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A Study on Initiating Event Models of Non-Mitigating System Induced by Fire in a Fire PSA

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1. Introduction

In this paper, if the initiating events (IEs) are modeled by only rooms ignition frequencies, this approach is called as 'lumped room IE model', and if IEs occurred by a fire are modeled by the fault trees (FTs) in which components are damaged by the fire, the approach is called as 'FT IE model' in the fire PRA.

In the 'one shot' calculation for the quantification in the fire PRA [1~4], the IEs were 'lumped room IE model'. Recently, IEs occurred by a fire are modeled by fault trees (FTs), and in the paper [5], the accuracy and advantage between 'lumped room IE model' and 'FT IE model' were discussed. However, in the paper [5], the FT IEs occurred by mitigating systems' fire only are discussed. In this paper, IEs occurred by non-mitigating systems' fire are modeled by 'lumped room IE model' and 'FT IE model', and their accuracy and advantage are discussed. In PSA, interfacing LOCA IE would be the typical IE incurred by non-mitigating systems' fire.

Since the lumped room IE model is relatively simple, it is well used in the automatic generation of the fire PRA model from an internal PRA model, also in the screening analysis in which core damage frequency (CDF) caused by a fire is estimated quickly, roughly, and conservatively. Meanwhile, it is natural trend that IEs induced by a fire are modeled by FTs based on the information acquired from circuit analysis, etc., even though it is complicated work, and thus cutsets review is usually necessary.

In this paper, how the two IEs models are related with each other, which one is more conservative, and the advantage and disadvantage between the two IEs models are discussed when IEs occurred by non-mitigating systems' fire.

2. Quantification Methods

Let's assume that an internal event PRA has the following two minimal cut sets (MCSs) [4]:

$$\{IE_1 \cdot A \cdot B \cdot C \cdot E,\ \ IE_2 \cdot A \cdot C \cdot D \cdot F\} \qquad (1)$$

Also, let's assume that the components A, B, C, D, G are located in room 1, room 2, and room 3 as shown in Fig. 1.

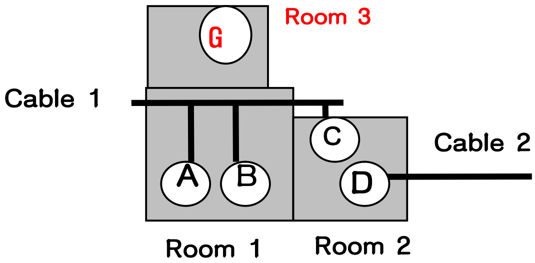

Fig. 1. Components Located in Rooms 1, 2 & 3

With the components and cable arrangement of Fig. 1, we could assume that, if there is a fire in room 1, then components A, B, and C are damaged, and if there is a fire in room 2, then components C and D are damaged. Also, component G would be damaged with room 3 fire. Another assumption is that if component A or C is damaged, then initiating event IE_1 occurs, and that if component D is damaged, then initiating event IE_2 occurs. These relationships are arranged in Table 1, and the events are defined in Table 2. In Fig. 1, we can also see that if a fire occurs in room 1, then an internal initiating event IE_1 occurs, and that if a fire occurs in room 2, then internal initiating events IE_1 and IE_2 occur. Also, let's assume that G failure causes IE_1. That is, $IE_1 \leftarrow R_1+R_2+R_3$, $IE_2 \leftarrow R_2$.

Table 1. Fire Induced Components Failures and Initiating Events

Fire Occurrence Events		Component Failures Given Room *i* Fire		Initiating Events
R_1	→	R_1B_{1f}	→	Φ
		R_1A_{1f} or R_1C_{1f}	→	IE_1
R_2	→	R_2C_{2f}		
	→	R_2D_{2f}	→	IE_2
R_3	→	R_3G	→	IE_1

Table 2. Definition of Events

Event Name	Event Description
R_1	Fire occurrence event including severity factor and non-suppression prob. in room 1 [freq.]
R_2	Fire occurrence event including severity factor and non-suppression prob. in room 2 [freq.]
R_3	Fire occurrence event including severity factor and non-suppression prob. in room 3 [freq.]
A_{1f}	Component A failure probability in case of room 1 fire [Prob.]
B_{1f}	Component B failure probability in case of room 1 fire [Prob.]
C_{1f}	Component C failure probability in case of room 1fire [Prob.]
C_{2f}	Component C failure probability in case of room 2 fire [Prob.]
D_{2f}	Component D failure probability in case of room 2 fire [Prob.]
G_{3f}	Component G failure probability in case of room 3 fire [Prob.]
A	Component A Failure due to Random Failure [Prob.]
B	Component B Failure due to Random Failure [Prob.]
C	Component C Failure due to Random Failure [Prob.]
D	Component D Failure due to Random Failure [Prob.]
E	Component E Failure due to Random Failure [Prob.]. Component E which is not shown in Fig. 1 is not damaged due to fire.
F	Component F Failure due to Random Failure [Prob.]. Component F which is not shown in Fig. 1 is not damaged due to fire.

