Redefining Emergency Planning Zones with Adaptive Protective Action

Bongseok Kim*, Kanghyeon Lee, Sohyeon Lee, Chanki Lee, Sol Jeong, Wi-Ho Ha
Nuclear Emergency Preparedness Section, Korea Atomic Energy Research Institute
**Corresponding author: kbs@kaeri.re.kr*

Keywords : Adaptive Protective Action, EPR, EPZ

1. Introduction

The concept of the Emergency Planning Zone (EPZ) has evolved toward refining response strategies based on the progression stage of an accident and the nature of radiological risks in Emergency Preparedness and Response (EPR). The IAEA has evolved its safety requirements by moving beyond comprehensive response concepts to clearly separate Zones and Distances, and by establishing priorities for initial responses. However, Small Modular Reactors (SMRs), which are being discussed for deployment near urban areas due to their enhanced inherent safety, are emerging globally. Furthermore, large Light Water Reactors (LWRs) adjacent to urban areas with massive populations of millions (e.g., Kori, Saeul) are already operating in South Korea. Under these geographic specificities, the existing uniform radiological emergency response framework inevitably reveals fundamental limitations. While recent regulatory approaches, such as the US NRC's methodology for SMRs, attempt to flexibly scale down EPZ sizes based on dose assessments, this approach primarily addresses radiological risk and does not inherently resolve the operational constraints of mass evacuation in densely populated urban environments. Since many countries, including South Korea, have legally adopted the IAEA's spatial framework (PAZ/UPZ), analyzing the structural rigidity of this widespread system is practically essential. Therefore, this study examines the historical evolution of the IAEA's EPZ concept, analyzes the contradictions of the current domestic EPR system, and proposes the introduction of 'Adaptive Protective Actions' based on the accident characteristics of the facilities and the spatial characteristics of their locations.

2. Historical Evolution of EPZ

For the correct understanding of the current EPR system, it is necessary to trace the historical context in which the EPZ concept was refined. The 1980s can be seen as the period when the initial concept of the EPZ was formed. Safety Series No. 50-SG-G6, published in 1982, took a comprehensive and functional response approach, defining it as an "affected area" off-site where intervention levels were likely to be exceeded in the event of an accident, rather than a fixed zone with a specific radius. The late 1990s to the 2000s marked a period when zones were separated and specified. It was recognized then that strategies should be applied differently, taking into account deterministic and stochastic effects, which correspond to the speed of accident progression and the nature of the risk. Starting with IAEA-TECDOC-953 in 1997, the Precautionary Action Zone (PAZ, 3~5km), requiring immediate evacuation even before a release to prevent severe deterministic effects, and the Urgent Protective Action Planning Zone (UPZ, 10~25km), aimed at reducing stochastic effects based on monitoring results, were clearly separated. In other words, the PAZ and UPZ were core zones fundamental to the EPZ even before the Fukushima accident. The period after 2010 is characterized by the dualization of zones and distances and the concept of preemptive response. GSR Part 7, reflecting the lessons of the Fukushima accident, was published in 2015. It introduced the new concept of Emergency Planning Distances (EPD, ICPD), which cover hundreds of kilometers for contamination monitoring and food control, in addition to the zones requiring urgent evacuation (PAZ, UPZ), thereby completing a four-tier spatial protection framework. Notably, GSR Part 7 specified two major paradigm shifts in the operation of the current UPZ and PAZ. First, considering the delays associated with extensive environmental monitoring in an emergency, it strengthened precautionary requirements so that urgent protective actions within the UPZ can be initiated based solely on significant pre-release facility conditions. Second, it added a requirement stating that actions within the UPZ must never delay or hinder the evacuation of residents in the most dangerous zone, the PAZ.

3. Problem Statement of Current EPR Framework

As examined above, the IAEA's latest safety requirements recommend the absolute priority of PAZ evacuation and flexible precautionary actions within the UPZ depending on the situation. In contrast, the current domestic emergency preparedness framework rigidly interprets the PAZ and UPZ as absolute criteria and boundaries where specific actions must be mechanically implemented, rather than as strategic zones to be operated flexibly according to the situation. This interpretation has solidified a static structure that orders simultaneous evacuation across entire zones when triggers such as Emergency Action Levels (EALs) or Operational Intervention Levels (OILs) are met, without considering road capacity or traffic conditions. Unlike the US NRC, which employs a single EPZ with spatially differentiated evacuation strategies (e.g., the keyhole approach) based on projected plume direction, the domestic framework applies uniform evacuation orders across entire zones. Furthermore, the validity of reducing the EPZ radius based on radiological risk is fundamentally distinct from the operational feasibility of physically evacuating residents within that established zone. Even if the EPZ for future SMRs is scaled down to only a few kilometers, mechanical evacuation orders within complex urban road networks will inevitably trigger the 'Paradox of Protective Action'. This limitation persists even under scalable EPZ frameworks such as those adopted by the US NRC, as reducing the EPZ radius does not eliminate the fundamental constraints imposed by urban infrastructure and population density. Particularly in urban environments (large nuclear power plants and SMRs) with complex road networks and high population densities, mechanical evacuation orders are highly likely to cause widespread traffic gridlock. This could lead to the so-called "Paradox of Protective Action", leaving residents stranded on roads for extended periods while a radioactive plume passes overhead, causing additional exposure along with non-radiological risks like traffic accidents and medical vacuums.

