Review of the NuScale Design Certification: RIPB Approach to GDC 27 and Implications for i-SMR Development

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1. Introduction

Small Modular Reactors (SMRs) have emerged as a next-generation nuclear energy option to address the climate crisis and pursue carbon neutrality. Compared with large Pressurized Water Reactors (PWRs), SMRs require a much smaller site footprint and allow reduced emergency planning zones, enabling wider deployment in diverse locations. Their modular design supports mass production and cost reduction, while simplified, integral configurations eliminate large external piping, thereby lowering the likelihood of severe accidents and enhancing inherent safety [1]. In addition, SMRs offer shorter construction schedules, improved safety through passive systems, and multipurpose applications such as hydrogen production and district heating, underscoring their role as a strategic alternative in future energy transition strategies. However, the current regulatory framework remains grounded in the General Design Criteria (GDC), originally developed for large PWRs, and thus faces limitations when directly applied to SMR designs with fundamentally different structures and safety philosophies.

The NuScale Power Module (approximately 77 MWe per module, six-module US460 plant) exemplifies these regulatory challenges. NuScale employs an integral pressure vessel, natural-circulation cooling, and passive safety systems, embodying a safety philosophy distinct from that of conventional large reactors. This design posed multiple conflicts with existing GDC requirements. Nevertheless, NuScale demonstrated that it could achieve equal or higher levels of safety by applying a Risk-Informed, Performance-Based (RIPB) regulatory approach that integrates Probabilistic Risk Assessment (PRA), Defense-in-Depth (DID), and Frequency–Consequence (F–C) curve analysis. The U.S. Nuclear Regulatory Commission (NRC) reviewed these methods, accepted NuScale's Principal Design Criteria (PDC), and ultimately granted the first-ever SMR design certification in 2020 (for an earlier design iteration).

Accordingly, this study analyzes the NuScale design certification as a case study to examine the limitations of applying GDC to SMRs and to evaluate how RIPB principles were applied to overcome these challenges. In particular, since Korea is currently developing the i-SMR with the goal of obtaining standard design approval by 2026, the NuScale case provides valuable insights for establishing a regulatory framework that can support safe and internationally credible deployment of domestic SMRs.

2. Case study: General Design Criterion (GDC) 27

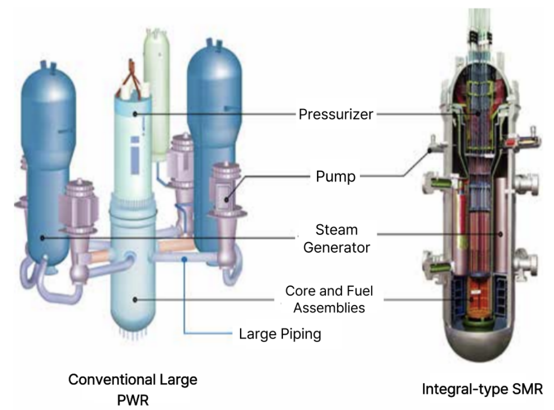

Fig. 1. Comparison of a conventional large PWR and an integral-type SMR (adapted from [2]).

SMRs have fundamental structural differences from conventional large PWRs, which limit the direct applicability of existing regulatory criteria. Fig. 1 illustrates the major design differences between large PWRs and the NuScale SMR, and these structural features directly affect the interpretation of safety requirements. This study selected GDC 27 as a representative case to highlight the regulatory inconsistency between the existing GDC framework and the design characteristics of SMRs. GDC 27 addresses reactivity control and long-term safe shutdown, making it a critical example for examining how prescriptive, PWR-based criteria may conflict with SMR-specific design philosophies.

2.1 GDC 27

GDC 27 requires reliable reactivity control to bring the reactor to a safe shutdown state following postulated accidents. Traditionally, this requirement has been interpreted as necessitating soluble boron injection. However, NuScale demonstrated that long-term reactivity control and safe shutdown can be achieved without soluble boron, relying instead on control rods and inherent passive features. The NRC accepted this approach as meeting the safety intent of GDC 27.

2.2 NuScale's PDC 27

Table I: Comparison of GDC 27, NuScale's PDC 27, and NRC's acceptance basis (adapted from [3]).

Category	GDC27	NuScale's PDC27	NRC's Acceptance Basis
Safety Objective	Maintain core in a safe, stable, subcritical condition during accidents	Ensure fuel integrity (SAFDLs) and passive cooling capability instead of long-term subcriticality	Recognized as meeting the same safety objective
Design Assumptions	Based on large PWR assumptions: control rod insertion, pressurizer, active pumps, and external power supply	No reliance on external power or pumps; passive safety systems with natural circulation	Consistent with integral, passive design features
Evaluation Criteria	Method-based compliance (e.g., coolant injection, power recovery, operator actions)	Performance-based verification: (1) Adequate thermal margin, (2) Very low probability of recriticality, (3) No increase in public risk under multi-module operation	Validated by PRA results and thermal-hydraulic safety analyses
Regulatory Approach	Compliance with prescriptive procedures	Verification of safety objective achievement	Acceptance of RIPB, results-oriented regulatory framework

