Inter-Module Dependency Analysis for the Innovative SMR: Loss of Offsite Power Initiating Event

Kibeom Son, Sung-Min Shin, Jin Hee Park*

Korea Atomic Energy Research Institute, 111, Daedeok-daero, Yuseong-gu, Daejeon-si, 34057, Korea
**Corresponding author: jhpark6@kaeri.re.kr*

***Keywords : i-SMR, Multi-Module PSA, Inter-Module Dependency**

1. Introduction

Multiple reactors located at the same site can be simultaneously affected by common initiating events, shared equipment, and common vulnerabilities. Accordingly, research on multi-unit probabilistic safety assessment (PSA) has been conducted internationally. Meanwhile, various small modular reactors (SMRs) currently under development have configurations different from those of conventional large nuclear power plants [1–4]. While each reactor in a large nuclear power plant generally has its own reactor building and supporting systems, SMRs may adopt configurations in which multiple reactor modules are deployed at a single site or within a single reactor building. Accordingly, multi-module PSA for SMRs has begun to receive increasing attention, and inter-module dependency analysis is an essential first step.

This study analyzes potential inter-module dependencies in the internal-event PSA model for the innovative SMR (i-SMR) under development in Korea, focusing on Loss of Offsite Power (LOOP), one of the representative multi-module initiating events.

2. Shared Equipment in the i-SMR

The structures, systems, and components (SSCs) that may affect inter-module dependencies in the i-SMR should be identified. Table 1 summarizes whether the interfacing systems included in the LOOP event tree of the single-module PSA model are shared among modules.

Table 1. Status of Inter-Module System Sharing in the i-SMR

Classification	System	Module No.				Inter-Module Sharing
		M1	M2	M3	M4	
Passive Safety Systems	PECCS	VV	VV	VV	VV	X
	PCCS	HX/ECT	HX/ECT	HX/ECT	HX/ECT	O
	PAFS	VV/HX/ECT	VV/HX/ECT	VV/HX/ECT	VV/HX/ECT	O
Passive Safety Components	PSRV	VV	VV	VV	VV	X
Active Safety Systems	NRHRS	VV/HX/PP		VV/HX/PP		O
Support Systems	EPS	SY/ADG/SDG				O
	HVAC	FAN				O
	CCWS	HX/PP				O
	SWS	PP				O
Control/ Operation	MCR	OPERATOR				O

PAFS: Passive Auxiliary Feedwater System
PCCS: Passive Containment Cooling System
PECCS: Passive Emergency Core Cooling System
PSRV: Pressurizer Safety Relief Valve
NRHRS: Normal Residual Heat Removal System
EPS: Electrical Power System
HVAC: Heating, Ventilation, and Air Conditioning System
CCWS: Component Cooling Water System
SWS: Service Water System

VV: Valve
HX: Heat Exchanger
ECT: Emergency Cooling Tank
PP: Pump
SY: Switchyard
ADG: Ancillary Diesel Generator
SDG: Standby Diesel Generator
MCR: Main Control Room

Table 1 summarizes the sharing status of the systems included in the current single-module LOOP PSA model for the i-SMR and their major components, based on the current design status. The i-SMR incorporates three passive safety systems: PAFS, PCCS, and PECCS. Among these, the PECCS, which consists only of valves, is independently configured for each module without inter-module sharing and is therefore not considered to introduce inter-module dependency. For the PCCS and PAFS, the HXs are independent for each module, whereas the ECT is shared, resulting in inter-module dependency. The PSRVs are also independently configured for each module.

The NRHRS is shared between Modules 1 and 2 and between Modules 3 and 4, and provides a coolant injection path using offsite power. In the EPS, the SY is the only common facility shared across the entire site. Two ADGs and two SDGs, which perform functions similar to those of the alternate AC diesel generators in conventional large nuclear power plants, are provided for the four modules. The HVAC system is also used to cool the ADGs and SDGs.

The CCWS, which is shared by all four modules, consists of four pumps and three HXs, while the SWS consists of four pumps. Finally, all four modules share a single integrated MCR, where three operators simultaneously operate the four modules. This configuration affects operator error probabilities in the PSA model.

3. Potential Inter-Module Dependency Analysis for i-SMR LOOP

Figure 1 presents a partially simplified LOOP event tree included in the current i-SMR PSA model. In conjunction with Table 1, inter-module dependencies caused by shared components should be identified for each heading. Differences in branch names for some headings are intended to distinguish different thermal-hydraulic conditions, and branches with the suffix "-OP" indicate that operator actions are involved.

