IAEA Project: Multiunit Probabilistic Safety Assessment

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Abstract: The majority of NPP sites worldwide have more than one operating reactor unit. Many new builds are using the infrastructure of the existing sites. Safety assessment of the multiunit sites received more attention after the Fukushima Daiichi accident. Significant interest among IAEA Member States triggered the first IAEA Multiunit PSA (MUPSA) project (2012-2015). The IAEA last General Conferences request the IAEA to continue efforts to provide assistance to Member States with respect to the evaluation of safety of multi-unit sites. It reflects the increased interest of the Member States for continuation of the IAEA activities related to this subject. This paper describes the current IAEA efforts related to the development of MUPSA methodology including a case study aimed to illustrate how the methodology works. The paper discusses the MUPSA methodology, assumptions and approaches to be used, based on the actual PSA state of practice. It presents the PSA tasks in multiunit context, considering site specific configuration and inter-units interactions. The focus for the ongoing project is on the PSA Level 1 including interactions with Level 2.

Keywords: Multiunit, MUPSA, IAEA, site wide, multi facility

1. INTRODUCTION

The use of PSA in supporting the safety related decision making for nuclear power plants is most often based on analyses of single reactor units, however the majority of the sites have more than one nuclear facility (e.g. 138 out of 192 sites are multiunit) [1]. The potential for accident sequences involving two or more reactor units, as occurred during the Fukushima Daiichi accident, are not explicitly considered.

Since 2012 IAEA initiated activities aimed to develop the framework and methods on safety assessment of multiunit sites under the impact of multiple hazards [2, 3]. Responding to the Member States request [4,5], in IAEA/NSNI launched a new MUPSA project which is coordinated by External Events Safety Section (EESS) and Safety Assessment Section (SAS). This effort is supported by the technical basis developed previously and supplemented by a State of the Art Review on MUPSA conducted by IAEA.

MUPSA state of the art review performed by IAEA was based on existing and ongoing IAEA publications in this field and references available worldwide (e.g. ASME/ANS PRA standard, International Workshop on Multi-Unit PSA (Ottawa, 2014), European ASAMPSA_E project, publications available in IAEA Member States). Review of the available technical basis lead to the following general conclusions:

- The main assumption for development of MUPSA model is that PSA for every single unit from a given site is available and are to be used as a starting base
- There are no international harmonized approaches for MUPSA and there is limited experience in development of such studies
- The state-of-practice in PSA is primarily confined to the consideration of single reactor accidents. Expansion of scope to multiple units will lead to some technical issues and challenges. These technical issues and challenges have been identified and documented during the review process.

It was concluded that worldwide there is a lack of MUPSA practical guidance and there is a need for illustrative examples and additional risk metrics beyond the ones used for single units (e.g. CDF, LERF) to fully express the risk profile in the multiunit context.

The IAEA/NSNI project on Multiunit PSA contains the following phases:

- Phase 1 – develop a document providing a methodology for implementation of MUPSA
- Phase 2 – develop a case study with the feedback on the applicability of the methodology
- Phase 3 – improve the methodology based on the lessons learned from the case study developed in Phase 2 and integrate the improved methodology and the case study in a single IAEA publication.

The project team includes more than 25 experts from 13 Member States (Belgium, Canada, Czech Republic, France, Germany, Hungary, Japan, Republic of Korea, Romania, Russia, Slovakia, UK and USA). A publication presenting the methodology improved based on the feedback from the case study will be the outcome of this project.

This paper discusses the MUPSA methodology, assumptions and approaches proposed in Phase 1 of IAEA/NSNI project. It also presents the general information of current activities on the case study (Phase 2, ongoing) and the path forward.

2. ASSUMPTIONS

The concept of MUPSA methodology is that it should be useable for site with a large number of units and should be able to identify MU risk contributors needed to support the site-wide risk management.

It is presumed that the Single unit models are available for each unit on the site and the scope of those models is in line with the MUPSA objectives (i.e., the scope of the MUPSA does not include hazards that are not already evaluated by the single unit PSA). In the meantime, it is assumed that Single unit PSA models are available with sufficient quality (i.e. according to the relevant IAEA Safety Standards [6,7]) as a prerequisite for MUPSA implementation.

Several assumptions are utilized in the MUPSA methodology. Main technical aspects are highlighted below:

