Enhancing Accuracy in Level 2 PSA: Application of Partial BDD Method for High-Failure Probability Portable Equipment

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ABSTRACT

This study addresses a critical issue in Level 2 Probabilistic Safety Assessment (PSA) models that include high-failure probability portable equipment. When using the Rare Event Approximation technique for quantification, these models often result in plant damage state frequencies that are disproportionately higher than core damage frequencies. To mitigate this discrepancy, we propose and evaluate the application of the Partial Binary Decision Diagram (BDD) method. The primary objective of this research is to verify that implementing the Partial BDD method in Level 2 PSA models with high-failure probability events reduces the gap between core damage frequency and plant damage state frequency. Our methodology involves applying the Partial BDD method to high-failure probability branches within a Level 2 PSA model that incorporates portable equipment, and subsequently analyzing the differences in frequencies. Key findings demonstrate that appropriate utilization of Partial BDD in quantifying Level 2 PSA models with portable equipment significantly narrows the disparity between core damage and plant damage state frequencies. Importantly, this is achieved without substantially increasing overall computation time. In conclusion, for PSA models of plants where high-failure probability portable equipment plays a significant role, the judicious application of Partial BDD in quantification effectively prevents the excessive divergence between core damage and plant damage state frequencies typically caused by Rare Event Approximation. This approach offers a valuable solution for enhancing the accuracy of Level 2 PSA models without compromising computational efficiency.

Keywords:

Level 2 PSA, PSA Quantification, Partial BDD, Portable Equipment, PDS Frequency

I. Introduction

Since the Fukushima accident in Japan, many countries operating nuclear power plants have established strategies to cope with severe accident scenarios caused by extreme hazard such as loss of ultimate heat sink (LUHS) and extended loss of AC power (ELAP). In the United States, accident mitigation strategies using portable equipment, represented by FLEX, have been introduced to many power plants. In Korea, a similar accident mitigation strategy using portable equipment, represented by MACST, has also been introduced.

In Korea, MACST was introduced after the Nuclear Safety Act Article 20 (Operation License) was fully legislated in June 2016, requiring the submission of accident management plans and the preparation of new portable equipment for extreme hazard preparedness in all nuclear power plants. Consequently, there was a growing need to conduct PSAs that include portable equipment to assess how much nuclear power plant safety is improved when accident mitigation strategies such as MACST are applied.

An investigation of FLEX in the U.S. and MACST in Korea, it was revealed that strategies using portable equipment are effective in maintaining containment integrity after core damage. Particularly, in LUHS or ELAP situations, where containment damage occurs later than core damage, containment heat remove through external water injection or power restoration using portable equipment can be very effective in preventing containment failure. However, since portable equipment requires implementation and installation at the time of an accident, compared to installed equipment that is always maintained under optimal operating conditions, portable equipment can have a higher unavailability.

In Level 2 Probabilistic Safety Assessment (PSA), the Plant Damage State Event Tree (PDSET) serves as an interface between Level 1 and Level 2 analysis. It classifies accident sequences into Plant Damage States, which represent the plant's condition from the time of core damage to containment failure. In theory, the sum of the frequencies of all accident sequences developed by expanding core damage scenarios in the PDSET should be equal to the Core Damage Frequency (CDF). However, due to limitations in current computer calculation capabilities for PSA, approximate solutions are used for quantification. When PSA models are expanded or include many non-rare events, the difference between the approximate solution and the accurate value increases. Therefore, when developing PDSETs for Level 2 PSA models that include many portable equipment with high failure probability, the PDS frequency can differ significantly from the CDF, which can lead to errors in interpreting Level 2 PSA results.

In this study, we confirmed the results of applying accident mitigation strategies using portable equipment with very high failure probabilities to maintain containment integrity in Level 2 PSA, and performed quantification using the Partial BDD method. We also compared how much the error was reduced compared to cases where the Partial BDD method was not used.

II. Method

PSA models have recently developed using hundreds to thousands of basic events and logic gates to develop fault trees for internal events at full power. When analyzing such large fault trees, it is impossible to solve exact Boolean algebra even with current advanced computer performance. Therefore, the Delete Term Approximation (DTA) method is generally used to process success branches and obtain minimal cut sets.