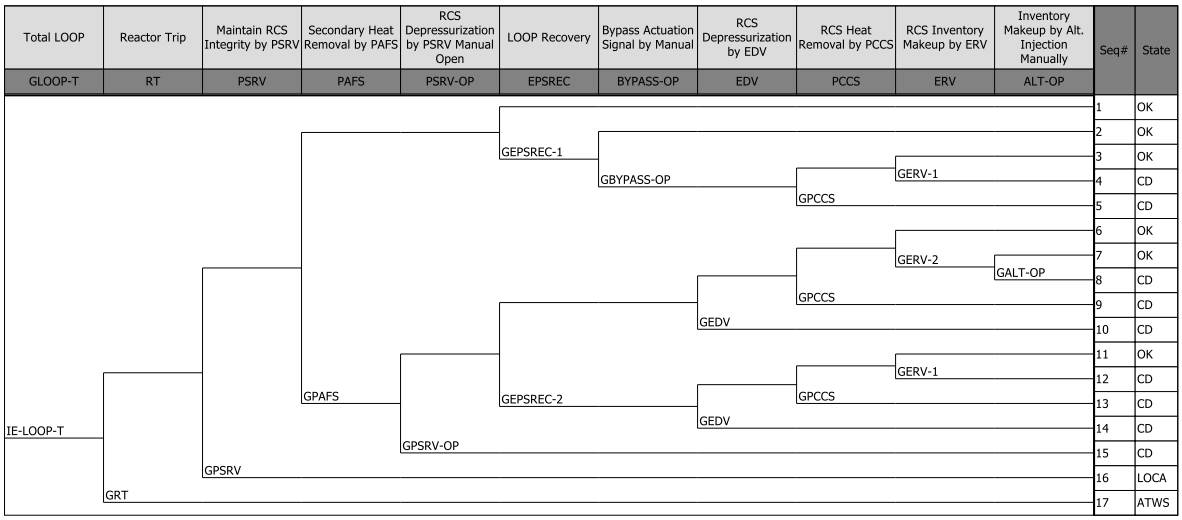

Figure 1. Simplified LOOP Event Tree of the i-SMR PSA Model

The following provides a brief summary of the phenomena associated with the success and failure branches of each heading. Inter-module dependencies are incorporated into the fault tree (FT) linked to each branch, and the logic of the four modules is integrated into a single top-level logic within the FT. Based on this structure, the multi-module LOOP event tree is ultimately constructed.

- IE-LOOP-T: LOOP occurs in all modules.
- GRT: Failure to trip the reactor leads to an Anticipated Transient Without Scram (ATWS).
- GPSRV: Opening of the PSRV is required in the early stage of the accident to prevent primary-side overpressure; failure of the PSRV to reclose leads to a LOCA.
- GPAFS: Secondary-side heat removal through the PAFS is required; failure requires Feed-and-Bleed operation.
- GPSRV-OP: The operator manually opens the PSRV to depressurize the RCS and enable EDV opening.
- GEPSREC-1: If offsite power recovery fails, operator intervention is required to prevent a LOCA.
- GEPSREC-2: If offsite power recovery fails, alternative coolant injection through the NRHRS is unavailable.
- GBYPASS-OP: The operator must bypass the signal to prevent automatic opening of the PECCS valves.
- GEDV: If the EDV fails to open following PAFS failure, core damage occurs.

- GPCCS: Even if the EDV opens, failure of the PCCS HX results in core damage.
- GERV-1: If the ERV fails under conditions where offsite power recovery has failed, core damage occurs.
- GERV-2: If offsite power has been recovered, alternative means are available even if the ERV fails.
- GALT-OP: Long-term cooling is achieved through alternative coolant injection.

Table 2. Multi-Module Dependencies and Their Impacts by Branch in the LOOP Event Tree

Branch	**Potential Inter-Module Dependency**		**Expected Level of Impact on Core Damage Frequency (CDF)**
	Systems	**Components**	
GRT	-	-	-
GPSRV	-	-	-
GPAFS	PAFS	ECT	High
	EPS	SY	Low
	EPS	ADG/SDG	Low
	HVAC	FAN	Low
GPSRV-OP	MCR	OPERATOR	High
GEPSREC-1/2	EPS	SY	High
	EPS	ADG/SDG	Low
GBYPASS-OP	MCR	OPERATOR	Low
GEDV	EPS	SY	Low
	EPS	ADG/SDG	Low
	HVAC	FAN	Low
GPCCS	PCCS	ECT	High
GERV-1/2	EPS	SY	Low
	EPS	ADG/SDG	Low
	HVAC	FAN	Low
GALT-OP	NRHRS	VV	Low
	NRHRS	HX	Low
	NRHRS	PP	High
	EPS	SY	High
	EPS	ADG/SDG	Low
	HVAC	FAN	Low
	CCWS	HX	Low
	CCWS	PP	Low
	SWS	PP	Low
	MCR	OPERATOR	High

Table 2 summarizes the systems and components with potential multi-module dependencies for each branch of the LOOP event tree and the expected level of their impact on CDF. The expected impact was qualitatively classified as High or Low based on the importance in the single-module PSA model and the anticipated strength of inter-module dependency.

