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RESEARCH REPORT

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Managing multi-module issues in SMR PRA

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Report's title

Managing multi-module issues in SMR PRA

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Summary

Small modular reactors (SMR) include special characteristics, such as multi-module issues and passive safety systems, that can pose challenges for probabilistic risk assessment (PRA) of SMRs. PRA method, tool and risk metric development is needed to account for the reliability and the uncertainties related to the different aspects of SMR risk. In this study, we focused on multi-module issues.

Even though SMR modules are not equivalent to units of large reactors, the challenges considering modelling of multi-module accidents in PRA are similar to those of modelling of multi-unit accidents. Therefore, multi-unit PRA approaches could provide a good starting point for multi-module accident modelling.

Most multi-unit PRA methods are based on a single-unit model (for each unit) developed conventionally using event trees and fault trees. If SMR PRA is developed using the conventional PRA approach for a single module, the multi-unit PRA methods seem in general quite well applicable to multi-module PRA. However, there are aspects in multi-module PRA of SMRs that can differ from multi-unit PRA of large reactors. These include risk metrics, plant operating states, initiating events, human dependencies and CCF groups. In summary, many analysis details may need to be reconsidered for SMRs compared to large reactors.

Both for multi-unit and multi-module PRA dynamic methodologies have been proposed. However, it is a bit unclear why a conventional PRA approach would not be sufficient.

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Contents

Acronyms

CCDF	complementary cumulative distribution function
CCF	common cause failure
CDF	core damage frequency
DPRA	dynamic probabilistic risk assessment
IAEA	International Atomic Energy Agency
HRA	human reliability analysis
LERF	large early release frequency
LOOP	loss of off-site power
MMAF	multi-module adjustment factor
MUCDF	multi-unit core damage frequency
MUPRA	multi-unit PRA
MUPSA	multi-unit probabilistic safety assessment
NPP	nuclear power plant
PRA	probabilistic risk assessment
PWR	pressurized water reactor
QHO	(site) quantitative health objectives for individual risk
RCF	release category frequency
RISMC	risk informed safety margin characterization
ROM	reduced order model
SCCDF	site complementary cumulative distribution function
SCDF	site core damage frequency
SFP	spent fuel pool
SITRON	SITe Risk Of Nuclear installations
SLERF	site large early release frequency
SMR	small modular reactor
SRCF	site release category frequency
SSC	structures, systems and components
SUCDF	single unit core damage frequency

1. Introduction

Small modular reactors (SMR) and non-light-water advanced small modular reactors (aSMR) are new approaches to nuclear reactor design, and practical experience about them is as of yet non-existent. This can pose challenges to probabilistic risk assessment (PRA) of SMRs. For SMR PRA, methodologies and tools need to be developed in order to assess and predict the safety, security, safeguards, performance, and deployment viability of SMR systems throughout their life cycle [1].

In 2019, we performed a literature review on SMR related PRA [2]. SMRs introduce several special characteristics that pose challenges from PRA perspective. Especially, methods to handle passive features and multi-module issues in PRA should be investigated or enhanced [3].

In this work, we focus on multi-module issues in PRA. The safety principles developed for multiple large units cannot be directly adapted for multiple SMR modules, because the SMR “module” is not equivalent to the large reactor “unit”. For example, a module may not include individual safety systems and safety support systems such as separate heat sinks or AC power.

Our goal in this study is to identify special characteristics of multi-module SMR accidents and the challenges they set for modelling multiple modules in PRA. We briefly review existing approaches developed, e.g., for site level PRA to see if they could be utilized or adapted to model multi-module issues.

2. Special characteristics of SMRs

We define a SMR similarly to [3], i.e. SMRs typically have several of the following features:

- Nuclear reactors typically <300 MWe or <1000 MWt per reactor
- Designed for commercial use, i.e., electricity production, desalination, process heat (as opposed to research and test reactors)
- Designed to allow addition of multiple reactors in close proximity to the same infrastructure (modular reactors)
- May be light or non-light water cooled
- Use novel designs that have not been widely analysed or licensed by regulators

2.1 SMR-specific features

In [3], special characteristics of SMRs are divided into four groups:

- Facility size: E.g. smaller plant footprint and small power of the core.
- Use of novel technologies: Novel technologies include passive cooling mechanisms, incorporation of primary system components into a single vessel, the use of non-traditional or different number of barriers to fission product release, and unique fuel designs.
- Modular design: Enables compact and simplified designs, production, assembly and testing in factory, and multi-module facilities.
- Deployment: Includes topics such as siting and module transportation.

