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Analytic expressions for the construction of a fire event PSA model

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1. Introduction

An internal fire event probabilistic safety assessment (PSA) model has been generally quantified by modifications of a pre-developed internal event PSA model. New accident sequence logics not covered in the internal events PSA model are separately developed to incorporate them into the fire PSA model. Currently, many fire PSA models have fire induced initiating event fault trees not shown in an internal event PSA model [1, 2]. Fire-induced initiating fault tree models are developed for addressing multiple initiating event issues. A single fire event within a fire compartment or fire scenario can cause multiple initiating events. As an example, a fire in a turbine building area can cause a loss of the main feed-water and loss of off-site power initiating events. Up to now, there has been no analytic study on the construction of a fire event PSA model using an internal event PSA model with fault trees of initiating events. In this study, the changing process of an internal event PSA model to a fire event PSA model is analytically presented and discussed.

2. Methods and Results

In this section, the changing process of an internal event PSA model to the fire event PSA model is analytically presented and discussed.

2.1.1 CDF equation and modification rules

The CDF (core damage frequency) from a fire can be represented by Eq. (1)[3].

$$\mathrm{CDF} = \sum_{k=1}^{n} \%R_k * S\%R_k * CCDP_k \qquad (1)$$

$\%R_k$ = fire frequency of fire scenario k,
$S\%R_k$ = severity for $\%R_k$ representing both the severity factor and non-suppression probability,
$CCDP_k$ = CCDP (conditional core damage probability) of fire scenario k

The modification rules of an internal event PSA model to a fire event PSA model are as follows [3]:

- Internal initiating events: If an internal initiating event occurs owing to a specific fire scenario, then replace the internal initiating event by an 'OR' logic combination of the specific fire scenario occurrence events including the severities.
- Internal basic events for the equipment failure: If the equipment, instrumentation, or cables are damaged by a specific fire scenario, then replace the internal basic events for the equipment failures related to them by an 'OR' logic combination of the internal basic events themselves and 'AND' logic combinations. The 'AND' logic combinations consist of the fire damage events for the equipment failures associated with the damaged equipment, instrumentation, or cables due to a fire, and of the specific fire scenario occurrence events including the severities.

The modification algorithm of an internal event PSA model into a fire event PSA model is as follows [4]:

- Internal PSA initiating event:
  $\%I => \Sigma\ \%R_k * S\%R_k$……………………….……(2)
- Internal PSA basic event for the component failure:
  $a => a + \sum \%R_k * S\%R_k * P\%R_k\text{-}a$ ….……….(3)

%I: internal PSA initiating event
a: basic event for the random component failure
$P\%R_k\text{-}a$: fire damage events for the basic events relating to the equipment or cables

2.2 Hypothetical plant

Fig. 1 of Reference [5] was used for the demonstration of the application of the modification rules with small changes. Let us assume that an internal event PSA model has the following two minimal cutsets (MCS):

$$\{ IE_1*a*b*c*e,\ IE_2*a*c*d*f \} \qquad (4)$$

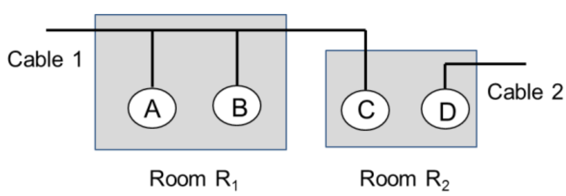

Fig. 1. Components located in fire rooms of hypothetical plant

The hypothetical plant, as shown Fig.1, has two fire rooms R_1 and R_2 that have equipment A, B, C and D, and cables 1 and 2. It is assumed that if the fire event $\%R_1$ occurs, then an internal initiating event IE_1

occurs, and that if the fire event $\%R_2$ occurs, then internal initiating events IE_1 and IE_2 occur. The probabilities of the failure modes, including spurious operations, for the components A, B, C, and D are assumed to be a_f, b_f, c_f, and d_f, respectively. The definitions of the events for the application of the modification rules are presented in Table I.

Table I: Event descriptions

Event name	Event description
$\%R_1$	Fire occurrence event or frequency in room 1
$\%R_2$	Fire occurrence event or frequency in room 2
$S\%R_1$	Severity for $\%R_1$
$S\%R_2$	Severity for $\%R_2$
a	Component A failure event or probability due to a random failure
b	Component B failure event or probability due to a random failure
c	Component C failure event or probability due to a random failure
d	Component D failure event or probability due to a random failure
e	Component E failure event or probability due to a random failure
f	Component F failure event or probability due to a random failure
a_f	Component A failure event or probability due to a fire in room 1
b_f	Component B failure event or probability due to a fire in room 1
c_{f-1}	Component C failure event or probability due to a fire in room 1
c_{f-2}	Component C failure event or probability due to a fire in room 2
d_f	Component D failure event or probability due to a fire in room 2

