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Application of Jung's Method for Accurate Risk Assessment in an Actual NPP PSA Model by Incorporating Human Failure Event Recovery into the Minimal Cut Set Generation Stage

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1. Introduction

Human reliability analysis (HRA) is a critical component of probabilistic safety assessment (PSA) and plays a vital role in evaluating the safety of nuclear power plants (NPPs). PSA enables the identification and management of potential hazards in NPPs and contributes to the development of safety technologies and safety improvements [1,2].

Various techniques and methods have been used to construct and quantify PSA models for NPPs. These include (1) calculating fault tree [4,5] to generate minimal cut sets (MCS), (2) performing human failure event (HFE) analysis and subsequent recovery to eliminate logically impossible combinations within MCS, and (3) computing the core damage frequency (CDF) using the recovered MCS with min-cut-upper-bound (MCUB).

When multiple HFEs exist in a single MCS, dependencies may arise where preceding HFEs influence subsequent ones. Analyzing this leads to assigning conditional probabilities to subsequent HFEs, increasing their likelihood, referred to as HFE recovery rules.

Due to computational limitations in PSA, truncation limits were employed to restrict MCS, potentially excluding combinations of high-probability HFEs from the results. In addition, inaccurate HFE dependency analysis and recovery rules can lead to MCS truncation, resulting in an underestimation of CDF. Professor Jung developed Jung's method, integrating HFE recovery into the MCS generation stage to prevent underestimation risks and ensure efficient HFE dependency analysis [6,7].

In Jung's method, (1) HFE recovery is performed simultaneously while calculating failure sequences to generate MCS, and (2) the computed CDF is derived using MCUB on the recovered MCS [8].

This study aims to apply Jung's method, previously demonstrated in theoretical and virtual models, to the operational PSA model of a domestic NPP for the first time and to verify its ability to provide accurate risk assessment through comparison with typical method.

Table 1. Three dependencies of PSA

PSA	Failure	Details
Fire/ Flood/ Internal/ Seismic PSA	HFE	In fault tree analysis, dependency among human errors occurs when a single MCS contains multiple human errors. The probability of subsequent errors increases due to psychological factors, such as a preceding error. This positive dependency is included in the fault tree recovery rules, which are then used to quantify the fault trees [2-5].
Fire/ Flood/ Internal PSA	Common cause failure (CCF)	Dependencies in component failures arise when multiple system parts fail due to a common cause. This is analyzed using historical data and reflected in fault trees, categorizing failures as independent or common cause failures (CCFs). CCF probabilities are quantified using parameters like alpha and beta factors from historical data [10,11].
Seismic PSA	Correlated seismic failure	Seismic dependency among component failures occurs when identical components fail together during an earthquake, influenced by shared characteristics and responses to seismic events. In seismic probabilistic safety assessment for nuclear power plants, this is addressed by treating similar component failures as a single seismic common cause failure (CCF) in the fault tree, with the combined failure probability quantified through multivariate normal (MVN) integration [12].

Chapter 2 introduces the HFE dependency analysis procedure. Chapter 3 outlines the existing PSA procedures. Chapter 4 details the procedure of Z_METHOD and Jung's method as implemented in fault tree reliability evaluation expert (FTREX). Chapter 5 presents the application results of Jung's method to NPP PSA, compares these results with existing methods, and identifies HFE combinations that require further analysis. Chapter 6 summarizes the conclusions.

2. HFE dependency analysis

2.1 Typical HFE dependency analysis

HFE dependency analysis aims to determine the level of dependency of each combination of HFEs. This is determined using a procedure that considers various human factors and the performance impact factors of the HFEs. MCS represents a minimal combination of initiating events, component failures, and HFEs that lead to core damage in NPPs. The HFEs in a single MCS can be arranged chronologically according to the corresponding incident sequence. These arrangements are used to analyze the dependency level of subsequent HFEs on preceding HFEs in each MCS and to determine human error probabilities (HEPs) for HFE recovery. The analysis procedure for HFE dependency analysis is depicted in Fig. 1. In a typical method, the dependent HEP of the subsequent HFE is calculated, as shown in Table 2 [2]. HFE dependencies were determined according to the dependency decision tree.