In conventional accident management plans that consider only installed equipment, the unavailability of single components is generally very low, with most having failure probabilities below 0.01. These events are defined as rare events. To overcome the limited computational capabilities, Rare Event Approximation (REA) or Minimal Cut Upper Bound (MCUB) methods are used for minimal cut set-based quantification. This process is illustrated in Figure 1.

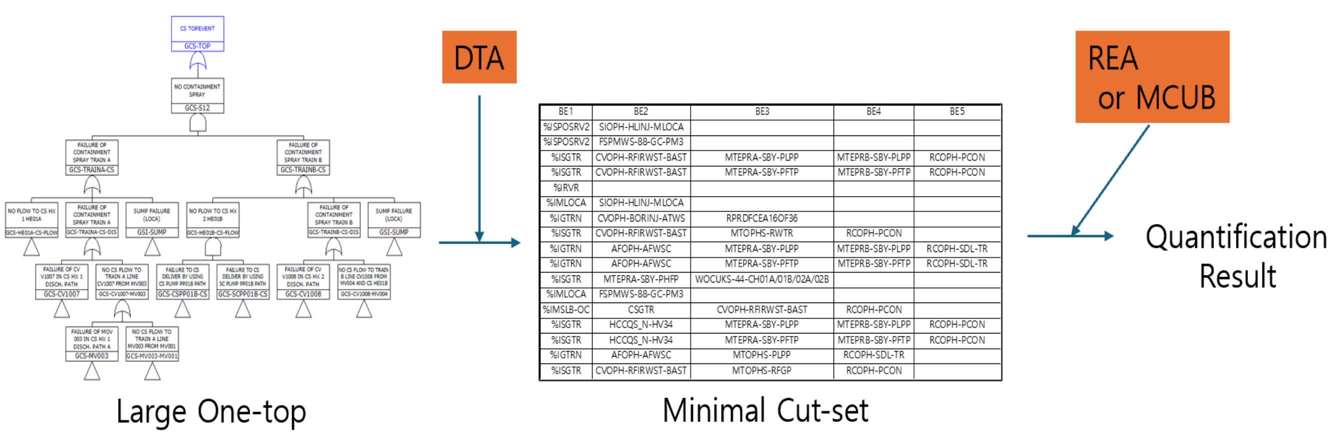

FIGURE 1. General Quantification Method

However, when there are many non-rare events with high failure probabilities, using the REA method can result in significant overestimation errors. Although the MCUB method can compensate for this, it can conversely cause underestimation.

In Korea, NUREG/CR-6928 is generally used as the data source for deciding equipment failure probabilities in PSA. NUREG/CR-6928 provides equipment failure probability for various equipment used in nuclear power plants based on empirical data. However, since accident mitigation strategies using portable equipment have been established relatively recently, data on equipment failure probability for portable equipment used in accident mitigation are limited. PWROG-18042-NP, which collected operational experience data related to portable equipment, provides the following generic failure probabilities for FLEX components:

TABLE I. Generic Failures Rates for FLEX Equipment

FLEX Component	Failure Mode	Mean
Portable Diesel Generator	Fail to Run	1.03E-02/hour
	Fail to Start	4.35E-02/demand
Portable Combustion Turbine Generator	Fail to Run	1.86E-02/hour
	Fail to Start	3.30E-02/demand
Portable Diesel-Driven Pump	Fail to Run	1.55E-02/hour
	Fail to Start	3.38E-02/demand

By applying the mission time of 24 hours, which is commonly used in PSA, to the values in Table I, the failure rate for each equipment type and failure mode can be calculated. For example, for a portable diesel generator, the probability of running failure is about 0.2472 (1.03E-02/h × 24 hours), and the probability of starting failure is 0.0435. Similarly, the running failure probabilities for portable combustion turbine generators and portable diesel-driven pumps are 0.4464 and 0.372, respectively. This shows that most basic events for portable equipment are non-rare events.

It is well known that accurate quantification results are difficult to obtain when quantifying fault trees that include many non-rare events using conventional methods. Therefore, the Partial BDD method, which was developed for quantifying seismic event models with many non-rare events, was applied to quantify Level 2 PSA models that include many portable equipment related events.

