Development of Comparison Methodologies of Importance Analyses for Level 1 PRA and Level 2 PRA using Multiple Indicators

KOJO, Retsu[a*]
[a] Nuclear Regulation Authority, Tokyo, JAPAN

Abstract: There are a number of significance evaluation examples in the risk-informed significance determination process (SDP) for light water reactors using core damage frequency (CDF) and large early release frequency (LERF). However, only a few significance evaluation examples exist using containment failure frequency (CFF) based on probabilistic risk assessment (PRA). Therefore, this study addresses the issues that arise when conducting significance evaluation in the SDP that includes CFF and establishes a method to determine whether CDF or CFF is the more significant indicator for degradation events of structures, systems, and components (SSCs). The method compares the relative significance of multiple indicators (CDF and CFF) using regression analysis on the importance analysis results. The method revealed that the importance of multiple indicators can be compared in a concise manner. Furthermore, in past practices of the SDP, the absolute values of change in the results of PRAs are generally applied. This study proposed to use the relative value of change to clearly determine the more significant indicator. This approach revealed that it is possible to determine whether a degradation event has a greater impact on CDF or CFF, considering the characteristics of the PRA model.

Keywords: Level 2 PRA, CDF, CFF, SDP, significance determination process

1. INTRODUCTION

Level 1 and Level 2 probabilistic risk assessments (PRAs) are used in the significance determination process (SDP). Core damage frequency (CDF) is a risk metric for Level 1 PRA and is used as an indicator in significance evaluations of the SDP [1][2]. Moreover, several types of risk metrics, such as large early release frequency (LERF), large release frequency, and containment failure frequency (CFF), are used for Level 2 PRA. The metrics are selected based on the specific purposes of the PRA or safety criteria. CDF and LERF are used as indicators for significance evaluations of the SDP in the USA [3]. The metrics are alternative objectives based on safety goals and quantitative health objectives (QHOs) of the U.S. nuclear regulatory commission (NRC) [4][5]. As for QHOs, the risk metrics CDF and LERF are used as surrogates for the individual latent cancer fatality risk and the individual early fatality risk, respectively [7]. LERF is defined as the total frequency of accident scenarios leading to rapid, unmitigated releases of fission products into the environment. Such accident scenarios generally include containment bypass sequences and loss of containment isolation sequences. Thus, LERF does not include partially mitigated scenarios, such as the Fukushima Daiichi Nuclear Power Plant (NPP) accident, while CFF includes all containment failure sequences. In Japan, CDF and CFF are used as indicators in the SDP [2][6], and the metrics are defined based on performance goals [7]. The new regulatory standard was issued after the Fukushima Daiichi NPP accident, and measures to prevent core damage and containment failure were implemented. Structures, systems, and components (SSCs) concerning the measures were subject to periodic inspections and were modeled in PRAs. Therefore, SSCs that can be treated as risk information have been extended to include containment protection measures. As a result, degradation events can affect both indicators, i.e., CDF and CFF, in significance evaluations in the SDP. In the case of using multiple indicators for the SDP, the significance of each indicator can be assessed considering differences in the models of Level 1 and Level 2 PRAs. Normally, each result is compared with target values. However, it is expected that the SDP method can be improved by analyzing the relationship between significance evaluation results for different indicators considering the characteristics of PRA models. Therefore, the objective of this study is to address the issues that arise by implementing the SDP with CFF and to establish a new method to determine suitable indicator for degradation events.

2. Issues using multiple indicators in SDP

2.1. Identification of problems using multiple indicators in SDP

In the SDP, the results of significance evaluation are compared with quantitative criteria for each indicator. In many cases, the criteria for Level 2 PRAs are an order of magnitude lower than those for Level 1 PRAs [1][2]. The inspection manual for the SDP of the containment barrier integrity in Japan is similar to that of the USA; however, CFF is used as an indicator instead of LERF [6]. Table 1 presents examples of evaluation results for

Level 1 and Level 2 PRAs. The conditional containment failure probabilities (CCFPs) correspond to probabilities of occurrence of CFF relative to CDF are larger than 0.1 for all models. The results show that many SSCs modeled in the PRA are not only used to prevent containment failure but also used as measures to prevent core damage. When CCFP values exceed 0.1, the severity of CFF in the SDP tends to be larger. Thus, significance evaluation using multiple indicators may be converged in a particular indicator, depending on the characteristics of the PRA models.