To address these limitations, NuScale proposed PDC 27. While maintaining the fundamental objective of GDC 27—reactivity control—PDC 27 replaced the long-term subcriticality requirement with alternative criteria focused on ensuring fuel integrity (SAFDLs: Specified Acceptable Fuel Design Limits) and verifying passive cooling capability. In other words, rather than placing absolute emphasis on eliminating any possibility of recriticality, PDC 27 adopts a results-oriented standard by demonstrating safety through evidence of fuel integrity and passive heat removal performance. In its FSER, the NRC confirmed that NuScale's PDC 27 satisfied its safety objectives based on three evaluation criteria: (1) adequate thermal margin, (2) a very low probability of recriticality over the module's lifetime, and (3) no increase in public risk during multi-module operation [3].

3. RIPB licensing

The RIPB regulatory approach integrates probabilistic methods with traditional deterministic reviews to quantitatively evaluate event frequencies and consequences, and to demonstrate the achievement of safety objectives on an evidence-based, results-oriented basis. NuScale adopted this approach by applying LBEs, PRA, F–C curve analyses, and DID evaluations to address the limitations of prescriptive GDC requirements [4].

NuScale established explicit performance-based safety objectives. Representative examples include: (1) maintaining passive cooling for 30 days without external makeup water, (2) ensuring at least 72 hours of subcriticality and passive cooling following a design-basis event, (3) securing a minimum 5% thermal margin during normal operation and AOOs, (4) maintaining a core damage frequency (CDF) of less than 1E-7 per module-year, and (5) limiting the conditional containment failure probability to 0.1 [3][4].

Furthermore, NuScale experimentally and analytically verified that the DHRS can sustain passive core cooling for more than 72 hours following an accident. Figure 2 illustrates DHRS performance, showing that core temperature rapidly decreases after the event and stabilizes at approximately 150 °C.

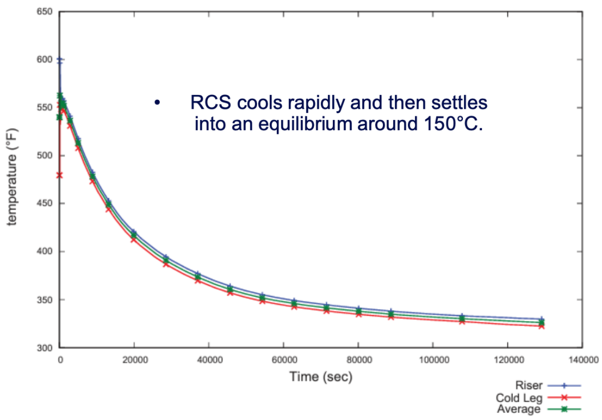

Fig. 2. NuScale DHRS performance: RCS cooling and stabilization near 150 °C [4].

3.1 LBEs

As the first step of the RIPB approach, NuScale established LBEs. LBEs are categorized into AOOs, DBEs, and BDBEs, with each event classified by its frequency and consequence. This framework enables systematic consideration of SMR-specific design features and risk scenarios that are not fully captured by the traditional GDC framework.

The Design Reliability Assurance Program (D-RAP) expert panel identified key LBEs including LOCA, LOOP, SGTR, dropped module, and FHA. These events were integrated with PRA and subsequently plotted on the F–C curve. Most events fell within NRC acceptance criteria. In particular, events within the frequency range of 10^{-6} to 10^{-3} per year demonstrated sufficient safety margins, indicating that additional DID measures were unnecessary [4].

3.2 PRA and the F–C Curve

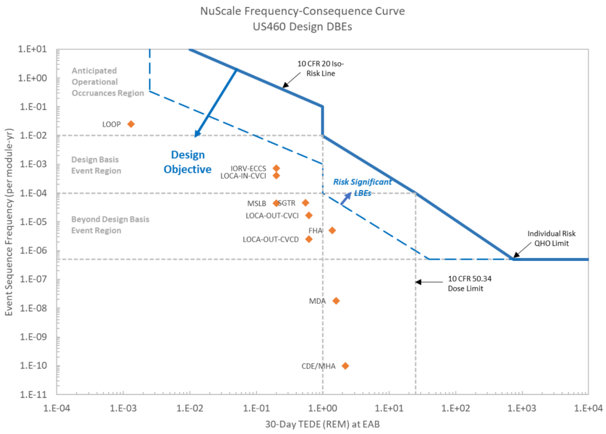

Fig. 3. F–C curve analysis of NuScale LBEs compared with NRC regulatory limits [4].

As part of the RIPB approach, NuScale conducted PRA-based F–C curve analyses, with results presented in Figure 3. All identified LBEs remained below NRC regulatory limits, including the Quantitative Health Objectives (QHO) and the 10 CFR 50.34 dose criteria. Notably, events within the frequency range of 10^{-6} to 10^{-3} per year demonstrated adequate safety margins, showing that no additional DID measures were required.

