# Supporting Risk Assessment Reviews for Innovative SMR in Korea

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## ABSTRACT

In Korea, the innovative small modular reactor development agency plans to complete the standard design by the end of 2025 and undergo standard design approval review for three years starting in 2026. Accordingly, the Nuclear Safety and Security Commission, the regulatory authority, has established the Regulatory Research Management Agency for SMR in accordance with Article 12 of the Nuclear Safety Act. The authors are currently carrying out tasks related to risk assessment among the detailed tasks of Regulatory Research Management Agency for SMR. This paper provides an overview of the project, which consists of a one-year Phase 1 and a two-year Phase 2 starting in 2024, including its key objectives, major achievements, and future plans. The two primary goals of Phase 1 are: (1) investigating international and domestic cases, regulations, and technical standards related to risk assessment for light water SMRs (both single and multi-module designs), and (2) developing the Multi-purpose Probabilistic Analysis of Safety model for independent risk assessment review of a single-module design. A gap analysis was conducted to identify necessary revisions for the existing safety review guidelines. In the development of the Multi-purpose Probabilistic Analysis of Safety, we established a foundation for the reliability analysis of a single-module by performing general probabilistic safety assessment procedures, including initiating event analysis and system analysis. In Phase 2, we will address technical challenges specific to innovative small modular reactor, such as multi-module risk quantification, passive safety systems, boric acid-free operation, and human reliability analysis. Addressing these issues will require international collaboration.

Keywords: Risk Assessment, PSA, Multi-Modules, Safety Goal, MPAS

## I. Introduction

In Korea, the innovative small modular reactor (i-SMR) development agency plans to complete the standard design by 2025 and undergo standard design approval (SDA) review for three years starting in 2026. One of the top-tier requirements (TTRs) for i-SMR is that the core damage frequency (CDF) should be less than $1.0E-9\ /module \cdot year$ [1]. As shown in Table I, to achieve the TTR, i-SMR has unique characteristics compared to existing nuclear power plants (NPPs). Therefore, new regulatory approaches, including those related to SDA, are required.

To support independent regulatory reviews of the i-SMR, the Nuclear Safety and Security Commission (NSSC), the regulatory authority, established the Regulatory Research Management Agency for SMR (RMAS). The authors are currently carrying out tasks related to risk assessment among the detailed tasks of RMAS. The ultimate goal of these tasks is to develop the methodology and database necessary for the safety review process during the SDA. To achieve this, we plan to analyze, refine, and develop methodologies that account for the unique design characteristics of SMRs in single-module probabilistic safety assessment (PSA). Additionally, we aim to construct a Multi-purpose Probabilistic Analysis of Safety (MPAS) model for multi-module PSA by integrating single-module PSA models [2].

The two primary objectives of Phase 1 (2024) are: (1) investigating international and domestic cases, regulations, and technical standards related to risk assessment for light water SMRs (both single and multi-module designs), and (2) developing a draft MPAS model for independent risk assessment review of a single-module design. The two primary objectives of Phase 2 (2025–2026) are: (1) improvement of the draft MPAS model developed in Phase 1 and its expansion to a multi-module configuration, and (2) proposing regulatory applications such as a review methodology, structure, system and components (SSCs) classification, safety goals multi-module for llight water SMR. Figure 1 provides an illustration of the step-by-step objectives. This paper provides an overview of the project spanning Phase 1 (2024) and Phase 2 (2025–2026), including its key objectives, major achievements, and future plans.