2.2 Multi-modules issues of SMRs

The following subsections focus on multi-module issues of SMRs. The discussion below is mainly based on work regarding Multi-unit/Multi-module aspects specific to SMRs [4] of the International Atomic Energy Agency (IAEA) SMR Regulators' Forum's [5] working group considering design and safety analysis.

2.2.1 Multi-module vs Multi-unit

A unit is a single nuclear facility. It can include one or more reactors and spent fuel pools. A large light water reactor unit includes typically one reactor and a spent fuel pool. Usually, a unit has an operating license of its own. A module is a separate nuclear reactor capable of being operated independent of the state of completion or operating condition of any other module co-located on the same site, even though the nuclear power station may have some shared or common systems [6]. A unit can consist of one or more modules. A nuclear power plant site can include multiple units, each of which can include multiple modules.

In [4], the differences between "multi-unit" and "multi-module" are discussed. The conclusion was that "multi-modules" could not be considered as equivalent to "multi-units", as with large reactors. However, the terms are not defined for SMRs. An SMR module may (or may not) be completely autonomous, include individual safety systems and safety support systems. For example, in some SMR designs several modules can share the control room, reactor building, reactor containment building and ultimate heat sink.

Based on the SMR definition used in [4], modular reactors are "designed to allow addition of multiple reactors in close proximity to the same infrastructure". The term multiple modules' unit refers to units including more than one nuclear reactor including features such as [4]:

1. A multiple modules' unit might include only one reactor module in the first stage of its planned development
2. Essential features of the multiple modules' unit approach typically include the following:
   a. Allow the addition of several modules in close proximity to the same infrastructure
   b. The modules may be deployed in compact configurations and share structures, systems and components to a larger extent than in units using a single reactor design approach
   c. Each module can be operated mostly independently of the state of completion or operating condition of any other module of the multiple modules' unit
   d. The different modules are essentially identical.

Multiple modules can introduce new safety considerations related to, e.g., common-cause failures, internal hazards, and human factors. In [4], the working group considered that existing multi-unit requirements were in general appropriate and applicable to SMRs. However, it was considered that they should be complemented by specific considerations for units consisting of multiple reactors.

2.2.2 Multi-module issues

Specific safety issues relevant for multiple modules have been listed in, e.g. [4], and they include:

- Potential for interactions among the modules
- Potential for sharing safety systems and features
- Multi-module failure in hazards conditions
- Modules' dependence/independence
- Human factors engineering including topics related to e.g.,
    - main control room
    - supplementary control and other emergency response facilities and locations
    - maintenance of the multiple modules
    - potential remote control of the main control room
    - minimum shift complement
    - training
- Emergency preparedness and response
- Capacity for the addition of future modules

3. Multi-module PRA of SMRs

3.1 Challenges to model multi-module accidents in PRA

Even though, multi-modules cannot be considered as equivalent to "multi-units" they share similar challenges from the PRA modelling point of view. The challenges that both multi-unit PRA and multi-module PRA share originates, e.g., from modelling dependencies between the units/modules and the need for new risk metrics. Multi-unit PRA (MUPRA) technical issues and challenges applicable to multi-unit or multi-module facilities are listed in [4] and they include for example:

- MUPRA infrastructure: Issues and challenges include lack of experience and guidance for performing MUPRA and lack of existing deterministic safety analyses of multi-unit accidents to support MUPRA.
- Selection of initiating events: Many traditional single-unit initiating events (e.g. loss of off-site power, loss of heat sink, external events) challenge multiple units. There is a need to delineate single-unit/facility and multi-unit/facility events. Extent of shared systems between units increases the importance of some internal initiating events (e.g. support system faults).
- Accident sequence modelling: Single- and multi-unit accidents sequences need to be defined. Common cause and causal dependencies between multiple units need to be accounted for. Negative impacts of single reactor accidents on other units need to be considered. New end states involving multi-unit accidents and interactions may be needed. In addition, for example, the re-evaluation of dynamic PRA approaches may be needed due to the limitations of static PRA modelling approach.
- Accident sequence quantification and site-based risk metrics: Additional risk metrics in addition to core damage frequency (CDF) and large early release frequency (LERF) are needed. Common cause failure (CCF) models and supporting data analysis need to be defined to address inter-unit and intra-unit CCFs. Mission times beyond 24 hours

