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A Study on Nuclear Safety-Security Inferface of Physical Protection

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1. Introduction

In general, nuclear safety and security have a common of protecting the public and the environment from radiation hazards, and their defense-in-depth (DiD) strategy such as prevention, protection, mitigation and accident response are the same. However, differences exist in prevention and response methods due to different causes of problems. Also, in 2021, the IAEA published "The Nuclear Safety and Nuclear Security Interface," [1] technical report Series No. 1000, sharing the status of safety-security interface in each country and recommending that best practices be reflected in each country's systems. And the N-STAR report "Establishment of 3S interface Infrastructure" [2] published by KINAC in 2016 presented three high-priority issues related to safety and security interface. The first was vital areas, the second was cybersecurity, and the third was spent nuclear fuel storage and transportation facilities. However, both reports approached the issue from an institutional perspective and did not mention the technical connection between safety and security interface. Therefore, this paper will focus on physical protection and examine the technical connections between key technologies, identify current issues, and propose solutions to these issues for each key technology.

2. Vital Area Identification

The vital area of a nuclear power plant contains various devices, cables, pipes, and other equipment that can affect the safety of the plant. Applying enhanced physical protection requirements to the vital area could inadvertently affect safety. In 2015, the Nuclear Safety Commission redefined the vital area in accordance with the IAEA's physical protection recommendations through an administrative order. However, the attack sets that must be calculated when redefining the vital area were not calculated, and therefore, the impact of the currently defined vital area on safety has not been analyzed in ROK.

2.1 International Trend

Meanwhile, the IAEA first mentioned this in its physical protection recommendation guidelines for nuclear facilities and nuclear materials, IFCIRC/225/Rev.4, as follows: "Areas within a protected zone that contain equipment, systems, or devices that could directly or indirectly cause radiation exposure exceeding acceptable levels in the event of sabotage, or nuclear materials." Subsequently, the INFCIRC/225/Rev.5[3] report published in 2011 further strengthened the previous version by identifying systems and events that could have a serious impact on the public, and published technical guidelines for the establishment of vital areas in nuclear facilities through Technical Guide No. 16 of the Nuclear Security Series, thereby further specifying the definition of vital areas. The definition of a vital area according to the IAEA document INFCIRC/225/Rev.5[3] is as follows: "A vital area is defined as a protected area within which equipment, systems, or devices that could indirectly or directly cause high radiological consequences (HRC) in the event of sabotage are located, or nuclear material is stored." The mention of radiological consequences here implies that a comprehensive review of safety is necessary, taking into account the human and environmental impacts that could arise in the establishment of vital areas. In the case of the United States, 10 CFR Part 73 "Physical Protection of Plants and Materials" (9) Vital Area requires as following. The vital area must include at least the control room, spent fuel storage pool, central alarm station (CAS), and secondary alarm station (SAS) that meets the requirements of 73.55. Furthermore, when designing physical protection, the Vital Area must be designed to prevent significant core damage and sabotage of spent fuel. The procedure for establishing the Vital Area in the United States is as follows: the failure trees generated from the probabilistic safety assessment are converted into sabotage failure trees, calculated using attack sets and defense sets, and the Vital Area is selected. And nuclear facilities follow the physical protection design procedures shown in Figure 1, and the physical protection design of nuclear power plants includes the selection of vital areas and the design of physical protection systems to protect those vital areas.

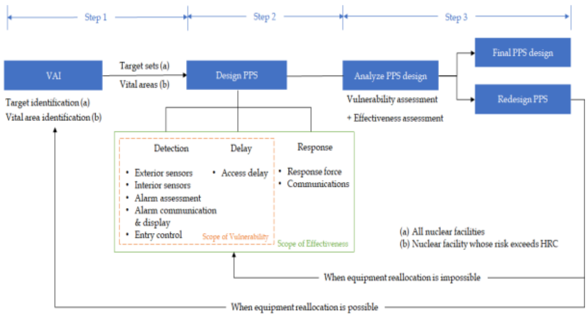


Fig 1. physical protection design procedures [4]

In step 1, in order to accurately define the physical protection objectives for nuclear facilities, (1) threats are defined, (2) target sets are calculated, and (3) for nuclear facilities exceeding HRC, vital areas are designated in accordance with the vital area identification procedure.