a) Administrative shutdowns of otherwise unaffected units do not need to be explicitly included as an initiating event in the MUPSA, including the cases when affected unit approached core damage.
b) Initiating events that affect only a single unit can be excluded from the model that is used to represent multiunit core damage scenarios.
c) Single unit core damage sequences in the multiunit model are not considered. These are evaluated using the existing single unit model and the results combined with the MUPSA model results after quantification. (guiding principles)
d) Inter-unit component common cause failure (CCF) generally may not apply when the units are of different type, model, or age, but still it needs to be verified that components (e.g., diesel generators) are indeed different. In addition, inter-unit CCF generally does not apply to passive components. However, situations such as heat exchanger plugging or strainer plugging when systems at different units draw from the same raw water source needs to be considered.
e) The CCF model for inter-unit CCF can be limited to “n-of-n” failures, where “n” is defined by the total number of components across all the units affected by the specific initiating event being evaluated.
f) Hazard-induced failures of individual SSCs that are screened from the single unit PSA for a given hazard can generally be screened from the MUPSA (i.e., the SSC screening criteria for each hazard used in the single unit PSA are still valid for the MUPSA). However, if hazard screening from a single unit PSA is based on crediting shared equipment across units, the MU risk needs to be considered.
g) Inter-unit seismic correlation failure generally does not apply when the units are of different type, or the components in the units are of a different model, or age.
h) For screening HRA where one or more units are in core damage (CD), the next unit in the sequential modelling assumes the worst-case CD progression (greatest challenge to the operators at that unit) of the unit(s) in CD.

i) The risk associated with very severe external hazards where the extent of expected failures is so great (CCDP >0.5) that dependencies and correlations are no longer as relevant.

It is important to mention that the risk significance of above listed assumptions and simplifications will be reviewed in Phase 2 (MUPSA case study) of IAEA/NSNI MUPSA project and the feedback from this review will considered in the final version of the methodology.

3. MUPSA METHODOLOGY

The overall flow chart for the Level 1 MUPSA methodology is presented on Figure 1. As it can be noted on Figure 1 the starting point for the MUPSA is an existing single unit PSA for each unit on the site.

Single unit Level 1 PSA models. Often there is a base model for only one representative unit at the site, that is used for the single unit quantifications of each of the units. Such models would have any unit-specific differences represented by sub-trees that are turned on and off depending on which unit is being quantified. If this is the case, it is necessary to spend efforts to create a complete independent model for each unit. In addition, the Single unit PSA models could require modifications aimed to avoid double counting and logic errors. For example, the contribution from grid-centred loss of offsite power (LOOP) needs to be adjusted correspondingly when evaluating the frequency of LOOP for individual units. Simplifications of individual single unit PSA models, to be used in MUPSA, is possible and needs to be well justified using the of single unit PSA results. The methodology provides practical guidance on how this could be implemented.

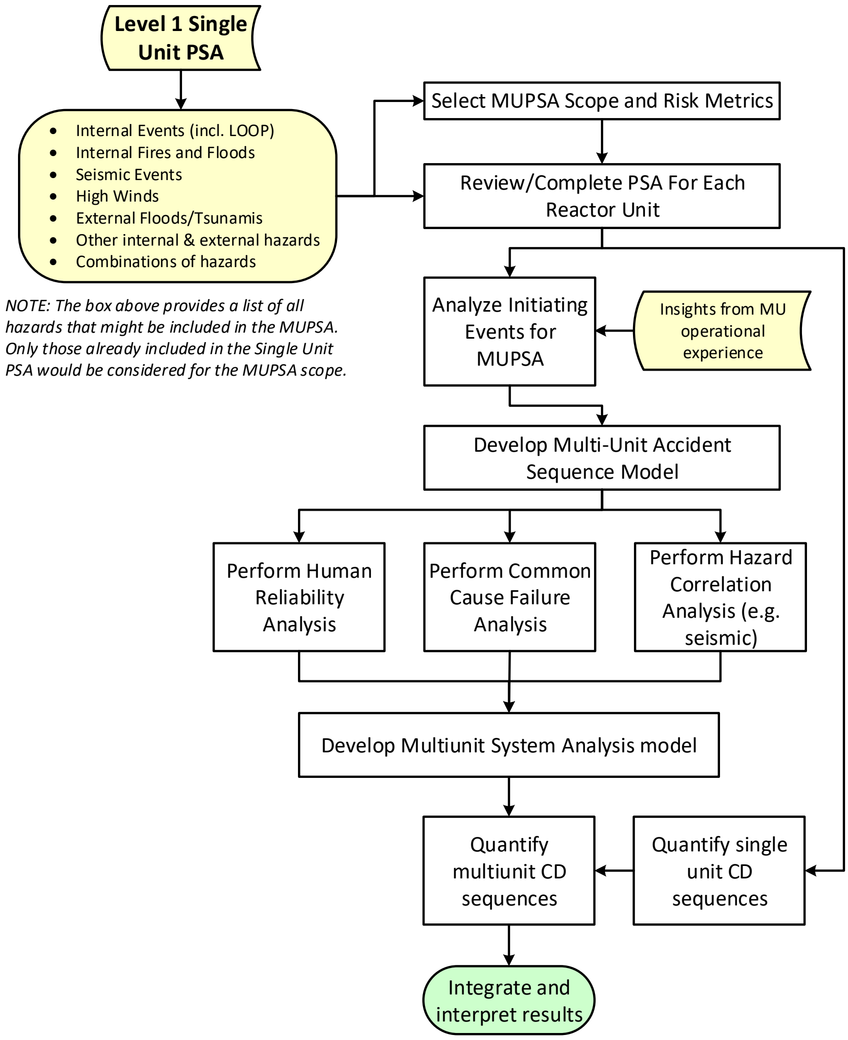
Initiating events analysis for MUPSA. The hazards and initiating events analysis begins with the list of hazards and initiating events considered in the single unit Level 1 PSA and generally includes Internal Events, Internal Hazards (Fires, Floods, etc.) and External Hazards (e.g., seismic, high wind, external flood etc.). The MUPSA methodology for Level 1 MUPSA is based on the careful application of screening to control the size and complexity of the model while still retaining the events and failures that are most important to risk. This concept is well established in PSA and the recent IAEA publication IAEA TECDOC-1804 [3] addresses screening out of MU events under Special Attribute HE-B06-S1, which states that for multiunit PSAs the screening of hazards needs to meet one of the following criteria:

a) The individual hazards or correlated hazards do not have the potential to cause a multiunit initiating event.