need to be considered. Treatment of human action in multi-reactor Level 2 PRA will be even more challenging than in single-reactor Level 2 PRAs.

- Accident progression and source term characterization: Single accident models limited to single-reactor accidents need to be complemented to consider multi-unit and fuel storage accidents. New release categories may be needed for multi-unit accidents.
- Evaluation of radiological consequences: For example, modelling of releases from multi-unit and multi-facility accidents.
- Site-based safety goals, risk integration and interpretation: Issues include, for example, lack of multi-unit site-based acceptance criteria for evaluating the integrated risks from a multi-unit site PRA and lack of methods for comparing calculated risk against existing and new safety goals.

3.2 Approaches for modelling multi-module accidents in PRA

The challenges considering modelling of multi-module accidents in PRA are similar to those of modelling of multi-unit accidents. Thus, approaches developed for MUPRA could provide a good starting point for multi-module accident modelling. MUPRA approaches can typically be classified either as a static or as a dynamic approach [7].

In the following subsection, we review approaches developed for multi-unit and multi-module accident modelling in PRA. We review first static approaches, and then dynamic approaches.

The reviewed approaches are mostly overall approaches that cover different analysis steps or areas related to multi-unit/module PRA, and some are purely overall risk quantification approaches. Methods that focus only on some multi-unit analysis details, such as inter-unit CCFs, correlated fragilities or human reliability analysis (HRA), are not included. A summary of such methods can be found in [7]. Methods for inter-unit CCFs are highly relevant for multi-module analysis, and the same methods can likely be applied. Multi-module analysis could however involve even larger CCF groups, which could impact to the choice of method. For correlated fragilities, the analysis is also expected to be quite similar in multi-module context as in multi-unit context. HRA methods, on the other hand, may not be directly applicable to SMRs, because the control room and crew can be common for several modules.

3.2.1 SITRON (SITe Risk Of Nuclear installations)

In the Nordic collaboration project SITRON, the goal was to search for practical approaches for Nordic utilities to assess the site level risk [8]. This included safety goals, risk criteria and PRA applications for a multi-unit site. Another objective was to develop methods to assess risk for multi-unit scenarios. This objective concerns with methods to identify, analyse and model dependencies between the units.

Since many of the MUPRA challenges listed in section 3.1 are common both to multi-unit and multi-module facilities, they have largely been considered in the SITRON development.

The SITRON approach is to utilise existing single-unit PRA models, and calculate the multi-unit risk metrics based on the single-unit models and multi-unit dependencies. There is no evident reason why this overall approach could not work for SMRs. It would not likely be practical to integrate several modules into the same event trees, so the development of a single-module model first seems to be a reasonable approach also for SMRs. However, some details of the analysis could be quite different for SMRs. The SITRON approach was also mainly developed for the analysis of two units, so larger number of modules would require some additional considerations.

The analysis process of SITRON, presented in Figure 1, consists of six steps. The project provided specific guidance for the analysis of plant operating state combinations, multi-unit initiating events and multi-unit dependencies, including quantification of inter-unit CCFs and human failure events in the multi-unit accident context. Two approaches for the computation of risk metrics were also developed. In addition, a set of site level risk metrics were proposed in the project. The risk metrics are site core/fuel damage frequency, multi-unit core/fuel damage frequency and frequencies of site release categories.

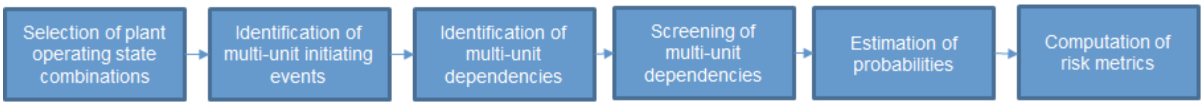

Figure 1: Site level PRA analysis process in SITRON.