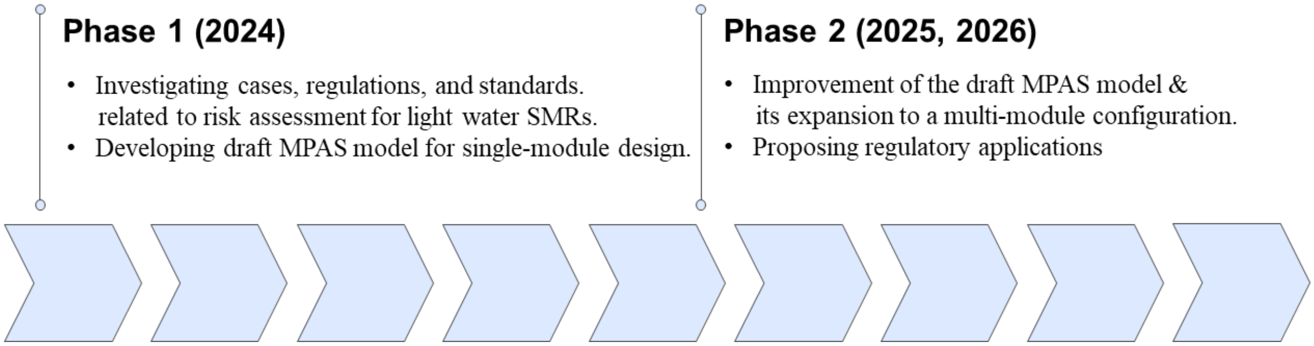


**FIGURE 1. The objectives of each phase**

**TABLE I. The differences between existing NPPs and i-SMR**

| Existing NPPs | i-SMR |
|---|---|
| ● Active safety system, safety class power system | ● Passive safety system, non-safety class power system |
| ● One unit operation in one control room | ● Multi(4)-module operation in one control room |
| ● I&C characteristics of reactor vessel and containment | ● Changes in I&C characteristics due to steel containment vessel, integral reactor, helical steam generator, boric acid-free operation, etc. |
| ● Unit concept | ● Module concept |
| ● Minimization of shared facilities between reactors | ● Expansion of shared facilities among modules. |

**II. Review of current status**

**II.A. SMART100**

In Korea, SMART100 is a reactor that enhances safety through the application of a passive safety system and improves economic efficiency by increasing its output to 365 MWt (110 MWe) from SMART, which was licensed in 2012. This reactor is equipped with passive safety systems and physical barriers, enabling it to remain safe for 72 hours without operator intervention, relying solely on batteries and natural forces in scenarios such as the Fukushima accident.

SMART100 has four passive safety systems: the passive safety injection system, the automatic depressurization system, the containment pressure and radioactivity suppression system, and the passive residual heat removal system. The phenomenological reliability of these systems was evaluated as 1.0, as their probability of failure is negligibly low [3].

**II.B. NuScale US600**

In the United States, NuScale is a reactor that enhances safety through its passive safety systems while offering scalability with a modular design. Each module generates 160 MWt (50 MWe) and can be deployed in plants with up to 12 modules. The reactor's passive safety system is designed to ensure safety without operator intervention or external power, leveraging natural phenomena such as gravity and convection.

It is an integral light water reactor, with the reactor coolant system (RCS) housed inside the reactor vessel, eliminating the need for coolant or safety pumps. The containment vessel (CV) is submerged in a pool, ensuring safety through natural circulation and passive safety mechanisms. The emergency core cooling system (ECCS) and the decay heat removal system (DHRS) were designed as passive safety systems, and their phenomenological reliability was evaluated using a response surface methodology.

NuScale also conducted a PSA for multi-modules, although this was not a mandatory requirement for design certification (DC). In assessing multi-module risk, the risk was estimated by assuming that the same accident occurred in two or more modules, rather than directly modeling the cascading effects of an accident in a specific module. This approach was realized on applying the multi-module adjustment factor (MMAF) and the multi-module performance shaping factor (MMPSF) to the minimal cut-set derived from the single-module risk model [4]. A more detailed distinction between SMART100 and US600 is outlined in Table II.

**TABLE II. The technical differences between the SMART100 and US600 [3, 4]**

| | SMART100 | US600 |
|---|---|---|
| Thermal Power | 365MWth | 160MWth |
| Electric Power | 110MWe | 50MWe |
| Safety System | Passive | Passive |
| Primary Loop Circulation Type | Forced circulation | Natural circulation |
| CDF | <1.0E-7/RY | <1.0E-8/RY |
| Internal control rod drive mechanism | X | O (Electromagnetic) |
| Reliability of Passive System | 1.0 | T-H analysis |
| Operator Response Time | 72 hour | 72 hour |
| Containment | Building | Vessel |
| Multi-module PSA | X | O |

## III. Development of MPAS Models for i-SMR

### III.A. Initiating event identification

The initiating events analysis is one of the key steps in PSA; however, it poses a challenge for newly designed reactors due to the lack of operating experience and design-specific data. The i-SMR falls into this category; therefore, initiating events were identified based on publicly available data and PSA expertise.