2.2 Domestic trend

In South Korea, vital areas were redefined in accordance with an administrative order issued in 2015, but unlike in the United States, failure trees based on probabilistic safety assessments were not applied. That is, it simplifies fault trees qualitatively (do not calculate attack sets or defense sets). Furthermore, the redefined vital areas are mostly defined on a building-by-building basis, and in some cases, on a room-by-room basis. This makes it difficult to comply with the legal requirements for vital areas (e.g., the two-man rule) when performing maintenance on crucial equipment located in the vital areas of power plants. In order to minimize the vital area and optimize the efficiency of protective resources, it is necessary to calculate the attack set and defense set by changing the failure trees generated in the probabilistic safety assessment to sabotage failure trees, and then set the vital area. Furthermore, as shown in Figure 1, when setting the vital area, it is necessary to consider physical protection design from the construction stage (Security-By-Design) to ensure the smooth maintenance of major equipment located within the vital area during vital area operation. By following the procedure in Figure 1, issues related to the vital area will be resolved.

3. Vulnerability/Effectiveness Assessment

In Step 3 from Fig. 1, vulnerability/effectiveness assessment is a tool used to evaluate whether the physical protection design meets the regulatory agency's performance requirements (target values). Vulnerability assessment is a step in physical protection design that verifies physical protection performance and confirms whether the regulatory agency's performance requirements are met. If the requirements are not met, physical protection devices may be rearranged, and important safety devices at the power plant may be rearranged if necessary. Vulnerability assessment is a process that analyzes whether detection and delay are timely (probability of interruption) along the entire path of an intruder, with the goal of identifying the most vulnerable path. If the target value is not met, detection and delay equipment is reinforced. The red-colored area in Figure 1 represents the scope of the vulnerability assessment. This can be expressed mathematically as Equation 3.1, which represents a single path.

$$P_{I_1} = 1-(1-P_{D_1})\times \dots \times(1-P_{D_n}) \qquad (3.1)$$

P_D : Probability of detection, P_I: Probability of Interruption

On the other hand, effectiveness assessment is a method of evaluating the effectiveness of protective and/or response forces in order to prevent the intruder from achieving its objectives. In other words, after the design of the physical protection system is complete, all vulnerable areas and response areas are evaluated. If the target value is not met, both the physical protection system and the response components must be reinforced and redesigned/reconfigured to meet the target value. The green-colored area in Figure 1 represents the scope of the effectiveness assessment. This can be expressed mathematically as Equation 3-2.

$$P_E = P_I \times P_N \qquad (3.2)$$

P_N: Probability of Neutralization, P_E: Probability of System Effectiveness

Meanwhile, looking at the vulnerability (VA)/effectiveness (EA)assessment tools developed to date summarized in Table 3.1.

Table 3.1. List of domestic and international physical protection's vulnerability/effectiveness assessments tool

	Tool		method
1st generation (before 2000 year)	VA	EASI(Excel,1D*), SAVI (window-based,1D*), ASSESS (window based,2D*), KAVI (window based, 1D*)	Expert judgement
	EA	ASSESS (Window based, 2D*)	Expert judgement & algorithm based
2nd generation (after 2000 year)	VA	SAPE (Window based, 2D*), TESS (Window based, 2D*), Pathtrace (Window based, 2D*)	algorithm based
	EA	AVERT(3D*), SCRIBE3D(3D*), EMRALD(2D*)	War game based

EASI: Estimation of Adversary Sequence Interruption, SAVI: Systematic Analysis of Vulnerability to Intrusion, ASSESS: Analytic System and Software for Evaluating Safeguards and Security, KAVI: Korean Analysis Vulnerability to Intrusion, SAPE: Systematic Analysis of Physical Protection Effectiveness, TESS: Tool for Evaluating Security System, AVERT, SCRIBE 3D, EMRALD: Event Modeling Risk Assessment using Linked Diagrams.

