Technical Status of EPZ Evaluation for SMRs in Korea

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ABSTRACT

Global interest in small modular reactors (SMRs) is rapidly increasing, and South Korea is developing an innovative SMR (i-SMR). Based on pressurized water reactor technology, the i-SMR offers various advantages in terms of safety, economic viability, resilience, and flexibility. The establishment of an emergency planning zone (EPZ) is mandatory for the construction and operation of innovative SMRs. Current domestic regulations require adherence to the basic area of EPZ structure comprising the precautionary action zone (PAZ) and urgent protective action planning zone (UPZ), which was established based on existing large light water reactors. This indicates that existing regulatory requirements do not correspond to the power capacity and safety characteristics of SMRs, making it impossible to apply appropriate regulations.

In the United States, 10 CFR 50.160 (Emergency preparedness for SMRs, non-LWRs, and non-power production or utilization facilities) was newly established for SMRs and other nuclear facilities. This regulation provides graded approach that considers the characteristics of individual next-generation nuclear technologies. Additionally, RG 1.242 (Performance-based emergency preparedness for SMRs, non-LWRs, and non-power production or utilization facilities) was published to provide detailed guidance on emergency planning requirements, including methodologies for evaluating emergency planning zones that licensees can follow.

This study organized the background necessary to understand this situation, analyzed the gaps with existing domestic regulatory standards, and proposed solutions. For this purpose, the study summarized the power capacity and safety characteristics of i-SMR and analyzed the inadequacies and limitations of applying the existing regulatory framework to i-SMR. This study also reviewed existing SMR EPZ assessment methodologies and proposed a draft EPZ assessment method for i-SMR based on the U.S. RG 1.242 approach. It further covered the development of the Radiological Consequence Analysis Program - Emergency Planning Zone (RCAP-EPZ) for evaluating EPZs. This study avoided specifying detailed criteria such as frequency criteria for accident scenario selection or dose criteria for EPZ evaluation, instead describing general methodologies.

It is expected that this study will aid in understanding the current situation and global technological level, and provide insights to bridge regulatory and technical gaps in establishing EPZs for SMRs, both domestically and internationally.

Keywords: *Emergency Planning Zone, Small Modular Reactor, Offsite Consequence Analysis, Dose Assessment, Probabilistic Safety Assessment*

1 INTRODUCTION

Small modular reactor (SMR) is generally a modular reactor with an output of 300 MWe or less. Based on electric power, it can be categorized as a small and medium-sized reactor (10 MWe–300 MWe) or a micro reactor (10 MWe or less). SMRs enable reduced manufacturing costs and shorter construction periods through integrated design of major components and factory-built modules, and their modular nature allows electric power to be adjusted according to demand.

The Innovative SMR (i-SMR), an SMR currently under development by Korea Hydro & Nuclear Power, is based on pressurized water reactor (PWR) technology and offers the following advantages compared to conventional large-scale nuclear power plants (NPPs):

- Safety: The passive safety system (natural circulation cooling) dramatically reduces the likelihood of severe accidents, while the simplified, integrated design minimizes the risk of accidents such as pipe ruptures;
- Economic viability: Mass production of standardized modules, combined with factory fabrication and on-site installation, reduces manufacturing costs and shortens construction time;
- Resilience: Capable of serving as a distributed power source to compensate for the intermittency of renewable energy and of load-following operation;
- Flexibility: Can be used for multiple purposes, such as seawater desalination, hydrogen production, district heating, and ship propulsion, near consumption sites in addition to power generation.

Compared to core damage accident sequences in large-scale NPPs, the accident sequence of an i-SMR allows for core cooling without power restoration or the supply of cooling water, enabled by the operation of passive safety systems such as the passive auxiliary feedwater system (PAFS) and the passive emergency core cooling system (PECCS). This allows for core cooling without the need to restore power or secure cooling water. This slow accident progression provides sufficient time to respond to core damage. In terms of design and accident progression, i-SMR offers the following enhanced safety characteristics regarding the establishment of radiation emergency planning zones:

- Low accident frequency;
- Low release of radioactive material;
- Slow accident progression and the resulting flexibility in response.