2.1 Lumped Room IE Model

One shot calculation in the fire PRA quantification was introduced in Ref.[1~4]. It could be said that the one shot calculation is using 'lumped room IE model'. In the lumped room IE model, the IEs are modeled by room fire occurrence frequency as like; $IE_1 \leftarrow R_1+R_2+R_3$, $IE_2 \leftarrow R_2$. Thus, from Table 1,

$$IE_1 A\cdot B\cdot C\cdot E + IE_2\cdot A\cdot C\cdot D\cdot F \quad (2)$$

$$\rightarrow (R_1+R_2+R_3)\cdot(A+R_1A_{1f})\cdot(B+R_1B_{1f})\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot E + R_2\cdot(A+R_1A_f)\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot(D+R_2D_{2f})\cdot F$$

$$\rightarrow R_1\cdot(A+R_1A_{1f})\cdot(B+R_1B_{1f})\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot E +R_2\cdot(A+R_1A_{1f})\cdot(B+R_1B_{1f})\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot E +R_3\cdot(A+R_1A_{1f})\cdot(B+R_1B_{1f})\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot E +R_2\cdot(A+R_1A_{1f})\cdot(C+R_1C_{1f}+R_2C_{2f})\cdot(D+R_2D_{2f})\cdot F \quad (3)$$

$$\rightarrow R_1\cdot(A+A_{1f})\cdot(B+B_{1f})\cdot(C+C_{1f})\cdot E + R_2\cdot A\cdot B\cdot(C+C_{2f})\cdot E + R_3\cdot A\cdot B\cdot C\cdot E + R_2\cdot A\cdot(C+C_{2f})\cdot(D+D_{2f})\cdot F$$

$$\rightarrow R_1(B+B_{1f})(AC+AC_{1f}+A_{1f}C+A_{1f}C_{1f})E + R_2(A)(B)(C+C_{2f})E + R_3\cdot A\cdot B\cdot C\cdot E + R_2(A)(C+C_{2f})(D+D_{2f})F \quad (4)$$

Lumped Room IE Model is modifying IE_1 and IE_2 with '$R_1+R_2+R_3$' and 'R_2', respectively, in Eq. (2).

2.2 FT based IE Model

In FT based IE model, fire induced initiating events are modeled by fault trees. An example is shown as below;

Let's assume that IE_1 is modeled by a fault tree, $R_1\cdot A_f + R_1\cdot C_{1f}+ R_2\cdot C_{2f} + R_3\cdot G_{3f}$, and IE_2 is modeled by R_2D_{2f}.

$$IE_1 A\cdot B\cdot C\cdot E + IE_2\cdot A\cdot C\cdot D\cdot F$$

$$\rightarrow (R_1\cdot A_{1f}+R_1\cdot C_{1f}+R_2\cdot C_{2f}+ R_3\cdot G_{3f})\cdot(A+R_1\cdot A_{1f})\cdot(B+R_1\cdot B_{1f})\cdot(C+R_1\cdot C_{1f}+ R_2\cdot C_{2f})\cdot E +R_2\cdot D_{2f}(A+R_1\cdot A_{1f})\cdot(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})\cdot(D+R_2\cdot D_{2f})\cdot F$$

$$\rightarrow (R_1\cdot A_{1f})\cdot(A+R_1\cdot A_{1f})\cdot(B+R_1\cdot B_{1f})\cdot(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})\cdot E +(R_1\cdot C_{1f})\cdot(A+R_1\cdot A_{1f})(B+R_1\cdot B_{1f})(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})\cdot E +(R_2\cdot C_{2f})\cdot(A+R_1\cdot A_{1f})(B+R_1\cdot B_{1f})(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})E +(R_3\cdot G_{3f})\cdot(A+R_1\cdot A_{1f})(B+R_1\cdot B_{1f})(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})E +(R_2\cdot D_{2f})\cdot(A+R_1A_{1f})(C+R_1\cdot C_{1f}+R_2\cdot C_{2f})(D+R_2\cdot D_{2f})F \quad (5)$$

$$\rightarrow (R_1\cdot A_{1f})\cdot(B+B_{1f})\cdot(C+C_{1f})\cdot E + (R_1\cdot C_{1f})(A+A_{1f})(B+B_{1f})\cdot E + (R_2\cdot C_{2f})(A)(B)\cdot E + (R_3\cdot G_{3f})(A)(B)\cdot E + (R_2\cdot D_{2f})(A)(C+C_{2f})\cdot F$$

$$\rightarrow (R_1)(B+B_{1f})(A_{1f}C+A_{1f}C_{1f}+AC_{1f})\cdot E + (R_2)(A)(B)\cdot C_{2f}\, E + (R_3\cdot)(A)(B)\cdot C\cdot G_{3f}\, E + (R_2)(A)(C+C_{2f})D_{2f}\cdot F \quad (6)$$

By comparing Eq. (4) with Eq. (6), all four terms of lumped room IE model in Eq.(4) is larger than those of FT based IE model in Eq.(6). Thus, CDF value of lumped room IE model is larger than one of FT based IE model.