The identification process involved:

1. Identifying plant transients that trigger manual or automatic reactor shutdown during normal operation.
2. Defining and categorizing all possible initiating events during plant operation.
3. Grouping similar initiating events based on the required safety functions or plant responses for accident mitigation.

The analysis methodology was developed using operational experience from commercial and similar NPPs, as well as engineering judgment. The initial draft consists of two categories and 15 initiators, as presented in Table III. The list of initiating events will be updated in Phase 2. The frequency of initiating events will be estimated in future work, reflecting the design characteristics of the i-SMR.

**TABLE III. The initial draft list of initiating events for internal events at-power Level 1 PSA**

| Category | Grouped initiators |
|---|---|
| Loss of Coolant Accident (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 (EDV) |
| | ECCS Spurious Operation (ERV) |
| | Steam Generator Tube Rupture |
| | RCS LOCA (in CV) |
| | Interfacing System LOCA |
| | LOCA-LODC |
| Transient | Large Secondary Side Break |
| | General Transient |
| | Loss of Main Feedwater |
| | Loss of Condenser Vacuum |
| | Loss of Offsite Power |

### III.B. System analysis

The key safety functions of the i-SMR consist of (1) reactor trip, (2) residual heat removal, and (3) containment of radioactive materials, similar to those of general NPPs. One notable difference is that the residual heat removal comprises the passive emergency core cooling system (PECCS), the passive containment cooling system (PCCS), and the passive auxiliary feedwater system (PAFS), all of which are passive safety systems operating through natural forces.

For instance, PECCS functions similarly to the "Feed & Bleed" system in conventional large NPPs. This passive system utilizes natural circulation and consists of an emergency depressurization valve (EDV), which releases steam from the top of the reactor vessel to depressurize the primary loop, and an emergency recirculation valve (ERV), which returns the condensed steam to the primary side.

The heading of the event tree (ET) in Level 1 PSA generally includes reactor trip, PECCS, PCCS, PAFS, the pilot-operated safety relief valve (POSRV), and the modular makeup and purification system (MMPS). The POSRV is mounted on top of the reactor vessel for primary side depressurization, and the MMPS replenishes the reactor coolant inventory independently of the PECCS. An example of an ET for a general transient (GTRN) is presented in Figure 2.

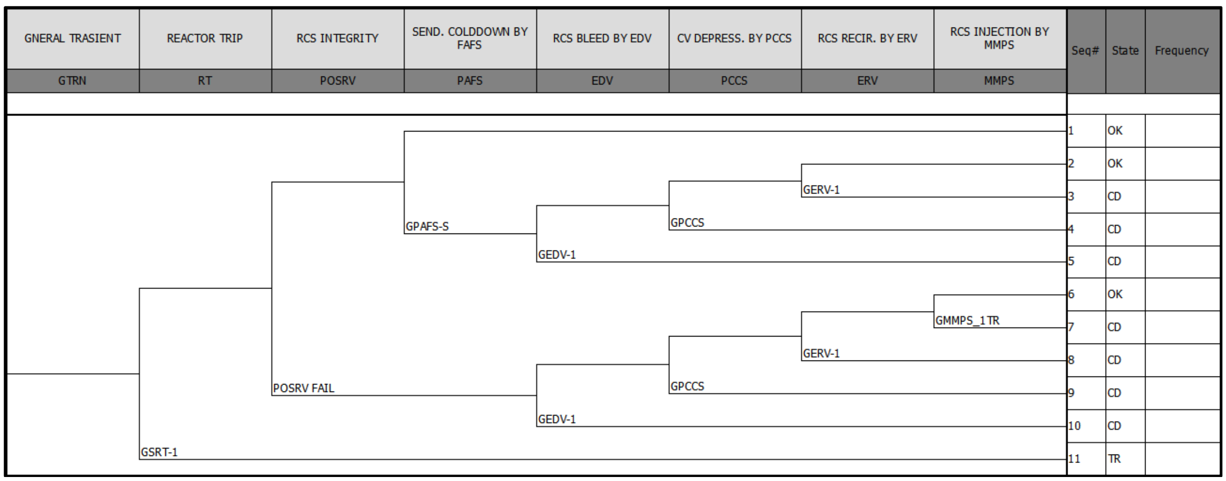


**FIGURE 2. GTRN ET example**

To develop fault trees (FTs), the simplified Piping and Instrumentation Diagram (P&ID) was initially developed using publicly available data, excluding support systems such as the primary component cooling water system (CCWS). This will be continuously updated as the applicant's design evolves. Figure 3 presents the P&ID of the PECCS, illustrating that two EDVs are positioned at the top of the reactor vessel, while two ERVs are located at the bottom. In Figure 4, valve failures and valve actuation signal failures are expected to be considered as basic events in the FT of PECCS based on the P&ID. FTs for other systems were also developed through a similar process.