Article 2 (Definitions) (1) of Act on Physical Protection and Radiological Emergency [1] classifies and defines radiation emergency planning zones (EPZ) as precautionary action zones (PAZ) and urgent protective action planning zones (UPZ) as follows:

- Precautionary action zones: Zones determined as requiring the implementation of preventive measures, such as evacuation of residents, to protect residents in cases of any radiological emergency that occurs in nuclear facilities;
- Urgent protective action planning zones: Zones determined as requiring urgent measures to protect residents, such as sheltering and evacuation, based on the results of radiological impact assessment or environmental monitoring, in cases of any radiological emergency or radioactive disaster that occurs in nuclear facilities.

Under Article 20-2 (Establishment of radiological emergency planning zones) of Act on Physical Protection and Radiological Emergency, the Nuclear Safety and Security Commission shall determine and announce an area that serves as a base for establishment of a radiological emergency planning zone by nuclear facilities (hereinafter referred to as "base area"). In such cases, if nuclear facilities consist of an electricity generating reactor and relevant facilities, the base area shall be determined in accordance with each of the following:

- Precautionary action zone: Area of a 3 to 5 km radius from the place in which the electricity generating power reactor and relevant facilities are installed;
- Urgent protective action planning zone: Area of a 20 to 30 km radius from the place in which the electricity generating power reactor and relevant facilities are installed.

Table 1: Base Area of Radiation Emergency Planning Zone for Each Nuclear Facility

Category		PAZ	UPZ
Power Reactors and Associated Facilities		3 – 5 km	20 – 30 km
Research Reactors and Associated Facilities	2 MWth ≤ P < 10MWth	N/A	0.5 km
	10 MWth ≤ P< 50MWth	N/A	1.5 km
	50 MWth ≤ P< 100MWth	N/A	5 km
Spent Fuel Storage/Treatment/Disposal Facilities	Treatment facilities not intended for testing or research (Evaluated individually by facility)	To be determined by facility-specific evaluation	5 km
	Storage and disposal facilities	N/A	1.5 km
	Treatment facilities for testing or research purposes	N/A	Site Boundary
Other Nuclear Facilities		N/A	Site Boundary

Table 1 listed base area of EPZ for each nuclear facility in Korea. Since i-SMR is a power reactor rather than research reactor and have a power more than 100 MWth, the existing legal framework necessitates the establishment of EPZ based on the base area designated for power reactors and related facilities. Consequently, under the current legal framework, it is impossible to even attempt an individual assessment of EPZ that takes into account the specific characteristics of i-SMR.

Therefore, based on the distinctive characteristics and safety features of i-SMR, which differ from the technological background considered in existing NPPs and regulatory requirements, a graded approach should be possible to establish EPZ and emergency preparedness (EP) that are not dependent on existing base area classifications. To achieve this, amendments to relevant laws or the establishment of exception clauses are necessary.

2 REGULATORY & TECHNICAL STATUS OF EPZ EVALUATION FOR SMR IN THE WORLD

Since it is not possible to cover all international cases in this paper, the U.S. case will be presented as a representative example.

2.1 The Plan of NRC to Establishing a New Regulatory Framework for SMR EP

Through the publication of SECY-11-0152 (Development of an Emergency Planning and Preparedness Framework for SMR) [2], the U.S. NRC expressed its commitment to developing and improving a technology-neutral, dose-based, and consequence-oriented emergency planning and preparedness framework for SMRs. Furthermore, through SECY-15-0077 (Options for Emergency Preparedness for Small Modular Reactors and Other New Technologies) [3], the U.S. NRC highlighted the need to establish new EP regulations suitable for new technologies such as SMRs and non-light-water reactors.

