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A Preliminary Study on Fault Tree Analysis for Fire Detection and Suppression Systems in Nuclear Power Plants

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1. Introduction

When a fire occurs inside a nuclear power plant (NPP), the most important thing is to detect and extinguish it in time before safety-related components or cables are damaged. To ensure the safety against fire events, a number of fire protection systems have been strategically installed and operated in NPPs. In addition, the reliabilities of the fire detection-suppression measures have also been addressed to evaluate their compatibility or effectiveness through the fire probability safety assessment (PSA).

In this context, estimating a non-suppression probability (NSP), which is defined as a failure probability of fire protection measures for a target set, would be of major interest in assessing the fire-induced risk. The NSP is generally estimated using the detection-suppression event tree (DSET) that consists of sequential headings with success or failure paths of the corresponding fire protection systems for a given fire scenario [1].

To quantify the NSP using the DSET, branch probabilities of each heading (e.g., a wet-pipe sprinkler fails to operate) should first be determined. In other words, the failure probabilities of each fire protection measures are required. Fortunately, NSAC-179L [2] investigated and provided the system unreliability of fire suppression systems installed in NPPs. In the conventional fire PSA, such calculated system unreliability or simple assumptions has just been employed as a branch probability of the DSET [1].

Although the generic data or assumptions are reliable enough to calculate the NSP, this approach may take away some opportunities to confirm important facts in assessing the fire-induced risks. For example, the generic system reliability cannot consider plant-specific characteristics. Within the current methodology, dependencies between fire detection and suppression measures may not be captured. Moreover, it is difficult to determine which components associated with fire protection significantly contribute to the safety against fires.

One way to deal with this troublesome issue is to further develop a fault tree for the fire protection systems. Therefore, in this paper, we perform a preliminary study on the simplified fault tree analysis for the detection-suppression systems of the reference NPP to figure out the feasibility of this study.

2. Calculating the non-suppression probability in the conventional fire PSA

2.1 Detection-suppression event tree

According to [1], the DSET method is employed to quantify the NSP for a given fire scenario. The DSET allows us to determine the end state of each mitigation paths considering whether the fire protection measures located in a target compartment successfully operate to extinguish a postulated fire. Figure 1 shows an example DSET for the NSP quantifications.

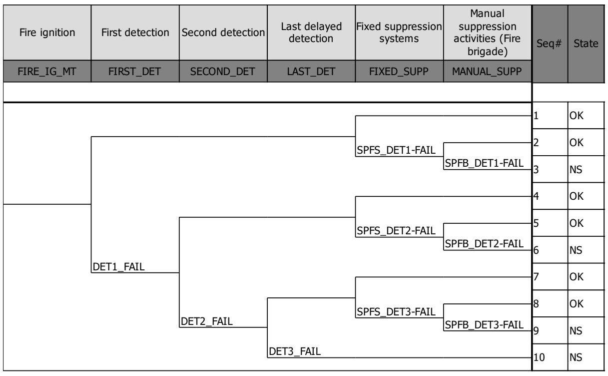

Fig. 1. An example DSET for the NSP quantifications

As depicted in Fig. 1, fire protection measures in a NPP can be divided into three categories: detection, automatic suppression, and manual suppression by a fire brigade. Note that the measures (i.e., heading in the DSET) may or may not be credited depending on the fire scenarios. Table 1 shows the brief descriptions of fire protection measures shown in Fig. 1 [1].

Table I: Descriptions of the fire protection measures in DSET

Measures	Headings	Descriptions
Detection	First	By plant personnel
	Second	By fixed systems
	Last delayed	By any means eventually
Suppression	Automatic	By fixed systems
	Manual*	By fire brigade

* Manual suppression is not covered in detail in this paper.

Consequently, the NSP can be calculated by summing the probabilities of having the specific end state, non-suppression (NS).

2.2 Estimating the branch probabilities in the DSET

Within one heading, one branch probability should be identified. The branch probability in the DSET can be identified by evaluating the failure probability of the corresponding fire protection measures. Specifically, the NUREG/CR-6850 [1] briefly described how to establish the failure probability of fire protection measures depending on the fire scenario. For example, the failure probability associated with detection can be determined with the following recommendations:

- Failure probability of detection
  - First detection: generally determined by the level of plant personnel presence (e.g., the probability of personnel presence in a target compartment);
  - Second detection: generally determined by the reliabilities or availabilities of detectors;
  - Last delayed detection: it is assumed to be 0 when the manual detection time is lower than the time to target damage. This assumption (i.e., no failure) is based on the fact that all fires will be eventually detected and suppressed.

In case of suppression, NSAC-179L [2] investigated the unreliability of automatic fixed suppression systems using the reported fire event data. As shown in Table II, the branch probability related with a suppression system can be easily defined.

Table II: Unreliability of automatic fixed suppression systems

Fixed suppression systems	**Unreliability**
Wet-pipe sprinkler	0.02
Halon system	0.05
Carbon dioxide system	0.04
Pre-action sprinkler	0.05

Lastly, the failure probability of the manual suppression by a fire brigade can be estimated using the suppression probability curves based on the reported fire event data [1, 2, 3]. Note that manual suppression is not covered in detail in this paper.

