Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Relative Comprehensive Safety Risk Assessment Methodology for Fire Area of Nuclear Power Plant

Young-Suk Jung *, Jae-Hwan Kim, Sung-Jin Kim, Jun-Hyun Park
STANDARD Testing & Engineering Inc., 168, Gajeong-ro, Yuseong-gu, Daejeon, 34129, Republic of KOREA
**Corresponding author: youngs@stdte.co.kr*

*Keywords: Fire Protection, Fire Hazard Analysis, Relative Safety Risk

1. Introduction

All nuclear power plants (NPPs) in Republic of Korea, are required by notifications [1, 2] of the Nuclear Safety and Security Commission (NSSC) to revise and manage the reports to reflect design and operating methods changes during operation after the initial fire hazard analysis (FHA) performed at the time of construction.

The FHA of NPP means quantitative or qualitative analysis to review the risk of a hypothetical fire in each fire area and evaluate the appropriateness of fire prevention and protection measures to ensure the safety shutdown capability and to demonstrate minimizing a possibility of radioactive material leakage out to the environment in the event of a fire in a reactor and related facilities.

The FHA report contains various fire protection analysis/estimation contents such as the designation of fire protection compartment, fire load calculation for fire areas, evaluation of the suitability of fire protection equipment, routing analysis of cables related safety-shutdown, multiple spurious operations (MSO) analysis, and evaluation of fire protection plans and procedures. It varies depending on plant type, in the case of the Korean standard NPP (OPR-1000), it consists of more than 200 fire areas, and so there are realistic limitations in reviewing the analysis results of all fire areas at the same level.

Therefore, it is necessary to intensive review the fire analysis results of high-priority fire areas through management priorities of fire areas by determining the overall safety risk index. Current FHA has been conducted to determine whether each fire protection evaluation factors are satisfied according to a deterministic method for each fire area, this method is useful for qualitatively assessing the risk of each fire area, but it has the disadvantage of not being able to display relative risk index of specific fire area among multiple fire areas.

2. Relative Comprehensive Safety Risk Assessment Methodology

The current FHA, which determines whether each fire protection evaluation factors meet reference values or criteria for each fire area, is useful for qualitative risk estimating for individual fire areas. However, it has the disadvantage of not being able to display the risk of a specific fire area among all areas, so we would like to present an estimation method to compensate for this. A overall workflow of the relative comprehensive safety risk assessment method for each fire area presented in this paper is shown in Figure 1 below.

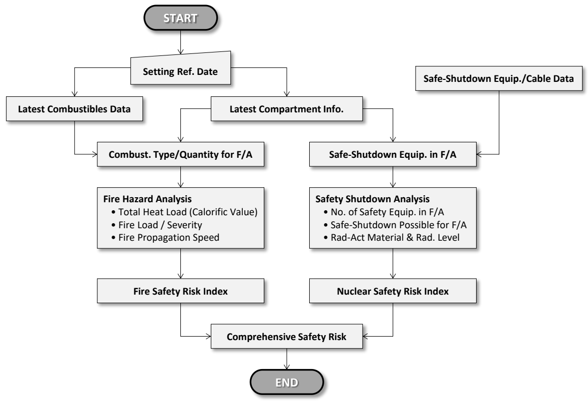

Fig. 1. Work flow of the relative comprehensive risk assessment for fire area

2.1 Fire Safety Risk

Total heat generation, fire load, and fire propagation speed in the event of a fire are selected for the fire safety risk factors for each fire area, and these factors are used to estimate the fire safety risk for the fire area.

2.1.1 Identifying Fire Safety Risk Factor

The fire safety risk factors are defined as a relative index that quantifies the fire risk in multiple fire areas. For example, the fire risk of a fire area is directly related to the fire load in the area, and a specific fire area with a large number of combustibles can be considered to have a greater fire risk factor than an area with no or fewer combustibles. The risk factors are selected as items can be evaluated in units of fire areas and have a large impact on fire risk.

A fire type, which indicates the fire spreads rate of combustibles, can be judged as having a high fire risk if the fire spreads rapidly, such as an ‘oil fire’, or as having a low fire risk if the fire spreads slowly or is limited, such as a ‘small electrical fire’. Depending on the type of combustibles stored in each fire area, it is classified into ‘General’, ‘Electrical’, and ‘Oil’ fires. And if the fire load which indicates the degree of heat load per unit area, is large then it can be judged that the fire risk is high.