In addition, the US Nuclear Regulatory Commission (NRC) published NUREG/CR-7145 "Nuclear Power Plant Security Assessment Guide" [5] in 2009, mandating vulnerability assessments not only for existing power plants but also for new power plants, and requiring operators to submit relevant results (values) in accordance with the guidelines when obtaining permits. Additionally, the UK regulatory body, the Office for Nuclear Regulation (ONR), established the ONR Technical Assessment Guide (TAG) CNS-TAST-GD-6.4 "Vulnerability Assessments Guide" [6]. Regulatory agency reviewers examine the vulnerability assessment content of new power plants in accordance with the guidelines when granting new licenses, and may request vulnerability assessment results (values) from operators as needed. Meanwhile, physical protection design has already been completed prior to the submission of physical protection regulations by law in ROK, making it impossible to change protective equipment or rearrange key equipment. As a result, VA/EA evaluations to verify the performance required by regulatory agencies have not been conducted to date. To resolve these issues, physical protection design should be implemented from the construction stage so that the performance required by regulatory agencies can be verified, as shown in Figure 1.

4. NPP extreme event

4.1 International Trend

After Fukushima accident, the USA continuously focused on the external event (e.g. seismic, flooding, high wind etc.) of NPPs. The probabilistic wind-born missile assessment was developed by Electric Power Research Institute (EPRI). In 2015, EPRI was published the high wind risk guideline which includes high wind and wind-born missile hazard assessment, fragility assessment and risk model of NPPs by high wind and the guideline for high wind was published in 2015[7]. In this guideline, the scope of wind-born missiles is Storage container, Fence Post, light pole, tree, Hydrogen Tanks, Electrical cabinet. That is, containers near switch yards, fence posts, streetlights, trees, hydrogen tanks outside turbine buildings, and unsecured electrical cabinets are potential sources of wind-born missile. And, the nuclear power plants (NPPs) were designed to resist the seismic and wind load. But old NPPs can be damaged by external hazards. Meanwhile, since 1983, the US Nuclear Regulatory Commission (NRC) has recommended the use of probability risk assessment (PRA) methods for protecting against debris in the event of a tornado when licensing nuclear power plants. In response, the Idaho National Laboratory in the United States conducted a seminar on extreme disasters in March 2016 with the support of the NRC [8]. The seminar presented risk assessment methods for all disasters related to extreme disasters (earthquakes, tsunamis, strong winds, floods, etc.).

4.2 Domestic Trend

Korea was annually attacked by 2~3 typhoons. Recent typhoon intensity (e.g. difference of central pressure and wind speed) has been increased by a climate change. From this reason, it is needed to perform the typhoon induced high wind risk assessment. For high wind risk assessment, high wind hazard and fragility analysis should be conducted. And the extreme event at nuclear power plants is to develop a methodology for quantitatively deriving risks related to extreme/complex disasters, rather than single disasters caused by climate change. As part of this initiative, this project related to extreme disasters, which began in 2022, is being carried out with four specific objectives. Among these, the wind vulnerability assessment technology was performed on structures exposed to the outside, analyzing the impact of debris (e.g., 6-inch pipes) on the CST (Condensate Storage Tank) when strong winds occur. If the CST is included in the vital area, the impact of debris caused by strong winds is similar to that of a vehicle bomb on the CST.

Table 4.1 is "CST compares impact values in collisions caused by strong winds and vehicle bomb".

Table 4.1. "CST compares impact values in collisions caused by strong winds and vehicle bomb"

collision caused by strong winds		collision caused by vehicle bomb	
goal	CST (outdoor concrete structure)	same	Horizontal x Vertical: 11.950m Height: 4.58 m depth: 0.45m
debris	6" pipe (Diameter: 0.168m, length: 4.58m, Mass: 130.2kg)	Attack type	vehicle bomb (compact sedan)
impact velocity	30.5m/s (shin-Kori FSAR max. velocity)	explosives	227kg
simulation	LS-DYNA	simulation	ABAQUS

Fig 4.1 is the collisions caused by strong winds and impacts caused by vehicle bomb.