The reason that the lumped room IE model is more conservative is that it does not fully perform Boolean reduction since IEs are not deeply modeled up to the level of the mitigating systems failure mode due to fire. For example, let's compare the last terms of Eq. (3) and Eq. (5).

In Eq. (3), since $IE_2 \leftarrow R_2$;

$R_2 \cdot (D+R_2D_f) \rightarrow R_2 \cdot (D+D_f)$.

Meanwhile, in Eq. (5), since $IE_2 \leftarrow R_2D_f$;

$R_2D_f \cdot (D+R_2D_f) \rightarrow R_2D_f$.

That is, in Eq. (5), IE_2 is modeled up to R_2D_f equivalent to the level of fire failure mode, R_2D_f, of mitigating system D, which enable to make Boolean reduction to be done fully. Its physical meaning is that if an initiating event occurs due to the mitigating system failure due to fire, then the random failure of the mitigating system does not occur.

For the non-mitigating system case, in Eq. (3), since $IE_1 \leftarrow R_3$;

$R_3 \cdot (C+R_1C_{1f}+R_2C_{2f}) \cdot E \rightarrow R_3 \cdot C \cdot E$.

Meanwhile, in Eq. (5), since $IE_1 \leftarrow R_3G_{3f}$;

$R_3G_{3f} \cdot (C+R_1C_{1f}+R_2C_{2f}) \cdot E \rightarrow R_3G_{3f} \cdot C \cdot E$.

Since the mitigating system term does not exist in the non-mitigating system's fire, the Boolean reduction could not occur fully. Thus, the 'lumped room IE model' is more conservative than the 'FT based IE model'.

2.3 Incomplete FT based IE Model

In the previous model, let's assume ($IE_1 \leftarrow R_1 \cdot A_{1f} + R_1 \cdot C_{1f} + R_2 \cdot C_{2f}$) instead of ($IE_1 \leftarrow R_1 \cdot A_{1f} + R_1 \cdot C_{1f} + R_2 \cdot C_{2f} + R_3 \cdot G_{3f}$). That is, an initiating event (IE_1) is not completely modeled by FT. Then,

$$
\begin{aligned}
& IE_1 A \cdot B \cdot C \cdot E + IE_2 \cdot A \cdot C \cdot D \cdot F \\
& \rightarrow (R_1 \cdot A_{1f} + R_1 \cdot C_{1f} + R_2 \cdot C_{2f}) \cdot (A+R_1 \cdot A_{1f}) \cdot (B+R_1 \cdot B_{1f}) \cdot \\
& \quad (C+R_1 \cdot C_{1f}+ R_2 \cdot C_{2f}) \cdot E \\
& \quad + R_2 \cdot D_{2f}(A+R_1 \cdot A_{1f}) \cdot (C+R_1 \cdot C_{1f}+ R_2 \cdot C_{2f}) \cdot \\
& \quad (D+R_2 \cdot D_{2f}) \cdot F \\
& \rightarrow (R_1 \cdot A_{1f}) \cdot (A+R_1 \cdot A_{1f}) \cdot (B+R_1 \cdot B_{1f}) \cdot \\
& \quad (C+R_1 \cdot C_{1f} + R_2 \cdot C_{2f}) \cdot E \\
& \quad + (R_1 \cdot C_{1f})(A+R_1 \cdot A_{1f})(B+R_1 \cdot B_{1f}) \cdot (C+R_1 \cdot C_{1f}+R_2 \cdot C_{2f}) \cdot E \\
& \quad +(R_2 \cdot C_{2f}) \cdot (A+R_1 \cdot A_{1f})(B+R_1 \cdot B_{1f})(C+R_1 \cdot C_{1f}+R_2 \cdot C_{2f})E \\
& \quad +(R_2 \cdot D_{2f})(A+R_1 \cdot A_{1f})(C+R_1 \cdot C_{1f}+R_2 \cdot C_{2f})(D+R_2 \cdot D_{2f})F \\
& \rightarrow (R_1 \cdot A_{1f})(B+B_{1f})(C+ C_{1f})E \\
& \quad + (R_1 \cdot C_{1f})(A+A_{1f})(B+B_{1f})E \\
& \quad +(R_2 \cdot C_{2f}) \cdot (A)(B)E \\
& \quad +(R_2 \cdot D_{2f})(A)(C+C_{2f})F \\
& \rightarrow (R_1)(B+B_{1f})(A_{1f}C+A_{1f} C_{1f}+ AC_{1f}) \cdot E \\
& \quad + (R_2)(A)(B) \cdot C_{2f} E \\
& \quad + (R_2)(A)(C+C_{2f})D_{2f} \cdot F
\end{aligned} \tag{7}
$$

