

Development Status of At-power Level 1 MPAS models for the i-SMR

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1. Introduction

In Korea, the innovative small modular reactor (i-SMR) development agency plans to complete the standard design by the end of 2025 and it will undergo standard design approval (SDA) review for three years starting in 2026. The i-SMR has unique characteristics compared to existing large commercial nuclear power plants (NPPs). Therefore, new regulatory approaches, including those related to SDA, are required [1].

To support independent regulatory reviews for the i-SMR, the regulatory authority, the Nuclear Safety and Security Commission (NSSC), established the Regulatory Research Management Agency for SMRs (RMAS). The authors of this paper are currently carrying out activities related to risk assessment among a variety of RMAS's projects. The ultimate goal of these activities is to develop the methodology and database necessary for the safety review during the SDA. To achieve the goal, we develop a single-module Multi-purpose Probabilistic Analysis of Safety (MPAS) model that account for the design characteristics of SMRs. Additionally, we aim at constructing a MPAS model for multi-module by integrating single-module MPAS models [2].

In the first phase, we focused on investigating risk assessment cases, regulations, and standards for light-water SMRs from a regulatory perspective. Based on these investigations, a gap analysis of domestic safety review guidelines was conducted [3]. In the first year of the second phase, development of the MPAS model for the i-SMR began in earnest, aiming to construct a single-module MPAS model. The scope of this effort includes both at-power internal events Level 1 and Level 2 probabilistic safety assessment (PSA), as well as external events. This paper presents the current status of MPAS model development for the i-SMR.

2. MPAS model: Internal Events Level 1 PSA

Currently, obtaining an SDA per the Korean Nuclear Safety Act requires the submission of a preliminary accident management plan (PAMP), which includes an at-power Level 1 PSA for both internal and external events. To construct the MPAS model, initiating events necessary for the at-power internal events Level 1 PSA were identified based on the available design data. Event trees and fault trees were subsequently developed using

the publicly available information on safety systems. It should be noted that the i-SMR design is still under development, and therefore, the event trees and fault trees are subject to change as further analyses are conducted.

2.1. Identifying Initiating Events

To support event tree development, initiating events were identified based on failure modes and effects analysis (FMEA) of i-SMR design and the available PSA reports and documents of NuScale's US600/460, APR1400DC, and so on. US600/460 have similar characteristics with the i-SMR, such as being PWR-type SMRs, employing passive safety systems and steel containment vessel. Their design and PSA information is publicly available [4]. Therefore, they are used as a reference to identify initiating events for the i-SMR PSA. The other initiating events were also identified through a FMEA. The list of initiating events is shown on Table 1. The initiating event frequencies were evaluated based on the update of NUREG/CR-6928 (INL/EXT-21-65055) and the available data from NuScale [5].

2.2. MPAS Modeling Overview

Unlike large conventional NPPs, the i-SMR employs passive safety systems and steel containment vessel, which allow for a relatively simplified event tree and fault tree modeling approach in PSA. In addition, the contribution of power system failures to overall plant risk is significantly lower in the i-SMR compared to conventional large NPPs. For the fault tree modeling, generic reliability data provided by the U.S. NRC was used [5]. A list of the systems currently included in the at-power internal event Level 1 PSA MPAS model is provided below.

1. Passive Auxiliary Feedwater System
2. Electric Power System
3. Normal Residual Heat Removal System
4. Module Makeup and Purification System
5. Passive Emergency Core Cooling System
6. Reactor Safety System
7. Component Cooling Water System
8. Essential Service Water System

For the Module Makeup and Purification System (MMPS), additional thermal-hydraulic analyses will be conducted to evaluate its potential capability in providing reactor coolant inventory makeup during a loss of coolant accident (LOCA) or other transients accidents.

