**Advances in Reliability, Safety and Security**

ESREL 2024
Collection of Extended Abstracts

# Multiple Module PSA For Small Modular Reactors

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*Keywords*: multi-module reactor, multi-unit PSA, probabilistic safety assessment, small modular reactor

Electricity suppliers in different European countries are planning to build new nuclear power plants (NPPs) based on small modular reactors (SMRs). Compared to traditional nuclear reactors, amongst others, SMRs provide less electrical output power per reactor module for enhancing safety. This also allows applying passive safety features. Jointly deployed SMR modules typically have identical designs and share structures, systems and components (SSC) and human resources. These features may increase the overall risk. A few concepts, i.e., the VOYGR™ plants from NuScale Power LLC, are designed to be deployed jointly in a single power plant or as part of multiple reactor units at a site because of economic attractiveness (Boarin, 2014). Typically, probabilistic safety assessments (PSAs) of most reactor units collocated at the same site are conducted individually for each single unit (IAEA 2010; OECD/NEA 2020; IAEA 2024). However, analyses focussing only on a single reactor unit (single unit PSA) may not always adequately consider potential effects from (i) SSC or human resources shared between different reactor units or between all nuclear sources at the site, or (ii) from external or external hazards that may impact more radioactive sources than the reactor unit under investigation (OECD/NEA 2019). PSA for multiple reactor units/modules must consider these aspects appropriately before adding up the risk contributions for all reactor units/modules.

A Level 1 multi-module SMR PSA plant model has been recently developed by GRS for a VOYGR™ type NPP (NuScale, 2020) with a maximum of twelve SMR modules in the frame of the PSA model in line with the requirements in (IAEA 2023). In this context, the effect of interdependencies between the modules with multiple identical SMRs on the core damage frequency (CDF) has been analysed. A methodological approach has been developed for reducing the overall modelling and calculation effort for any plant with twelve identical reactor modules compared to the effort for plants with only four modules. It is based on the approach for twelve identical modules and considers four representative modules within the twelve ones. The exact position of the four representative modules within the plant is not relevant because they can be distinguished by SSC failures in the minimal cut sets of the PSA. A careful implementation of correction factors based on binominal coefficients ensures a correct quantification of the PSA plant model with the representative modules. Namely, the frequency of an initiating event correlated by a common cause affecting all modules with additional SSC failures occurring in two modules (e.g. failure of multiple valves of the emergency cooling system) is multiplied by a binominal coefficient of “12 choose 2” to account for all possible realizations of such failures in two arbitrary modules of the plant.

The development of the multi-module PSA has been carried out as a stepwise process:

1. Single module PSA:

- Implementation of the single-module PSA of NuScale in the RiskSpectrum® PSA code based on the published manufacturer’s PSA (NuScale, 2020), in particular the event trees;
- Development of the respective fault trees using detailed information regarding SSC, including the implementation of common cause failures (CCFs);
- Extension of the single-module PSA plant model based on the analysis of additional initiating events, e.g., failure of the natural circulation in the primary cooling system, or reactivity transient without scram;

2. Multi-module PSA:
- Quadruplication of the fault trees for module-specific SSC;
- Generation of multi-module event trees for common cause initiators (CCIs);
- Extension of the CCFs for multiple modules;
- Implementation of a rather simple model for human risk assessment, i.e., the failure probability for a human action increases if the human action is required in multiple units.

Six different CCIs have been analysed in the multi-module PSA, i.e., loss of offsite power (LOOP) and loss of coolant accident (LOCA) inside the containment. A preliminary result of the LOCA by a CCI inside the containment is shown in Fig. 1. The loss of coolant from the primary system triggers the emergency core cooling system (ECCS) in the affected modules (first function event). The system failures in up to four modules are analysed and implemented in the PSA plant model using branch point alternatives. In the event of a (module-specific) ECCS failure in one or more modules, the (module-specific) chemical and volume control system (CVCS) can be used to add inventory to the primary cooling system. If an ECCS failure in one or more reactor modules occurs together with a failure of adding inventory, the reactor core of the affected modules may get damaged.

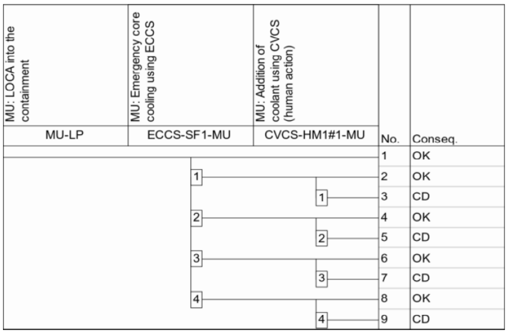


Fig. 1. LOCA by a common cause inside the containment.

Preliminary results from the analyses will be presented with the focus on a comparison of the multi-module PSA results and the single-module results. Multi-module cut sets, particularly long-lasting LOOPs, are found to be among the most frequent cut sets in the PSA with significant contributions from inter-module CCF and human failure. The results show that it is worth to develop a multi-module PSA to study the risk contributions of inter-module CCF, human failure and shared SSC.

**Acknowledgements**

This research and development activity has been funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The authors acknowledge the support and contributions by Gerhard Mayer, Marina Röwekamp and Jan Stiller.

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