Improvement of Risk Quantification Procedure for High-Speed Computing

Tomohiko Ikegawa[a*], Naoki Hirokawa[b],
Hiroki Nakamura[c], Yuki Hirai[c], Kazunobu Noriyasu[c]
[a]Hitachi, Ltd., Hitachi-city, Japan
[b]Hitachi-GE Nuclear Energy, Ltd., Hitachi-city, Japan
[c]The Chugoku Electric Power Company, Incorporated, Hiroshima-city, Japan

Abstract: The objective of this study is to investigate how to increase the calculation speed effectively. In the current risk quantification method, the one top fault tree (OTFT), which includes all initiating events (IEs) and basic events, is constructed first, and the total core damage frequency (CDF) is calculated by adding each CDF for a specific IE. Each CDF of a specific IE can be evaluated by intentionally setting frequencies of IE occurrence in the OTFT as zero, except for the specific IE. Though the CDFs for each IE are calculated in parallel, calculation time is almost completely restricted by the specific IE quantification which need longer calculation times. In this study, an OTFT division method was developed in consideration of their independency, and the calculation time was decreased effectively. As a result, there was a six-fold improvement of the calculation speed by dividing the OTFT appropriately.

Keywords: PRA, Risk monitor, One top fault tree, High-speed computing

1. INTRODUCTION

In order to balance safety and economic performances of Japanese nuclear power plants (NPPs), the reactor oversight process (ROP) [1], which was developed in the U.S. and applied to U.S. NPPs for a long time, should be implemented in the Japanese plants. The ROP is the U.S. Nuclear Regulatory Commission (NRC)'s program to inspect, measure, and assess the safety and security performance of operating commercial NPPs, and to respond to any decline in their performance. After a customized ROP is implemented in Japan [2], Japanese electric power companies will have to manage the safety performance of their NPPs in consideration with risk.

Probabilistic risk assessment (PRA) has been used for safety risk evaluation for a long time, and PRA models for risk quantification are being improved continuously [3]. As a result, risk can be quantified with high accuracy, however, its calculation time becomes long [4]. Long calculation times result in design obsolescence and may have an impact on the risk monitor (one of the PRA applications) which requires high speed risk quantification. The objective of this study is to investigate how to raise the risk quantification calculation speed effectively.

2. OVERVIEW OF RISK QUANTIFICATION PROCESS AND ITS ISSUES

2.1. Overview of Risk Quantification Process

PRA consists of event trees (ETs) and fault trees (FTs) to quantify such risks as core damage frequency (CDF). Figure 1 shows examples of an ET and an FT. The ET starts from an initiating event (IE) and expresses time progress of an accident with branches of success or failure for the operation of various safety systems (the upward direction means a success and downward direction means a failure). The ET identifies combinations of system failures that lead to an undesirable condition such as core damage. Frequency of an undesirable condition occurrence can be quantified by using the frequency of IE occurrence and the probability of system failure (i.e., branch probability).

Each branch probability is evaluated in the FT. The FT is a failure tree in which a system failure is set at the top event (top gate), and events (gates) that cause the top event are expanded downward. The upper-level event and the lower-level events which cause the upper-level event are connected by an operator. For example, the operator AND(*) means an upper-level event occurs when all lower-level events occur, and the operator OR(+) means a upper-level event occurs when one or more lower-level events occur. At the bottom of the FT, the failure probabilities of a basic event (BE), such as a pump mechanical failure probability, are set. By multiplication of lower-level failure probabilities in the case of the AND operator, and addition of lower-level failure probabilities in the case of the OR operator, system failure probability of a top event (i.e., the branch probability) can be evaluated quantitatively.