Table 2. HFE dependency level [2]

P(HFE-FNB-DP) = P(HFE-FNB)	for zero dependency
P(HFE-FNB-DP) = (1+19*P(HFE-FNB))/20	for low dependency
P(HFE-FNB-DP) = (1+6*P(HFE-FNB))/7	for medium dependency
P(HFE-FNB-DP) = (1+P(HFE-FNB))/2	for high dependency
P(HFE-FNB-DP) = 1	for complete dependency

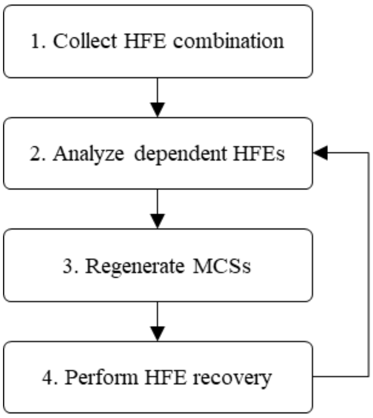

Fig. 1. HFE dependency analysis [3]

HFE dependency analysis consists of four activities: (1) collecting HFE combinations, (2) analyzing dependent HFEs to determine dependency levels between subsequent and preceding HFEs, (3) regenerating MCSs, and (4) performing HFE recovery. In this paper, HFE recovery is defined as the recovery of MCSs to reflect the dependent probabilities of HFEs within MCS probabilities [3]. Typically, HFEs exhibit a positive dependency on their preceding HFEs. It is widely acknowledged that neglecting HFE dependency could lead to underestimating the CDF (see section 2.3). Conversely, assuming complete HFE dependency could lead to overestimating the CDF.

2.2 Issues in typical HFE dependency analysis

The issues of HFE dependency analysis in Fig. 2 are summarized as follows [3]:

1. Collecting HFE combinations poses challenges due to the high computational burden involved in solving fault trees and generating MCSs, either by assigning very high HEP to all HFEs, reducing the cut-off limit, or using both methods.
2. Analyzing dependent HFEs is complex, especially when the number of HFE combinations in MCSs often exceeds 10,000, significantly higher than the typical range of 1 to 10 in a standard PSA.
3. Regenerating MCSs is challenging; MCSs with HFEs above the set dependency level must be recalculated with a higher HEP to prevent being truncated.
4. Performing HFE recovery is a time-consuming process, often taking longer than the computation of the MCS itself, and it must be repeated for each MCS recalculation.

Jung's method integrates HFE recovery into MCS generation to address issues 3 and 4, overcoming limitations of typical HFE dependency analysis like potential oversight of HFE combinations and the need for repeated, complex quantification, which can lead to inaccurate HFE dependency analysis and underestimation of the CDF (refer to section 2.3).

2.3 HFE recovery

Once the dependency levels between HFEs are determined, the dependent HFE in a single MCS must be replaced by a new HFE with dependent HEPs or a new HFE with a joint probability of a combination of HFEs. This procedure is usually facilitated by dedicated tools [3,6]. As shown in Eqs. (1) and (2), the first step in performing an HFE recovery is as follows: First, replace dependent HFEs (H2 and H3) with new HFEs (H2' and H3') that have conditional probabilities in Eq. (3) or replace the whole HFE combination (H1H2H3) with a single HFE (H123) that has the product of conditional probabilities in Eq. (4) [3].

$$H1H2H3 \rightarrow H1H2'H3' \quad (1)$$

$$H1H2H3 \rightarrow H123 \quad (2)$$

where

$$p(H2') = p(H2|H1) and\ p(H3') = p(H3|H1H2) \approx (H3|H2) \quad (3)$$

$$p(H123) = p(H1)p(H2|H1)p(H3|H1H2) \approx p(H1)P(H2|H1)p(H3|H2) \quad (4)$$

To avoid underestimating the CDF, unanalyzed HFE combinations are treated conservatively. If some HFEs match the combination (H1H2H3), the probability of HFEs not included in the combination (H4H5) is set to 1.0.