Table 1. Examples of CDF and CFF results

Case	Code	CCFP	Reference
Case 1	SAPHIRE	0.66	NRC, Full Scope Level 3 PRA [9] 1)
Case 2	Risk Spectrum	0.34	ASAMPSA2[10] 2)
Case 3	SAPHIRE	0.50	NRA, S/NRA/R Research Report [11] 3)

Note: CCFPs described in the table are calculated as follows:
1) The frequencies for CCFP have been summarized based on the results in Table 3.2-2 of "Cria-2012 Case" in the full scope Level 3 PRA report [9]. Table.2.2-3 describes the release categories contributing to CCFP.
2) The frequencies of containment function within the design range (Category FKJ) have been excluded from all release category frequencies based on the results presented in Table 4 of the ASAMPSA2 report [10].
3) The frequencies were recalculated using the CCFP for core damage and containment failure listed in Table 2.2.3 of the S/NRA/R research report [11].

2.2. Discussions of modeling of Level 2 PRA and quantification of CDF and CFF

Some international organizations have issued guidelines for modeling of Level 2 PRAs [12][13][14][15]. Several methods have been proposed for the interface between Level 1 and Level 2 PRAs. Plant damage status (PDS) is used to categorize and address a large number of sequences when transferring the results of Level 1 PRA to Level 2 PRA. Two types of methods can be considered for classifying the results of Level 1 PRA by PDS and transferring them to Level 2 PRA. These include (A) transferring the minimal cut set (MCS) for each PDS and (B) transferring only the frequency, i.e., the quantified value of each PDS. Since the development of computer resources has made it relatively easy to transfer the results of thousands Level 1 PRA sequences to Level 2 PRA in recent years, Level 1 and Level 2 PRAs have been treated as a single model and integrated at the MCS level. The number of integrated models has been increasing.

Figure 1 shows the schematics of the analyses. Event trees (ETs) for Level 1 PRA are defined for each initiating event (IE), where end states are mainly defined as intact or core damage. Sequences resulting in core damage are summarized for each PDS and transferred to the containment event tree (CET) for each PDS. End states of the CET include not only containment failure but also design leaks and controlled releases. The quantification process for both methods is presented below. For simplicity, upper bound approximation is used here.

(A) **<u>Transferring MCSs from Level 1 PRA to Level 2 PRA</u>**

CDF is quantified using MCSs for core damage, as shown in Eq. (1). Similarly, CFF can be quantified using MCSs for the sequence for containment failure, as shown in Eq. (2). To use Eq. (2), Level 1 and Level 2 PRAs should be combined using Boolean algebraic methods. MCSs for containment failure need to be treated as continuous sequences from IE, core damage (*CD*), to containment failure (*CF*) and need to be Boolean for all headings appeared in each sequence.

$$CDF = 1 - \prod_{i}^{N} (1 - F_{mcs_i}^{CD}) \tag{1}$$

$$CFF = 1 - \prod_{j}^{M} (1 - F_{mcs_j}^{CF}) \tag{2}$$

where $F_{mcs_i}^{CD}$ is the frequency of MCS_i for CD, in which i represents the i-th MCS_i out of the total number of N, and $F_{mcs_j}^{CF}$ is the frequency of MCS_j for CF, in which j represents the j-th MCS_j out of the total number of M.

(B) **<u>Transferring quantified frequencies of PDS from Level 1 PRA to Level 2 PRA</u>**

Equations (3) - (5) describe the method using quantified values of CDF as the interface to Level 2 PRA. In this method, MCSs in each PDS are summed and quantified to CDF, as shown in Eq. (3). CCFP, which is analyzed in CET, is quantified for each PDS according to Eq. (4) in this method. CDFs are then multiplied by the CCFPs of each PDS to obtain the CFF, as shown in Eq. (5).