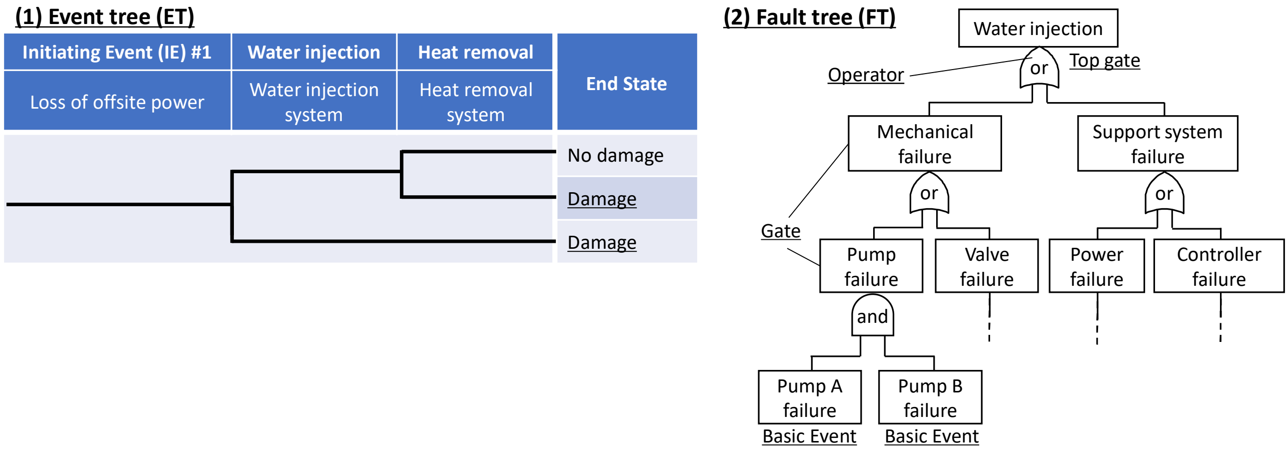

Figure 1. Example of an event tree (ET) and a fault tree (FT)

Generally, when evaluating CDF, it is necessary to consider multiple IEs (e.g., manual scram, loss of off-site power, pipe break) that might potentially occur in a nuclear power plant. So, multiple ETs are prepared for multiple IEs. When quantifying risk (e.g., CDF) in PRA, a one top FT (OTFT) that integrates all ETs and FTs into one tree to facilitate case management (Figure 2).

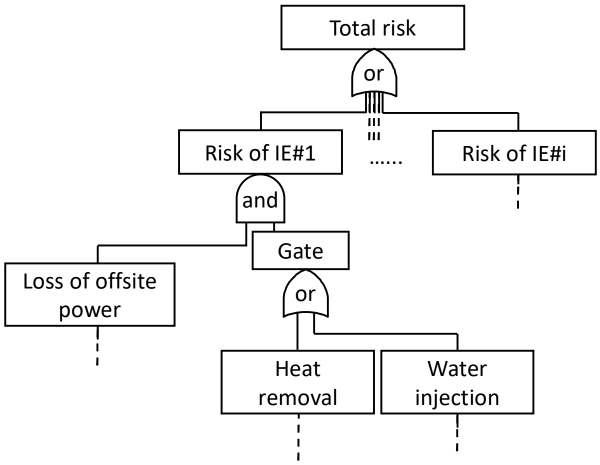

Figure 2. Example of a one top fault tree (OTFT)

Frequency of the total risk in Figure 2 is quantified by FTREX [5] developed by the Korea Atomic Energy Research Institute (KAERI). Risk (e.g., CDF) initiated from each IE can be quantified separately because each IE is exclusive of the others. The Electric Power Research Institute (EPRI) developed FTREW [5] as a wrapper for FTREX. FTREW uses OTFT as input and call multiple FTREXs in parallel to quantify risk of each IE. Risk of a specific IE can be evaluated with FTREX by intentionally setting frequencies of IE occurrence in the OTFT as zero, except for the specific IE. Finally, FTREW quantifies the total risk by merging each IE risk. As an example, Figure 3 shows a risk quantification procedure when the number of IEs is 3.