II.A. Application of Partial BDD

To obtain exact solutions for Boolean expressions that include non-rare events, methods such as Binary Decision Diagram (BDD) and Monte Carlo are available. When quantifying fault trees using the Monte Carlo method, relatively accurate results can be obtained in a short time, but only simple quantification results are provided, and it is not possible to evaluate the importance of basic events or perform cut set-based follow-up actions through post-processing, which limits its usefulness. Applying the BDD method to the entire fault tree to obtain an exact solution is possible only for small fault trees, as described above, and is difficult to apply to current nuclear power plant PSA models.

Suppose that many non-rare events are included in a single gate A, and there are few or no transfer gates shared with other gates. In this case, instead of applying the BDD method to the entire fault tree, the Partial BDD method introduced in reference 2 can be applied to gate A for conversion, reducing errors due to non-rare events in the overall quantification results without significantly slowing down the quantification speed.

The AIMS-PSA code developed by the Korea Atomic Energy Research Institute (KAERI) provides a function that allows the user to convert a specified gate to a BDD. Using this function, a one-top model can be created by partially converting a heading that includes many non-rare events to a BDD.

II.B. Development of Level 2 PSA Model with Partial BDD Applied

To apply the Partial BDD method, as described above, it is advantageous for many non-rare events to be included in a single gate and for there to be few transfer gates shared with other equipment. Otherwise, if BDD conversion is performed for many events including shared gates, the overall size of the fault tree can become too large, making quantification impossible or very time-consuming.

II.B.1. Separate Model for Accident Mitigation Strategies Using Portable Equipment

Accident management strategies using portable equipment are highly likely to satisfy the above two conditions. In particular, since portable equipment can be used for accident mitigation even when existing installed equipment is completely unavailable, such as in ELAP or LUHS, there are few shared equipment with installed equipment. Also, when reflecting accident management strategies using portable equipment in the event tree, strategies using installed equipment for the same purpose can be considered simultaneously in the same heading, but they can also be separated according to the developer's judgment. As shown in Figure 2, an alternative containment spray strategy using a high-capacity portable pump can be reflected in the containment spray heading using the containment spray pump with AND logic, or, as shown in Figure 3, the headings can be separated so that failure of the containment spray heading using the containment spray pump is considered in different headings.