b) An individual hazard or correlated hazards if subjected to detailed realistic analysis would not make a significant contribution to the selected multiunit PSA risk metrics

The MUPSA methodology suggests that any initiating event can be screened from the MUPSA if its contribution to single-unit CDF is less than 0.1% of the total single-unit CDF. The rationale is that even if an event that contributes 0.1% of single unit CDF had a conditional multiunit CDF probability of 1.0 and all higher CDF contributors had an average conditional multi-unit CDF probability of 0.1, the most the screened event could contribute would be 1% of the total multi-unit CDF, which is not significant. Nevertheless, according to the methodology once the MUPSA is complete, the validity of this screening criterion needs to be confirmed.

Figure 1: Flow Chart for Level 1 MUPSA



Eventually the following considerations would be a basis for inclusion of an initiating event (including consideration of internal and external hazards) in the MUPSA study:

- the event immediately results in trip of both units.
- the event results in immediate trip of one unit and a degraded condition at another unit that will eventually lead to a trip.
- the event results in a degraded condition at multiple units that will eventually lead to trip of the units.

Accident sequence analysis for MUPSA. The accident sequence analysis is only performed on initiating events identified during the previous step described above, which means only for initiating events that affect multiple units. The MUPSA methodology describes two ways of combining MU Accident Sequences:

1) based on combining the Event Trees from different units (referred as the Master Event Tree approach)
2) based on representation of core damage at individual unit as a functional event in the multiunit event tree for all units (referred as the Single Top Fault tree Approach).

The first approach involves combining of accident sequences from different units and implies certain simplifications. In the context of accident sequence analysis for MUPSA some possible permutations of unit core damage results could be screened out. This approach allows analyst to select an order of units that would form a “chain” of core damage results and that as soon as one unit in the chain does not go to core damage, the chain is broken and the accident sequence is terminated (see Figure 2). This is not to state that other permutations are not possible, but that assessing a single permutation of a given order (e.g., two-unit CD, three-unit CD, etc) and in a given sequential order as representative of the set of permutations is sufficient and the "missing" combinations are to be added to the results in the stage of the post-processing. Eventually this approach is expected to get a reasonable estimate of the total frequency of all permutations of a given order.

The second approach implies conversion of the accident sequence models for individual units into the equivalent Fault Tree logic, which then are used as functional events in the multiunit event tree, which represents the possible combinations of core damages at different units. This approach implies consideration of inter-unit CCFs, inter-unit dependencies between human actions, inter-unit seismic correlations and other inter-unit dependencies on the level of the Fault Trees representing the core damage of individual unit. Eventually, this approach allows to cover all possible permutations of unit core damage results, but is expected to require more efforts and computational time than the first approach.

Both approaches are currently applied for the implementation of the case study on MUPSA.