3. Probabilistic safety assessment

PSA is a technical method used to evaluate the safety of NPPs and other complex systems. PSA assesses various events and potential risks that can occur within the system, predicting and evaluating their likelihood and consequences through quantitative analysis, as depicted in Fig. 1. MCSs are first generated by solving a fault tree [4,5]. Second, MCS recovery is performed to delete nonsensical MCSs with impossible failure combinations and to perform HFE recovery [6,7]. Thirdly, the CDF was calculated from recovered MCSs by the MCUB method [8]. An accurate CDF for seismic PSA can also be calculated by converting MCSs into a binary decision diagram (BDD) [8]. NPPs are complex systems consisting of interconnected subsystems. As a result of this interconnectivity, problems in one system can affect other systems. Various human factors are also involved in plant operation. If errors occur when humans perform tasks, the probability of errors during subsequent tasks increases because of psychological factors. HFEs increase interdependencies within the plant due to these human factors, as well as different dependencies arising from plant operating rules, procedures and required resources.

To create effective HFE recovery rules, as many HFE combinations as possible must be collected in the PSA model. To generate many MCSs, (1) a low truncation limit can be used or the probability of HFE intentionally set to a high value, (2) the probability values of HFE combinations in MCS can be adjusted through HRA, and (3) the adjusted HFE combinations and probabilities are stored in the MCS recovery rule file. Subsequently, the HFE combinations and probabilities within the MCS are recovered according to the recovery rules every time an MCS is generated [9]. It should be noted, however, that many HFE combinations included in the recovery rules may be deleted by the truncation limit during the MCS generation stage.

Due to computational limitations during PSA, truncation limits are used to restrict MCS, potentially excluding combinations of high probability (frequencies) HFEs from the results. In addition, inaccurate HFE dependency analysis and HFE recovery rules can lead to MCS truncation, resulting in an underestimation of CDF. To address these issues, Jung's method, proposed by Professor Jung of Sejong University [3], has been suggested.

Jung's method simultaneously performs HFE recovery during the MCS generation stage and calculates CDF from the recovered MCS. Unlike existing methods, performing MCS generation and HFE recovery simultaneously can prevent underestimation of CDF due to MCS truncation, thus improving the accuracy of PSA.

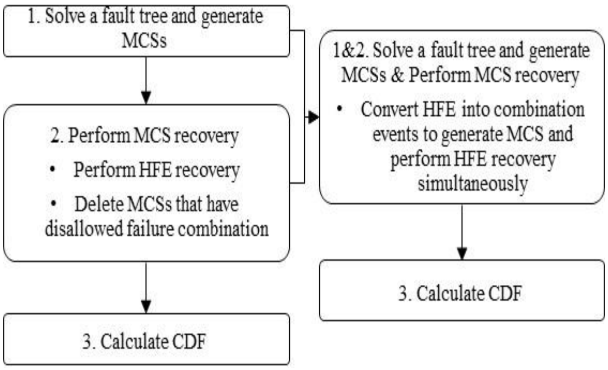

Fig. 2. PSA procedure [3]
(Typical method and Jung's method)

4. Jung's HFE quantification method

Jung's HFE quantification method [3] focuses on (1) collecting the maximum number of HFE combinations without lowering the MCS truncation limit and (2) simultaneously performing MCS generation and HFE recovery. Fig. 3 describes the procedure of Jung's method.

Jung's method has been integrated into the FTREX [4-6]. A detailed example of applying this method to a basic fault tree is provided in Appendix A. Fig. 4 describes the relationship between Jung's method and the typical method.