4. Spatial Risk Profiling Analysis

To identify the flaws in implementing uniform protective actions, this study analyzed the physical and social environments where nuclear facilities are located by subdividing them into a 3-Tier risk profile. First, non-urban large nuclear power plants are located in areas with low population densities and simple, linear road networks. The dominant constraint in these zones is distances, and the rapid mobilization and distribution of long-distance transport (buses, ambulances) for the vulnerable populations serves as the core risk. Second, urban large nuclear power plants are complex zones with large source terms and millions of densely packed residents. The most critical response risk is widespread traffic paralysis due to the physical capacity of the road network being exceeded during the simultaneous evacuation of a massive population. The risk stemming from evacuation failure reaches a critical point faster than the radiological risk itself. Finally, in the case of urban SMRs and research reactors, although their source terms are relatively small, these facilities are located within the immediate living areas of residents. In such environments, as observed during the Three Mile Island (TMI) accident in the US, voluntary evacuation driven by high public risk perception can significantly amplify unsynchronized traffic congestion. Thus, managing time pressure and controlling overreactions are top priorities.

5. Recommendation

The first recommendation is to redefine the PAZ and UPZ as strategic zones. To overcome the limitations of the current framework, the PAZ and UPZ should be reconsidered beyond the conventional perception that they function as fixed physical boundaries; instead, they should be redefined as strategic priority zones for efficiently allocating limited emergency resources and securing the golden time for residents' survival. This also emphasizes that the zones are functional divisions for radiological emergency response rather than physically fixed, distinct boundaries. Through this redefinition, it will be possible to correct the false perception that protective actions are unnecessary even for future facilities like SMRs, where the PAZ may be drastically reduced or unestablished. This enables flexible and effective integrated zone operations tailored to facility characteristics and social features (source terms, road networks, etc.) without leaving gaps in EPR.

The second recommendation is the introduction of ‘Adaptive Protective Action (APA)' based on conditional triggers. A system utilizing uniform triggers is effective in preventing delayed decision-making amidst the high uncertainty of radioactive plume dispersion. However, applying it uniformly in densely populated urban environments results in deterministic harm, such as radiation exposure on roads due to traffic paralysis. Therefore, this study proposes a transition to APA based on real-time conditional triggers that integrate not only radiological indicators (e.g., dose projections, release conditions) but also spatial constraints such as traffic capacity and road network saturation. The introduction of the APA framework is not merely a supplementary measure for the existing IAEA PAZ/UPZ system. It is an essential operational strategy that must be implemented regardless of the EPZ sizing methodology. This necessity holds even under dose-based scalable EPZ frameworks, such as those adopted by the US NRC, as these approaches alone cannot address the physical limitations of evacuation in urban settings. When spatial constraints exceed radiological risks, dynamically transitioning to sheltering-in-place is universally critical for ensuring safety in urban nuclear facilities. This is not about delaying decision-making while waiting for perfect data; rather, it is an active system that fundamentally prevents the side effects of forced evacuations by immediately switching to sheltering-in-place, which should be considered the default protective action when evacuation capacity is exceeded in urban environments. While non-urban nuclear power plants should maintain rapid evacuation, large nuclear power plants adjacent to urban areas must utilize sheltering for UPZ residents as a bridge strategy to prevent wide-area paralysis and thoroughly guarantee top-priority evacuation routes for PAZ residents. For urban SMRs, utilizing high-performance shielding buildings for sheltering should be considered the primary protective measure over forced physical evacuations, and dynamic responses are required according to the physical and socio-environmental circumstances of the nuclear facilities.

6. Conclusion

To achieve the fundamental principles of radiation protection, 'Justification' and 'Optimization', in disasters, the EPR system must also possess 'Adaptability' to evolve according to the situation and space, moving beyond the mechanical implementation of manuals. The strategic redefinition of the EPZ and the APA framework proposed in this study represent not only practical improvements but also a necessary shift in operational logic for EPR systems in complex urban contexts. Furthermore, this will serve as the foundation for a rational and future-oriented regulatory logic to ensure the safety and social acceptability of SMRs and other facilities expected to function as distributed urban power sources in the future.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs(RMAS) and the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea.(No. RS-2025-02310628)

REFERENCES

[1] IAEA, Preparedness of Public Authorities for Emergencies at Nuclear Power Plants: A Safety Guide, Safety Series No. 50-SG-G6, Vienna, 1982.

[2] IAEA, Method for the development of emergency response preparedness for nuclear or radiological accidents, IAEA-TECDOC-953, Vienna, 1997.

[3] IAEA, Preparedness and Response for a Nuclear or Radiological Emergency, Safety Standards Series No. GS-R-2, Vienna, 2002.

[4] IAEA, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, Vienna, 2007.

[5] IAEA, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, Vienna, 2015.