Figure 2: The Example of combining Accident Sequences

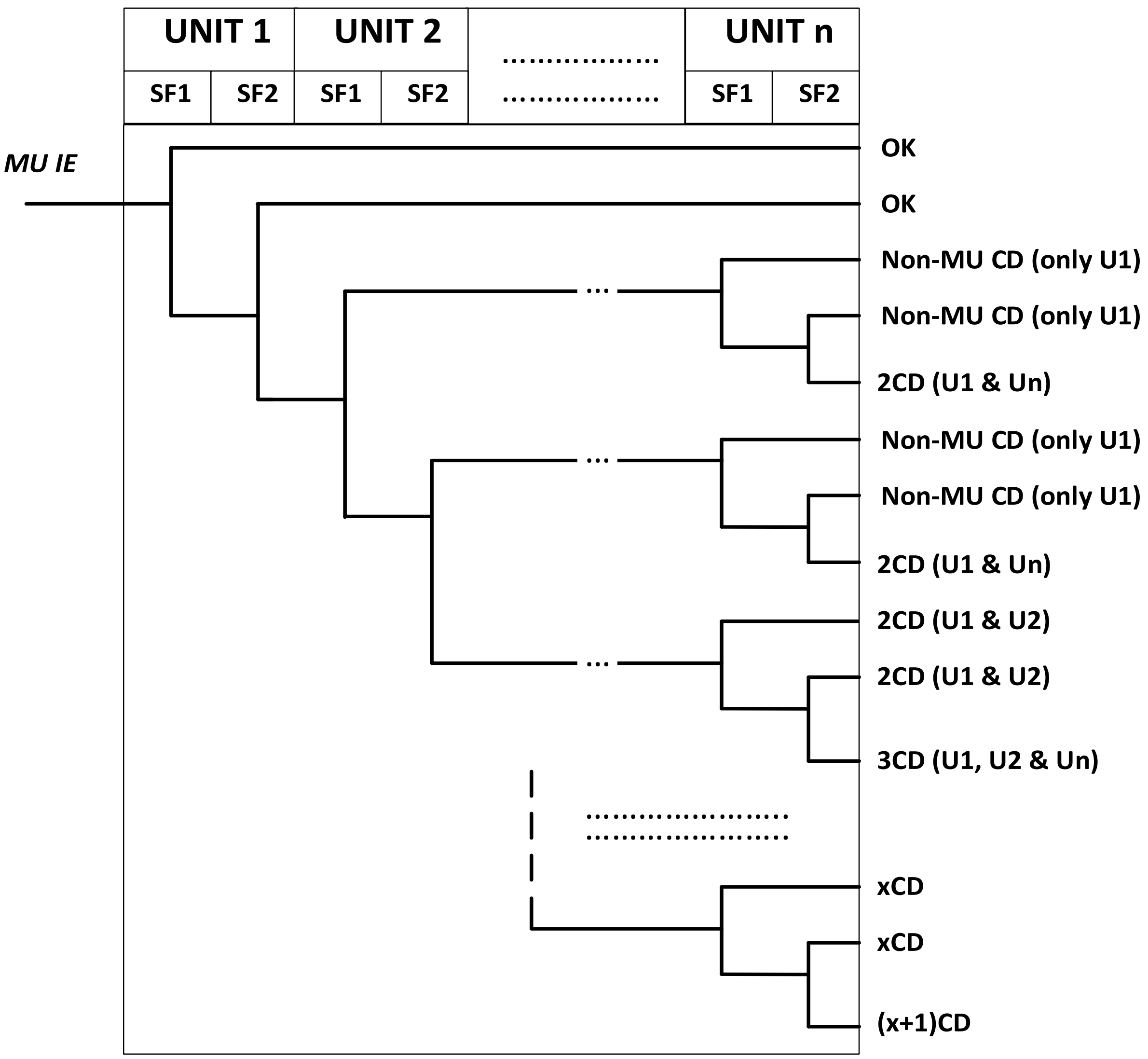
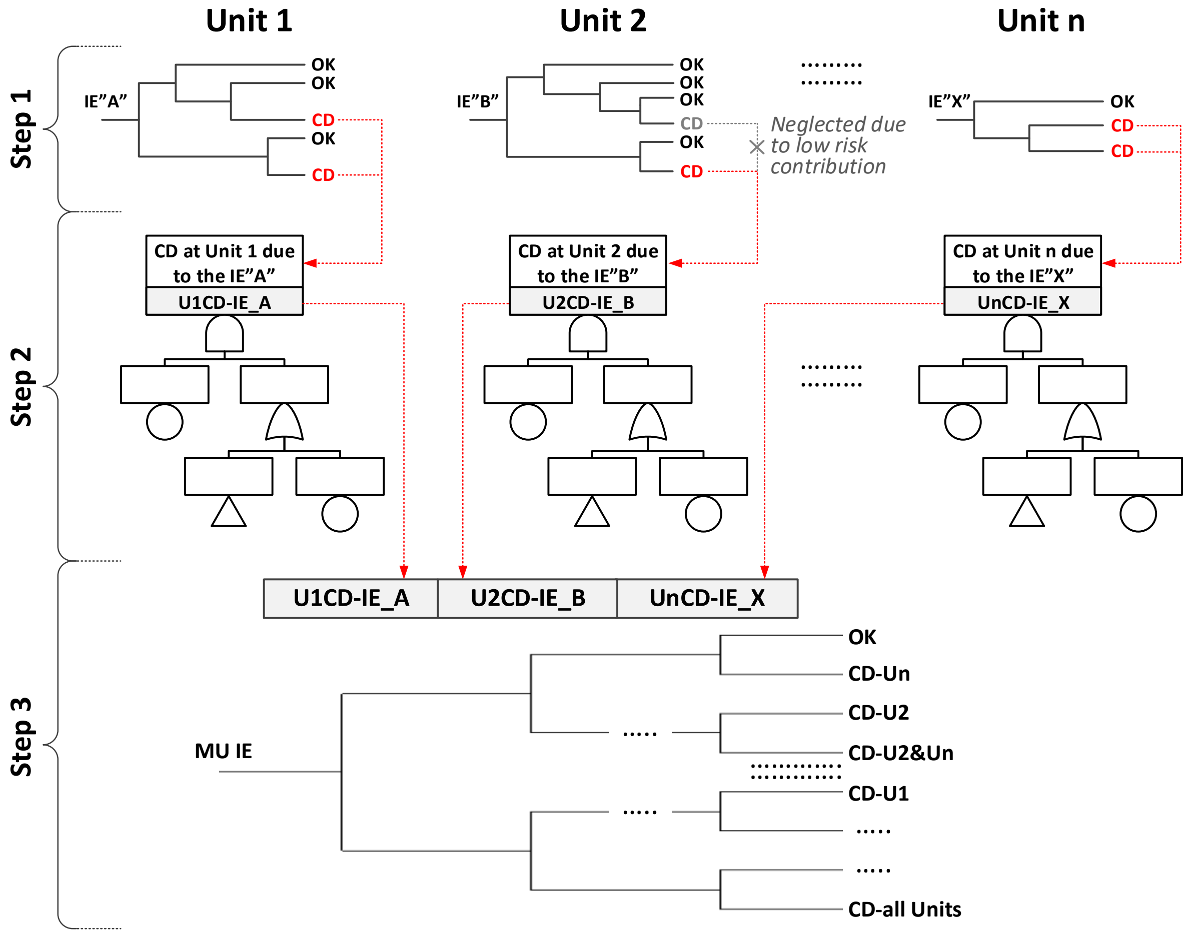