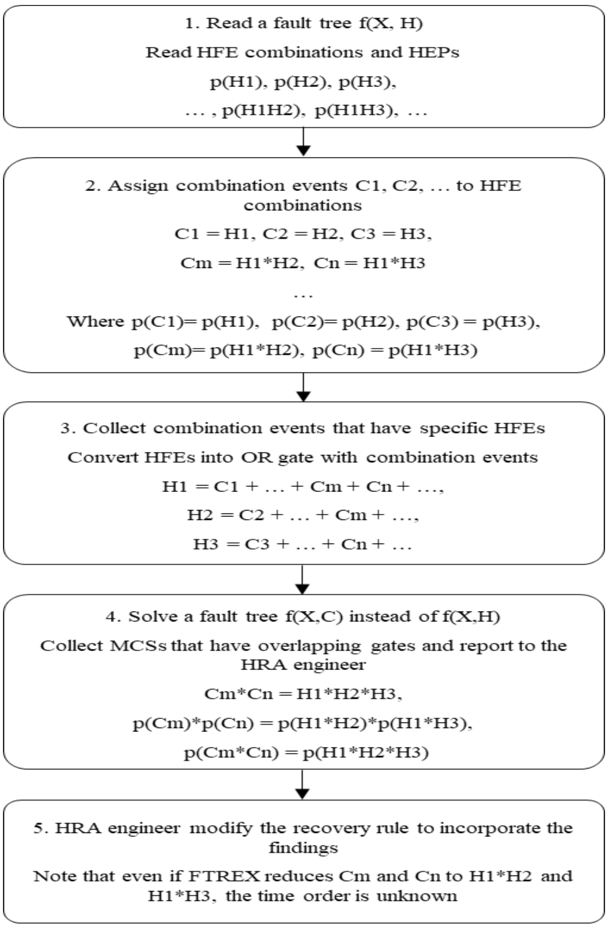

Fig. 3. Procedure of Jung's HFE method

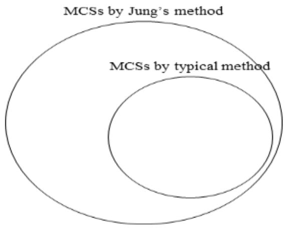

Fig. 4. Relationship between MCSs generated by Jung's method and typical method

Eq. (5) presents the results of the delete-term approximation (DTA) [8] between Jung's method and the typical method. When the delete-term approximation was applied to Jung's method for removing MCSs generated through the typical method, only additional MCSs remained. In the opposite case, no MCSs remained. This confirms that Jung's method consistently generates a higher number of MCSs compared to the typical method under the same truncation limit. Moreover, MCSs remain untruncated when employing this method. Eq. (5) validates the computational results presented in Table 6.

$$Delterm(J,T) \neq \emptyset \quad (5)$$
$$Delterm(T,J) = \emptyset \quad (6)$$

"J" means MCSs generated by Jung's method
"T" means MCSs generated by the typical method

5. Application of Jung's method to actual NPP PSA model

5.1 Application of Jung's method to APR 1400 PSA

Jung's method can be applied by FTREX [4-6], and this feature has already been implemented. If this method is applied to FTREX, recovery rules must be defined. This makes it possible to incorporate HFE recovery in the MCS generation stage. The HFE recovery rule specifies the probabilities of HFEs and HFE combinations for which dependencies have been completed. The fault tree information for APR 1400 is presented in Table 2. Tables 3 and 4 show the details of the recovery rule, which includes the probabilities of HFE and HFE combinations. In addition, other recovery rules that do not include HFEs remain unchanged. HFE names and probabilities are based on the APR 1400 PSA.

Table 2. Fault tree information for APR 1400

Gate	13,811
Event	4,499
-Gate	237
-Event	0
Event (P=1)	237
Initiating event	19

Table 3. Probabilities of HFE

HFE	Probability
H01	0.1
H02	6.36E-04
H03	6.36E-04
H04	5.77E-04
H05	1.39E-03
H06	2.14E-02
H07	1.47E-03
H08	7.85E-03

Table 4. Probabilities of HFE combination

HFE combination			Probability
H07	H01		2.11E-04
H04	H01		2.12E-04
H07	H04		2.53E-04
H02	H03		5.06E-03
H07	H02		5.77E-04
H03	H03		6.36E-04
…			
H01	H03	H02	5.06E-03
H02	H04	H03	5.77E-04
…			

This facilitates the incorporation of HFE recovery into the MCS generation stage and the implementation of recovery rules that do not include an HFE combination. Changes in fault trees, MCSs, and CDF can be observed by applying Jung's method to the APR 1400 PSA. Tables 5 and 6 show the PSA quantification results obtained using Jung's method and typical methods. PSA quantification was performed using FTREX.

Fig. 4 depicts the correlation between Jung's approach and the typical method. The additional MCSs generated by Jung's method do not overlap with those from the typical method, which has already been validated through Eq. (5). Table 7 compares the outcomes of Tables 5 and 6. This table illustrates the difference between MCSs generated by Jung's method and those generated by the typical method. Given our prior confirmation that the generated MCSs are distinct (as outlined in Section 5.1), this subtraction can easily be carried out. Since the CDF is very small, it has been decided to present it as a percentage.