For the GPAFS branch, inter-module dependency exists in the ECT of the PAFS, one of the three passive safety systems. Because these components also have high importance in the single-module model, their impact is expected to be high. The PAFS includes isolation valves, and the EPS and HVAC may affect the control system that generates actuation signals for these valves. However, because the isolation valves actuate early in the accident, incorporate a fail-safe design, and are powered by DC sources, the supporting systems are not expected to have a significant impact.

The FT for the GPSRV-OP branch consists solely of operator actions. Because a small number of operators operate all modules from an integrated MCR, failure of an operator action in one module is likely to increase the probability of failure of the corresponding actions in other modules. In addition, failure of this operator action prevents entry into Feed-and-Bleed operation, and therefore the action also has a significant impact in the single-module model.

The GEPSREC-1/2 branches are related to offsite power recovery. Because offsite power is shared by all modules, a strong inter-module dependency is expected. In addition, whether alternative coolant injection is available depends on the recovery of offsite power, and thus its impact is expected to be high. In contrast, the ADGs and SDGs are not expected to have a significant impact because the i-SMR electrical power system has multiple buses cross-tied between modules.

The GBYPASS-OP branch is also associated with the integrated MCR. However, because the corresponding operator action has a relatively small impact in the single-module model, its impact on the multi-module model is also expected to be low. The GEDV and GERV branches have characteristics similar to those described for the EPS and HVAC in the GPAFS branch, while the GPCCS branch is similar to the ECT dependency in the GPAFS branch.

For the GALT-OP branch, the expected level of impact differs among NRHRS components due to differences in the reliability of the associated basic events. Among the supporting systems for the NRHRS pumps, systems other than the SY of the EPS are expected to have a relatively low impact because they consist of multiple trains. In the event tree, GALT-OP is available only when GEPSREC-1/2 succeeds. Because GEPSREC-1/2 is strongly affected by the SY, the SY is also expected to have a significant impact on GALT-OP. Finally, because successful GALT-OP requires appropriate operator actions, the dependency associated with the integrated MCR is also expected to have a significant impact.

4. Conclusions

This study analyzed potential inter-module dependencies associated with LOOP to support the development of a multi-module PSA model for the i-SMR. The analysis identified shared components in the PAFS and PCCS, offsite power and the SY, and operator actions performed in the integrated MCR as major dependency factors. In particular, shared components and operator actions with high importance in the single-module PSA are expected to have relatively significant impacts in the multi-module model, whereas components with fail-safe characteristics and supporting systems configured with multiple trains are expected to have relatively limited impacts. Therefore, multi-module PSA should consider not only equipment sharing but also SSC reliability, importance in the single-module PSA, system configuration, and dependencies among operator actions. In future work, the dependencies identified in this study will be quantitatively incorporated into the FTs to construct a multi-module LOOP PSA model and evaluate their impacts on CDF.

ACKNOWLEDGMENTS

This work was supported by an Innovative Small Modular Reactor Development Agency grant funded by the Korean Government (MSIT) (No. RS-2023-00258118).

REFERENCES

[1] NuScale Power, LLC, Submittal of the NuScale Standard Design Approval Application Part 2 – Final Safety Analysis Report, Chapter 19: Probabilistic Risk Assessment and Severe Accident Evaluation, Revision 0, 2022.
[2] C. Morin, K. Gromek, A. Bounagui, “Licensing of New and Advanced Reactors in Canada: Application of the Canadian PSA Requirements and Lessons Learned from New Nuclear Reactor Development,” International Conference on Topical Issues in Nuclear Installation Safety: Learning from the Past to Accelerate the Future, Canadian Nuclear Safety Commission (CNSC), 2026.
[3] U.S. Nuclear Regulatory Commission, “Long Mott Energy, LLC – Long Mott Generating Station Xe-100 Power Reactor Application,” U.S. NRC, 2026.
[4] Innovative Small Modular Reactor Development Agency, i-SMR Official Website, https://www.ismr.or.kr/, 2026