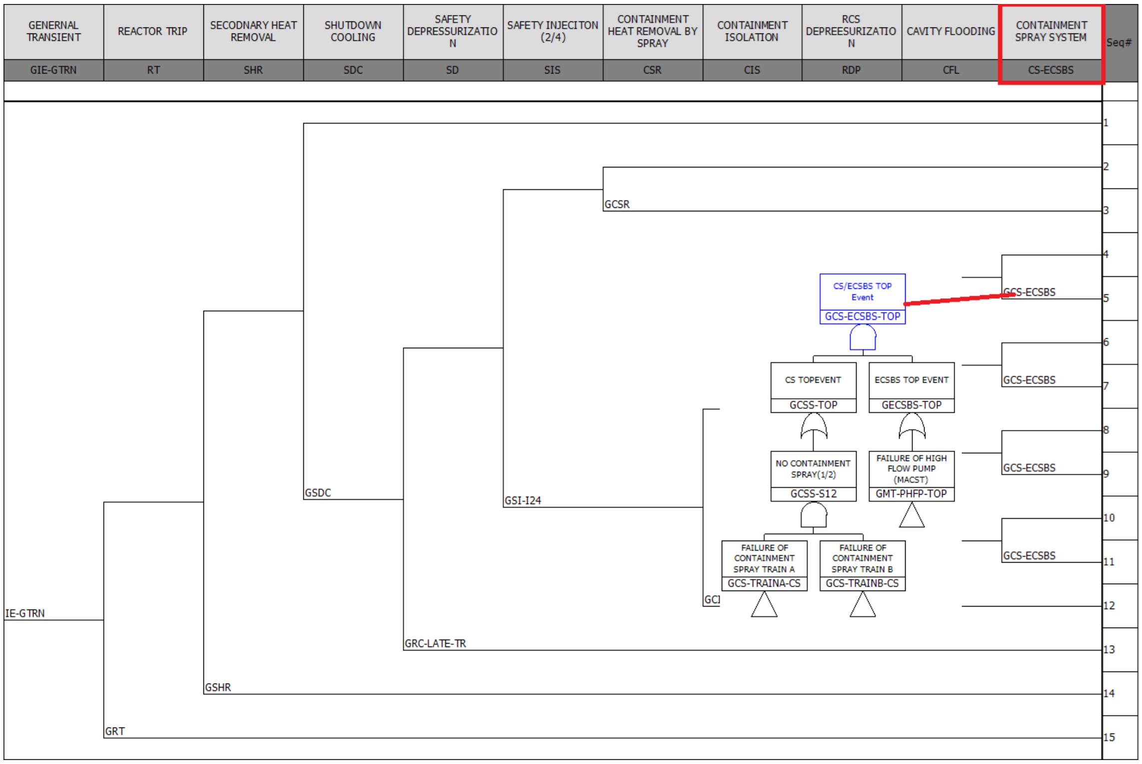

FIGURE 2. Portable Equipment Strategy Merged Event Tree

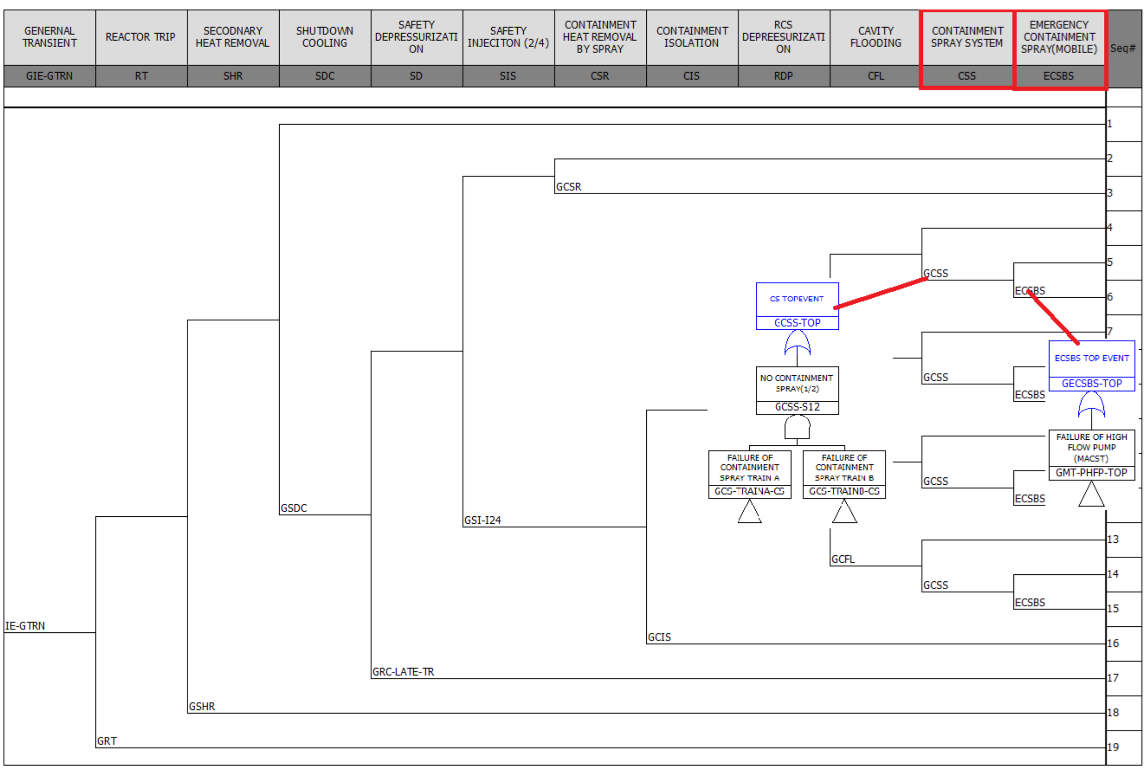

FIGURE 3. Portable Equipment Strategy Separated Event Tree

Generally, as the number of headings increases, the number of branches increases, making it difficult for model developers or reviewers to understand the structure. Therefore, analysts prefer the method shown in Figure 2. However, to perform the Partial BDD method, it is advantageous to separate gates that include many non-rare events for quantification speed and results. Therefore, as shown in Figure 3, accident management strategies using portable equipment were developed as separate headings.