$$CDF^{PDS_l} = 1 - \prod_{i}^{N_l} (1 - F_{mcs_i}^{CD_l}) \tag{3}$$

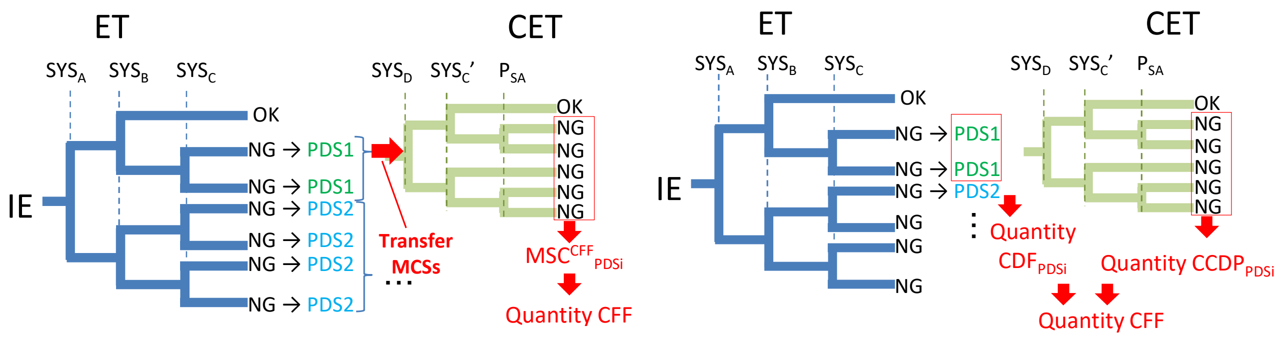
$$CCFP^{PDS_l} = 1 - \prod_{j}^{M_l} (1 - P_{mcs_j}^{CET_l}) \tag{4}$$

$$CFF = \sum_{l}^{L} CCFP^{PDS_l} * CDF^{PDS_l} \tag{5}$$

where CDF^{PDS_l} is the frequency of MCS_i for CD in PDS_l, in which l represents a specific PDS, $CCFP^{PDS_l}$ is the probability of containment failure for PDS_l, $P_{mcs_j}^{CET_l}$ is the quantified probability of MCS_j for CET in PDS_l, calculated only for CET, and L is the total number of PDS. To calculate the CFF using this approach, the CDFs for each PDS need to be multiplied by the corresponding CCFPs.

In Level 2 PRA, Method (A) is more detailed than Method (B). It is because, for SSCs modeled in both Level 1 and Level 2 PRAs, basic events modeled in Level 1 are processed in a Boolean algebraic manner in Method (A). In both methods, PDS classifications are used at the interface, and it is known from previous studies that detailed PDS classifications and conditioning can represent the spectrum of risk in Level 2 PRA.

The interfaces should be selected according to the purpose of PRAs. Method (A) is more appropriate for PRAs that use CFF as an indicator and require significance evaluation for targeting NPPs with numerous SSCs for containment protection. This is because modeling various SSCs is necessary in Level 2 PRA and dependencies between Level 1 and Level 2 PRAs are to be considered. Meanwhile, Method (B) is suitable for PRAs that use LERF as an indicator and aim to assess the entire risk spectrum. This is because the number of SSCs that need to be modeled in Level 2 PRAs is limited.



(A) Method of transferring MCSs (B) Method of transferring frequencies

Figure 1. Images of the interface between Level 1 PRA and Level 2 PRA

3. Present proposed new methodologies

3.1. Analysis of SSCs in importance analysis using multiple indicators

The amount of change in frequency for CDF and CFF is calculated for the degradation event to evaluate the significance of inspection findings in the SDP. This study proposes a method to predict the trends of individual SSCs by using general importance analysis as a reference for significance evaluation in the SDP with multiple indicators. The Fussell - Vesely (FV) importance and risk achievement worth (RAW) importance are generally used in importance analysis and are calculated using Eqs. (6) and (7):

$$FV_i^S = \{F^s(x) - F^s(0)\}/F^s(x) \tag{6}$$

$$RAW_i^S = F^s(1)/F^s(x) \tag{7}$$

where RAW_i^S and FV_i^S are RAW importance and FV importance for the basic event i, respectively. The superscript s is the index of CDF or CFF. $F^s(1)$ and $F^s(0)$ are values obtained by substituting 1.0 and 0.0 for the target basic event i, respectively. In the significance evaluation of the SDP degradation events, the evaluation is based on the assumption that the target basic event is *true* or in a degraded condition with a higher probability. Equations (6) and (7) show that the evaluation results with RAW importance correspond to the results of significance evaluation. In the importance analysis by consistent analysis models (Method (A)), it is possible to perform importance analysis for the indicators CDF and CFF for each basic event.