Figure 3: The process of application of Single Top Fault Tree approach for N units



Human Reliability Assessment (HRA). HRA for MUPSA needs to be done along with the comprehensive investigation of the multiunit context in which certain human actions are expected to be implemented. Most obvious issues of the HRA in multiunit context are the one of shared resources between units and the accessibility issue associated with the impact of one unit to the neighbouring one. In the framework of MUPSA these and other factors need to be analysed adequately.

The human resources, whether they be shift managers (SM), shift technical advisors (STA), or field operators (FO) who support multiple units, may be limited in ability to support an event at more than one unit. In case if the plant procedures specifically address the case of multiunit initiating events and instruct that the shared staff are assigned to specific unit, then it could be explicitly considered in HRA. In this context, the HRA in MUPSA is expected to highlight the areas where development of additional procedures would be necessary to address multiunit accident sequences. For the allocation of resources, shared resources may reasonably be available to multiple units depending on the dynamic context. To determine if this is the case for any given action in any given dynamic context, it will be necessary to evaluate the dynamics of an incidental evolution and particularly to conduct walk and talk throughs with the NPP crews.

Another issue that is unique for multiunit context is the accessibility issue connected with the impact from one unit to another. An early release from one unit on site might create obstacles for human interactions on another units. In particular the on-site actions (i.e. local actions) might be affected, taking into account implications such as increased stress level, need for frequent change of the working shifts due to high radiation, reduced time windows, additional stress and obstacles related to the necessity to use protective clothing. Above mentioned considerations need to be taken into account during the implementation of HRA for relevant multiunit scenarios. Analysis of such scenarios implies considerations of dynamic interactions, such as timing of the release from one of the unit and states of the accident scenario at the other units.

The consideration of inter unit HRA dependency is unique to MUPSA. This goes beyond the consideration of available resources, which may have a more significant impact of feasibility than on dependency. A dependency level needs to be assigned between actions at different units if:

- One or more of the operators supporting the decision are doing so for multiple units
- One or more of the operators executing an action are doing so for multiple units

The level of dependency is expected to be greater if the action being done is the same at the multiple units, however there will still be some level of dependency even if the actions are different. If the crews for each unit are completely self-contained (i.e., not sharing), then it could be expected that the level of dependency is low or could be even neglected if justified.

In case of the initiating events that could potentially affect the spent fuel pool together with the reactor units (e.g. LOOP, Fire, Seismic etc.), certain human resources could be allocated for spent fuel pool (SFP). The methodology does not explicitly address the SFP related accident sequences, nevertheless, in the above-mentioned cases those resources are not to be credited to prevent the core damage at corresponding units. During the discussions within the IAEA NSNI Project on Multiunit PSA it was concluded that current HRA methods could be in general applicable for MUPSA, but might require certain adjustment considering MU context.

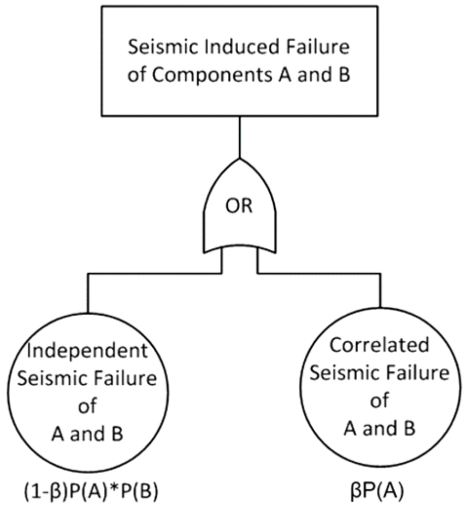
Data, CCF and fragility analysis. There are two aspects related to this topic that are specific for MUPSA: inter-unit common cause failure and inter-unit seismic correlations. The data analysis and fragility analysis are conducted in the same manner as for single unit PSA, and can be carried over to the MUPSA applying the approaches used in traditional PSA.