II.B.2. Development of Fault Tree for Partial BDD Application

To consider long-term containment heat removal strategies using portable equipment, an LTHR fault tree was developed. In the LTHR fault tree, when containment heat removal using installed equipment fails, strategies to restore containment heat removal function using a portable high-flow pump (diesel-driven pump) and portable generator (portable combustion turbine generator) were simulated. In addition, since the portable pump uses diesel fuel, two portable fuel transfer pumps (diesel-driven pumps) for fuel replenishment were considered in the fault tree. The developed LTHR fault tree is shown in Figure 4. Reliability data for the portable diesel-driven pump and portable combustion turbine generator were taken from the data in Table I from PWROG-18042-NP.

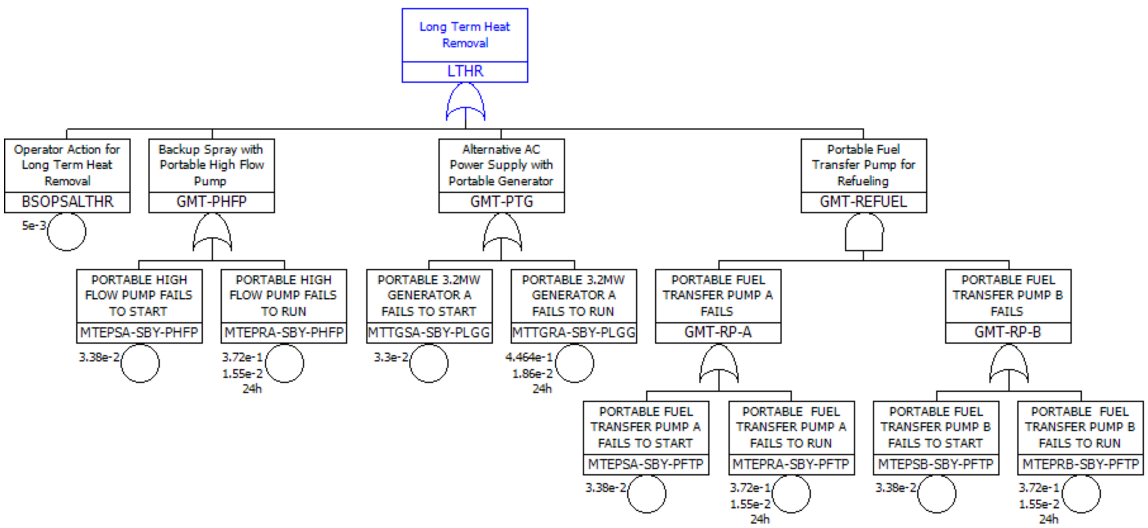

FIGURE 4. LTHR Fault Tree

II.C. Application of Partial BDD Using AIMS

The AIMS-PSA code provides an option that allows the user to convert a specified gate to BDD logic according to user settings. Using this function, some of the gates connected to the failure branch of the LTHR heading were changed, as shown in Figure 5.

