New method for an efficient risk quantification of external events

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1. Introduction

External events in a probabilistic safety assessment (PSA) include internal fire, internal flooding, seismic, external fire, typhoon, hurricane, and others. In order to quantify external event-induced core damage frequency (CDF), internal event PSA model is modified to reflect external event attributes.

For the fire or flooding PSA, external event scenarios are carefully developed and quantified in a sequential and iterative way. This study provides a new method that facilitates quantification of all or several external event scenarios in a single run (see Section 4). Furthermore, this study proposes an explicit method to build a single top external event PSA model.

2. Fire PSA Modeling

During the iterative processes [1] in Fig. 1, the internal event PSA model is converted into a fire PSA model in Task 5 after collecting all possible information.

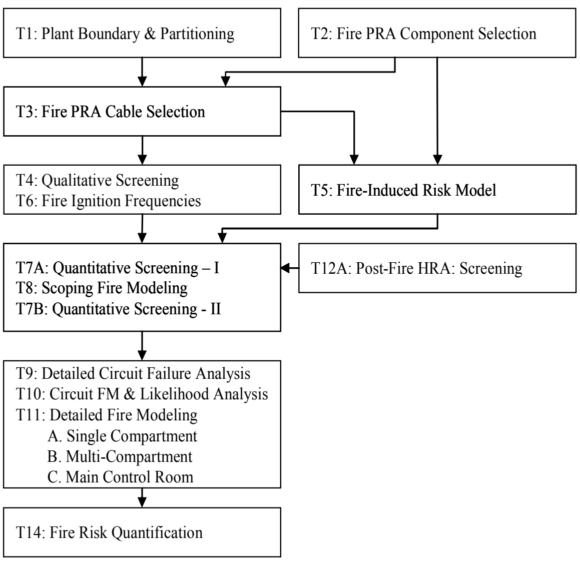

Fig. 1. Fire PSA process

At the final stages of the model development process, flag events are explicitly added into the logic model to mimic fire-induced equipment failures that directly disable or degrade systems, trains, and functions credited in the fire PSA model. A fire PSA model is developed in Task 5 with (1) an internal event PSA model, (2) unscreened fire compartments from Task 4, (3) PSA equipment and fire-induced initiating event information from Task 2, and (4) human reliability analysis (HRA) events developed in Task 12.

All inputs and outputs of each Task are recommended to be stored in the fire PSA database [1] that contains the essential information for conducting a fire PSA. The fire PSA database provides the data structure and functional relationships necessary to correlate the various data elements and generate desired sorts and queries for assessing failures based on the fire PSA model. The database is populated with equipment, cable, raceway, fire compartment, and other relevant data needed to support a fire PSA, and provides a structured framework for maintaining the data.

When a fire ignition in the ith fire compartment is postulated, the two following fire scenarios are possible

$$FIG_i \times SEV_i \times DET_i \quad (1)$$
$$FIG_i \times SEV_i \times /DET_i \times SUP_i \quad (2)$$

where FIG_i=fire ignition frequency, SEV_i=fire severity level, DET_i=fire detected, and SUP_i=fire suppressed. Lots of fire scenarios are developed and some fire scenarios could be merged into a typical scenario. If the fire spreads from a compartment to another one, further fire scenarios should be developed [1, 2].

Attributes for the fire PSA quantification are assigned to each fire scenario or sequence. The attributes include (1) a fire scenario frequency R_i, (2) equipments (basic events) damaged by fire scenarios, and (3) internal initiating events caused by fire scenario. Based on the mapping information from fire scenarios to basic events and initiators, flag events are explicitly added into the logic model to develop a fire PSA model.

A conditional core damage probability (CCDP) of the ith scenario $CCDP_i$ is calculated with a fire PSA model by turning on the flag events required for the ith scenario and turning off the other flag events. Then, the CDF_i is calculated by multiplying ith scenario frequency R_i and $CCDP_i$. The fire CDF is

$$CDF = \sum_i (R_i \times CCDP_i) \,. \quad (3)$$

3. Conventional Quantification Method

Let us consider a hypothetical plant in Fig. 2 and an internal event PSA model that has 2 initiators I_1 and I_2 and 6 basic events A, B, C, D, E, F as

$$I_1 \times A \times B \times C \times E + I_2 \times A \times C \times D \times F \,. \quad (4)$$

For a fire PSA model in Fig. 2, flag events are added into the internal PSA model in Eq. (4).

$$I_1(A+A_f)(B+B_f)(C+C_f)E + I_2(A+A_f)(C+C_f)(D+D_f)F \,. \quad (5)$$

The events A_f, B_f, C_f, and D_f are flag events that are prepared to be set to Ω or Φ (TRUE or FALSE).

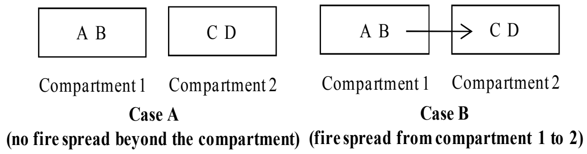

Fig. 2 Sample fire PSA model

3.1 Case A (single compartment fire)

The fire PSA model has 2 scenarios and their frequencies are R_1 and R_2. The fire PSA model has 2 conditions as

Condition 1: $R_1 \rightarrow A, B$ and $R_1 \rightarrow I_1$
Condition 2: $R_2 \rightarrow C, D$ and $R_2 \rightarrow I_1, I_2$.