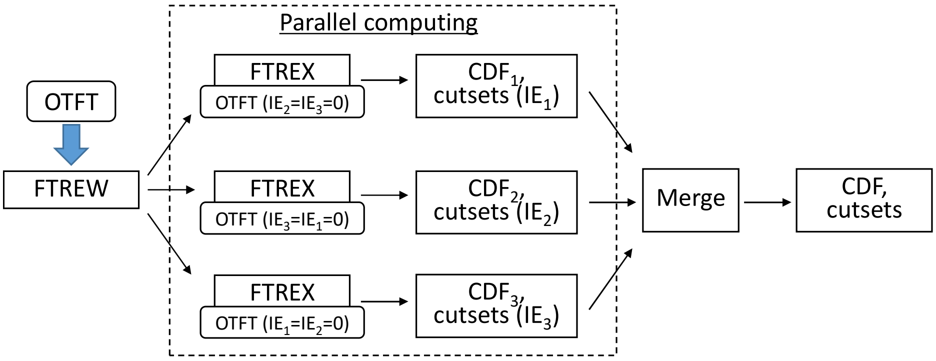

Figure 3. Example of the current risk quantification procedure using FTREW (Number of IEs=3)

2.2. Issues to be Addressed for Risk Quantification

When quantifying the total risk (e.g., CDF), truncation, which defines cutting off the negligible contribution of the results of the fault tree/event tree analysis, is set manually. If truncation is set smaller, the number of cutsets, which define combinations of BEs resulting in core damage, taken into account when calculating CDF will increase. To ensures convergence of the CDF value, the American Society of Mechanical Engineers (ASME) / American Nuclear Society (ANS) PRA standard (2013) (ΔCDF / CDF≦5%, ΔCDF: CDF change when truncation changes 1 order of magnitude) [7] is applied to determine truncation value.

However, recent advances in the risk quantification model (i.e., more detailed ETs and FTs) have led to increased numbers of cutsets in use, and the convergence performance of CDF, which is the sum of the frequencies of occurrence of each IE, has gotten worse, and smaller truncation values are required. As a rule of thumb, the reducing truncation value by one order of magnitude increases the calculation time by approximately three to five times, so increasing quantification speed is an important issue to be addressed [4]. Also, long calculation times for risk may have a bad influence on the risk monitor application, which need to immediately display risk changes on a display.

2.3. Previous Study and Development Strategy of the Study

We conducted a literature search on how to improve the calculation speed of risk quantification, and found 15 documents [4],[6],[8]-[20]. From them we were able to extract and prioritize five candidate procedures to develop as shown in Table 1.

Table 1. Candidate procedures for improving calculation speed

No.	Procedure	Issue	Priority
1	Customize the OTFT structure so that the quantification tool (FTREX) can analyze the OTFT faster	Feasibility	High
2	Divide the OTFT and use parallel computing	Implementation method	High
3	Improve the quantification tool (FTREX)	Method development, verification	Low
4	Use a high performance computer	Cost	Low
5	Use cloud computing	Computing method, security	Intermediate

✓ Candidate 1 (Customize OTFT structure)
In our study, we found that calculation speed of FTREX drastically dropped when the OTFT includes a Negate operator. Examples of Negate tree structures are shown in Figure 4. In Figure 4 (a), the Negate tree is the AND operator tree which consists of gate A, gate B, and gate NOT C. In the FTREX risk quantification process, gate C and whole trees below gate C must be completely ignored, i.e., A=B is assumed in Figure 4 (a). We note that a location of NOT is not limited to being directly below gate A as shown in Figure 4 (b). Also, gate C and whole trees below gate C must be completely ignored, i.e., A=B

is assumed in Figure 4 (b). To achieve high-speed computing, all of the Negate tree structure has to be eliminated. The priority of this candidate was set as high because elimination of Negate from the OTFT is feasible.