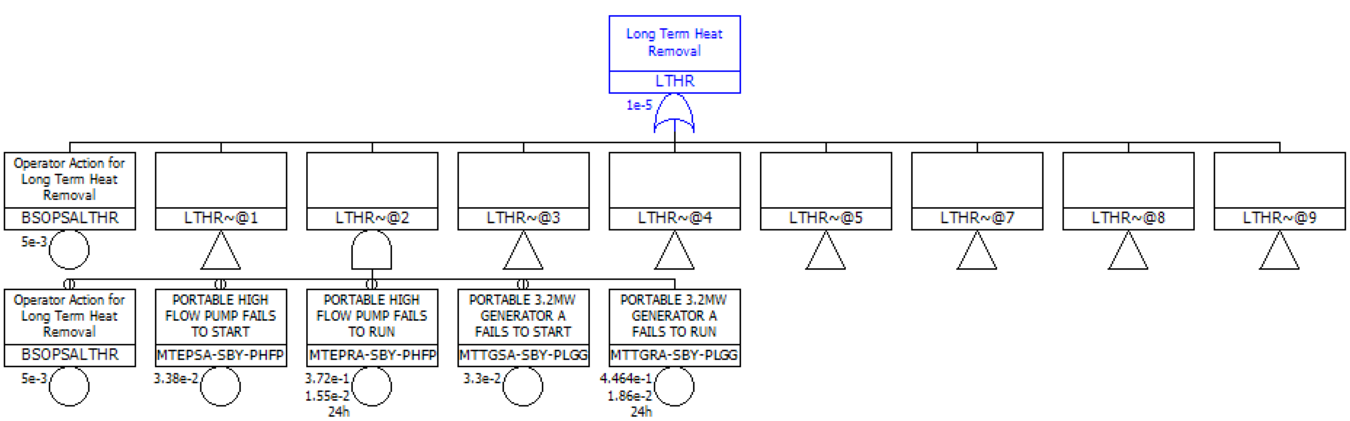

FIGURE 5. Converted LTHR Fault Tree(Failure Branch)

On the other hand, the fault tree connected to the success branch of the LTHR heading is shown in Figure 6.

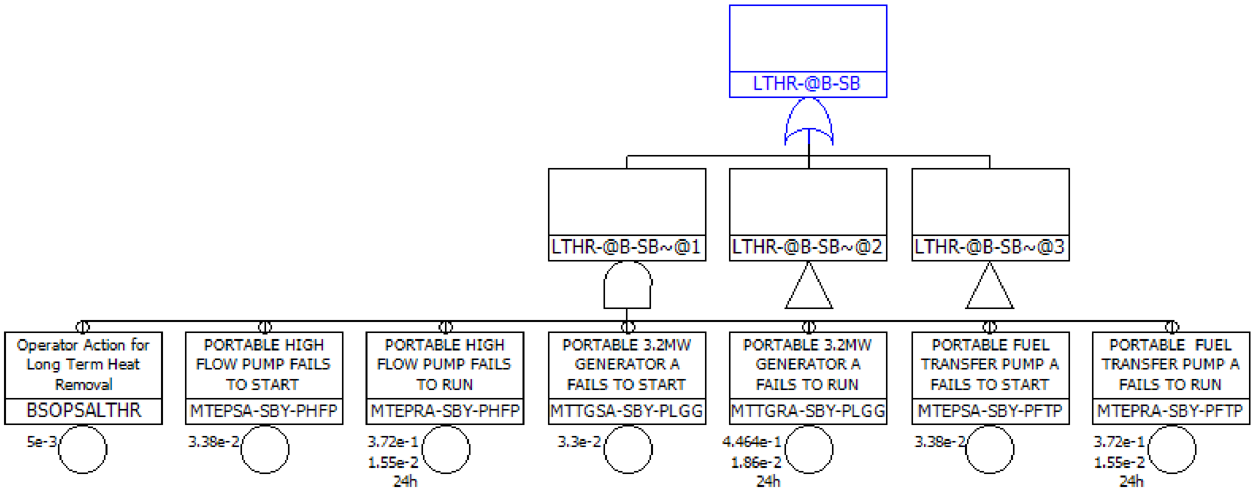

FIGURE 6. Converted LTHR Fault Tree(Success Branch)

III. Quantification Results

The results of quantifying the PDS event tree of a Level 2 PSA model that reflects accident coping strategy using portable equipment with high failure probability, with the Partial BDD method applied, were compared with the core damage frequency from Level 1 PSA. The results of quantification without applying the Partial BDD method were also compared. The computer used for quantification had the following specifications, typical for office laptops:

- CPU : Intel(R) Core(TM) Ultra 7 258V
- RAM : 32.0GB
- VGA : Intel(R) Arc(TM) 140V 16GB

III.A. Quantification Results with Partial BDD Applied

The results of quantification with the Partial BDD method applied to the LTHR heading are shown in Table II.