### III.C. Accident sequence analysis

Accident sequence analysis will be conducted using MARS-KS or MELCOR, and a model is currently under development. Since multi-module operation and load-following operation may be challenging to analyze with MARS-KS or MELCOR, Flownex was chosen as an alternative for such analyses. Flownex is a computational tool that efficiently models complex thermal-fluid networks and performs simulations. It is capable of power plant physical analysis, including thermal-fluid analysis, instrumentation and control (I&C) modeling, application programming interface (API) integration, heat transfer analysis, and transient analysis [5]. Figure 5 presents a single-module model that is currently under development using Flownex.

### IV. Conclusions

One of the key significances of the MPAS model is its ability to independently verify the applicant's PSA model. From a regulatory perspective, the MPAS model facilitates the following tasks:

1. Verifying whether the applicant's design meets quantitative requirements (e.g., CDF).
2. Validating the authenticity of the top (major) cut-set presented by the applicant.
3. Reviewing the applicant's assessments (e.g., SSCs classification) based on PSA results (risk information).

The MPAS model is not yet fully developed because the i-SMR design is still in progress, the applicant's design is subject to frequent changes, and much of the design data remains unavailable. The model will be continuously updated to best reflect the progress of the applicant's design.

An uncertainty analysis will be conducted by applying reliability data (e.g., the latest NUREG/CR-6928) to the MPAS model at appropriate stages. In addition, uncertainties related to the phenomenological failure assessment of passive systems and the failure probability assessment of EDVs (or ERVs) will be analyzed by developing or applying appropriate methodologies. At present, we are focusing on gaining insights from multi-module PSA and aim to refine the classification of structures, systems, and components (SSCs) by incorporating results from both single- and multi-module PSA.