Considerations related to risk metrics should be revised for SMRs. It likely depends on the SMR type, which risk metrics should be used. For instance, the concept of core damage is not applicable to all SMRs [9]. Anyhow, frequencies of core damage combinations could be possible multi-module risk metrics for some SMRs as well as site-level core damage frequency. However, risk metrics related to radioactive releases can be more interesting for SMRs, particularly if potential release from one module is small. In SITRON, no distinction was made between large release from one unit and large release from two units, but for SMRs, it could be that the limit value for a large release could be exceeded only by a release from several modules. The simplified treatment of release categories would probably not be applicable for SMRs. Anyhow, as in SITRON, each multi-module accident sequence should be placed in a release category, and the computation of the frequencies of release categories would be performed by summing the frequencies of the relevant accident sequences.

Two multi-unit risk quantification approaches were developed in SITRON. One is based on combining minimal cut sets from different units, and the other one is based on conditional quantifications of single-unit models based on multi-unit event combinations. The quantification approaches would need to be generalised for more than two modules, but it would not be a problem. However, the computations would become significantly more complex if there were several modules. If different combinations with the same number of modules would be identical, it would simplify the calculations though. An automatic tool to perform the calculations and handle module combinations would anyway be useful.

The screening criteria might need to be revised from [8]. Screening out occurrence of multiple single-module initiating events would probably be applicable also to SMRs, but it should be reconsidered for SMRs.

Plant operating state analysis could be different for SMRs. If there were several modules, the number of plant operating state combinations could possibly be very large. Then, the number of combinations for analysis should be limited somehow, like in SITRON for large reactors.

As multi-unit initiating events are analysed in SITRON, multi-module initiating events would need to be analysed for SMRs. The considerations could be quite similar. Since SMRs can be located very close to each other and can have more common systems, there could be even more common initiating events. Also, propagation of accident from one module to another would need to be considered, whereas that kind of accidents received quite little attention in SITRON.

There are multi-module related dependencies that can be more challenging to analyse than those dependencies considered in SITRON, particularly if there are several modules. There could be large inter-module CCF groups for which both data and suitable models are lacking. In SITRON, it was found useful to simplify CCF analysis by merging those CCF combinations that have same impacts. Similar approach would likely be useful also for SMRs. CCFs of passive systems could be even more challenging analysis problem related to SMRs. In addition, SMRs would require new HRA considerations as the control room and the crew can be common for several modules. The number of dependencies could also affect the selection of the analysis method, e.g. if there would be significantly more dependencies than in SITRON analyses.

3.2.2 Conceptual procedure for multi-unit PRA

A conceptual procedure for evaluating multi-unit risk for PRA analyses is presented in [10]. Four types of dependencies were identified and modelled [10]:

1. Common (identical) structures, systems and components (SSCs) shared between multiple units
2. Causal dependence of an event (SSC state) in one unit to another event(s) in other units
3. Causal dependence of an initiating event and/or SSC failures in one unit to an event external to the SSCs of other units (seismic, flood, loss of power)
4. Parametric (traditional) common cause events within one unit and across multiple-units among similar SSCs, initiating events or human errors

A two-unit logic example was used to demonstrate the approach. Based on the example, all dependencies are important. However, the traditional CCF events dominate the results, and they can be addressed through traditional parametric methods. Causal core damage sequences starting from another unit could also be significant according to [10].

On a conceptual level, this approach seems applicable to multi-module PRA of SMRs, because the same dependency types are relevant for SMRs.

3.2.3 Technical Approach to Probabilistic Safety Assessment for Multiple Reactor Units

In [11], a PRA approach for multiple reactor units is discussed. The discussed MUPRA process consists of several steps (see Figure 2). The approach covers most of the challenges listed in section 3.1. The report focuses mainly on what needs to be included in the analysis and taken into account, and does not specify which methods should be used.

Risk metrics and the scope of the analysis are determined in step 1. The following risk metrics are defined to complement the traditional single-unit PRA metrics; Frequency per site-year of core damage to one or more reactor units (SCDF), Frequency per site-year of a large early release from one or more reactors or on-site facilities (SLERF), and Frequency per site-year of each distinct release category for a multi-unit Level 2 PRA (SRCF).