2.1.2 Estimating/Computing Fire Safety Risk

The fire safety risk factor for a specific fire area is computed by selecting the total heat generation (a), fire load (b), and fire spread speed (c) for each fire area in the event of a fire, using them to estimate the fire safety risk (F_n) for each fire area as shown below.

First, as shown in Fig. 1 above, based on the estimation reference date, the latest fire compartment information and combustibles data are combined to collect the type and quantity of combustibles for each fire area, and the total heat load and fire load are computed using these data. The fire growth rate is categorized into 'Ultra-Fast', 'Fast', and 'Medium Slow' depending on the fire type by combustibles, and the fire propagation factor is assigned.

The three fire safety risk factors computed in this way are normalized by dividing them by the average of each factor, and using this, the fire safety risk is computed as the area of a triangle with the three vertexes for three evaluation factors as shown in Figure 2 below.

$$F_n = \sqrt{(RMS_F)^2 + (\Delta abc)^2}$$

Where

$RMS_F = \sqrt{{x_1}^2 + {y_1}^2}$ *(RMS; Root-Mean-Square)*

$x_1 = (a_n + b_n + c_n)/3$ *(x_1: Arithmetic Mean)*

$y_1 = \sqrt[3]{a_n \times b_n \times c_n}$ *(y_1: Geometric Mean)*

$\Delta abc = \Delta 1 + \Delta 2 + \Delta 3$ *(Area of Δabc)*

$\Delta 1 = \Delta abo = (a_n \times b_n \times sin\,120°)/2$

$\Delta 2 = \Delta bco = (b_n \times c_n \times sin\,120°)/2$

$\Delta 3 = \Delta cao = (c_n \times a_n \times sin\,120°)/2$

a_n: Heat Load Index of Fire Area n

If $\{\overline{a_n} > a_{avg}\ \&\ \overline{a_n} > 1\}$

Then $a_n = a_{avg} + \log \overline{a_n}$

Else $a_n = \overline{a_n}$

($\overline{a_n} = Heat\ Load\ of\ Area\ n\ / a_{avg}$,

a_{avg}: Average Heat Load of All Fire Area)

b_n: Fire Load Index of Fire Area n

If $\{\overline{b_n} > b_{avg}\ \&\ \overline{b_n} > 1\}$

Then $b_n = b_{avg} + \log \overline{b_n}$

Else $b_n = \overline{b_n}$

($\overline{b_n} = Fire\ Load\ of\ Area\ n\ / b_{avg}$,

b_{avg}: Average Fire Load of All Fire Area)

c_n: Fire Propagation Index of Fire Area n

If $\{\overline{c_n} > c_{avg}\ \&\ \overline{c_n} > 1\}$

Then $c_n = c_{avg} + \log \overline{c_n}$

Else $c_n = \overline{c_n}$

($\overline{c_n} = Fire\ Growth\ Rate\ of\ Area\ n\ / c_{avg}$,

c_{avg}: Average Growth Rate Index of All Fire Area)

Table I: Fire Growth Rate and It's Index

Fire Growth Rate	Growth Rate Index
Ultra-Fast	3
Fast	2
Medium-Slow	1
-	0

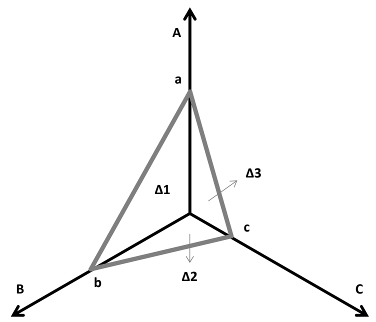

Fig. 2. Safety risk computing method by area of triangle with 3 vertexes for 3 evaluation factors

2.2 Nuclear Safety Risk

The nuclear safety risk factors for each fire area are selected from success of reactor safety shutdown in the event of a fire in a specific fire area, the density of safety equipment and cables in the area, and the radiation level in the fire area, and the nuclear safety risk for each fire area is estimated by combining them.

2.2.1 Identifying Nuclear Safety Risk Factor

The nuclear safety risk factors are numerical indexes that indicate the risk level of nuclear or radiation accidents in a specific fire area relative to the entire area. The success of reactor safety shutdown in the event of a fire in fire area is the most important item, and the density of equipment and cables in the area related to the reactor safety shutdown are selected as a risk factor. In addition, the radiation level of the fire area is selected too as a risk factor to determine the possibility of radioactive materials leakage to adjacent areas.