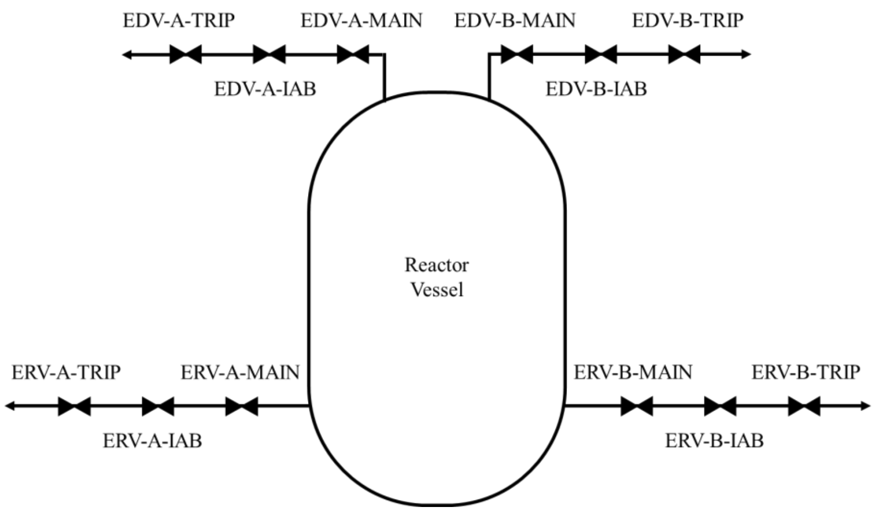


**FIGURE 3. Simplified P&ID of PECCS (draft)**

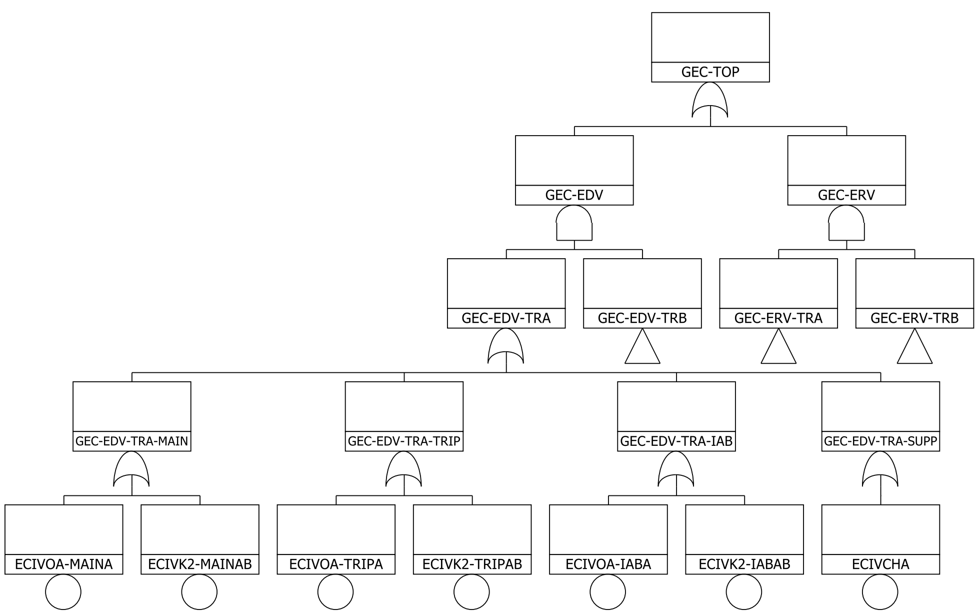


**FIGURE 4. FT of PECCS (draft) [6]**

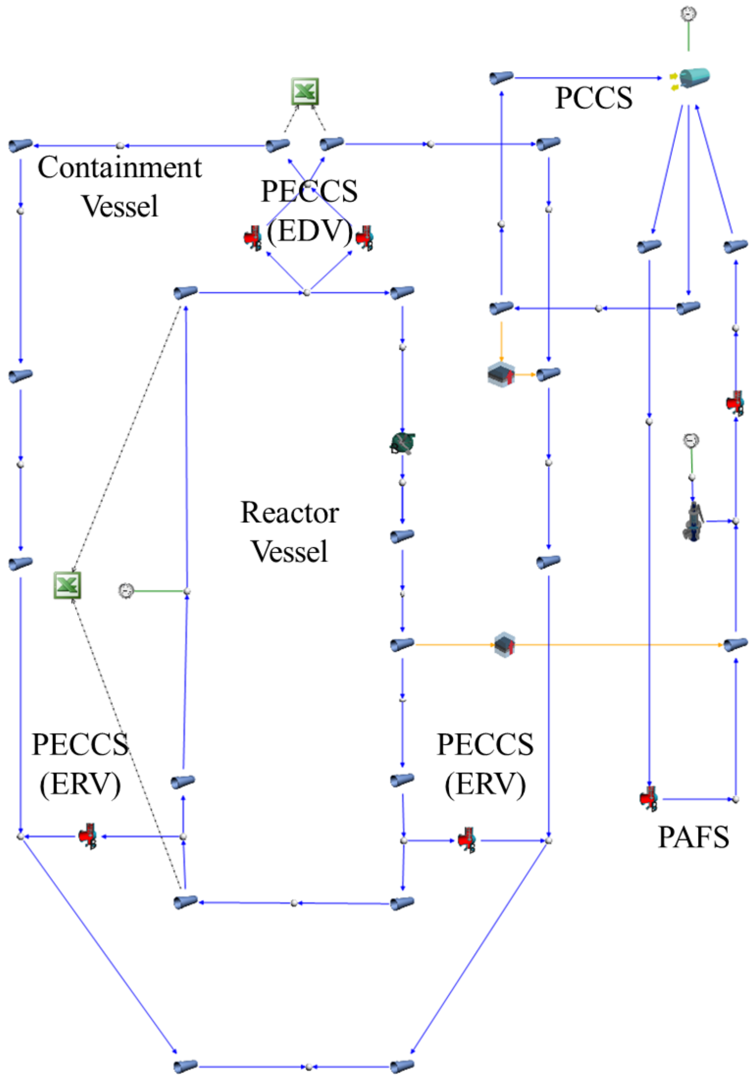


**FIGURE 5. Simplified Flownex model**

## ACKNOWLEDGMENTS

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