The selection of initiating events includes the identification of initiating event categories, initiating event screening and the selection of initiating events. For initiating event identification the following general categories can be used; initiating events impacting each reactor separately and independently, initiating events impacting specific combinations of reactor units, and initiating events that may impact two or more reactor units depending on the severity, circumstances or plant conditions at the time of the event. When selecting initiating events, first internal events should be addressed, then internal hazard, and finally external hazards.

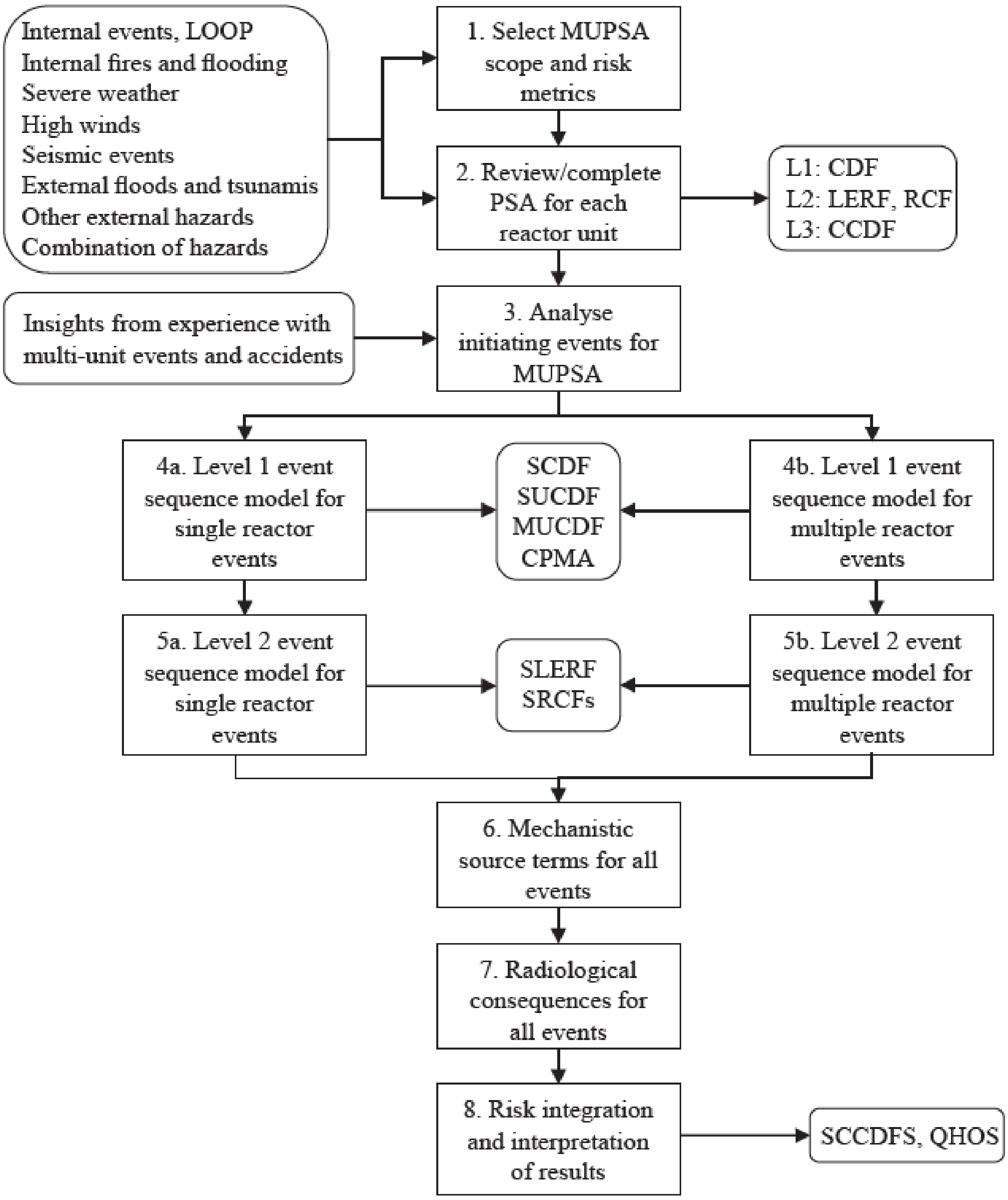

Figure 2. Overview of the process for MUPRA [11]. (CCDF — complementary cumulative distribution function; CDF — core damage frequency; CPMA — conditional probability of multi-unit accident; LERF — large early release frequency; LOOP — loss of off-site power; MUCDF — multi-unit core damage frequency; MUPSA — multi-unit probabilistic safety assessment; PSA — probabilistic safety assessment; QHOs — (site) quantitative health objectives for individual risk; RCF — release category frequency; SCCDF — complementary cumulative distribution function; SCDF — site core damage frequency; SLERF — site large early release frequency; SRCF — site release category frequency; SUCDF — single-unit core damage frequency)

The event sequence model (step 4) for level 1 for a single unit may need to be updated, e.g., to account for the selection of initiating events. In addition, a new event sequence model is needed to be developed to consider event sequences involving core damage of more than one unit. It is not specified how this event sequence model should be developed, i.e. the choice of method is left to the analyst. The quantification of the models of step 4 enables the computation of site core damage frequency (SCDF).

Similarly to level 1 event sequence model, the level 2 event sequence models need to be developed. The quantification of level 2 event sequence models enables to compute site large early release frequency (SLERF). If the end states have sufficient information also the site release category frequencies (SRCFs) can be computed.

Source terms are considered in step 6. For all event sequences and release categories (of step 5) source terms are developed. In step 7, radiological consequences are developed for all release categories and source terms. Finally, in step 8, event sequence frequencies and consequences are combined into level 3 risk metrics and compared against risk criteria and safety goals.

Safety goals are discussed in [11]. However, the discussion relates mainly to the issues of applying typically used single-unit safety goals as site level safety goal. In addition, reference [11] highlights the modelling of CCFs and the estimation of the corresponding CCF parameters as the main difference between an MUPRA and a traditional single reactor PRA regarding the systems and data analyses. Two types of CCFs are defined:

- Single-unit CCF: CCF of two or more components at a single unit either on a single site or multi-unit site.
- Multi-unit CCF: CCF of two or more components at different units or facilities on a multi-unit site.

This high level analysis process seems largely applicable to multi-module analysis of SMRs. Risk metrics could however possibly be different depending on the SMR design.

3.2.4 NuScale multi-module PRA

A simplified multi-module PRA has been developed for NuScale SMR design [12]. The multi-module analysis was performed based on the minimal cut sets of a single-module. Post-processing rules were developed to transform the single-module minimal cut sets into multi-module minimal cut sets. The analysis was simplified so that different module combinations were not considered, but a multi-module core damage automatically meant a core damage in all modules.

The dependencies between modules were analysed by estimating multi-module adjustment factors (MMAFs) and multi-module performance shaping factors. A MMAF is the conditional probability that an event occurs in multiple modules if it occurs in one. The MMAFs were estimated for initiating events, single failures, CCFs and failures of passive systems roughly based on expert judgment. The probabilities of single-unit basic events were simply multiplied by the MMAFs to calculate the multi-module results. It is notable that coupling of internal initiating events was also modelled, because it has not usually been credited in multi-unit PRA methods. The multi-module performance shaping factors were applied to the probabilities of human failure events to take into account the added complexity from the management of multiple modules.

This approach may be sufficient for preliminary multi-module PRA or for conservative demonstration that the multi-module risk is small enough, but not for realistic quantification of multi-module risks, because it does not consider different module combinations. The expert judgment -based quantification in [12] seems very conservative. The minimal cut set post-processing approach might however work also for more realistic analysis, but it would get more complex when analysing combinations of more than two modules. It may be a limitation if the approach cannot handle combinations of different failures in different modules.

3.2.5 Top fault tree approach

Kim et al. [13] present a multi-unit risk quantification approach, where core damage sequences of each unit are converted into one top fault tree, and those top fault trees are integrated in the same model to calculate multi-unit risk metrics. This approach enables explicit modelling of multi-unit dependencies in a PRA model. The size of the model also does not become such a problem as with integrated event trees. The method was applied to a six-unit site, so it seems well applicable to cases with several SMR modules.