To capture the potential for common cause failure (CCF) in a multiunit PSA it is necessary to extend the intra-unit common cause approach used for single unit PSA. To address this issue more broadly and to support the analysis of larger numbers of units, it is necessary to review and analyse CCF experience data. More recent research done at the University of Maryland has shown that a significant fraction of experienced CCF events have involved components in different units (see [8], [9]). Thus, one of the main assumptions for inter-unit CCFs applied in the MUPSA methodology states that if the single unit PSA doesn't consider that a set of components are susceptible to CCF within the single unit, then it does not consider that they would be susceptible to CCF between units.

The concept of intra-unit seismic correlation is well established in single unit SPSA. The typical approach is to consider SSCs to be either fully correlated (correlation probability 1.0) or fully independent (correlation probability 0.0). Full correlation is assumed when a set of SSCs meet all the following conditions: SSCs are essentially identical, are located in the same building, are located on the same level and oriented in the same direction. Although imperfect, this approach has been in use for over 20 years and essentially all SPSA currently being performed continue to use it. The issue in this project is how to extend it to inter-unit correlation. In the context of MUPSA SSC is considered seismically correlated with other SSCs at a different unit if besides being essentially identical and having the same orientation, the SSCs are located on the same level in the identical structures, with the condition that the seismic input to the structures is essentially the same. As with other modelling assumptions it is important that the impact of the above suggested seismic correlation modelling assumptions be reviewed in the course of analysing the results of the MUPSA. Seismic correlation for Multi-Units has high interest since full correlation versus not correlated seismic failures may have significant impact to MUPSA seismic risk insights.

For sensitivity analysis a simplified approach based on Split Fraction Method could be used: (a) Estimate the Split Fraction factor β (b) combine the independent failure and correlated failure as shown in Figure 4 (combination of independent seismic failure with correlated seismic failure is illustrated in Figure 4)

Figure 4: Combination of independent and correlated failure

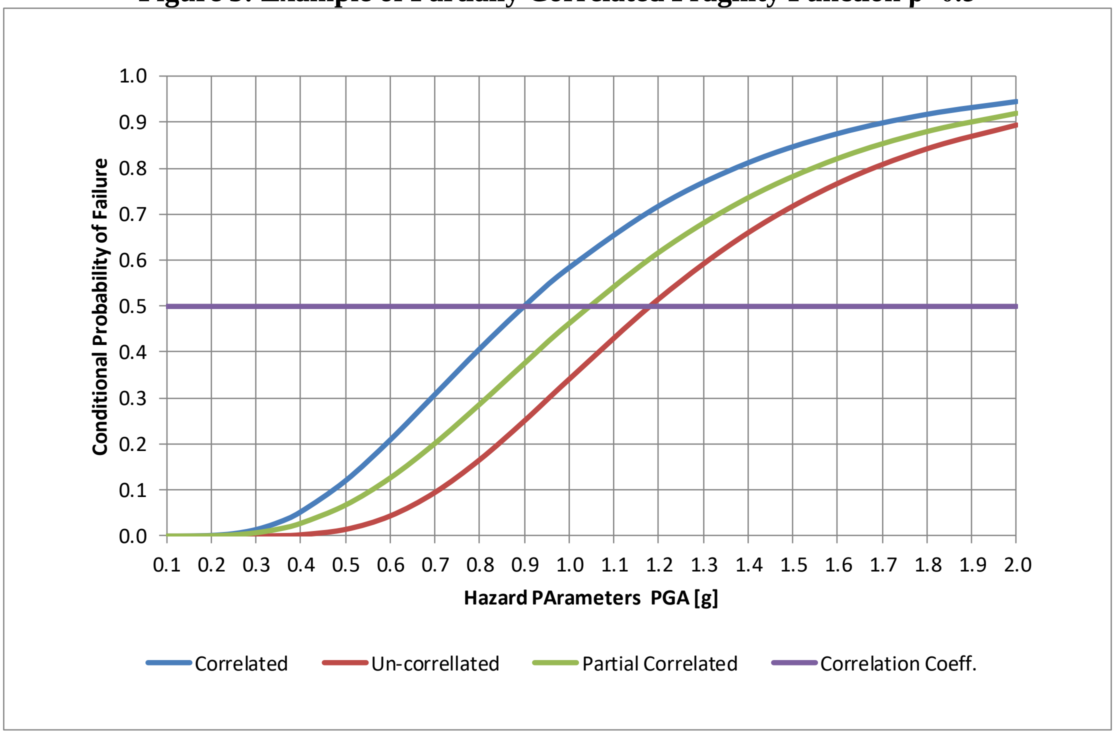


This simple approach can be extended to different components from different units. The example illustrated in Figure 5 uses Frag-A and Frag-B representing two groups of seismic failures from different units:

- Frag-A: $A_m = 0.9$, $\beta_c = 0.5$, HCLPF = 2.82E-01
- Frag-B: $A_m = 0.9$, $\beta_c = 0.5$, HCLPF = 2.82E-01

For this particular example fragility parameters for full correlation, uncorrelated and partial correlation are presented in Figure 5.