By comparing Eq. (7) with Eq. (6), the 3rd terms of FT based IE model, i.e., $(R_3 \cdot)(A)(B) \cdot C \cdot G_{3f}$ E of Eq. (6) is missing, and so the CDF of incomplete FT based IE model becomes smaller value. Thus, when FT based IE model is developed, it should be careful to include all FTs for IE.

2.4 Hybrid IE Model

Hybrid IE model is to use lumped room IE model and FT based IE model together. In the previous example, let's assume that room 1 is too complicate to build up FT based IE, and that room 2 is simple for FT based IE modeling. In this case, a hybrid IE model, in which a lumped room IE model is used for room 1 and a FT based IE model for room 2, is adequate. Let's assume that ($IE_1 \leftarrow R_1 + R_2 \cdot C_{2f}$), and ($IE_1 \leftarrow R_2D_f$). Then,

$$
\begin{aligned}
& IE_1 A \cdot B \cdot C \cdot E + IE_2 \cdot A \cdot C \cdot D \cdot F \\
& \rightarrow (R_1 + R_2 \cdot C_{2f} + R_3 \cdot G_{3f}) \cdot \\
& \quad (A+R_1 \cdot A_{1f})(B+R_1 \cdot B_{1f})(C+R_1 \cdot C_{1f}+ R_2 \cdot C_{2f})E \\
& \quad + R_2 \cdot D_{2f}(A+R_1 \cdot A_{1f})(C+R_1 \cdot C_{1f}+R_2 \cdot C_{2f})(D+R_2 \cdot D_{2f})F \\
& \quad \rightarrow (R_1)(A+A_{1f})(B+B_{1f})(C+C_{1f})E + \\
& \quad (R_2 \cdot C_{2f})(A)(B)E + (R_3 \cdot G_{3f})(A)(B) \cdot E \\
& \quad + (R_2 \cdot D_{2f})(A)(C+C_{2f})F \\
& \rightarrow (R_1)(B+B_{1f})(AC+AC_{1f}+A_{1f}C+A_{1f}C_{1f}) \cdot E \\
& \quad + (R_2 \cdot C_{2f})(A)(B) \cdot E \\
& \quad + (R_3)(A)(B) \cdot C \cdot G_{3f} E \\
& \quad + (R_2)(A)(C+C_{2f})D_{2f} \cdot F
\end{aligned} \tag{8}
$$

By comparing Eq. (4) and (6) with (8), the first term of hybrid IE model (i.e., Eq. (8)) is the same 1st term of lumped room IE model, and the 2nd, 3rd and 4th term of hybrid IE model(i.e., Eq. (8)) is the same ones of FT based IE model. In other words, for the room 1, we are roughly modeling IE since the room is so complicated, and thus a conservative value is achieved, and for room 2, since we can make a FT based IE model with confidence, the optimal low CDF values could be derived. Thus, the CDF value of the hybrid IE model usually locates between the values derived from the FT based IE model and the lumped room IE model.

3. Results and Conclusions

The lumped room IE model and the FT based IE model are compared when IEs are modeled according to the fire of non-mitigating systems. The compared results for non-mitigating systems are exactly same ones for the mitigating systems. For example, the lumped room IE model derives a conservative CDF, and the FT based IE model derives a more realistic CDF value for the non-mitigating systems. Since the lumped room IE model is relatively easy to build up, it is suitable in the automatic fire PRA modeling from internal events and screening analysis. In a new nuclear power plant, it may be difficult to develop a FT based IE model. In this case, the lumped room model for the initiating events is good conservative model. The disadvantage of the FT based IE model is that we should carefully review the cutsets since it is easy to make a wrong fault tree model for the IEs, and furthermore, if incomplete FTs are used for IEs, then CDF could be underestimated. For a complicated room where FT based IE model is not easily prepared, a lumped room IE model is good since the lumped room IE model is conservative. The useful appoach is to use a hybrid IE model which is using a lumped room IE model for a complicated room, and a FT based IE model for the simple room. The derived CDF value by the hybrid IE model locates between the conservative and optimistic value.

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