TABLE II. Quantification Result with Partial BDD

Cut-off Value	CDF (/ry)	PDS Frequency (/ry)	No. of Cutset (#)	Quant. Time (sec)	Difference (%)
1.00E-11	1.70E-06	1.66E-06	9205	6.9	(2.4)
1.00E-12	1.78E-06	1.78E-06	49553	12.2	0.0
1.00E-13	1.82E-06	1.84E-06	231215	33.1	1.1
1.00E-14	1.83E-06	1.86E-06	975924	128.0	1.6

Table II shows that when quantification is performed with the Partial BDD method applied, the core damage frequency calculated by quantifying Level 1 PSA event trees and the result calculated by quantifying PDSETs developed by expanding core damage scenarios are similar. When a high cut-off value is used for quantification, there are cases where the PDS frequency is lower than the CDF, but this problem does not occur when a sufficiently low cut-off value is selected for convergence. Even when a sufficiently low cut-off value is selected to ensure enough cut sets and convergence, the time required for quantification remains at an acceptable level.

III.B. Quantification Results without Partial BDD Applied

To check how much the PDS frequency differs from the core damage frequency when the Partial BDD method is not applied, the results of quantification without applying the Partial BDD method to the LTHR gate are shown in Table III.

TABLE III. Quantification Result without Partial BDD

Cut-off Value	CDF (/ry)	PDS Frequency (/ry)	No. of Cutset (#)	Quant. Time (sec)	Difference (%)
1.00E-11	1.70E-06	2.03E-06	11663	6.9	19.4
1.00E-12	1.78E-06	2.17E-06	61129	12.8	21.9
1.00E-13	1.82E-06	2.24E-06	277622	33.9	23.1
1.00E-14	1.83E-06	2.26E-06	1141833	111.3	23.5

The results in Table III show that when quantification is performed without the Partial BDD method, the core damage frequency and PDS frequency differ significantly. The current quantification model considered only one accident management strategy using portable equipment, but if multiple strategies using portable equipment are considered, this error is expected to increase.

III.C. Quantification Results with Partial BDD Applied to Multiple Gates

To check how the results change when the Partial BDD method is applied to multiple gates, quantification was performed by changing the model so that other mitigation strategies are performed using portable equipment, and the results are shown in Table IV.

TABLE IV. Quantification Result with Partial BDD

Cut-off Value	CDF (/ry)	PDS Frequency (/ry)	No. of Cutset (#)	Quant. Time (sec)	Difference (%)
1.00E-11	1.70E-06	1.52E-06	12379	7.3	(10.6)
1.00E-12	1.78E-06	1.68E-06	49553	15.1	(5.6)
1.00E-13	1.82E-06	1.76E-06	331839	43.6	(3.3)
1.00E-14	1.83E-06	1.79E-06	1446739	225.2	(2.2)
1.00E-15	1.84E-06	1.81E-06	5933891	610.1	(1.6)

The results in Table IV show that when the Partial BDD method is applied to multiple gates, the PDS frequency can be underestimated compared to the core damage frequency from Level 1 PSA. When quantification is performed using Partial BDD, the success event probability is multiplied for accident sequences corresponding to the success branch to calculate the exact value. In this process, minimal cut sets with frequencies that are not cut off are multiplied by success event probability and truncated. As described above, when a sufficiently low cut-off value is selected for convergence, the error gradually decreases, but the time required for quantification increases significantly.

IV. CONCLUSIONS

This study analyzed the effect of applying the Partial BDD method in Level 2 PSA models that include portable equipment with high failure probability. The results showed that when the Partial BDD method is applied, the discrepancy between core damage frequency (CDF) and plant damage state (PDS) frequency is significantly reduced. According to PWROG-18042-NP data, many portable equipment has failure probabilities exceeding 0.1, which causes significant errors in conventional quantification methods.

The Partial BDD method has the advantage of improving accuracy without significantly increasing computational burden. Even when a sufficiently low cut-off value is used, the quantification time remains at an acceptable level. However, when the Partial BDD method is applied to multiple gates, even if a sufficiently low cut-off value is used for convergence, the PDS frequency can be somewhat underestimated compared to the CDF.

In conclusion, in nuclear power plants where portable equipment with high failure probability plays an important role in accident mitigation strategies, the application of the Partial BDD quantification method effectively prevents excessive differences between core damage frequency and plant damage state frequency. When the Partial BDD method is applied to multiple gates, the PDS frequency may be somewhat underestimated compared to the CDF, but if a sufficiently low cut-off value is used for convergence, the error is at an acceptable level.

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