Kim et al. [13] applied a mapping up technique to large inter-unit CCF groups. Impact vectors were estimated to the large groups based on data of smaller groups, and the alpha-factors were estimated based on the impact vectors. This is one possible approach to deal with large CCF groups in the SMR context also when there is no sufficient data available for a large group.

3.2.6 Integrated event trees

One possibility to perform multi-module PRA is to integrate the modules into the same PRA model, i.e. the same event trees, as presented e.g. in [14]. Benefits of such an integrated model are that the multi-module dependencies can be modelled explicitly in one PRA model, and that all the single-module and multi-module results can be calculated directly from a single PRA model. However, integrated event trees may become very large as the number of accident sequences increases exponentially as a function of the number of modules. For two modules, the size of such a model could be reasonable, but the approach does not seem well applicable to larger number of modules.

Zhang et al. [14] have applied integrated event tree modelling to a high temperature gas cooled reactor-pebble bed module with two reactor-steam generator modules. To keep the sizes of the event trees reasonable, they used so-called phased evolution method, where accident progression is divided into phases that are modelled using separate event trees that are linked. Using this approach, a pilot study was executed successfully, but the case was quite limited. The phased modelling could also be quite complex if more than two modules were included. With several linked event trees, the traceability of minimal cut sets can also be difficult to ensure.

3.2.7 Multi-module dynamic PRA

A methodology to estimate the relative risk of multi-module reactors is presented in [15, 16]. The focus is on SMR designs. The methodology consists of the following steps (assumes that a base PRA model for single modules has been developed): [15]

1. Define taxonomy of connections within and between units in a nuclear plant site that affect performance and functionality of critical SSCs, e.g. according to commonality classifications presented in [17].
2. Develop a dependency matrix. The matrix can then be used to bin systems into one or more commonality classifications (see step 1).
3. Rank base PRA accident sequences of single module to facilitate the development of a focused multi-module PRA.
4. Use traditional importance measures in the base PRA to determine the components and systems that may be risk significant and compare to a list of multi-module dependencies.
5. Establish a thermal-hydraulic model of the nuclear reactor system.
6. Expand fault trees to include dependencies across adjacent units or modules.
7. Build ADS-IDAC (a dynamic PRA (DPRA) tool e.g. [18]) simulator multi-module model.
8. Prune accident sequences based on probability truncation, event time or end state conditions.

In the methodology, site-level CDF is considered instead of the frequency of core damage per unit, per year irrespective of the operating states of other units. For a proof of concept base case some of the steps have been performed, e.g. a system classification matrix has been developed for an iPWR (integral pressurized water reactor) to support and front-line systems. However, the methodology seems to be at a tool development phase [15].

3.2.8 Risk Informed Safety Margin Characterization

In [19], a DPRA approach for multi-unit PRA modelling is presented. In the Risk Informed Safety Margin Characterization (RISMC) approach, dynamic risk analysis software RAVEN [20] is utilized as stochastic tool coupled with accident analysis software RELAP5-3D [21]. The approach was used to analyse a 3-unit plant site of pressurized water reactors (PWRs). The RELAP5-3D models are used for determining the temporal response of all PWRs and spent fuel pools (SFPs) while for the plant connections and dependencies RAVEN is utilized. The modelled accident scenario resembles a station black out event and the analyses accident concentrated on the recovery strategy in order to place all PWRs and SFPs in a safe condition.

In the work, timing and sequencing of events for all units are implicitly considered in a single PRA framework. Plant accident progression is predicted by the simulation codes given the set of initial boundary conditions instead of defining it before the analysis. The example site and accident scenario was modelled in detail from both a deterministic and stochastic point of view. In the example, the stochastic modelling focused on the NPP recovery actions and, thus, additional potential failures of systems and components were not included in the model.

A key challenge in utilising DPRA is the high computational cost. In [19], the challenge is tackled by using Reduced Order Models (ROMs [22]) instead of running RELAP5-3D models. ROMs are surrogates of the original model whose predictions are close to the original model.