Table 5. Results of PSA using typical method (APR 1400)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.58	152	7.356E-07
1.0E-10	2.36	1,165	1.139E-06
1.0E-11	2.48	5,398	1.264E-06
1.0E-12	4.25	24,022	1.335E-06
1.0E-13	9.20	95,117	1.364E-06
1.0E-14	23.23	356,508	1.376E-06
1.0E-15	64.10	1,287,943	1.398E-06

Table 6. Results of PSA using Jung's method (APR 1400)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.56	166	8.566E-07
1.0E-10	2.08	1,212	1.181E-06
1.0E-11	2.71	5,699	1.313E-06
1.0E-12	4.40	25,328	1.376E-06
1.0E-13	9.33	100,052	1.394E-06
1.0E-14	26.90	374,350	1.402E-06
1.0E-15	67.84	1,357,756	1.405E-06

Table 7. Comparison of Jung's method and typical method using DTA (APR 1400)

Truncation limit	Eq. (5) Increase in MCSs (a)	Eq. (6)	ΔCDF (b)
1.0E-09	14	0	16.45%
1.0E-10	47	0	3.69%
1.0E-11	301	0	3.84%
1.0E-12	1,306	0	2.70%
1.0E-13	4,935	0	2.13%
1.0E-14	17,842	0	1.88%
1.0E-15	69,813	0	0.47%

(a) $No.\left(MCS_{Jung}\right) - No.\left(MCS_{typical}\right)$
(b) $\frac{CDF(MCS_{Jung}) - CDF(MCS_{typical})}{CDF(MCS_{typical})} * 100(\%)$

Table 6 demonstrates that Jung's method consistently generates more MCSs than the typical method. Because it discovers a greater number of MCSs, the CDF also increases. Regardless of the truncation limit, the overall count of MCSs increased when using this method. As the truncation limit decreases, the difference in the CDF decreases because MCSs that contribute to increasing the CDF have already been discovered. Usually, the truncation limit falls within the range of 1.0E-12 to 1.0E-13 in the quantification procedure of PSA, thus rendering Jung's method highly effective. In the current domestic PSA, recovery rules for a maximum of three combinations of HFEs are formulated through dependency analysis. However, Jung's method identified MCSs consisting of up to three HFE combinations and revealed HFE combinations where dependency analysis was incomplete. Using a truncation limit of 1.0E-10, we detected nine HFE combinations that necessitated the addition of recovery rules, as shown in Table 7. For HFE combinations shown in Table 7, additional dependency analysis work by HRA experts is required to obtain a more accurate PSA. More HFE combinations can be identified by re-quantifying to consider the analyzed dependencies. Through iterative execution of this procedure, more precise PSA results can be achieved.

Table 8. HFE combinations requiring the addition of a recovery rule (APR 1400, 1.0E-10)

HFE combination		
H04	H14	
H04	H29	
H10	H21	
H15	H30	
H15	H30	H31
H15	H11	H30
H15	H31	H03
H15	H22	H30
H30	H10	H22

5.2 Application of Jung's method to OPR 1000 PSA

Jung's method has been applied not only to the APR 1400 PSA model but also to other domestic NPP models for comparison with existing methods. Jung's method can be applied to the OPR 1000 NPP PSA model in the same method as the APR 1400 PSA model through the Z_METHOD option in FTREX. The fault tree information of the OPR 1000 PSA model is shown in Table 9. The quantification results obtained using the existing method are presented in Table 10, and those obtained using Jung's method are presented in Table 11. Table 12 compares the existing method and Jung's method. The HFE and HFE combinations for the OPR 1000 PSA model have been omitted.

Table 9. Fault tree information for OPR 1000

Gate	7,759
Event	4,006
-Gate	54
-Event	12
Event (P=1)	183
Initiating event	17

Table 10. Results of PSA using typical method (OPR 1000)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	5.38	250	2.060E-06
1.0E-10	5.98	1,368	2.445E-06
1.0E-11	6.94	6,346	2.600E-06
1.0E-12	8.63	26,385	2.660E-06
1.0E-13	12.04	103,410	2.685E-06
1.0E-14	21.07	386,993	2.695E-06
1.0E-15	44.54	1,359,372	2.698E-06

Table 11. Results of PSA using Jung's method (OPR 1000)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	5.44	262	2.114E-06
1.0E-10	6.21	1,413	2.466E-06
1.0E-11	7.44	6,565	2.607E-06
1.0E-12	9.35	27,330	2.664E-06
1.0E-13	14.06	107,325	2.687E-06
1.0E-14	27.28	401,008	2.696E-06
1.0E-15	59.97	1,403,373	2.699E-06