Fire areas where safety shutdown devices are installed are judged to have a higher nuclear safety risk than not installed areas, as they are more important in terms of fire protection. Although protective measures are in place to prevent the leakage of radioactive materials in the event of a fire in a specific area, the risk of fire in areas with high radiation level is judged higher than in areas with normal level.

2.2.2 Estimating/Computing Nuclear Safety Risk

The success of reactor safety shutdown in the event of a fire in a specific area (i), the density of safety shutdown equipment and cables (j), and the radiation level of the fire area (k) are selected as risk factors, and the nuclear safety risk (N_n) for each fire area is estimated applying these factors.

When a fire occurs in a specific fire area, the safety shutdown equipment affected by fire for each fire area are checked as shown in Figure 3 below. In the event of a fire in a specific room within a fire area, it is assumed that not only the equipment in the room are affected by the fire but also all equipment in the same fire area and equipment connected to wire through the fire area are affected by the fire. The safety shutdown analysis is performed with fault tree reflecting the fire affected equipment checked for each fire area as shown in Figure 4 below.

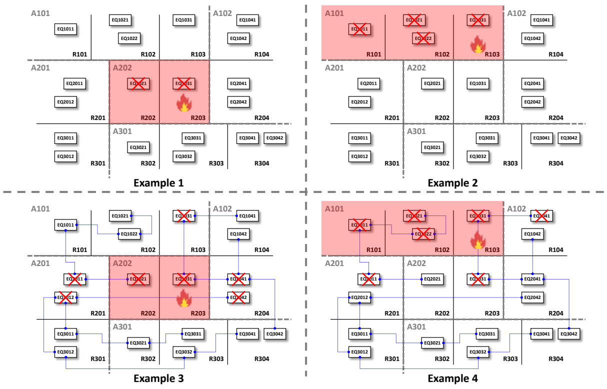

Fig. 3. Example of affected equipment in the event of a fire for fire area

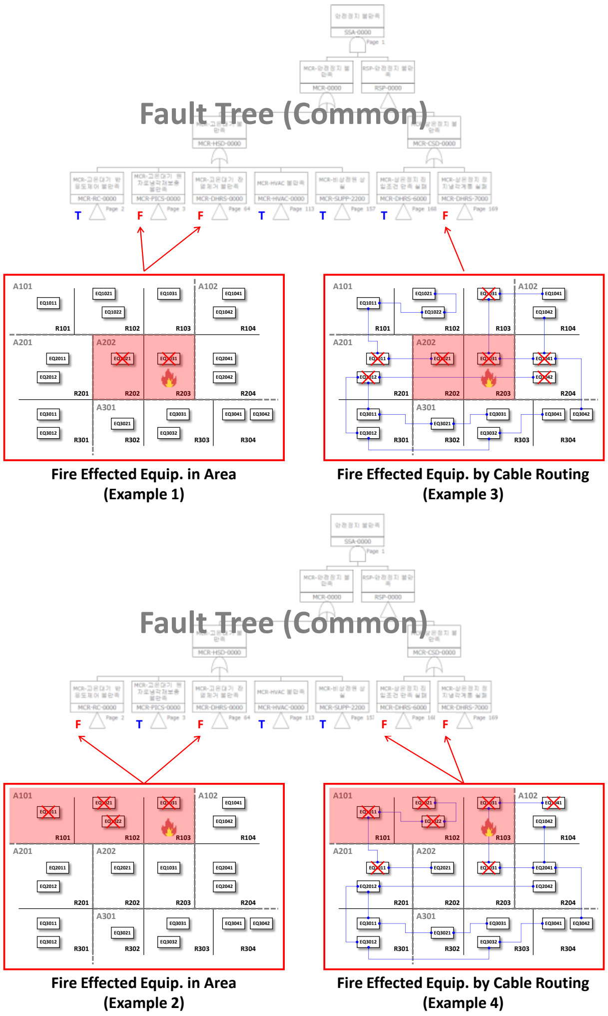

Fig. 4. Example of performing safety-shutdown analysis using a fault-tree reflecting the affected equip. in each area

For each fire area, three nuclear safety risk factors are derived; the success of reactor safety shutdown in the event of a fire, the normalized density of a number of safety-related equipment and cables affected by a fire, and the normalized radiation level of the fire area.