We have identified no reason why this method would not be applicable to SMRs. The main concerns with regards to practical application of the method are the complexity of modelling and computation time.

3.2.9 Framework for SMR PRA

A framework for SMR PRA is discussed in [1, 9, 23, 24]. The framework is outlined in [23] and discussed in more detail in [1]. The framework considers the following aspects [1]:

- Use of probabilistic models to provide information specific to SMR-applicable performance metrics.
- Representation of specific SMR design issues such as having co-located modules and passive safety features.
- Use of modern open-source or readily available analysis methods and software to support the probabilistic modelling.
- Emergency planning and management, including source term evaluation.
- Internal and external events resulting in impacts to safety.
- All-hazards considerations including the reactor core, storage/movement of spent fuel, and hazardous gases.
- Risks that may be present during low-power and shutdown conditions.
- Methods to support the identification of design vulnerabilities.
- Mechanistic and probabilistic data needs to support the modelling and tools development effort.

The framework should include multi-module aspects. However, there is very little discussion on how they should be accounted for.

3.2.10 Continuous Markov-chain approach

Sawada et al. [25] have applied a continuous Markov-chain method to multi-unit PRA. They have developed a simplified model of three boiling water reactor units. The model is coupled with deterministic accident progression calculation. Time-dependent evolution of accident sequences is calculated using the model. An interesting feature of the model is that the impact of a release from an adjacent unit is taken into account in the probability of the manual action to perform containment venting. The model is however very simplified. The approach would probably be computationally too demanding for real application, although SMR PRAs may be significantly simpler than PRAs of large reactors.

4. Conclusions

The special characteristics of small modular reactors, such as multi-module issues and passive safety systems, can pose challenges for PRA of SMRs. PRA method, tool and risk metric development is needed to account for the reliability and the uncertainties related to the different aspects of SMR risk. In this study, we focused on multi-module issues.

Even though modules are not equivalent to units of large reactors, the challenges considering modelling of multi-module accidents in PRA are similar to those of modelling of multi-unit accidents. Therefore, MUPRA approaches could provide a good starting point for multi-module accident modelling.

The basis for most multi-unit PRA methods is a single-unit model (for each unit) developed conventionally using event trees and fault trees. If SMR PRA is developed using the conventional PRA approach for a single module (like in [12]), multi-unit PRA methods seem in general quite well applicable to multi-module PRA. One issue is that multi-unit PRA methods have mostly been developed for two units rather than several units. This can restrict the usability of some methods to multi-module PRA, though it is possible to generalize most methods for larger number of units/modules. The top fault tree approach (converting core damage sequences into top fault trees and integrating those) [13] is a method that is clearly suitable for a larger number of modules, but there are other possible methods for that as well.

Development of an integrated PRA model for multiple SMR modules, e.g. so that different modules are represented in the same event trees, is not necessarily a good idea as the number of sequences can become very large. Nevertheless, it is one possible approach that can be considered depending on the SMR design, e.g. if there are many shared systems.

There are aspects in multi-module PRA of SMRs that possibly differ from multi-unit PRA of large reactors. These include risk metrics, plant operating states, initiating events, human dependencies and CCF groups. Risk metrics and plant operating states can particularly depend on the SMR design in question and require new considerations compared to multi-unit PRA methods. HRA considerations for multi-unit sites are also likely not applicable to SMRs as such. With regard to CCFs, passive systems are a challenge not considered by the multi-unit PRA methods, and larger CCF groups in SMR plants could also cause challenges compared with multi-unit PRA. In summary, many analysis details may need to be reconsidered for SMRs compared to large reactors.

Even though dynamic multi-module PRA methodology has been proposed e.g. in [15], there is no evident reason why PRA of SMRs would require such dynamic approach and the conventional PRA approach would not be sufficient. For NuScale SMR design, the conventional approach has been applied [12]. However, the most suitable PRA approach can depend on the SMR design in question, as there are quite many types of SMR designs.

This review of SMR PRAs and multi-unit PRA methods provides a basis for multi-module PRA research. For example, the NuScale SMR design and PRA documentation [12] could be a good basis for developing a multi-module PRA case study. In such case study, the suitability of one or more multi-unit PRA methods to multi-module analysis could be studied more in detail.

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