Figure 2 shows the evaluation results of the RAW importance for CDF and CFF. Two RAW importance values can be calculated for both CDF and CFF in one basic event. The importance values can be compared to determine which importance value is larger. This figure shows the importance of CDF and CFF on the horizontal axis and the vertical axis, respectively. This result includes results from two PRA models.

The RAW importance was analyzed using regression analysis, and the predicted values and upper or lower 95% estimated values of CFF against CDF were predicted. In this analysis, the population of RAW results was assumed to follow a t-distribution, and all basic events were included except for IEs, human error, common cause failure, and severe accident phenomena that have unique characteristics compared to a typical basic event involving a single failure mode.

As shown in Fig. 2, the results clearly determine the importance between systems that strongly affect CFF (such as specific basic events of residual heat removal (RHR) and component cooling waters system (CCW) systems) and systems that strongly affect CDF (such as specific basic events of direct current (DC) and accumulator (ACC) systems). Thus, the region where the importance exceeds the predicted value means that the degradation events of SSCs have a greater impact on CFF, and it enables to indicate which indicator a particular basic event is more important to.

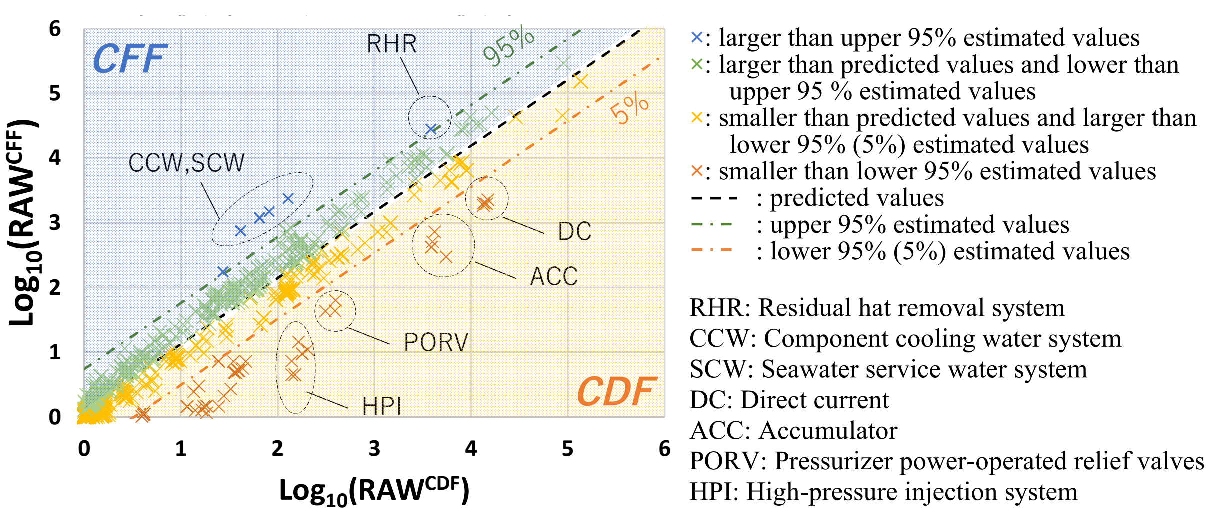


Figure 2. Analysis results comparison of RAW importance for CDF and CFF

Note: This figure includes results from two PRA models. The system groups described in the figure are representative basic events, but not all of the basic events are included in the systems.

3.2. Advanced significance evaluation using multiple indicators for SDP

Referring to the comparison method used in Section 3.1, a significance evaluation method for the SDP is developed using CDF and CFF. In the SDP, the significance of a degradation event is evaluated by calculating ΔCDF and ΔCFF, which represents the change in CDF and the change in CFF, respectively, as shown in Eqs. (8) and (9):