2.3 Construction of a fire PSA model without fault trees of initiating events

First, we constructed a fire PSA model for an internal event PSA model without fault trees of the initiating events. With the information in Table 1, the modification rules in Eqs. (2) and (3) were applied to two MCS in Eq. (4). The events IE1, IE2, a, b, c, d in Eq. (4) were replaced by the right side Boolean formulas as follows:

$$\begin{aligned} IE_1 &=> \%R_1*S\%\,R_1+\%R_2*S\%\,R_2 \\ IE_2 &=> \%R_2*S\%\,R_2 \\ a &=> a+\%R_1*S\%\,R_1*a_f \\ b &=> b+\%R_1*S\%\,R_1*b_f \\ c &=> c+\%R_1*S\%\,R_1*c_{f-1}+\%R_2*S\%\,R_2*c_{f-2} \\ d &=> d+\%R_2*S\%\,R_2*d_f \end{aligned} \quad (5)$$

For the simplification of the changing process, let us assume that the probabilities of all fire related events except $\%R_1$, $\%R_2$, and c_{f-1} are 1. Then, the above Boolean formulas can be represented as follows:

$$\begin{aligned} IE_1 &=> \%R_1+\%R_2 \\ IE_2 &=> \%R_2 \\ a &=> a+\%R_1 \\ b &=> b+\%R_1 \\ c &=> c+\%R_1*c_{f-1}+\%R_2 \\ d &=> d+\%R_2 \end{aligned} \quad (6)$$

Consequently, the following fire PSA MCS were obtained:

$$\{\%R_1*c*e,\ \%R_1*c_{f-1}*e,\ \%R_2*a*b*e,\ \%R_2*a*f\} \quad (7)$$

2.4 Construction of a fire PSA model with fault trees of initiating events

Second, we constructed a fire PSA model for an internal event PSA model with fault trees of initiating events. Since the internal initiating event IE_1 occurs due to the fire events $\%R_1$ or $\%R_2$, the internal initiating event IE_2 occurs due to the fire event $\%R_2$, and the components in each room fail, we can assume that IE_1 occurs owing to the failure of component A, B, or C, and IE_2 occurs owing to the failure of component C or D. Thus, fault trees of IE_1 and IE_2 can be represented as the following Boolean formulas:

$$\begin{aligned} IE_1 &=> \%I\text{-}a+\%I\text{-}b+\%I\text{-}c \\ IE_2 &=> \%I\text{-}c+\%I\text{-}d \end{aligned} \quad (8)$$

In Eq. (8), %I-x means the basic event or frequency of component X for fault trees of initiating events. Even though there is a possibility of component C failure for the fire event $\%R_1$, the fire event $\%R_1$ does not lead to the initiating event IE_2. Thus, the initiating event IE_2 can be represented as

$$IE_2 => \%I\text{-}c * \%I\text{-}d + \%I\text{-}d = \%I\text{-}d \quad (9)$$

In Eq. (9), the fault trees of IE_1 and IE_2 are represented by component failure events. Thus, the component modification rule of Eq. (3) can be applied to Eq. (9). Let us further assume that the frequencies of the component failure events for Eq. (9) are zero. Then, %I-a, %I-b, %I-c, %I-d, IE_1 and IE_2 can be represented as follows:

$$\begin{aligned} \%I\text{-}a &=> 0+\%R_1 \\ \%I\text{-}b &=> 0+\%R_1 \\ \%I\text{-}c &=> 0+\%R_1*c_{f1}+\%R_2 \\ \%I\text{-}d &=> 0+\%R_2 \\ IE_1 &=> \%I\text{-}a+\%I\text{-}b+\%I\text{-}c = \\ &\quad \%R_1+\%R_1+\%R_1*c_{f1}+\%R_2=\%R_1+\%R_2 \\ IE_2 &=> \%I\text{-}d=\%R_2 \end{aligned} \quad (10)$$

Since the Boolean formulas of initiating events in Eq. (10) are the same as those in Eq. (6), the same MCS of Eq. (7) was obtained. As the real fault trees of initiating events for the construction of a fire PSA model may have a lot of component failure events, it is not easy to exactly represent initiating events using Boolean equations, as shown in Eq. (9). If Eq. (8) is used for the construction of a fire PSA model instead of Eq. (9), the following fire PSA MCS is obtained:

$$\{\%R_1*c*e,\ \%R_1*c_{f-1}*e,\ \%R_2*a*b*e,\ \%R_2*a*f,\ \%R_1*c_{f-1}*d*f\} \quad (11)$$

Comparing with Eq. (7), additional cutset $\%R_1*c_{f-1}*d*f$ was obtained.

3. Conclusions

In this paper, the changing process of an internal event PSA model to a fire event PSA model was analytically presented and discussed. This study results show that additional cutsets can be obtained if the fault trees of initiating events for a fire event PSA model are not exactly developed. Further studies are needed for the actual implementation of the approaches presented in this paper.

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