Table 1. The list of initiating events for internal events at-power Level 1 PSA

Category	Initiating Event Name
LOCA	MMPS CHG Line Break (in CV)
	MMPS CHG Line Break (out CV)
	MMPS LD Line Break (in CV)
	MMPS LD Line Break (out CV)
	ECCS Spurious Operation
	Steam Generator Tube Rupture
	RCS LOCA (in CV)
	Interfacing System LOCA
	LOCA-LODC
Transient	Large Secondary Side Break
	General Transient
	Loss of Main Feedwater
	Total Loss of CCW
	Loss of Offsite Power
	Loss of class N1E Direct Current (TBD)
	Loss of class N1E 4.16 kV (TBD)

3. MPAS model: External Events Level 1 PSA

The only external event currently under consideration is a seismic event, which is analyzed using the PSA-based seismic margin assessment (SMA) method. Since the specific site for deployment of the i-SMR has not yet been determined, performing a full scope seismic PSA that incorporates site-specific seismic hazard analysis is not feasible at this stage. The PSA-based SMA is a methodology used to evaluate whether the plant's seismic capacity exceeds the review level earthquake (RLE) [6]. The RLE is defined by applying a conservative multiplier of 1.67 to the safe shutdown earthquake (SSE). In this study, the SSE is assumed to be 0.3g.

3.1. Identifying SEL

Structures, systems, and components (SSCs) that are not classified as seismically qualified are assumed to be failed in the PSA-based SMA. In contrast, for SSCs that are seismically qualified, a fragility analysis is conducted, and the high confidence of low probability of failure (HCLPF) values are incorporated into the model as basic events prior to cutsets generation. Cutsets are then generated to determine the plant-level HCLPF.

Because seismic qualification data for the i-SMR SSCs have not been available, several assumptions were made to establish the seismic equipment list (SEL). For example, since many components of the electric power

system (EPS) are not considered seismically qualified in the i-SMR, it was assumed that those components from the offsite power to battery chargers are not seismically qualified and were therefore excluded from the SEL. All other SSCs were included in the SEL, and a PSA-based SMA was performed based on these assumptions. The SEL will be revised as seismic qualification data for the i-SMR SSCs becomes available.

3.2. SIET Modeling

To support the development of the seismic initiating event tree (SIET), an FMEA was conducted for each SSC identified in the SEL. The objective of the FMEA was to identify failure effect that could contribute to core damage in the event of an earthquake. Based on these results, SSCs with similar impacts were grouped together to serve as headings in the SIET.

The draft version of the SIET was developed based on the FMEA results and available documents such as the final safety analysis report (FSAR) of the NuScale US600 [4]. This draft will be updated and refined as the design data of the i-SMR becomes available. An illustration of the current draft SIET is presented in Fig. 1.

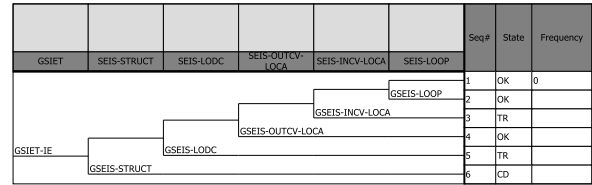


Fig. 1. SIET draft for the i-SMR PSA-based SMA.

4. Conclusions

For support of the safety review of SMRs, including the i-SMR which is expected to complete its standard design by the end of 2025 and undergo the SDA review beginning in 2026, the Korean regulatory authority has established RMAS as an independent regulatory research institute. RMAS is conducting studies on how to regulate the unique characteristics of the i-SMR compared to conventional NPPs. The authors are participating in regulatory research on risk assessment under RMAS. Phase 1 focused primarily on gap analysis, while Phase 2 is dedicated to the development of a comprehensive MPAS model (Level 1&2 PSA for internal & external events).

The at-power internal event Level 1 MPAS model draft for the i-SMR was developed based on available design data and generic reliability data provided by the U.S. NRC. A draft of at-power seismic events Level 1 PSA MPAS model is currently under development using a PSA-based SMA, with an SSE of 0.3g assumed. At present, HCLPF values are largely based on assumptions and will be refined as design data becomes available. In particular, seismic classification data for SSCs is essential for accurate identification of the SEL.

The at-power internal and external event Level 1 PSA MPAS model are currently undergoing minor revisions, while the development of the Level 2 PSA MPAS model is in progress. As noted earlier, certain uncertainties remain due to ongoing design changes, but the full suite of MPAS models will be continuously updated in accordance with the availability of detailed design data. In parallel, research is being conducted on methodologies for assessing the reliability of passive safety systems and evaluating multi-module risks, both of which are essential for the advancement of the MPAS model.

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