A Review of External Event Probabilistic Risk Assessment for NuScale SMRs

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1. Introduction

Nuclear power plants must ensure safety against various natural events, including natural hazards (e.g., earthquakes, fires, heavy rain, and typhoons) and intentional events (e.g., aircraft impact). As climate change increases the frequency and intensity of external events, it has become significantly important to demonstrate safety for beyond-design-basis external events.

Small modular reactors (SMRs) are being developed worldwide. In Korea, efforts to secure SMR technologies have progressed, including obtaining standard design approval for SMART and SMART100. However, because the construction sites have not yet been determined, comprehensive external event safety evaluations for SMRs remain limited, and related standards and guidance are still insufficient.

NuScale (U.S.) submitted a Final Safety Analysis Report (FSAR) for design certification that includes Probabilistic Risk Assessment (PRA) and severe accident evaluation results, and SMR-related requirements were incorporated into 10 CFR Part 52, Appendix G [1]. To support the development of a domestic SMR regulatory framework, it is necessary to refer to the U.S. SMR regulatory framework. Therefore, this study reviews the PRA methodology and results for external events described in Chapter 19 ("Probabilistic Risk Assessment and Severe Accident Evaluation") of the NuScale FSAR [2]. In addition, we discuss the applicability of existing domestic regulations and guidance for large nuclear power plants to innovative SMR (i-SMR) designs under development in Korea, considering differences in design characteristics.

2. External event probabilistic risk assessment analysis of NuScale

External event PRA of NuScale was conducted for earthquakes, floods, and high winds, and follows procedures and standards commonly used for large nuclear power plants including ASME/ANS RA-Sa-2009 [3] and DC/COL-ISG-020 [4].

2.1 Seismic PRA

Seismic risk assessment of NuScale was conducted using the PRA-based Seismic Margin Assessment (SMA). The scope of SMA included seismic fragility analysis of structures, systems, and components (SSCs) associated with a single module, along plant seismic response analysis. High Confidence of Low Probability of Failure (HCLPF) values were calculated for each SSC. As a result of the PRA, the HCLPF at the plant level was calculated to be 0.88g, which was confirmed to meet the DC/COL-ISG-020 standard of safe shutdown earthquake by more than 1.67 times. The dominant cutset was confirmed to be the collapse of the crane to a failure of the welded bridge seismic restraints of the reactor building crane, which could lead to core damage and large release. Additionally, because NuScale's passive safety features do not require operator intervention, operator actions had little effect on the conditional core damage probability, even under increased human error assumptions.

2.2 Flood and high wind PRA

Flood and high wind PRAs were performed using the methodology and procedures presented in ASME/ANS RA-Sa-2009. External events were assumed based on the frequency of external events described in the ASME standard, and in the case of high wind, they were classified into tornadoes and hurricanes and evaluated. The PRA results showed a core damage frequency (CDF) of 8.7E-10/yr for floods. For tornadoes and hurricanes, the CDF values were 9.9E-11/yr and 7.2E-10/yr, respectively, which are approximately 10,000 times lower than the typical target CDF (1.0E-06/yr) used for large nuclear power plants. The large release frequency (LRF) was also very low for both events, close to 1.0E-15/yr. The dominant cutset was emergency core cooling system (ECCS) malfunctioned caused by the loss of off-site power, which could interrupt the coolant recirculation path between the reactor pressure vessel and the containment vessel, leading to core damage and large release. Even under conservative assumptions, the overall risk remained very low, reflecting the passive safety design characteristics of NuScale.

2.3 Multi-modules PRA

The analyses above were performed for a single module. Because SMRs consist of multi-modules, external events that could affect multi-modules simultaneously (e.g., earthquakes) require additional evaluation. In NuScale, CDF and LRF for multi-module were calculated by applying multi-module adjustment factors and multi-module performance shaping factors to the single module PRA results, without changing the base PRA procedure. For seismic events, simultaneous failure of multiple crane bridge seismic restraints was assessed as very unlikely. Flooding could affect all modules; however, the passive safety design does not require additional operator actions or power for safe shutdown, and no combined effects that could challenge multi-modules safe shutdown were identified. High winds could trigger safe shutdown requirements in several modules, but damage of one module was not expected to affect others because passive safety functions were designed to operate independently.

2.4 Implications for applying external event PRA to SMR

Based on the NuScale report, many established PRA methods and guidance for large nuclear power plants can be applied to SMRs. However, SMR-specific design characteristics, such as underground buried structures, fully passive safety systems, and multi-modules configurations, may require modifications or additional considerations in some evaluation elements. For example, for SMR design with an underground buried structure, flood hazard zones should explicitly include below-grade compartments. For high winds, missile impact loads may be reduced depending on shielding and structural configuration. Even for fully passive safety designs, passive operation is time-limited (e.g., SMART100 is designed for 72 hours), and post-accident operator actions must be feasible under beyond-design-basis external event conditions. Therefore, a PRA methodology tailored to SMRs should be developed by refining existing procedures and defining SMR-specific requirements and exclusions.

3. Conclusions

This study reviewed the external event PRA methodology and results presented in the NuScale FSAR to support the development of a regulatory basis for domestic SMR safety assessment under beyond-design-basis external events. NuScale’s PRA results for earthquakes, floods, and high winds indicate very low risk values even under conservative assumptions (Table 1), largely caused by passive safety design features. The passive safety design has also been shown to reduce the potential for multi-modules interactions in which a failure in one moule could affect others. Although SMRs may have different accident scenarios caused by their unique design characteristics, the overall PRA framework remains broadly consistent with that used for large nuclear power plants. For i-SMR designs under development in Korea that also adopt fully passive safety design, it is important to apply established PRA methods while additionally considering SMR-specific and new accident scenarios.

Table 1: Summary of external event PRA results

<table>
<tr><th>Event</th><th>CDF</th><th>LRF</th><th>Cutset</th></tr>
<tr><td>Seismic</td><td colspan="2">HCLPF 0.88 g</td><td>Failure of the welded bridge seismic restraints of the reactor building crane</td></tr>
<tr><td>Flood</td><td>8.7E-10/yr</td><td>7.9E-14/yr</td><td rowspan="3">(CDF) ECCS incomplete operation
(LRF) ECCS incomplete operation and containment failure</td></tr>
<tr><td>High wind (Tornado)</td><td>9.9E-11/yr</td><td>Less than 1.0E-15/yr</td></tr>
<tr><td>High wind (Hurricane)</td><td>7.2E-10/yr</td><td>6.4E-14/yr</td></tr>
</table>

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