Basic events A, B and an initiator I_1 could be occurred by the fire scenario R_1. Basic events C, D and 2 initiators I_1 and I_2 could be induced by R_2.

The CCDP of a fire scenario R_1 is calculated by setting $I_1=A_f=B_f=\Omega$, $I_2=\Phi$, and the other flags=Φ as

$$CCDP_1 = \Omega\,(A+\Omega)(B+\Omega)CE = CE\,. \qquad (6)$$

As a next step, the CCDP of a fire scenario R_2 is calculated by setting $I_1=I_2=C_f=D_f=\Omega$ and the other flags=Φ as

$$CCDP_2 = AB(C+\Omega)E+A(C+\Omega)(D+\Omega)F=ABE+AF. \quad (7)$$

Finally, the fire PSA has 3 minimal cut sets (MCSs) as

$$\text{MCSs} = \{R_1CE,\ R_2ABE,\ R_2AF\}. \qquad (8)$$

3.2 Case B (multi-compartment fire)

In the fire PSA, it is postulated that a fire may spread from one compartment to another and damage target elements in multiple compartments. Let us assume the fire at the compartment 1 spreads to the compartment 2 with a probability P_{12} as

Condition 1: $R_1 \rightarrow A, B$ and $R_1 \rightarrow I_1$
Condition 2: $R_2 \rightarrow C, D$ and $R_2 \rightarrow I_1, I_2$
Condition 3: $R_1 \rightarrow R_2$ with a probability P_{12} .

The transferred fire $CCDP_{12}$ is calculated by setting $I_1 = I_2=A_f=B_f=C_f=D_f=\Omega$ as

$$(A+\Omega)(B+\Omega)(C+\Omega)E+(A+\Omega)(C+\Omega)(D+\Omega)F$$
$$=E+F\,. \qquad (9)$$

From Eqs. (8) and (9), the fire PSA has 5 MCSs as

$$\text{MCSs}=\{R_1CE,\ R_2ABE,\ R_2AF,\ R_1P_{12}E,\ R_1P_{12}F\}. \quad (10)$$

4. New Quantification Method

The new fire PSA quantification method [3] is illustrated with the same model and conditions of Cases A and B in Section 3.

4.1 Case A (single compartment fire)

Basic events and initiators in Eq. (4) have the following reverse relations from the Conditions 1 and 2 in Section 3.1.

$$A \rightarrow A+R_1,\ B \rightarrow B+R_1,$$
$$C \rightarrow C+R_2,\ D \rightarrow D+R_2$$
$$I_1 \rightarrow R_1+R_2,\ I_2 \rightarrow R_2\ . \qquad (11)$$

After replacing the basic events and initiators with mappings in Eq. (11), Eq. (4) becomes

$$(R_1+R_2)(A+R_1)(B+R_1)(C+R_2)E+$$
$$R_2(A+R_1)(C+R_2)(D+R_2)F$$
$$= (R_1+R_2A)(B+R_1)(C+R_2)E + R_2A(C+R_2)(D+R_2)F$$
$$= (R_1+R_2AB)(C+R_2)E + R_2A(D+R_2)F$$
$$= R_1CE+R_2ABE+R_2AF\,. \qquad (12)$$

Here, $R_1 \times R_2$ are deleted since they are frequency events. The MCSs $\{R_1E,\ R_2ABE,\ R_2AF\}$ in Eq. (12) are equivalent to those in Eq. (8).

4.2 Case B (multi-compartment fire)

The following reverse relations are obtained by adding the transferred fire R_1P_{12} next to R_2 in Eq. (11)

$$A \rightarrow A+R_1,\ B \rightarrow B+R_1,$$
$$C \rightarrow C+R_2+R_1P_{12},\ \ D \rightarrow D+R_2+R_1P_{12}$$
$$I_1 \rightarrow R_1+R_2+R_1P_{12}= R_1+R_2,\ I_2 \rightarrow R_2+R_1P_{12}. \quad (13)$$

After replacing the basic events and initiators with reverse mappings in Eq. (13), Eq. (4) becomes

$$(R_1+R_2)(A+R_1)(B+R_1)(C+R_2+R_1P_{12})E+$$
$$(R_2+R_1P_{12})(A+R_1)(C+R_2+R_1P_{12})(D+R_2+R_1P_{12})F$$
$$= (R_1+R_2A)(B+R_1)(C+R_2+R_1P_{12})E +$$
$$(R_2A+R_1P_{12})(C+R_2+R_1P_{12})(D+R_2+R_1P_{12})F$$
$$= (R_1+R_2AB)(C+R_2+R_1P_{12})E +$$
$$(R_2A+R_1P_{12})(D+R_2+R_1P_{12})F$$
$$= R_1CE+R_1P_{12}E+R_2ABE+R_2AF+R_1P_{12}F\,. \qquad (14)$$

The MCSs $\{R_1E,\ R_2ABE,\ R_2AF,\ R_1P_{12}E,\ R_1P_{12}F\}$ in Eq. (14) are equivalent to those in Eq. (10).

3. Conclusions

This paper presents a new method to build a single top external event PSA model. All external event scenarios could be quantified in a single run by reading and combining an internal PSA model and mapping information in a database. This automatic feature might be accomplished by developing a combining tool. This will result in a minimized manual modification of internal event PSA. The similar method could be applied to the flooding PSA.

REFERENCES

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[3] W.S. Jung, et al., "A Method for Quantitative Evaluation of the Damage Frequencies of Reactor Core on External Accidents at Nuclear Power Plant," Patent 10-2007-28638.