Table 12. Comparison of Jung's method and typical method using DTA (OPR 1000)

Truncation limit	Eq. (5) Increase in MCSs (a)	Eq. (6)	ΔCDF (b)
1.0E-09	12	0	2.62%
1.0E-10	45	0	0.86%
1.0E-11	219	0	0.27%
1.0E-12	945	0	0.15%
1.0E-13	3,915	0	0.07%

1.0E-14	14,015	0	0.04%
1.0E-15	44,001	0	0.04%

(a) $No.(MCS_{Jung}) - No.(MCS_{typical})$
(b) $\frac{CDF(MCS_{Jung}) - CDF(MCS_{typical})}{CDF(MCS_{typical})} * 100(\%)$

Jung's method was applied to the OPR 1000 PSA model and compared with the typical method. Consequently, Jung's method consistently generates more MCS and HFE combinations than the existing method.

5.3 Application of Jung's method to CANDU PSA

Jung's method was further applied to the CANDU NPP PSA model using the Z_METHOD option in FTREX. The fault tree information for the CANDU PSA model is presented in Table 13. The quantification results using the existing method are shown in Table 14, while the results obtained through Jung's method are represented in Table 15. The comparison between the existing and Jung's methods is depicted in Table 16.

Table 13. Fault tree information for CANDU

Gate	9,857
Event	5,250
-Gate	311
-Event	4
Event (P=1)	369
Initiating event	44

Table 14. Results of PSA using typical method (CANDU)

Truncation limit	**Calculation time (sec)**	**Number of MCSs**	**CDF**
1.0E-09	1.14	106	2.821E-06
1.0E-10	1.35	511	3.177E-06
1.0E-11	1.52	2,608	3.309E-06
1.0E-12	1.90	11,314	3.375E-06
1.0E-13	3.01	39,539	3.403E-06
1.0E-14	5.04	125,645	3.410E-06
1.0E-15	10.21	383,960	3.411E-06

Table 15. Results of PSA using Jung's method (CANDU)

Truncation limit	**Calculation time (sec)**	**Number of MCSs**	**CDF**
1.0E-09	1.50	158	3.120E-06
1.0E-10	1.63	773	3.298E-06
1.0E-11	1.79	3,725	3.361E-06
1.0E-12	2.79	14,617	3.402E-06
1.0E-13	4.13	47,353	3.411E-06
1.0E-14	6.88	144,543	3.411E-06
1.0E-15	14.85	428,220	3.412E-06

Table 16. Comparison of Jung's method and typical method using DTA (CANDU)

Truncation limit	**Eq. (5) Increase in MCSs (a)**	**Eq. (6)**	**ΔCDF (b)**
1.0E-09	52	0	10.60%
1.0E-10	262	0	3.81%
1.0E-11	1,117	0	1.57%
1.0E-12	3,303	0	0.80%
1.0E-13	7,814	0	0.24%
1.0E-14	18,898	0	0.03%
1.0E-15	44,260	0	0.03%

(a) $No.(MCS_{Jung}) - No.(MCS_{typical})$
(b) $\frac{CDF(MCS_{Jung}) - CDF(MCS_{typical})}{CDF(MCS_{typical})} * 100(\%)$

5.4 Application of Jung's Method to Framatome PSA

Jung's method was applied in the Framatome NPP PSA model using the Z_METHOD option in FTREX. The fault tree information for the Framatome PSA model is indicated in Table 17. The quantification results using the existing method are outlined in Table 18, and the results achieved through Jung's method are in Table 19. The comparison between the existing and Jung's methods is illustrated in Table 20.