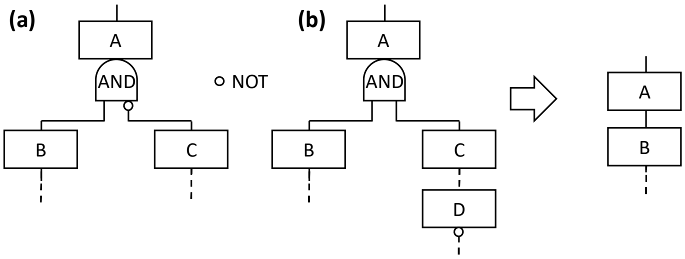

Figure 4. Examples of Negate tree structures

- ✓ Candidate 2 (Divide OTFT)
  FTREW makes multiple exclusive OTFTs by setting IE frequencies as zero except for the target IE, and it quantifies total risk by quantifying multiple OTFT risks in parallel. However, actually, risk quantifications of almost all IEs are finished quickly, and quantifications of several IEs just take time. In such a case, FTREW is unable to merge each IE risk until all the IE risk quantifications are fully completed, and parallelization efficiency decreases due to several IEs with long calculation times. Parallelization efficiency could be improved if several OTFTs with long calculation time IEs could be divided more finely, but FTREW does not have such a function. Therefore, we tried to create an additional procedure for dividing a large OTFT into some relatively small OTFTs. This candidate was set as high priority because it has high feasibility.

- ✓ Candidate 3 (Improve FTREX algorithm)
  FTREX uses the ZBDD (zero-suppressed binary decision diagram) algorithm [20], which is one of the fastest algorithms at present, to quantify risk. Since we expected that it would be difficult to develop a new algorithm that exceeds ZBDD, and even if the development were successful, it would take time to verify the developed code, we set this candidate as low priority.

- ✓ Candidate 4 (High performance computer)
  We already use a high performance computer, so we set this candidate as low priority.

- ✓ Candidate 5 (Cloud computing)
  Now that more secure networks than ever before are available, there is interest in applying this method again, and the Legacy PRA Project in the U.S. is proceeding with proof-of-concept research on massively parallel computing [12]. Using this technology will make it possible to quantify risks using countless PCs on a network instead of using a single high-performance computer, so cloud computing is considered a promising development target. However, as described for candidate 2, our risk quantification is limited by the risk quantification speed of several specific IEs, which take the longest calculation time, and we determined improving parallelization efficiency has a higher priority than cloud computing. So, we decided that the priority was lower than that of candidate 2, and set the priority to intermediate.

3. IMPROVEMENT OF THE PROCEDURE FOR HIGH-SPEED COMPUTING

3.1. OTFT dividing procedure (1)

At first, we developed an OTFT division algorithm. The OTFT was divided into multiple exclusive OTFTs, in which each OTFT includes just one IE. In addition, as described in section 2.3, we found that the calculation speed of FTREX drastically fell when the OTFT included the Negate operator. So we eliminated the Negate operator from the OTFT to be divided to speed up risk quantification. Figure 5 shows the algorithm for obtaining multiple exclusive OTFTs without including the Negate tree. In order to detect all Negate structures as shown in the Figure 4, we developed a recursive subroutine implemented as one of functions in Fortran 90.

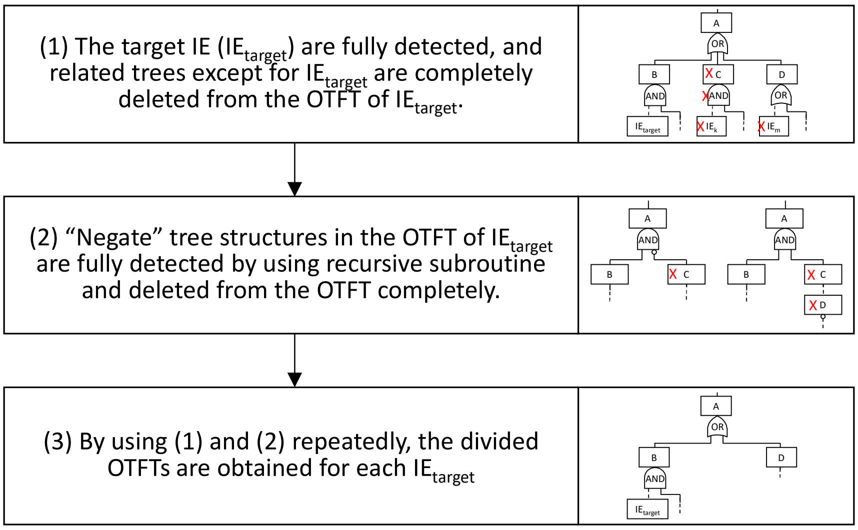

Figure 5. Algorithm of the OTFT division procedure (1)

3.2. Trial analysis result (1)

Trial risk quantification analysis (1) was performed for the enhanced Shimane Unit 2 OTFT [21]. Table 2 shows tools, inputs, and outputs for the trial analysis (1). Since the scale of the problem (number of gates, BEs, and IEs) was large and the truncation value was assumed to be small (1.0E-13), the number of cutsets was 1.5E+09, and the risk quantification time with the current procedure (i.e., using FTREW) was about 5.8 hours.

