penalty factor or dependency category [1] in each multi-unit analysis case

h. Probability in each multi-unit analysis case

Add the table to the site PSA document.

5. If other types of multi-unit basic events have been screened in, their probabilities also need to be estimated and documented (possibly separately for each multi-unit analysis case). Section 7 of [1] provides some guidance on the data analysis of different types of multi-unit dependencies.

7.8 Quantification of multi-unit risks

Two methods for the quantification of multi-unit risks are presented in [1]. One is based on computation of conditional core damage probabilities of multi-unit event combinations, and the other one is based on combination of the minimal cut sets of the units. They are discussed separately in the following subsections.

7.8.1 Multi-unit event combinations approach

For each multi-unit analysis case (multi-unit initiator and POS group combination) that has been screened in:

1. Create an event tree with relevant multi-unit basic events.

2. Calculate the frequencies of the multi-unit scenarios based on the event tree.

3. For each multi-unit scenario that has a frequency larger than the selected screening threshold (e.g. 1E-8/year for level 1 and 1E-9/year for level 2), calculate the CCDP in each relevant unit. If there is no advanced computation support available, the calculations can be performed in the following way:

   a. Set the initiating event frequency to 1 and the probabilities of the basic events related to the multi-unit basic events to 1 (or statuses to "failed"). If needed, select also the correct POS. For example, if there is a basic event representing the time share of the POS, its probability needs to be set to 1.

   b. Make sure that other initiating events do not skew the result. It should be possible to focus on the initiating event specific results. Even if multiple initiating events appear in the same event tree, the result can be calculated by multiplying the total frequency with the Fussell-Vesely of the initiating event. Alternatively, the frequencies of other initiating events can be set to 0.

   c. Successes of multi-unit basic events can also be taken into account (optional). It should be noticed that even though a multi-unit basic event does not occur, a related single-unit basic event may occur. A portion of the probability of the single-unit basic event comes from the multi-unit event. This portion can be subtracted from the probability of the basic event to make the computation more accurate.

   d. Calculate the event tree in the single-unit model, or reminimize and recalculate the corresponding minimal cut set list to get the conditional core damage probability.

If the analysis covers level 2, the CSTP is calculated for each considered source term category in each relevant unit.

The following concerns all multi-unit analysis cases together.

4. Make a table of the multi-unit scenarios (can be initiating event specific or cover all initiating events). For each multi-unit scenario, it can include the following information:

   a. identifier of the multi-unit initiator

   b. Identifiers/names of the multi-unit basic events

   c. The POS group combination

   d. The frequency of the scenario

   e. The related basic events in the single-unit PSA models

   f. The CCDP in each unit

   g. The MUCDF of the scenario (for each combination of units if there are more than two units)

   If the analysis covers level 2, the CSTP value of each source term category in each unit, and the MUSTF of each source term category combination (for each combination of units if there are more than two units) are included.

   Add the table(s) to the site PSA document.

5. For each unit combination (if there are more than two units), calculate the MUCDF by summing the MUCDF values (related to the analysed unit combination) of all multi-unit scenarios. Report the calculated MUCDF values in the site PSA document.

   If the analysis covers level 2, calculate the MUSTF of each relevant source term category combination for each unit combination.

6. Calculate the SCDF.

   If the analysis covers level 2, calculate the site level frequencies of release categories.

7. Calculate and document relevant risk importance measure values.

8. Make conclusions on the results and write them to the site PSA document.

7.8.2 Minimal cut set list approach

1. Pre-process minimal cut sets of individual units if needed. If different units have single-unit events with the same names, the names of the single-unit events need to be made unit specific.

2. Combine minimal cut sets of different units to make the minimal cut set list(s) needed for the quantification. One option is to make a minimal cut set list for "site level core/fuel damage", i.e. a list containing the minimal cut sets of all units. Another option is to create a minimal cut set list for "multi-unit core/fuel damage" by multiplying the minimal cut sets of different units (according to Boolean algebra). If there are more than two units, minimal cut sets lists can be created for different unit combinations. Both options can be used to calculate the site core/fuel damage frequency. The needed minimal cut set lists depend on the selected risk metrics.

If the analysis covers level 2, one option is to make a minimal cut set list for each analysed release category at the site level. Alternatively, minimal cut set lists can be generated for different source term combinations, and the risk metrics can be calculated based on the frequencies of the combinations.

3. Prepare the database and rules for the quantification of the minimal cut sets (if not ready already based on the previous analysis phases).

4. Calculate the selected risk metrics from the minimal cut set lists.

5. Calculate relevant risk importance measure values from the minimal cut set lists and document them.

6. Make conclusions on the results and write them to the site PSA document.

8. Maintenance of site PSA

It is recommended that the names and locations of documents and files used in the analysis are listed in the site PSA document chapter Documents and files used in the analysis. All files and documents should also have version numbers.

To maintain the site PSA, a log of changes needs to be maintained. All changes in site PSA input data need to be documented in the log. The model changes need to be documented so that they can be traced back to the inputs. Single-unit models need to always be updated before site PSA. When the site PSA is updated, it is recommended that the whole analysis procedure and site PSA document are gone through with the list of changes, and the relevant parts of the database, site PSA document and calculations are updated step by step. Summary of those updates should also be added to the log. New versions of modified documents and files should be created.

If special versions of single-unit models are needed for site PSA, it is likely better to create the special versions based on the current single-unit models every time when the site PSA is updated, instead of maintaining alternative versions of the single-unit models along with the main versions.

9. Conclusions

In this report, guidance for site PSA model management is given and requirements for a site PSA database are specified. This report follows the developed site PSA approach [1] and it considers the same analysis phases.

Site PSA's requirements for single-unit PSA models are discussed, and documentation and database needs for site PSA are presented. Analysis phase by phase guidelines for site PSA documentation and model management tasks are given. Also site PSA maintenance is discussed. The guidelines can also guide the performance of the actual analysis and serve as a checklist. The focus of the report is on level 1 issues, but also level 2 aspects are covered.

The guidelines presented in this report are meant to support the developed site PSA approach [1] and they are not applicable as such to alternative approaches. These guidelines need to be kept up-to-date with possible method updates and modifications.

References

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