$$\Delta CDF = (CDF_A - CDF_{BS}) * \dot{T} \quad (8)$$

$$\Delta CFF = (CFF_A - CFF_{BS}) * \dot{T} \quad (9)$$

where CDF_A and CFF_A represent the CDF and CFF values assuming a failure or in a degraded condition with a higher probability due to degradation event A. $\dot{T}$ is a coefficient for the duration of the degradation event and converts the frequency unit (per plant year) to the degradation duration unit ($\dot{T}$ = t/8760), with the *t* being the duration of the degradation event. ΔCDF and ΔCFF are the absolute values of the change and are compared to the criteria. The criteria value for the CFF is typically one order smaller than the CDF. As presented in Table 1, the CCFP value is often larger than 0.1. Therefore, when comparing ΔCDF and ΔCFF, which are absolute values of change, ΔCFF tends to have greater significance. Since CCFP is different in plant models, comparing only the absolute values of ΔCDF and ΔCFF cannot consider model-specific weights, such as CCFP. Therefore, this study proposes adding ΔCDF/CDF and ΔCFF/CFF, which represent the relative changes, into the indicators in the SDP. This enables to evaluate the significance of including weights from Level 1 PRA and Level 2 PRA results.

For validation purposes, the evaluation for a total of 1,801 basic events was performed using previously described methods. Table 2 presents the comparison results of the significance using absolute values, relative values, and RAW importance in PRA. The evaluation conditions assume that the target basic event failure has continued for 24 h. Comparing the absolute values, such as ΔCDF and ΔCFF, shows that the values of ΔCDF itself and ΔCFF multiplied by 0.1 were used to adjust for the criterion. As a result, it was confirmed that the evaluation of absolute values does not always agree with the RAW importance of the PRA. However, when using relative values, such as ΔCDF/CDF and ΔCFF/CFF, the results agree with the those using RAW importance.

Significance evaluation using the proposed method was conducted for the five specific basic events for detailed analysis. Table 3 presents the evaluation results. Specifically, the following equipment were chosen: (a) equipment that made large contributions to CFF (larger than 95% of the predicted value), (b) equipment that made large contributions to CDF (smaller than 5% of the predicted value), (c) front systems with results close to the predicted value, (d) support systems with results close to the predicted value, and (e) equipment for power supply systems, which are included in both Level 1 and Level 2 PRAs. The degradation duration is 24 h. The discussion of the results is as follows: (a) For SSCs with larger importance than 95% of the predicted value, the CFF results were significant for all indicators because SSCs were obviously significant for CFF. (b) For SSCs with smaller importance than 5% of the predicted value, the CDF results were significant for all indicators. (c) - (e) For SSCs that were used in both Level 1 and Level 2 PRAs and were distributed around the predicted value, the absolute values show greater significance for the indicator CFF, but the relative values show greater significance for the indicator CDF. Although the results are opposite, the evaluation results of the relative value are also consistent with the RAW importance, indicating that the degradation events have a larger impact on CDF when the characteristics of the PRA model are considered. Thus, using relative values enables to express the impact of indicators more clearly using multiple indicators. Determining significance quantitatively based on absolute values from the SDP results is essential because the values should be confirmed against performance criteria or safety criteria as surrogates for social risks. As a further detailed support information, the evaluation methodology developed in this study can be used to select significant indicators for the SDP using multiple indicators.

The author has demonstrated potential methods for detailed assessment of SSC in the case of multiple indicators in SDP. The scope of application and precautions of the methods are needed to be discussed for implementation of SDP.

Table2. Summary of results of comparing multiple indicators

Comparison of multiple indicators	Number of basic events that have greater significance for each indicator	
	CDF	*CFF*
*ΔCFF vs ΔCDF*0.1*	1,689	112
ΔCDF /CDF vs ΔCFF/CFF	1,278	523
RAW^{CDF} vs RAW^{CFF}	1,278	523

Table3. Examples of significance evaluation results of degradation events with multiple indicators

No.	Basic events	Absolute values		Relative values		RAW
		ΔCDF	*ΔCFF*	*ΔCDF ／CDF*	*ΔCFF ／CFF*	*RAW^{CDF} ／RAW^{CFF}*
1	Inner leak of a motor-operated valve on RHR system	1.0E-08	9.3E-08	1.1E-01	1.0E+00	18.2
2	Error open of a pilot-operated relief valve on pressurizer system	2.0E-06	9.8E-08	1.1E+00	5.4E-02	0.2
3	Fail to start of a pump on the low-pressure injection system	3.9E-06	7.6E-07	2.2E+00	4.2E-01	0.6
4	Blockade of a manual valve on component cooling water system	3.0E-08	1.0E-08	3.4E-01	1.1E-01	0.7
5	Failure of a control center	1.5E-06	2.2E-07	8.2E-01	1.2E-01	0.5

Note: This table includes results from two PRA models .