Table 2. Tools, inputs, and outputs for the trial risk quantification analysis

Item		Value	Note
Tool	Risk quantification tool	FTREX64 Ver.2.0	The latest version
	Wrapper tool which controls the risk quantification tool	FTREW	Just used for the base case, and not used for the trial analysis
Input	Number of gates	About 24,000	These values were counted for L1 tree though the OTFT includes L1 and L1.5 trees.
	Number of basic events (BEs)	About 6,500	
	Number of initiating events (IEs)	About 150	
	Truncation	1.0E-13	Assumption
Output*	Number of cutsets	About 1.5E+09	-
	Calculation time (in parallel)	About 21,000 s (5.8 h)	Base case

*: These results were obtained by using the original procedure (i.e., FTREW results)

Figure 6 shows an example of the risk quantification procedure for trial analysis (1). Each OTFT(IE_i) was obtained by using the developed program, thus, FTREW was not used for this analysis. Also, all Negate operators were completely deleted from the OTFT(IE_i)s. OTFT(IE_i)s were quantified in parallel, and calculation time was reduced from about 21,000 s (5.8 h) to about 7,000 s (1.9 h). As a result, the risk quantification time is three times faster than the original calculation procedure (Figure 3). However, there remained the issue that parallelization efficiency decreased due to several IEs with long calculation times.

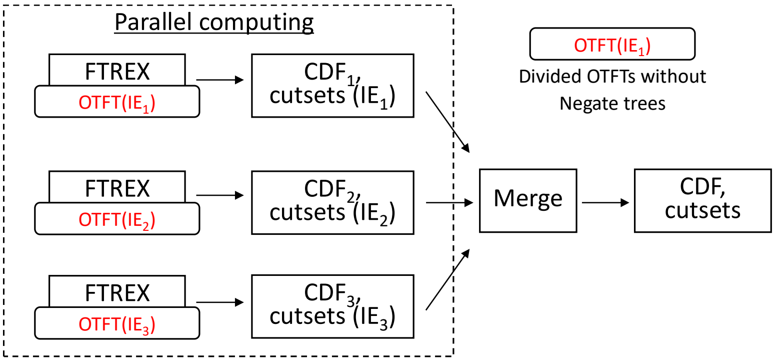

Figure 6. Example of risk quantification procedure (1) (Number of IEs=3)

3.3. OTFT sub-dividing procedure (2)

Secondly, a more detailed OTFT division algorithm was developed. The divided OTFTs which required long calculation times were sub-divided into detailed multiple exclusive OTFTs. Figure 7 shows the algorithm for obtaining the more divided OTFTs. For our present study, the automated algorithm could not be developed to credit exclusiveness. Thus, the gate with OR operator which is suitable for sub-dividing was determined manually in this study. For the practical use of the risk monitor, an automated algorithm should be developed.

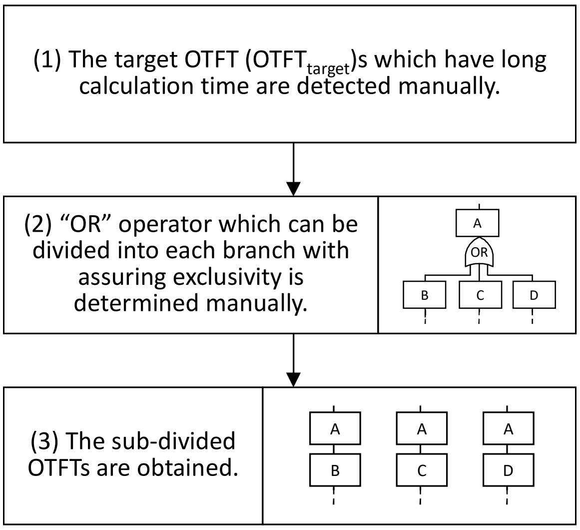

Figure 7. Algorithm of the OTFT dividing procedure (2)