Figure 5: Example of Partially Correlated Fragility Function β=0.5

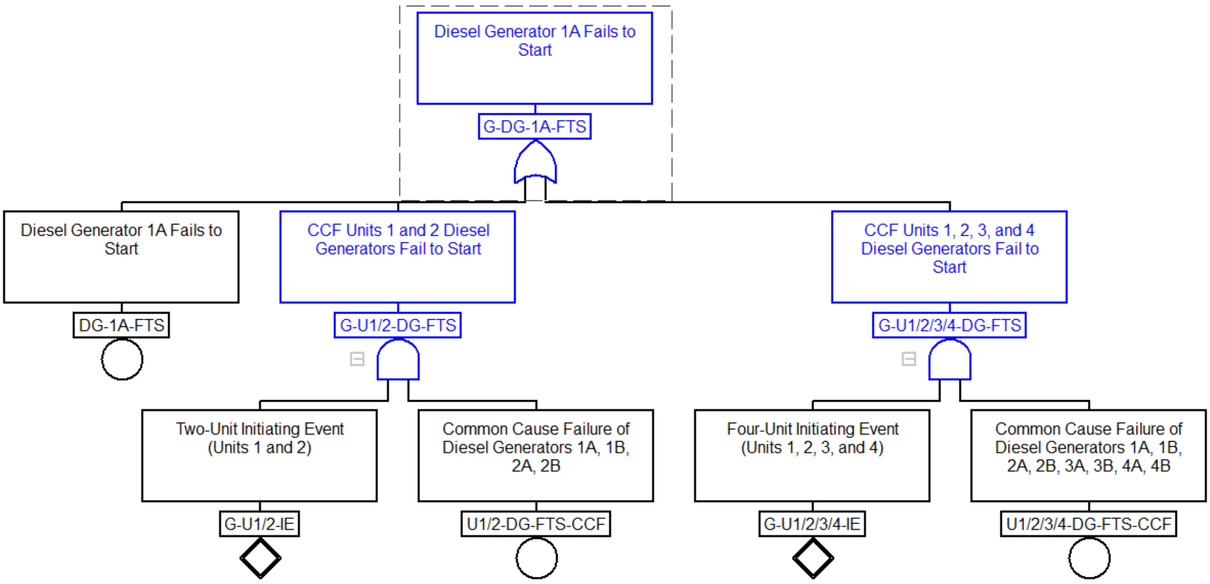


The process is repeated for different β values to allow the judgment if seismic correlation is important or not. If it is important further refinement can be made using seismic correlation methods described in [11].

System analysis. The principles for system analysis for MUPSA are the same as in traditional PSA. The specific of multiunit context is that the use of shared-resources (common systems and components) needs to be reflected in the system models (e.g. if there is a shared EDG between 2 units, the assumption needs to be made that it will be used only for one of the units). As it was noted for HRA, in system analysis the shared resources (e.g. water reserves or other systems) that are allocated to be used both for spent fuel pool (SFP) and reactor core are not to be credited to prevent the reactor core damage.

System reliability models (i.e fault trees) used for single unit PSA need to be supplement by new human failure events, CCF events, and fragility events to reflect the multiunit considerations. For instance, if there is a four-unit site where each unit has two diesel generators for emergency power. In this configuration, there are two CCF cases that need to be incorporated in the model: CCF within a pair given a two-unit initiating event and CCF across both pairs given a four-unit initiating event. An example of one possible modelling approach for one of the diesel-generators is shown in Figure 6.

Figure 6: Example of addition of CCF events for a four-unit site (two identical pairs of units)



Eventually, the interactions between the units, if any, need to be considered in system analysis (e.g. impact of steaming and flooding on neighbouring units in case of steam line break, impact of fire in case of fire propagation from one unit to another, etc.).

Quantification and interpretation of results. The final step in the MUPSA process is the quantification. Quantification process is conducted by quantifying each initiating events for the MUPSA model and the same for the individual unit models. Also, it needs to be done for the end states groups associated to the MU risk metrics.

Quantification can affect essentially all the previous tasks since the results of the quantification can identify areas for model improvement and iteration. Because of the simplifications used in the model, there could be certain issues regarding interpretation of the results.

One of the interpretation issues is the asymmetry created by setting a pre-defined order of progression of the core damage sequence from unit to unit and not modelling all the possible unique combinations of units in core damage (see method for accident sequence analysis presented on Figure 2). This requires aspects of results interpretation not present in single unit PSA. Another interpretation issue is the characterization of overall risk of the multiunit NPP, in terms of risk aggregation, biases, uncertainties, risk metrics and the broader considerations of a decision making framework.

4. CASE STUDY

Currently ongoing Case Study is an essential part of the MUPSA project aimed to complete the efforts implemented in project's Phase 1 – Development of MUPSA methodology and to support finalization of the project in Phase 3.