The D-RAP expert panel further concluded that no additional programmatic or plant-capability DID was necessary for events such as LOOP and CDE/MHA, given their extremely low probabilities and the high reliability of passive safety-related SSCs. Moreover, no risk-significant LBEs were identified, and no systems were classified as risk-significant solely due to DID considerations, since multiple layers of redundancy were deemed sufficient.

These findings confirm that the NuScale design simultaneously satisfies both low accident frequencies and limited radiological consequences. More importantly, this case illustrates a regulatory paradigm shift—from prescriptive, procedure-oriented compliance toward results-oriented, risk-informed evaluation of actual safety performance. In this sense, NuScale effectively demonstrated that RIPB methods, supported by PRA and the F–C curve, can overcome the limitations of traditional GDC requirements while ensuring the achievement of fundamental safety objectives (Fig. 3).

3.3 DID and Passive Safety

NuScale applied the principle of DID to ensure multiple layers of safety barriers and to avoid reliance on any single function [4]. Unlike large PWRs, which depend on more than 20 active safety systems and operator interventions, NuScale achieves the same safety objectives with fewer than 10 safety-related systems, all of which are passively operated.

As summarized in Table II, NuScale demonstrates distinct advantages in DID implementation. During Design-Basis Events (DBEs), no operator action is required to prevent core uncovering. For severe accident management, the Core Damage Frequency (CDF) is reduced to below 10^{-7} per reactor-year, with radiological releases limited to small and delayed discharges. This level of inherent safety allows the Emergency Planning Zone (EPZ) to be reduced to the site boundary, representing a significant departure from conventional large PWR requirements.

Table II: Comparison of DID implementation between conventional LWRs and the NuScale SMR [4].

DID Level	Conventional Light Water Reactor (LWR)	NuScale SMR
1. Prevent abnormal operation and failures	~20 active safety-related systems, power-dependent	<10 safety systems, simplified design, passive safety
2. Control of abnormal operation and detection of failures	Manual operator action, multiple active systems	Automated monitoring, passive protection
3. Control of accidents within the design basis	Operator reliance; several DBEs may cause core damage	No operator action; no DBEs lead to core uncover*
4. Control of severe accident conditions	Many active systems, CDF $\sim 1\times10^{-5}$	Passive systems, CDF $<1\times10^{-7}$, extra fission barriers
5. Mitigation of consequences of significant radiological releases	Large early release, EPZ ~10 miles	Small delayed release, EPZ ≈ site boundary

(*IAEA DID improvement recommendation, INSAG-12, *Basic Safety Principles for Nuclear Power Plants*)

4. Conclusion

The i-SMR, jointly developed by Korea Hydro & Nuclear Power (KHNP) and the Korea Atomic Energy Research Institute (KAERI), is an integral pressurized water reactor currently under development with the goal of obtaining Standard Design Approval (SDA) by 2028. A preliminary design report was submitted to the Nuclear

Safety and Security Commission in 2023, and the SDA review is scheduled to commence in 2026. The 11th Basic Plan for Electricity Supply and Demand also includes a plan to construct a 700 MWe demonstration plant by 2036. To support this initiative, both the government and KHNP have committed significant funding for research, development, and demonstration. In parallel, the "SMR Alliance," launched in 2023, has expanded domestic supply chain capabilities, while international cooperation with countries such as Indonesia and Norway is being actively pursued. These efforts highlight i-SMR as one of the few SMR projects worldwide with a concrete commercialization and export strategy [6].

The NuScale case provides an important reference point for i-SMR development. Although NuScale's design introduced features that conflicted with the prescriptive requirements of GDC 27, it demonstrated compliance with the underlying safety objectives through a Risk-Informed, Performance-Based (RIPB) approach that integrated Probabilistic Risk Assessment (PRA), Defense-in-Depth (DID), and Frequency–Consequence (F–C) analyses. By relying on passive safety systems to maintain core cooling and fuel integrity under accident conditions, NuScale ensured long-term subcriticality and safe shutdown. This outcome confirmed that NuScale could meet the fundamental intent of GDC 27 while departing from traditional prescriptive methods, thereby setting a regulatory precedent for SMRs.

Similarly, the i-SMR incorporates design simplification and innovative concepts, including boron-free core operation, the declassification of power systems from safety-related status, and the removal of the Diverse Protection System (DPS) as a design consideration. While DPS has traditionally provided redundancy for reactor shutdown in large PWRs, the i-SMR aims to achieve equivalent functionality through streamlined systems informed by international precedents. Consequently, i-SMR will need to employ probabilistic safety assessments and code-based analyses to substantiate the safety of these design innovations, while also engaging proactively with regulators to establish their acceptability within the licensing framework [7].

Ultimately, the NuScale experience illustrates that the RIPB approach is not only a means of addressing specific licensing challenges but also an effective mechanism for achieving regulatory recognition of innovative SMR designs on an international scale. The findings presented in this study are intended to inform the licensing discussions of i-SMR, supporting the justification of its novel design concepts within regulatory processes and contributing to both the successful achievement of SDA and the enhancement of its competitiveness in the global SMR market.

Acknowledgement

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