Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Scalable EPZ regulation for Coal Repowering with Small Modular Reactors (SMR)

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***Keywords : Coal Repowering, Small Modular Reactor (SMR)**

1. Introduction

The most prominent topic in the current energy industry is decarbonization. In the case of South Korea, the country has joined the Paris Agreement and set a goal of achieving net-zero carbon emissions by 2050.

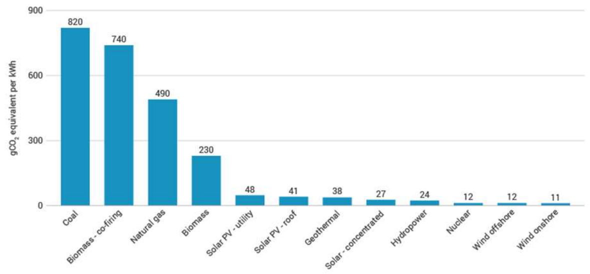

Fig. 1. Average life-cycle CO_2 equivalent emissions [1]

The greatest obstacle to decarbonization in the energy industry is fossil fuel-based power generation, particularly coal-fired power plants. According to Fig. 1, greenhouse gas emissions of coal-fired electricity generation corresponds to 820g of CO_2 per kWh, which is more than 60 times of greenhouse gas emissions of nuclear power electricity generation.

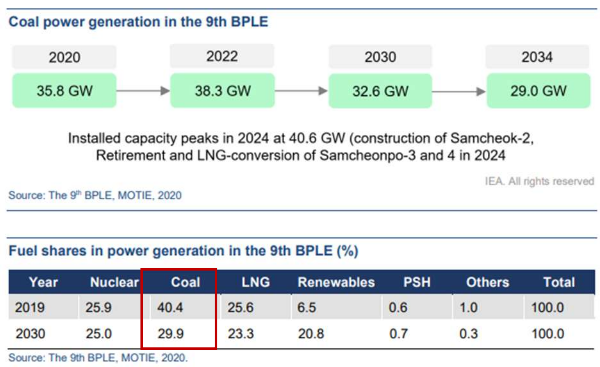

Fig. 2. Share of coal-fired power plant generation [2]

Coal-fired power generation is one of the most dominant energy sources in South Korea, which produces 40.4% of total electricity in 2019 (Fig. 2). Thus, it is essential to find strategies that decrease the share of coal-fired power in total electricity generation while maintaining overall energy output.

Coal repowering is a concept of repurposing coal-fired power plant with alternative low carbon energy sources. For cost-effective coal repowering, an energy source that can maximize the reutilization ratio of currently existing coal-fired power plant facility is essential. In this regard, Small Modular Reactor (SMR) is considered one of the most promising candidates as an energy source for coal repowering due to its high energy density and simplified structure.

2. Characteristics of SMRs

Small Modular Reactors are a type of advanced nuclear reactor designed to generate up to 300 MWe of electricity per unit.

Compared to conventional nuclear reactors, SMRs have lower power output and a higher surface area-to-volume ratio, which is better to adopt passive safety systems. This, in turn, enables a significantly simplified reactor design.

From an economic perspective, a key advantage of SMRs is their modular design, which contrasts with the large-scale structure of conventional nuclear power plants. This modular configuration allows a factory-based manufacturing of power plant components, facilitating on-site assembly rather than complex construction processes. As a result, SMRs offer high productivity and improved efficiency in nuclear power plant deployment.

Table 1. SMR data sheet [3][4]

	Steam outlet T (℃)	Outlet Pressure (MPa)	Volumetric flow rate (m^3/s)
HTGR-1	630	6	5.44
HTGR-2	750	6	5.60
PWR-1	296	5.2	16.33
PWR-2	321	10.3	7.19

There are various kinds of SMRs that are under development worldwide and each of them has different characteristics (Table 1). When selecting an SMR design for coal repowering, thermal-hydraulic characteristic of SMR should be considered.

General steam turbines for coal-fired power plants are typically designed to operate with steam at temperatures exceeding 500°C [5]. In contrast, a conventional PWR generates steam at approximately 300°C, which may result in lower efficiency or not feasible. To address this, an SMR design capable of supplying high-temperature steam or a design that incorporates additional energy sources to elevate steam temperature is necessary. Compared to PWR, HTGR can produce high temperature steam which can match the temperature requirement of coal-fired power plant steam turbine. However, due to low volumetric flow rate of steam, multiple SMR units are needed for HTGR coal repowering.