The objective of the case study is to verify the proposed MUPSA methodology by applying it to the realistic NPP configuration using realistic PSA model and to provide the feedback on the applicability of the proposed methodology for standard PSA tasks. In addition, it is expected that the case study will provide a base for improvement and increase level of details reflected in the methodology. The specification of the case study has been developed considering the following:

- The case study was designed in a way to touch upon and verify various aspects of the MUPSA methodology
- The case study reflects the potential complexity of MUPSA task depending on the number of units available at typical NPP site, their type and configuration
- The case study covers various categories of multiunit initiating events with the aim to address the wider variety of typical accident scenarios

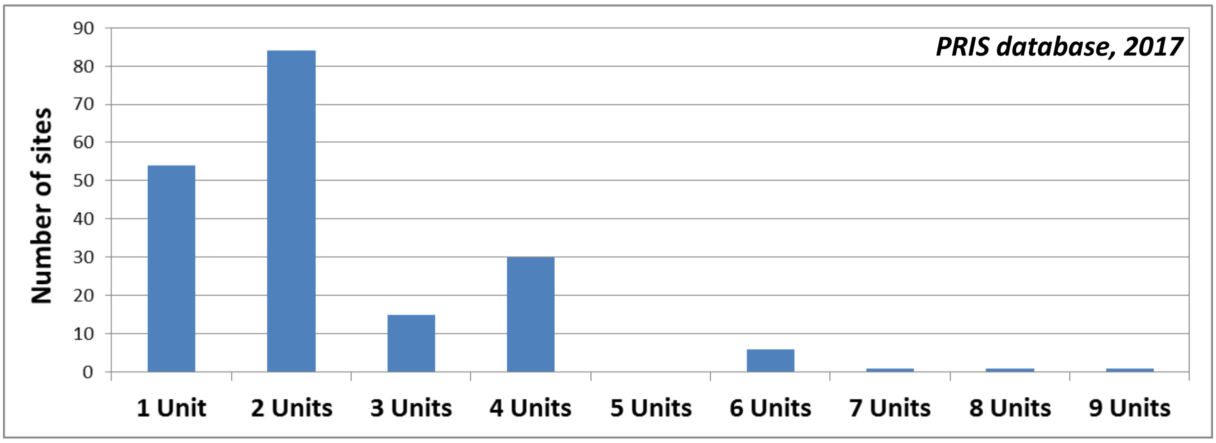
The case study is aimed to consider applicability of the main assumptions to the extent possible. It is understood that the case study could not cover complete set of assumptions listed in Section 2.

The scope of MUPSA case study is mainly defined by the following aspects: Site general characteristics (type and number of units on site to be considered), undesirable consequences (characterisation of the extent of the plant damage to be considered), plant operational states and multiunit initiating events to be considered.

According to the Power Reactor Information System (PRIS) database [1] for 2017 the total number of operating reactors is 447, 64.8% of which are Pressurized Light-Water-Moderated and Cooled Reactor (PWR).

The reactors operating worldwide are distributed through 192 NPP sites, 138 of which are multiunit sites (with 2 or more reactors on site). The distribution of the number of units on sites with operating reactors is presented in Figure 6.

Figure 6: Distribution of reactor types on multiunit sites



According to the Figure 6 most multiunit sites contain 2 or 4 operating units (both identical and non-identical units). Whereas, consideration of 4 units represents the complexity of the task that analyst could potentially face during MUPSA implementation. Thus, the selected scope of the case study is summarized in Table 1.

Table 1: Scope of the Case Study on MUPSA (Phase 2 of IAEA MUPSA project)

Scope	Description
Site general characteristics	4 PWR type Units are being considered in the case study. 2 units of relatively old design ("old" units) and 2 units with the new design ("new" units). It is considered that the "old" units have more shared areas (e.g. turbine hall) and shared systems (e.g. service water, RHR, etc.), than the "new" units. The electrical grid is considered to be common for all units.
Undesirable consequences	Multiunit core damage
Plant Operational States	At the time of the occurrence of the initiating event all 4 units are in full power operation mode.
Multiunit initiating events	Steam line break outside of the containment (SLB)
	Loss of offsite power (LOOP)
	Fire in Turbine Hall and propagation to the neighbouring unit
	Seismic induced LOOP and LOCA
	Radioactive release from one of the units and impact of the unit releasing radioactive materials to the atmosphere to the other units on-site that are in the process of prevention of the core damage (it is considered that all 4 units are exposed to the same IE, e.g. Seismic induces LOOP). The impact of the release on mitigation capabilities (e.g. human actions) of other units is expected to be considered.

5. CONCLUSIONS AND PATH FORWARD

The IAEA project on Multiunit PSA project was initiated as a response to the Member States request, it is coordinated by External Events Safety Section (EESS) and Safety Assessment Section (SAS) and supported by the technical basis developed previously and supplemented by a State of the Art Review on MUPSA conducted by IAEA.

The objective of the project is to develop a detailed MUPSA methodology based on the actual state of practice for addressing potential safety issues related to Multi Unit sites. The methodology is planned to be illustrated by results of a currently ongoing Case Study designed to demonstrate the application of the methodology using the realistic PSA model.

This project is addressing only MUPSA aspects for Level 1 for nuclear reactors. It is considered that this project will provide a good technical basis for moving forward to Level 2 and Level 3 MUPSA.

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