Comparative Studies on the Modeling Approaches of Fire-Induced Component Failure Events for a Fire Event PSA

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1. Introduction

An internal fire event probabilistic safety assessment (PSA) model has generally been quantified by modifications of a pre-developed internal events PSA model [1]. New accident sequence logic not covered in the internal events PSA model are separately developed to be incorporated into a fire PSA model.

The probability of fire-induced component failure is generally estimated to be higher than 0.1 [2]. Applying a commonly used rare event approximation (REA) of fault tree (FT) analysis to the quantification of fire PSA model may result in high quantification results [3, 4]. In addition, to accurately evaluate the probability of a fire-induced component failure, the circuit analysis should be done. Detailed Fault tree (FT) approach may or may not be employed for modeling IEs for a fire event PSA. When modeling the detailed IE FTs, additional efforts are required to construct them. If the detailed IE FTs are not modeled, it is necessary to determine what IEs occur in the fire scenarios. In the case of not modeling the detailed IE FT, it is also difficult to treat the fire-induced multiple IEs [5].

In this paper, comparative analyses were made on the modeling approaches for the fire-induced component failure events in a fire event PSA. With the fire PSA model of the domestic reference nuclear power plant (NPP), the analyses were conducted for the IEs of loss of direct current A (LODCA), loss of off-site power (LOOP) and total loss of component cooling water (TLOCCW). The comparative studies for those events were done for the cases where the detailed IE FTs were constructed or not and those where the fire-induced component failure probabilities were estimated to be one or not.

2. Methods and Results

2.1 CDF equation and modification rules

The total core damage frequency (CDF) of a nuclear power plant from a fire can be represented by Eq. (1).

$$CDF=\sum_{k=1}^{m} CDF_k \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

In Eq. (1), CDF_k represents the CDF of each zone or scenario. The CDF_k can be further represented as [1,5]

$$CDF_k=\%R_k*S\%R_k*N\%R_k*CCDP_k \ldots\ldots\ldots(2)$$

$\%R_k$= fire frequency of zone or scenario k
$S\%R_k$= severity factor of zone or scenario k
$N\%R_k$ = non-suppression probability of zone or scenario k
$CCDP_k$ = conditional core damage probability (CCDP) of zone or scenario k

The modification approach of an internal event PSA model into a fire event PSA model is as follows [1,5]:

- Internal PSA initiating event:
  $\%I => \%I + \Sigma\, \%R_k*S\%R_k*N\%R_k \ldots\ldots\ldots(3)$
- Internal PSA basic event for the component failure:
  $a => a + \sum \%R_k*S\%R_k*N\%R_k*P\%R_k\text{-}a \ldots\ldots(4)$

where,
%I: internal PSA initiating event or frequency
a: basic event for component failure
$P\%R_k\text{-}a$: fire-induced component failure event for the basic event relating to the equipment or cables

Eq. (3) indicates that an internal IE is replaced by an 'OR' logic combination of the internal IE itself and the specific zone or scenario fire occurrence events including the severity factor and non-suppression event [1,5]. Eq. (3) is used for the case where there is no detailed IE FTs for a fire event PSA. Eq. (4) indicates that an internal basic event for a component failure is replaced by an 'OR' logic combination of the internal basic event itself and 'AND' logic combinations. For the case where there are detailed IE FTs for a fire event PSA, Eq. (4) is applied to those for the construction of IE FT for a fire PSA.

In this study, in place of the basic event for component failure, the zero fire damage events were used for the construction of a fire PSA model [1,5]. In other words, the zero fire damage event was additionally modeled for the corresponding component failure events of active components in all mitigating system FTs. IE FTs were constructed by using only the zero damage events. Using the information on the fire scenarios corresponding to the zero fire damage events, the right terms in Eq. (4) were modeled in the IE and mitigating system FTs. The zero fire damage events have zero failure probabilities and they were used as the navigators for the construction of a fire event PSA model.