The three nuclear safety risk factors derived in this way are normalized for each factor, and the nuclear safety risk is computed as the area of a triangle with the three vertexes for three evaluation factors as shown in Figure 2 above.

$$N_n = \sqrt{(RMS_N)^2 + (\Delta ijk)^2}$$

Where

$$RMS_N = \sqrt{{x_2}^2 + {y_2}^2} \quad \text{(RMS; Root-Mean-Square)}$$

$$x_2 = (i_n + j_n + k_n)/3 \quad (x_2\text{: Arithmetic Mean})$$

$$y_2 = \sqrt[3]{i_n \times j_n \times k_n} \quad (y_2\text{: Geometric Mean})$$

$$\Delta ijk = \Delta 4 + \Delta 5 + \Delta 6 \quad (\text{Area of } \Delta abc)$$

$$\Delta 4 = \Delta ijo = (i_n \times j_n \times sin\, 120°)/2$$

$$\Delta 5 = \Delta jko = (j_n \times k_n \times sin\, 120°)/2$$

$$\Delta 6 = \Delta kio = (k_n \times i_n \times sin\, 120°)/2$$

i_n: Safe-Shutdown Fail Index of Fire Area n
In case of Fire in Fire Area n,
If Reactor Safety Shutdown is impossible, $i_n = 3$
If Reactor Safety Shutdown is possible, $i_n = 1$
If Fire Area n is not related to Safety Shutdown, Then $i_n = 0$

j_n: Safety Shutdown Equipment and Cable Density Index of Fire Area n

$$\text{If } \{\overline{j_n} > j_{avg} \;\&\; \overline{j_n} > 1\}$$

$$\text{Then } \; j_n = j_{avg} + \log \overline{j_n}$$

$$\text{Else } \; j_n = \overline{j_n}$$

$$(\overline{j_n} = \sqrt{{E_n}^2 + {C_n}^2} \Big/ b_{avg},$$

$$j_{avg}\text{: Average } \sqrt{{E_n}^2 + {C_n}^2} \text{ of All Fire Area)}$$

E_n: Affected Safety Equip. Index of Fire Area n
(= No. of Affected Safe Equip. / Avg. No. of All Area)
C_n: Affected Safety Cable Index of Fire Area n
(= No. of Affected Safe Cable / Avg. No. of All Area)

k_n: Radiation Level Index of Fire Area n
(= Radiation Level No. / Avg. Rad-Level No.)

Table II: Radiation Level and It's Index

Radiation Level	Rad. Level Index
$\leq$ 0.001 mSv/hr	1
$\leq$ 0.01 mSv/hr	2
$\leq$ 0.05 mSv/hr	3
$\leq$ 0.2 mSv/hr	4
$\leq$ 1 mSv/hr	5
$\leq$ 10 mSv/hr	6
$\leq$ 5000 mSv/hr	7
> 5000 mSv/hr	8

2.3 Comprehensive Safety Risk

The relative comprehensive safety risk (A) of a specific fire area is computed using the fire safety risk (F) and the nuclear safety risk (N) derived using the method described above, as shown in Table III and IV below. Since the fire safety risk and the nuclear safety risk computed in this way have a significant difference in the magnitude of the calculated absolute value, to compensate for this, the relative comprehensive safety risk is calculated by multiplying a weight for the fire safety risk (w_F) and a weight for the nuclear safety risk (w_N).

Table III: Risk Assessment Items by Safety Risk Factor

Risk Assessment Item		
Fire Safety Risk	1. Total Heat Load	F_1
	2. Fire Load	F_2
	3. Fire Growth Rate	F_3
Nuclear Safety Risk	1. Safety Shutdown Success	N_1
	2. Safe Equip./Cable Density	N_2
	3. Radiation Level	N_3

Table IV: Computing Method
of the Relative Comprehensive Safety Risk

Relative Comprehensive Safety Risk Computing Method	
Fire Safety Risk (F: Area of $\Delta F_1F_2F_3$)	Relative Comprehensive Safety Risk $A = \sqrt{(F \times w_F)^2 + (N \times w_N)^2}$
Nuclear Safety Risk (N: Area of $\Delta N_1N_2N_3$)	