3. Regulatory issues on Coal repowering with SMR

Although SMRs are an economically efficient candidate for coal repowering, several regulatory challenges currently exist. Due to substantial consequence in case of a rare severe accident in a nuclear power plant, whole lifecycle of nuclear power plant including licensing, construction, operation and decommissioning is controlled by strict regulation. If the same prescribed regulation is applied to SMRs without re-evaluating the smaller consequence of SMR, this can indeed make difficult to utilize SMR for various purposes.

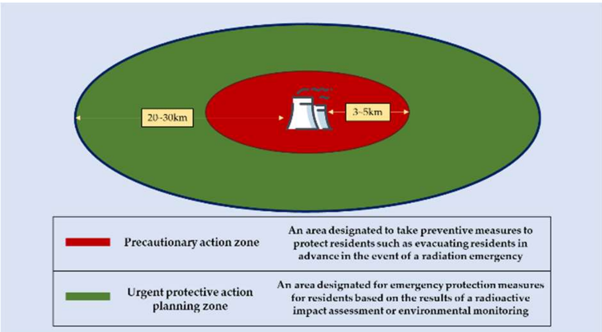

Fig. 3. Concept of emergency planning zone

Emergency planning zone (EPZ) is one of the most important topics on safety regulation issues related to SMR. EPZ is a designated area where emergency measures are intensively planned to protect residents and mitigate the consequences in the event of a radiological emergency or nuclear disaster at a nuclear facility [7]. 'Act on Physical Protection and Radiological Emergency' defines the EPZ by categorizing it into two types, Preventive protection action zone (PAZ) and Urgent protection action planning zone (UPZ) (Fig. 3).

PAZ is a designated zone for implementing precautionary actions in the event of a radiation emergency, including the evacuation of residents. UPZ, on the other hand, is an area established for emergency protective measures, which are carried out based on radiological impact evaluations and environmental monitoring.

The concept of EPZ as a regulatory concept did not exist before the 1950s. In the 1950s, as the United States began the commercial construction of reactors, it established the regulatory definition of the Exclusion Area Boundary (EAB). After the TMI accident in 1978, EPZ criteria which describes about radiological dose. were introduced through NUREG-0396 based on improved PSA technology[8].

The IAEA adopted EPZ regulatory standards in 1979, following the U.S. framework, and further strengthened these standards after the Chernobyl accident in 1986. The definitions of the Plume Emergency Planning Zone (PEPZ) and the Ingestion Emergency Planning Zone (IPEZ) established by the U.S. during this period have continued to influence modern nuclear regulatory frameworks [8].

Under the current nuclear regulatory framework in South Korea, regardless of the reactor type, the PAZ is uniformly designated within a radius of 3–5 km from the nuclear power plant, while the UPZ is set within a 20–30 km radius.

Current regulation criteria of EPZ pose great challenges for utilizing SMRs to assist for accelerating the carbon neutrality. SMRs are characterized by low power output and high inherent safety, which leads to lower consequence in case of severe accident. Therefore, the prescribed regulation for large reactors should be re-evaluated to reflect the characteristics of SMRs before applying.

In order to adjust EPZ regulations, an analysis of the safety features about SMRs including radioactive dose under both normal operation and accident conditions is required. However, since SMRs are currently under development and licensing stages, the precise design parameters necessary for a detailed safety analysis are not yet available. As a result, it is challenging to produce an accurate analysis that considers reactor type and safety features. Nevertheless, a rough estimation can be made based on the reactor's power output if we assume SMRs have the same safety characteristics with large nuclear power plant.

According to Gaussian plume model for continuous release, dispersion factor of radioactive material can be estimated [9].

$$\text{Dispersion factor} = \frac{\chi(x,y,z)}{\Gamma} = \frac{1}{2\pi u \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \left(e^{-\frac{(z-h)^2}{2\sigma_z^2}} + e^{-\frac{(z+h)^2}{2\sigma_z^2}} \right) \quad (1)$$

where Γ is the integrated source term (Bq), $\chi(x,y,z)$ is the integrated radioactivity concentration at the point in space (x,y,z), u is wind speed in the x direction which is determined as 2.3m/s in this study which corresponds to the average wind speed in South Korea. $\sigma_y = 0.11x(1 + 0.0004x)^{-0.5}, \sigma_z = 0.08x(1 + 0.0015x)^{-0.5}$, h is height of release which is assumed to be zero in this study.