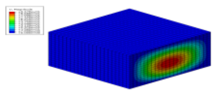
collision caused by strong winds	Impact of vehicle bomb
	

Fig 4.1. the collisions caused by strong winds and impacts caused by vehicle bomb In the case of sabotage caused by vehicle bomb, the maximum displacement of the explosion was compared at a point 5 m away from the wall in a straight line, and the results showed that the displacement was approximately 306 mm when the concrete thickness was 450 mm and approximately 94 mm when the thickness was 600 mm. On the other hand, since the stress was calculated by converting the distance from the center of the collision caused by strong winds, a direct comparison is not possible, but it is expected that similar results to those of vehicle terrorism will be obtained.

5. Radiological Emergency Plan & Contingency Plan

Normally, the contingency plan controls the number of people entering and exiting the vital area through a minimum number of entrances and exits. On the other hand, radiological emergency plans require all personnel in the vital area to evacuate as quickly as possible in accordance with the emergency plan, so all entrances to the vital area are opened. To resolve this contradiction, the IAEA technical report Series No. 1000, "The Nuclear Safety and Nuclear Security Interface," [1] recommends the following. First, during the preparedness process, it is crucial to allocate roles and responsibilities for decision making at all levels, taking into account the synergies between nuclear safety and nuclear security. High level decision making ultimately needs to be performed by a single authority or a designated person that can take account of the interface between nuclear safety and nuclear security. In order to improve the decision-making process at all levels, training of responsible organizations specifically on this interface are conducted by State. Secondly, State needed to implement a mechanism for coordinating any revisions to the nuclear security response plans and the nuclear or radiological emergency plans before they are implemented. Thirdly, the interface between nuclear safety and nuclear security is addressed in the conduct of exercises involving scenarios of an emergency triggered by a nuclear security event as well as any other scenario that may warrant a response that can challenge both nuclear security and nuclear safety. Table 5.1 summarized SSI issues and solution.

Table 5.1. SSI technical issues and solution

item	issues	solution
Utilization of probabilistic safety analysis results when establishing vital area	failure trees based on probabilistic safety assessments were not applied. simplify fault trees qualitatively	failure trees based on probabilistic safety assessments were applied when establishing vital area
Relocation of crucial equipment when setting up vital areas	Physical protection design was completed before security plan were submitted, making it impossible to change protection equipment or rearrange key equipment.	consider physical protection design from the construction stage (Security-By-Design)
Maintenance of key equipment located within the vital area during vital area operation	The vital areas that were reset after 2015 are not linked to safety and do not comply with the security requirements stipulated in the Act on Physical Protection and Radiological Emergency Preparedness.	consider physical protection design from the construction stage (Security-By-Design)
Analysis of safety-related severe accidents when assessing vulnerabilities in the design of physical protection systems	In the U.S, the Modular Accident Analysis Program (MAAP) severe accident analysis code developed by the Electric Power Research Institute (EPRI) is used in the industry. (Safety Analysis Code) (Similar to MELCORE) code to evaluate the source term spreading inside and outside the containment vessel in the event of sabotage. In ROK, such analysis is not performed.	Need to link vulnerability assessment with severe accident analysis
Correlation between extreme event and physical protection	Physical protection equipment (e.g., fences, CCTV structures, etc.) is not included for debris related to high winds or tornadoes.	Need to analysis the impact of PP equipment's debris when occur to high winds or tornadoes
The relationship between contingency plan and radiological emergency plan	No link between contingency plan and radiation emergency plan	Compliance with recommendations made in IAEA report

3. Conclusions

The paper outlines the technical connections between key technologies, identify current issues, and propose solutions to these issues for each key technology for SSI and summarized in Table 5.1. It is significant that the paper presents issues and solutions for each field separately.

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