※w_F, w_N: *relative weighting factor*

The relative comprehensive safety risk (A) of a specific fire area is computed using the fire safety risk (F) and the nuclear safety risk (N) calculated by the method described above, as follows. The calculating method for the weights (the weight of the fire safety risk (w_F), and the weight of the nuclear safety risk (w_N)) to compensate for the absolute difference between the calculated value of the fire and nuclear safety risk is as follows.

$$A_n = \sqrt{(F_n \times w_F)^2 + (N_n \times w_N)^2}$$

Where

$$w_F = {N_{avg}}\Big/{(F_{avg} + N_{avg})}$$
$$w_N = {F_{avg}}\Big/{(F_{avg} + N_{avg})}$$

A_n: *Relative Comprehensive Safety Risk of Area n*
F_n: *Fire Safety Risk of Area n*
N_n: *Nuclear Safety Risk of Area n*
w_F: *Relative Weighting Factor for Fire Safety Risk*
w_N: *Nuclear Safety Risk Relative Weighting Factor*
F_{avg}: *Average Fire Safety Risk of All Area*
N_{avg}: Average Nuclear Safety Risk of All Area

By synthesizing the aforementioned process, the relative comprehensive safety risk for each fire area be derived as shown in Figure 6 below, and the relative comprehensive safety risk of the entire fire area can be diagrammed.

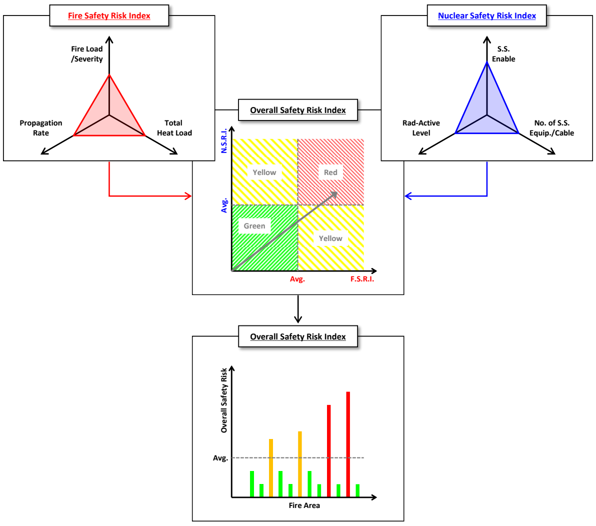

Fig. 5. Relative Comprehensive Safety Risk Deriving Method based on the Fire & Nuclear Safety Risk

3. Examples of Applying the Relative Comprehensive Safety Risk Assessment Method

The above-mentioned risk assessment methodology is applied to a specific OPR-1000 NPP to calculate the fire safety risk and nuclear safety risk for each fire area, and the relative comprehensive safety risk is derived based on this.

3.1 Examples of the Fire Safety Risk Assessment

A distribution of the fire safety risk of the OPR-1000 NPP evaluated based on the total heat generation, fire load, and fire growth rate for each fire area is as shown in Figure 6 below. Among the total number of fire areas (284), 17.3% (49) have the fire safety risk above the average (0.68), and 82.7% (235) have the risk below the average.

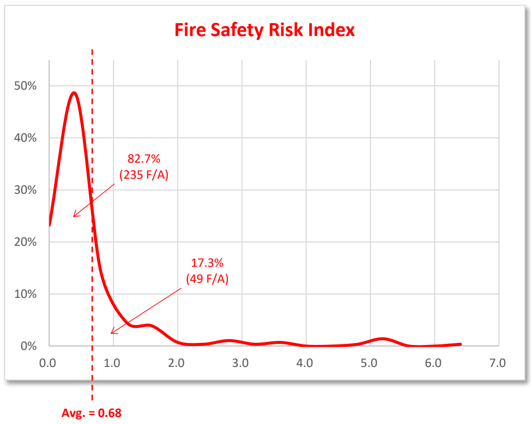

Fig. 6. Example of a Fire Safety Risk Distribution of OPR-1000 NPP

3.2 Examples of the Nuclear Safety Risk Assessment

A distribution of the nuclear safety risk of the OPR-1000 NPP evaluated based on success of reactor safety shutdown in the event of a fire, the density of equipment and cables related safety shutdown in each fire area, and radiation level of fire area is as shown Figure 7 below. Among the total number of fire areas (284), 32.0% (91) have the nuclear safety risk above the average (1.13), and 68.0% (193) have the risk below the average.