2.2 Cases for the Comparative Studies

Three IEs (LODCA, LOOP, and TLOCCW) of the reference NPP were selected for the comparative studies. The LODCA IE is defined as [6] sustained de-energization of a safety-related DC bus A due to the inability to connect to any of the normal or alternative electrical power supplies. The LOOP IE is defined as [6] a simultaneous loss of electrical power to all safety-related buses that causes emergency power generators to start and supply power to the safety-related buses. The TLOCCW IE is defined as [6] a total loss of the CCW system that impairs the ability of the system to perform its function. It include the total loss of essential service water system and the failure of heating, ventilation and air conditioning system for CCW system.

As shown in Table I, five cases were considered for the comparative studies depending on the detailed approaches of IE FT modeling and of the estimation of the probability for fire-induced component failure. In the case of 'M2' in Table I, as shown in Fig. 1, detailed FT modeling approach was used for the IE FT. The probabilities ($P_{fire-IE}$) of fire-induced component failures in the IE FT were estimated to be one and those ($P_{fire-MIT}$) in the mitigating system FT were estimated to be not greater than one according to the circuit analysis results. Fig. 2 shows the changed IE FT of LODCA after the application of Eq.(4) to Fig. 1. All internal IEs were set to be 'FALSE'. Fig. 3 shows the changed IE FT of LODCA after the application of Eq.(1) to the IE '%ILODCA' of Fig. 1.

Table I: Descriptions of the Cases for the Comparative Studies

Cases	Detailed FT	Use of Eqs	Proba.
M1	Yes	Eq.(4)	$P_{fire-IE} \leq 1$, $P_{fire-MIT} \leq 1$
M2	Yes	Eq.(4)	$P_{fire-IE} = 1$, $P_{fire-MIT} \leq 1$
M3	Yes	Eq.(4)	$P_{fire-IE} = 1$, $P_{fire-MIT} = 1$
M4	No	Eq.(3) & (4)	$P_{fire-IE} = 1$, $P_{fire-MIT} \leq 1$
M5	No	Eq.(3) & (4)	$P_{fire-IE} = 1$, $P_{fire-MIT} = 1$

$P_{fire-IE}$: probability of fire-induced component failure in the IE FT

$P_{fire-MIT}$: probability of fire-induced component failure in the mitigating system FT