3.4. Trial analysis result (2)

Tools, inputs, and outputs for the trial analysis (2) were the same as Table 2. Figure 8 shows an example of the risk quantification procedure in the trial analysis (2). In this example, the heavy load OTFT(IE_3) was divided into sub-divided OTFTs (from OTFT($E_{3\text{-}1}$) to ($E_{3\text{-}3}$)) manually by using the developed program.

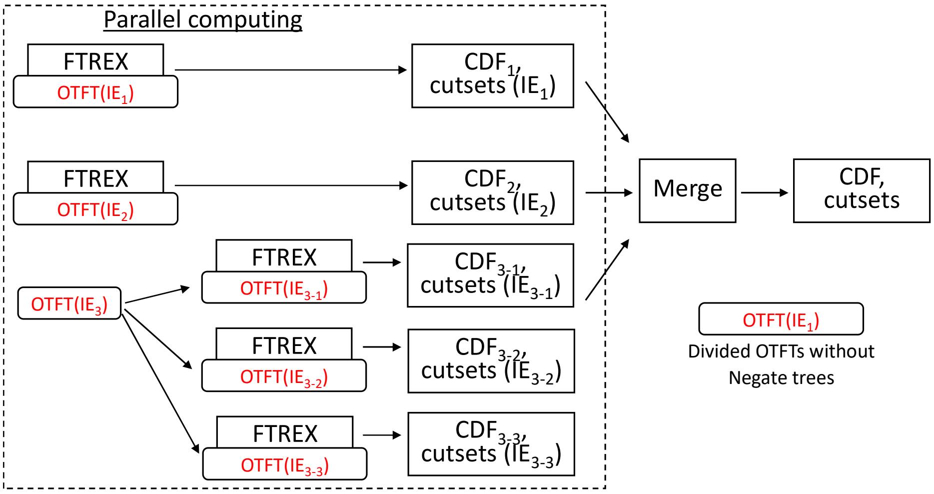

Figure 8. Example of risk quantification procedure (2) (Number of IEs=3)

Table 3 summarizes analysis results. Since all sub-divided OTFT(IE_i)s were quantified in parallel with high parallelization efficiency, calculation time was finally reduced from about 21,000 s (5.8 h) to about 3,600 s (1.0 h). As a result, the risk quantification time was about six times faster than the original calculation procedure (i.e., base case) while getting the same number of cutsets and CDF.

Table 3. Summary of the trial risk quantification results

Item	Base case	Trial (1)	Trial (2)
Calculation time (h)	About 5.8	About 1.9	About 1.0
Number of cutsets (-)	About 1.5E+09	About 1.5E+09	About 1.5E+09
CDF (relative value to Base Case)	-	1.00000	1.00000

4. CONCLUSION

In this study, we investigated how to improve the calculation speed effectively. In the current risk quantification method, the one top fault tree (OTFT), which includes all initiating events (IEs) and basic events (BEs), is constructed first, and total risk such as core damage frequency (CDF) is calculated by adding each CDF for a specific IE. Each CDF of a specific IE can be evaluated by intentionally setting frequencies of IE occurrence in the OTFT as zero, except for the specific IE. Though the CDFs for each IE are calculated in parallel, calculation time is almost completely restricted by the OTFTs which need longer calculation times. The following conclusions were obtained.

(1) Investigation of the previous studies
We conducted a literature search on how to improve the calculation speed of the risk quantification, and found 15 documents. Based on the searched documents, we determined the following two items as our development strategy: (i) customize the OTFT structure and (ii) divide the OTFT.