4. CONCLUSION

In the use of risk information using PRAs, such as the SDP, this study clarified the characteristics of importance analysis using PRA models that integrates Level 1 and Level 2 PRAs to evaluate degradation events using CDF and CFF as indicators. Based on the results, a method was proposed to determine the priority of multiple indicators for SSCs modeled in PRAs.

In the significance evaluation of the SDP, detailed insights are available by comparing the relative value, ΔCDF/CDF and ΔCFF/CFF, for a degradation event to be evaluated for multiple indicators of PRAs, in addition to the absolute value, ΔCDF and ΔCFF, to compare with quantitative criteria as surrogate risk indicators. The method enables to determine whether CDF or CFF is the more significant indicator considering characteristics of PRA models. Further discussion for application of the methods is needed for implementation of SDP .

References

[1] U.S.NRC, Significance Determination Process, Inspection Manual, Chapter 0609, U.S.Nuclear Regulatory Commission, U.S.A, pp.3-4, 2020.
[2] NRA, Guide for Significance Determination Assessment for Nuclear Safety, Risk Management Office, Nuclear Regulation Authority, Japan, https://www2.nra.go.jp/data/000436823.pdf (Accessed, May.7, 2024).
[3] U.S.NRC, Basis Document for Large Early Release Frequency (LERF) Significance Determination Process (SDP) Inspection Findings that May Affect LERF, U.S. Nuclear Regulatory Commission, pp3-4, 2020.
[4] M. Drouin, Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing Appendices A through L, NUREG-1860, Vol. 2, Appendix D, U.S. Nuclear Regulatory Commission, 2007.
[5] U.S.NRC, Risk Metrics for Operating New Reactors, U.S. Nuclear Regulatory Commission, 2009.
[6] NRA, Guide for Significance Determination Assessment for Nuclear Safety, Appendix.7, Guide for Significant Determination Process for Barrier Integrity, Risk Management Office, Nuclear Regulation Authority, Japan, https://www2.nra.go.jp/data/000360578.pdf (Accessed, May.7, 2024).
[7] U.S.NRC, An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis, Regulatory Guide 1.174, Revision 3, U.S.NRC, 2018.
[8] Nuclear Safety Commission, Performance Goals for Commercial Nuclear Power Reactors -Performance Goals for the Proposed Safety Goals-, Special Committee on Safety Goals, Nuclear Safety Commission, Japan, 2006.
[9] S. Sancaktar, et. al., U.S. NRC Level 3 Probabilistic Risk Assessment (PRA) Project, Volume 3c: Reactor, At-Power, Level 2 PRA for Internal Events and Floods (Draft), U.S.NRC, 2022. https://www.nrc.gov/docs/ML2206/ML22067A214.pdf (Accessed, May.7, 2024).
[10] ASAMPSA2, Best-Practices Guidelines for L2PSA Development and Applications, Volume 2 - Best Practices for the Gen II PWR, Gen II BWR L2PSAs (draft), Extension to Gen III Reactors, Technical Report ASAMPSA2/WP2&3/2010-28, 2010.
[11] R. KOJO, et. al., Development of Analysis Methods for the Containment Failure and Probabilistic Assessment of Risks Associated with Severe Accidents Involving Light Water Reactors, S/NRA/R Research Report, RREP-2023-2002, Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority (S/NRA/R), 2023.
[12] IAEA, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, pp. 17-23, IAEA, 2010.
[13] OECD/NEA, Level 2 PSA Methodology and Severe Accident Management, NEA/CSNI/R(1997)11, OCDE/GD(97)198, pp.154-165, CNRA Working Group on Inspection Practices (WGIP), 1997.
[14] ASME, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-S-1.1-2022, American National Standard Institute, 2022.
[15] ASME, Severe Accident Progression and Radiological Release (Level 2) PRA Standard for Nuclear Power Plant Applications for Light Water Reactors (LWRs), ASME/ASN RA-S-1.2-2014, American National Standard Institute, 2014.