It is assumed that the released radioactivity concentration of reactor is proportional to the generation capacity of nuclear power plant. Again, this is assuming that SMRs have the same fractional amount of released source from the core as the large nuclear reactor, which is not crediting additional radiological barriers or safety features those can be in place for SMRs. Furthermore, this also shows that how much additional safety features can be important for SMR when EPZ can be reduced to the site boundary.

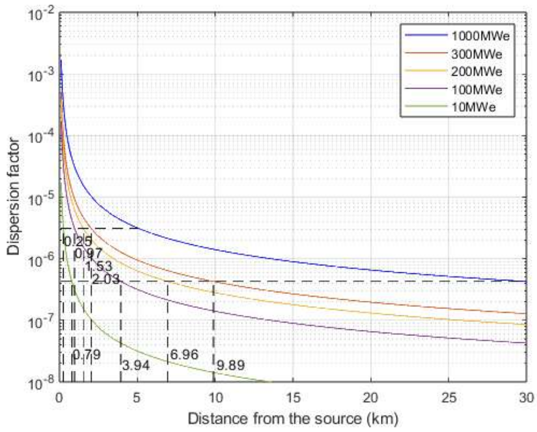

Fig. 4. Assumed EPZ for nuclear power plant with different generation capacity

The EPZ is assumed to be scalable so that its size can be determined to yield the same radiological consequences. In this study, reactors with generation capacities of 1000 MWe, 300 MWe, 200 MWe, 100 MWe, and 10 MWe are evaluated to assess the expected differences in dispersion distance using Eq. 1 (Fig. 4, Table 2). The EPZ can be estimated by assuming that the same radiological consequence is expected when the product of the dispersion factor and the source strength for smaller reactors matches that of large reactors. Therefore, this study focuses solely on the effect of the reduced source term due to lower power, while maintaining the same dispersion characteristics.

Table 2. Radius of predicted EPZ to have the same radiological consequence for different reactor power level with the same dispersion characteristics

	PAZ radius	UPZ radius
1000MWe	5 km	30 km
300MWe	2.03 km	9.89 km
200MWe	1.53 km	6.96 km
100MWe	0.97 km	3.94 km
10MWe	0.25 km	0.79 km

According to Fig. 4 and Table 2, the EPZ range decreases significantly as the reactor power output decreases. A tendency of linear proportionality to some extent between the EPZ radius and the reactor power generation capacity can be observed. Furthermore, if SMRs with power level 300MWe would like to achieve UPZ size equal to the site boundary (e.g. 0.4km), the fractional term should be reduced approximately 25 times through the implementation of additional or alternative safety features compared to large reactors.

The reduction of the EPZ range corresponds to a decrease of the residential area included within the EPZ, which in turn signifies a significant reduction in the economic and regulatory burden for the utilization of SMRs.

4. Summary and Conclusions

In the current global context, where the importance of decarbonization is increasingly emphasized, the swift replacement of coal-fired power generation, which has a high share of greenhouse gas emissions and electricity production, is becoming a critical priority. In this regard, coal repowering through SMRs is receiving significant attention due to its high energy density and simplified structure which is advantageous for various purposes.

Even if SMRs offer numerous advantages, current nuclear power plant regulations in Korea are not best suited for SMRs, leading to unfavorable implications, particularly regarding EPZ regulations. In response, a few countries are currently discussing improving regulatory framework to address this issue.

The EPZ for SMRs with generation capacity 300MWe~10MWe is reduced to approximately 40%~2.5% of that for the large-scale conventional reactors with 1000MWe, assuming that the released source term is simply proportional to the reactor power and no additional safety features are credited.. However, the reduction is still not enough to reduce EPZ to the site boundary, and this emphasizes that for successful development of SMR and reducing its EPZ to the site boundary, additional safety features of SMRs have to be developed and evaluated appropriately.

If the development of SMR is successful and the regulatory framework can fairly evaluate this, repowering of coal-fired power plant with SMR can be one step closer. The reduction of the residential area within the EPZ would provide significant economic advantages for SMR operators. Therefore, precise analysis of EPZ criteria for SMRs is a highly important research topic from economic and regulatory perspective.

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