Table 17. Fault tree information for Framatome

Gate	4,012
Event	3,957
-Gate	153
-Event	6
Event (P=1)	161
Initiating event	22

Table 18. Results of PSA using typical method (Framatome)

Truncation limit	**Calculation time (sec)**	**Number of MCSs**	**CDF**
1.0E-09	0.76	99	7.831E-07
1.0E-10	0.76	649	9.550E-07
1.0E-11	0.87	3,373	1.041E-06
1.0E-12	1.31	12,535	1.077E-06
1.0E-13	2.07	41,848	1.102E-06
1.0E-14	4.36	145,089	1.116E-06
1.0E-15	10.57	512,386	1.119E-06

Table 19. Results of PSA using Jung's method (Framatome)

Truncation limit	**Calculation time (sec)**	**Number of MCSs**	**CDF**
1.0E-09	0.86	108	8.041E-07
1.0E-10	0.98	693	9.677E-07
1.0E-11	1.16	3,625	1.068E-06
1.0E-12	1.61	13,351	1.105E-06
1.0E-13	2.58	44,039	1.114E-06
1.0E-14	5.75	150,764	1.118E-06
1.0E-15	14.31	526,509	1.119E-06

Table 20. Comparison of Jung's method and typical method using DTA (Framatome)

Truncation limit	Eq. (5) Increase in MCSs (a)	Eq. (6)	ΔCDF (b)
1.0E-09	9	0	2.38%
1.0E-10	44	0	1.33%
1.0E-11	252	0	2.59%
1.0E-12	816	0	2.60%
1.0E-13	2,191	0	1.09%
1.0E-14	5,675	0	0.18%
1.0E-15	14,123	0	0.01%

(a) $No.(MCS_{Jung}) - No.(MCS_{typical})$
(b) $\frac{CDF(MCS_{Jung}) - CDF(MCS_{typical})}{CDF(MCS_{typical})} * 100(\%)$

5.5 Application of Jung's method to Westinghouse PSA

Jung's method was applied in the Westinghouse NPP PSA model using the Z_METHOD option in FTREX. The fault tree information for the Westinghouse PSA model is shown in Table 21. The quantification results using the existing method are presented in Table 22, and the results through Jung's method are in Table 23. The comparison between the existing and Jung's methods is detailed in Table 24.

Table 21. Fault tree information for Westinghouse

Gate	6,667
Event	3,974
-Gate	148
-Event	6
Event (P=1)	145
Initiating event	70

Table 22. Results of PSA using typical method (Westinghouse)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.44	175	2.621E-06
1.0E-10	1.97	953	2.894E-06
1.0E-11	2.95	4,564	3.078E-06
1.0E-12	5.17	18,932	3.148E-06
1.0E-13	9.83	73,737	3.182E-06
1.0E-14	22.65	264,261	3.201E-06
1.0E-15	47.73	892,168	3.211E-06

Table 23. Results of PSA using Jung's method (Westinghouse)

Truncation limit	Calculation time (sec)	Number of MCSs	CDF
1.0E-09	1.81	204	2.769E-06
1.0E-10	2.39	1,114	2.996E-06
1.0E-11	4.02	5,476	3.128E-06
1.0E-12	6.84	22,905	3.185E-06
1.0E-13	14.26	89,110	3.205E-06
1.0E-14	30.67	312,098	3.212E-06
1.0E-15	79.13	1,029,204	3.214E-06

Table 24. Comparison of Jung's method and typical method using DTA (Westinghouse)

Truncation limit	Eq. (5) Increase in MCSs (a)	Eq. (6)	ΔCDF (b)
1.0E-09	29	0	5.66%
1.0E-10	161	0	3.51%
1.0E-11	912	0	1.63%
1.0E-12	3,973	0	1.17%
1.0E-13	15,373	0	0.74%
1.0E-14	47,837	0	0.35%
1.0E-15	137,036	0	0.10%

(a) $No.(MCS_{Jung}) - No.(MCS_{typical})$
(b) $\frac{CDF(MCS_{Jung}) - CDF(MCS_{typical})}{CDF(MCS_{typical})} * 100(\%)$

When Jung's method was applied and compared in actual NPPs, it exhibited the greatest effectiveness in the latest model, APR 1400.

5. Conclusions

Jung's method, applied for the first time to a real NPP PSA model, demonstrated significant effectiveness compared to existing methods. It reduces time for HFE dependency analysis, prevents CDF underestimation by avoiding deletion of dependent HFEs, and identifies incomplete HFE dependencies for further analysis. Implemented in FTREX, this method is also applicable to other PSA tools. Jung's method enables more efficient and comprehensive identification of MCSs and HFE combinations than existing methods. It helps in conducting more conservative and accurate PSA evaluations, overcoming limitations of traditional methods like MCS truncation and potential CDF underestimation. This approach holds promise for enhancing nuclear safety in future PSA research and applications.

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