2.2 ESP of TVA

In 2016, the Tennessee Valley Authority (TVA) applied for an early site permit (ESP) to construct two or more SMRs at the Clinch River site and received final approval from the NRC in 2019. In its assessment, the TVA proposed a site boundary EPZ, a 2-mile EPZ, and an individual assessment EPZ. It did not specify a particular reactor model and instead assumed hypothetical design data from four reference models (BWXT, NuScale, SMR-160, and Westinghouse). TVA classify accident scenarios according to the three criteria in NUREG-0396 [4] and apply the EPA Protective Action Guides (PAG) dose criteria [5]:

ⓐ Design basis accident (DBA): 1 rem (10 mSv);

ⓑ Less-severe accident (CDF > 1×10^{-6}/rx-yr): 1 rem (10 mSv);

ⓒ More-severe accident (CDF > 1×10^{-7}/rx-yr): Distance at which the conditional probability of a whole-body acute dose of 200 rem (2 Sv) is 1×10^{-3}/rx-yr.

2.3 NuScale

NuScale submitted this Topical Report (TR) [6] to the NRC to demonstrate the appropriateness of the EPZ distance calculations for its SMR design. This report was prepared with the aim of adapting the EPZ criteria previously applied to conventional large-scale NPPs to be suitable for SMRs, based on the characteristics of NuScale design. While the report generally follows the NUREG-0396 methodology previously applied to EPZ distance calculations for conventional NPPs, it reevaluates the appropriateness of existing EPZ regulations by incorporating NuScale design characteristics and accident analysis results. NuScale proposed a method for classifying accident scenarios based on the three criteria in NUREG-0396, applying the EPA PAG dose criteria, and determining the EPZ as the greatest of the following four distances, including the site boundary:

ⓐ Design basis accident (DBA): The distance encompassing the area where radiation doses may exceed 1 rem (10 mSv) per 96 hours under average meteorological conditions and 5 rem (50 mSv) per 96 hours under 95th percentile meteorological conditions;

ⓑ Less-severe accident: The distance encompassing the area where radiation doses may exceed 1 rem (10 mSv) per 96 hours under average meteorological conditions and 5 rem (50 mSv) per 96 hours under 95th percentile meteorological conditions;

ⓒ More-severe accident: A distance sufficient to significantly reduce early health effects (red bone marrow dose of 200 rem (2 Sv) per 24 hours) (It was noted that to satisfy the criteria in Condition G, it must be demonstrated that the probability of high radiation doses is significantly reduced, which is consistent with NUREG-0396.).

ⓓ Site boundary

2.4 New Regulatory Framework and Guide

Consequently, the U.S. NRC established 10 CFR 50.160 (Emergency Preparedness for SMRs, Non-LWRs, and Non-Power Production or Utilization Facilities) [7] for SMRs and other nuclear facilities, and published RG 1.242 (Performance-Based Emergency Preparedness for SMRs, Non-LWRs, and Non-Power Production or Utilization Facilities) [8] to establish regulatory criteria for determining EPZs suitable for SMRs and to develop corresponding evaluation methods.

2.5 TerraPower

TerraPower Natrium® reactor (345 MWe sodium-cooled fast reactor) has achieved key regulatory milestones regarding EPZ sizing with the U.S. NRC. In April 2025, the NRC approved Topical Report of TerraPower [9] establishing a risk-informed, performance-based methodology for Plume Exposure Pathway (PEP) EPZ sizing, consistent with 10 CFR 50.160 and RG 1.242. The methodology determines EPZ boundaries based on a projected public dose threshold of 10 mSv (1 rem) TEDE over 96 hours, incorporating probabilistic risk assessment (PRA), site-specific meteorology, and accident sequence analysis. Subsequently, in March 2026, the NRC issued a construction permit (CP) for Kemmerer Power Station Unit 1 in Wyoming, the first commercial-scale advanced non-light-water reactor CP in U.S. history [10]. The site-specific EPZ size will be finalized at the operating license stage.

3 TECHNICAL STATUS OF EPZ EVALUATION IN KOREA

3.1 EPZ Evaluation Methodology for i-SMR

EPZ evaluation methodology appropriate to the characteristics of i-SMR, based on the RG 1.242 has been developed and proposed. Unlike conventional base-area approach, this methodology adopts a graded approach reflecting reactor power and design-specific characteristics. The evaluation follows a five-step procedure as presented in Figure 1.