(2) Trial risk quantification results with the developed algorithm
At first, we developed the OTFT division algorithm. The OTFT was physically divided into multiple exclusive OTFTs, and each of these OTFT included just one IE. In addition, we eliminated the Negate operator from the multiple exclusive OTFTs to speed up risk quantification. As a result, calculation time was reduced from about 21,000 s (5.8 h) to about 7,000 s (1.9 h).

Secondly, a more detailed OTFT division algorithm was developed. The OTFTs from the division which required long calculation times were further divided into multiple exclusive sub-divided OTFTs. In the present study, an automated algorithm could not be developed to credit exclusiveness. Thus, the gate with the OR operator which is suitable for sub-dividing was determined manually. All divided OTFT(IE_i)s were quantified in parallel, and the calculation time was reduced from about 21,000 s (5.8 h) to about 3,600 s

(1.0 h). Finally, the risk quantification time was obtained that was about six times faster than the original calculation procedure.

References

[1] U.S. NRC, Reactor Oversight Process, NUREG-1649 Rev.6, July 2016.
[2] NEA, 2024 ROP Learning Workshop on the Implementation of the Reactor Oversight Process in Japan, September, 2023.
[3] Y. Moriya, K. Ihara, H. Nakamura, and H. Nojima, Development of advanced PRA model for Shimane Unit 2 internal event at-power, Mechanical Engineering Journal 11(2), February, 2024.
[4] ANS, Helping to solve the plant safety puzzle: an overview of PRA, ANS, 2021/9.
[5] EPRI website "https://www.epri.com/research/programs/061177/results/3002018234"
[6] NEA, Use and Development of Probabilistic Safety Assessment, NEA/CSNI/R(2012)11, 2012/12.
[7] ASME/ANS, "Addenda to ASME/ANS RA-S-2008 Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications", RA-Sb-2013, 2013.
[8] K.K. Gunter, et al., New Functions and Features Associated with EPRI HRA Calculator Version 5.2, Proceedings of International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2019), Pages 793-797.
[9] INL, R&D Roadmap to Enhance Industry Legacy Probabilistic Risk Assessment Methods and Tools, INL/EXT-20-59202, 2020/8.
[10] Y. Dutuit, A. Rauzy, A Linear-Time Algorithm to Find Modules of Fault Trees, IEEE Transactions on Reliability, Vol.45, No.3, 1996.
[11] IAEA, Application and development of probabilistic safety assessment for nuclear power plant operations, IAEA-TECDOC-873, 1993/9.
[12] INL, Light Water Reactor Sustainability Program: Enhancement of Industry Legacy Probabilistic Risk Assessment Methods and Tools, INL/EXT-21-64448, 2021/9.
[13] A. Rauzy, Notes on Computational Uncertainties in Probabilistic Risk Safety Assessment, Entropy 2018, 20, 162.
[14] Z.W. Birnbaum, J.D. Esary, Modules of Coherent Binary Systems, J. Soc. Indust. Appl. Math., Vol.13, No.2, June, 1965.
[15] O. Nusbaumer, A. Rauzy, Fault tree linking versus event tree linking approaches: a reasoned comparison, Proc. IMechE Part O: J Risk and Reliability 227(3).
[16] K. Oh, et al., Study on Quantification for Multi-unit Seismic PSA Model using Monte Carlo Sampling, Transaction of the Korean Nuclear Society Autumn Meeting, 2015.
[17] J. Choi, Improved Monte Carlo Method for PSA Uncertainty Analysis, Transaction of the Korean Nuclear Society Autumn Meeting, 2016.
[18] M. Bouissou, et al., Various Ways to Quantify BDMPs, MARS2020, EPTCS 316 2020, pp. 1-14.
[19] A. Rauzy, Mathematical Foundations of Minimal Cutsets, IEEE Transactions on Reliability, Vol.50, No.4, 2001.
[20] S. Minato, Zero-Suppressed BDDs for Set Manipulation in Combinatorial Problems, 30th ACM/IEEE Design Automation Conference, 1993.
[21] Y.Moriya et.al. Development of advanced PRA model for Shimane Unit 2 internal event at-power, Mechanical Engineering Journal/Volume 11 (2024) Issue 2, 2024.