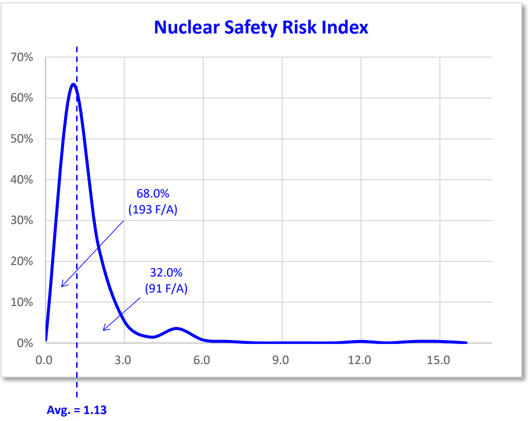

Fig. 7. Example of a Nuclear Safety Risk Distribution of OPR-1000 NPP

3.3 Examples of the Comprehensive Safety Risk Assessment

The relative comprehensive safety risk for each fire area is derived based on the previously evaluated the fire safety risk and the nuclear safety risk. The distribution of fire area using the two axes of the fire safety risk and the nuclear safety risk is as shown in Figure 8 below. In the example below, there are 19 fire areas (6.7%) where both the fire safety risk and the nuclear safety risk are above the each average and 163 areas (57.4%) where both risks are below the each average.

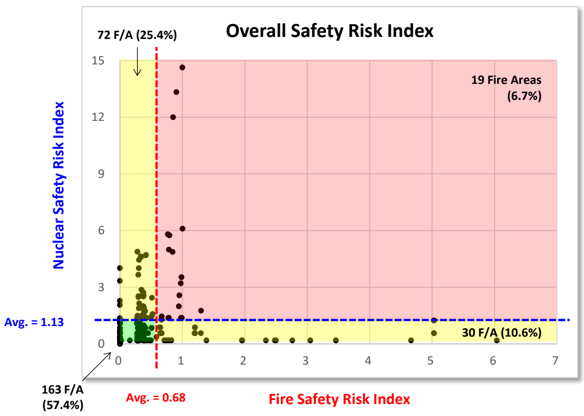

Fig. 8. Example Graph showing the Fire & Nuclear Safety Risk of OPR-1000 NPP on simultaneously 2 axes

4. Conclusions

This paper presents the method for deriving fire and nuclear safety risk factors based on NPP fire protection information, and estimating the relative comprehensive safety risk for fire areas in NPPs applying these risk factors.

To indicate the relative risk of a specific fire area, the relative comprehensive safety risk can be assessed by multiple evaluation factors that quantitatively indicate the risk level of the fire area. Then it is expected that the risk level of all fire areas in the NPP can be sequenced, and more efficient fire protection and safety management can be achieved by giving management priority and concentrating management on high-ranking fire areas with high risk.

REFERENCES

[1] Nuclear Safety and Security Commission Notification No. 2018-9, Technical Standard for Fire Risk Analysis.
[2] Nuclear Safety and Security Commission Notification No. 2020-2, Regulation on the Establishment and Implementation of Fire Protection Plan.
[3] KEPIC FPN 2000 Nuclear Power Plant Fire Prevention, Appendix A.
[4] Korean Patent No. 10-1062306, “Integrated Management System and Method for Fire Safety” (August 2011)
[5] Korean Patent No. 10-1861118, “Relative Comprehensive Safety Risk Management Method for Fire Area in Nuclear Power Plant” (May 2018)
[6] Korean Patent No. 10-0000000, “Relative Comprehensive Safety Risk Assessment Methodology for Fire Area of NPP” (July 2024)
[7] Jun-Hyun Park, “Fire Risk Ranking of Fire Areas by Multi-attribute Measurement, Korean Institute of Fire Science & Engineering 2008 Autumn Meeting (Nov. 2008)

Acknowledgement

This work is a result of project “Development of a computer program to support the fire protection safety issues and regulatory activities” (Project No. 1075001519, Detailed No. 2204016-0122-SB110) supported by Korea Foundation of Nuclear Safety (KOFONS) grant funded by Korean Government (Nuclear Safety and Security Commission).