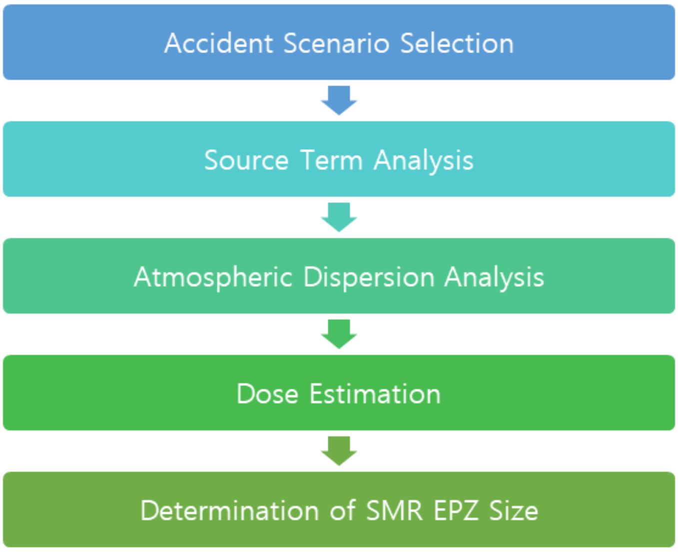

Figure 1: Procedure for EPZ evaluation

Step 1. Accident Scenario Selection

A spectrum of accident sequences is considered, incorporating both design basis accidents (DBAs) and beyond design basis accidents (BDBAs) as licensing basis events (LBEs). Accident frequencies derived from probabilistic safety assessment (PSA) are used for screening. Cliff-edge effects must be verified, and release timing is considered to assess the need for pre-planned protective actions. Based on risk analysis results for multi-unit sites in Korea, the probability of simultaneous core damage across multiple units due to external events such as earthquakes is significantly lower than that for a single unit. Although i-SMR consists of multiple modules, the safety systems for each module are configured independently, therefore, it is expected that they may exhibit a risk profile similar to that of multiple-unit nuclear power plants. However, evaluations during the licensing phase will consider external events and inter-module correlations, and if the risk level is very low, screening will be conducted in accordance with established criteria.

Step 2. Source Term Analysis

Source term analysis is performed for each accident sequence using validated severe accident analysis codes. Key outputs include radionuclide release rates over time, release duration, location, physical/chemical form, and plume energy, consistent with the safety analysis report (SAR).

Step 3. Atmospheric Dispersion Analysis

A Gaussian plume model is selected as the primary dispersion tool. Given that SMR EPZs are expected to be smaller than those of large reactors, near-field accuracy is improved by accounting for plume rise, building wake effects, plume meander, wet/dry deposition. Site-specific meteorological data (wind direction/speed, atmospheric stability, precipitation, mixing height) are used and generic multi-site data are applied when the site is not yet specified.

Step 4. Dose Estimation

Both internal and external exposure pathways are evaluated. Appropriate dose coefficients, breathing rates, shielding/protection factors, and exposure durations are applied. Dose reduction from protective actions (sheltering, evacuation, relocation) is not considered in the EPZ sizing analysis.

Step 5. EPZ Size Determination

Accident sequences are categorized into three groups: (1) DBAs, (2) less-severe accidents (containment integrity maintained; release via containment leakage), and (3) more-severe accidents (containment failure; release via bypass pathways). For DBAs and less-severe accidents, EPZ size is determined deterministically against dose criteria based on emergency protective action guidelines in Korea. For more-severe accidents, EPZ size is determined probabilistically using frequency-weighted exceedance probability curves, referencing dose thresholds from NUREG-0396 [4], EPA PAG Manual [5], NUREG-6454 [11], and NUREG-7161 [12].

Additionally, a fundamental judgment must be made as to whether pre-planned rapid protective actions are necessary at all. If analysis demonstrates that no area requires such actions, the EPZ may not be defined, provided the determination is fully justified.