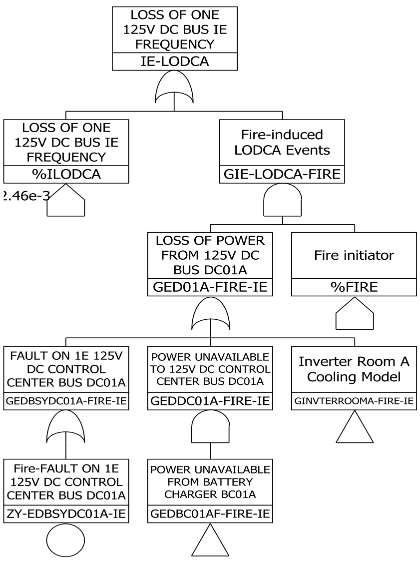

Fig. 1 Detailed Fault Tree of LODCA IE before modification

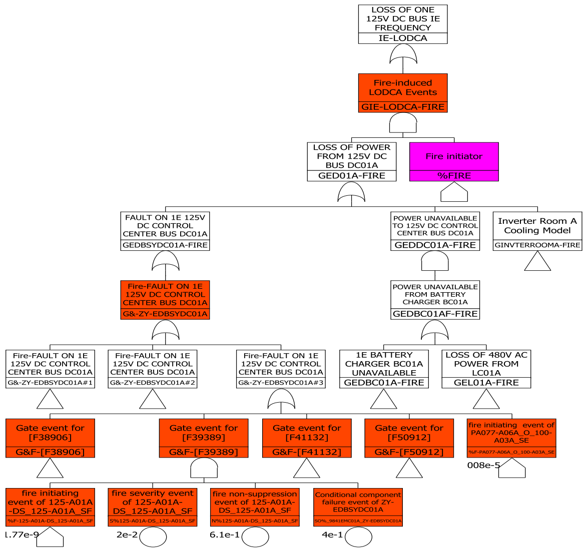

Fig. 2 Detailed Fault Tree of LODCA IE after modification

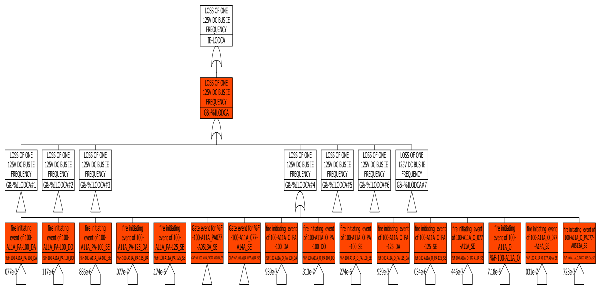

Fig. 3 Fault Tree of LODCA IE (%ILODCA) after modification

2.3 Quantification results

As mentioned in Introduction, a fire event PSA model is quantified by using the internal event PSA model. The quantification results for the five cases are presented in Table II. AIMS-PSA [7] code was used for the quantifications. In Table II, all quantification results were normalized based on the core damage frequency (CDF) of Case M1. Case M1 was estimated to be the smallest among all quantification results. For the cases (M3 and M5) where the probabilities of fire-induced component failure were estimated to be one, it was found that there was little difference between their quantification results. In case of the applications of detailed approach to the IE FTs, the quantification results of M3 except LOOP case are lower than those of M2.

Table II: Quantification results by using AIMS-PSA

REA	detailed IE FT			No detailed IE FT	
IEs	M1	M2	M3	M4	M5
LODCA	1	1.56	1.18	1.80	1.43
LOOP	1	3.10	3.12	3.10	3.12
TLOCCWS	1	2.19	1.09	2.19	1.09

The PSA quantification work using the traditional PSA code have been conducted based on mainly rare event approximation(REA) method. Thus, real CDF of

NPP has been overestimated. To accurately estimate the CDF from the minimal cut-sets, BeEAST(Boolean Equation Evaluation, Analysis, and Sensitivity Tool) [4] was developed. Its quantification is based on the Binary Decision Diagram (BDD) algorithm. Table III shows that the overestimates using REA method range from 3% to 154%. Table IV shows the quantification results for the five cases by using BeEAST. Compared with Table II, the quantification results of M2 are lower than those of M3.

Table III: Quantification Results for the Overestimation

REA/BeEAST	detailed IE FT			No detailed IE FT	
IEs	M1	M2	M3	M4	M5
LODCA	1.27	1.45	1.02	1.37	1.02
LOOP	1.23	1.03	1.03	1.03	1.03
TLOCCWS	2.43	2.52	1.03	2.54	1.03

Table IV: Quantification results by using BeEAST

BeEAST	detailed IE FT			No detailed IE FT	
IEs	M1	M2	M3	M4	M5
LODCA	1	1.36	1.46	1.66	1.77
LOOP	1	3.70	3.73	3.70	3.73
TLOCCWS	1	2.12	2.58	2.10	2.56

3. Concluding remarks

In this paper, comparative analyses were made on the modeling approaches for the fire-induced component failure events in a fire event PSA. Analyses were conducted for the IEs of LODCA, LOOP, and TLOCCW. Five cases were considered for the comparative studies depending on the detailed approaches of IE FT modeling and of the estimation of the probability for fire-induced component failure. Through the comparative analyses, we can confirm that the realistic fire risk can be estimated by employing the detailed approaches to the constructions of IE FTs and to the estimations of the fire-induced component failure probability. In order to resolve the overestimation problem in the quantification results of PSA model, it is necessary to actively use BDD code such as BeEAST.

Acknowledgments

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea grant, funded by the Korean government, Ministry of Science and ICT (Grant number 2017M2A8A4016659).

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