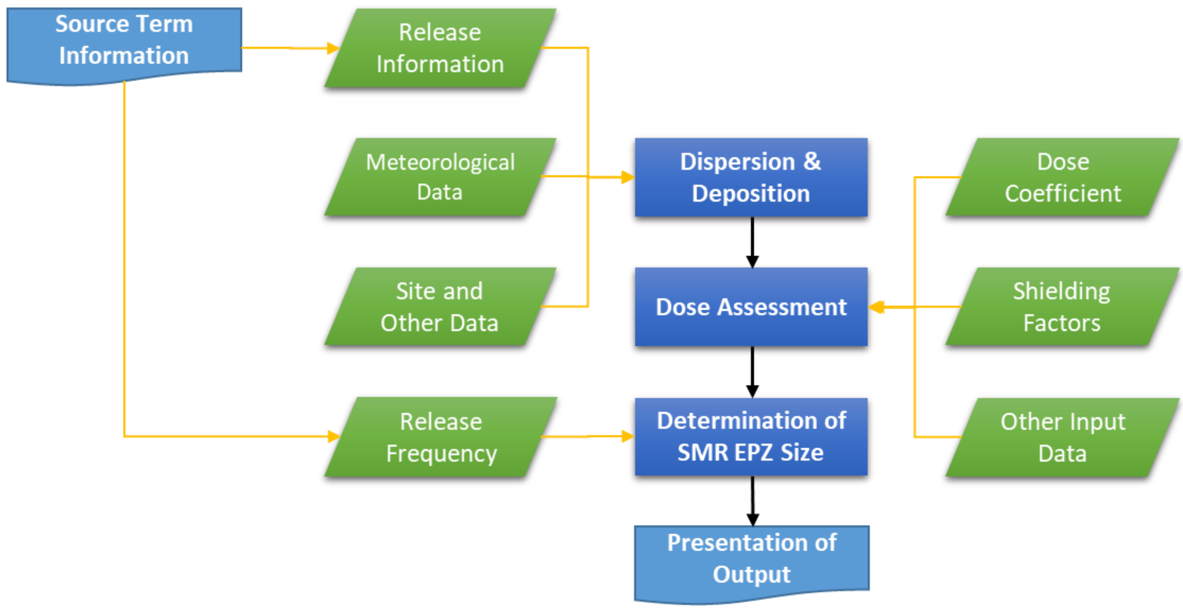

Figure 2: Overall algorithm for EPZ evaluation in RCAP-EPZ

3.2 EPZ Evaluation Code for i-SMR

Radiological Consequence Analysis Program for EPZ (RCAP-EPZ), a code that implements the method described in Section 3.1, has been developed. The overall evaluation algorithm and required inputs of RCAP-EPZ are illustrated in Figure 2.

4 CONCLUSION

To establish an EPZ for i-SMR, the base-area criteria for power reactors as defined in the current Act on Physical Protection and Radiological Emergency must be followed in Korea. This implies that it is not possible to establish an EPZ which is appropriate and suitable for i-SMR, given their power generation capacity and safety characteristics. Therefore, legislative amendments are necessary to bridge this gap and establish EPZ in a reasonable manner that reflects the characteristics of i-SMR. The United States has established 10 CFR 50.160 and published RG 1.242 to establish regulatory standards and evaluation methods for defining EPZ in a manner suitable for SMRs.

This study summarizes the background necessary to understand this situation, analyzes the gaps with existing domestic regulatory standards, and proposes solutions. To this end, the study summarizes the safety characteristics of i-SMR and analyzes the inadequacies and limitations of applying the existing regulatory framework to them. This study also reviews existing SMR EPZ evaluation methodologies and presents a proposed evaluation method for i-SMR EPZ based on the U.S. RG 1.242 methodology. This report refrained from specifying criteria such as the frequency threshold for accident selection or the dose criteria for EPZ assessment, instead describing a general methodology.

It is expected that this study will aid in understanding the current global situation and technological status and will be utilized to bridge the gap in regulatory and technical standards regarding the establishment of EPZ for SMRs.

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