3. Simplified fault tree analysis for the fire detection-suppression systems of the reference NPP

Normally, in PSAs, branch probabilities of an event tree are evaluated by developing a fault tree of the corresponding system to comprehensively consider complex interactions between systems and components. Until now, however, simple assumptions or calculated system reliabilities have been assigned to the branch probability of the DSET as described in Sec. 2.2. As the NUREG/CR-6850 pointed out, the unreliability presented in Table II do not include unavailability due to maintenance, manual actuation, and plant specific data [1]. Furthermore, the current NSP evaluation methods do not even consider the complex dependencies between detection and suppression systems.

Therefore, to derive more practical NSP results, it is necessary to further develop the fault tree of the detection and suppression systems for the branch probability considering plant-specific characteristics. Another benefit of developing fault trees is that they can provide minimal cut sets (MCSs) for fire protection systems that facilitate identification of plant vulnerabilities.

This preliminary study focuses on the development of simplified fault trees for automatic detection-suppression systems of the reference plant in Korea. Unfortunately, there are no available data associated with components for fire protection systems install in NPPs at this writing. For this reason, quantifying the fault tree will be taken into account in the next study after gathering the relevant component reliability data.

3.1 Fire protection systems in the reference plant

Table III shows the summary of the fire protection systems installed in the reference plant to be considered in fault tree analysis.

Table III: The fire protection systems in the reference plant

Components	**Type**
Detector	Smoke detector Flame detector Heat detector, and so on
Suppression (Sprinkler)	Wet-pipe sprinkler Water spray sprinkler Pre-action sprinkler
Fire pump	Motor-driven Diesel-driven Motor-driven – Seismic Cat. I
Fire water tank	Fire water tank Fire water tank – Seismic Cat. I
Valve	Deluge valve Solenoid valve Check valve

The sprinklers in the reference plant receive pressurized water from the fire water supply system consisting of fire pumps and water tanks. Fire pumps operates automatically when the pressure of the fire water reaches the set point. Although the gaseous suppression systems (e.g., high pressure CO_2) are also operated in the reference plant, they are not covered in this study.

3.2 Development of simplified fault trees

While a wet pipe sprinkler is able to operate without detection signals, a water spray or pre-action sprinkler requires detectors or manual operation to start suppression because the pressurized water can be discharged by opening the deluge valve after the solenoid valve is excited by a detection signal or manual operation. Using fault tree analysis, this complex dependency can be included in the NSP evaluations.

Hence, the simplified fault trees for typical detector and sprinkler systems were developed by considering following important logics or events that is not considered in the system reliability in Table II:

- Sprinkler failure due to the failure of detector
- Unavailability due to test and maintenance
- Failure of manual actuation when component fails to operate
- Dependencies between fire protection measures

Figure 2 shows an example of the simplified fault tree for the fixed water spray sprinkler in the reference plant. It should be noted that the probabilities of the basic events in Fig. 2 were simply assumed to be 0.1 to derive MCSs; quantification will be carried out in the next study.

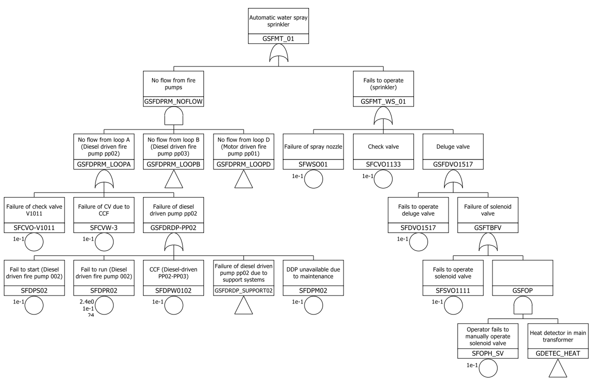

Fig. 2. An example of the simplified fault tree for the fixed water spray sprinkler in the reference plant

4. Preliminary results: notable MCSs

Using the developed fault tree (Fig. 2) and the DSET (Fig.1), MCSs for a postulated fire scenario were experimentally derived to ensure that plant-specific features or dependency can be included in the NSP. The fire scenario is assumed to be fire-induced loss of offsite power (LOOP). The notable results are summarized in Table IV.

Table IV: Four notable MCSs on the postulated fire scenario

1	Fire-induced LOOP	SFOPH_SV & SFOPH_FBR
2	Fire-induced LOOP	SFDPR01 & SFDPM02 & SFOPH_FBR
3	Fire-induced LOOP	SFDPR01 & SFDPS02-SIG & SFOPH_DP02 & SFOPH_FBR
4	Fire-induced LOOP	SFCVW-3 & SFOPH_FBR

(MCS 1)
- Operator fails to operate solenoid valve manually
- Fire brigade fails to extinguish a fire before target damage

(MCS 2)
- Diesel-driven fire pump 01 fails to run
- Diesel-driven fire pump 02 fails to operate due to test & maintenance
- Fire brigade fails to extinguish a fire before target damage

(MCS 3)
- Diesel-driven fire pump 01 fails to run
- Diesel-driven fire pump 02 fails to start due to loss of signal & operator fails to manually actuate pump 02
- Fire brigade fails to extinguish a fire before target damage

(MCS 4)
- Three check valves fail to open due to common cause failures
- Fire brigade fails to extinguish a fire before target damage

It should be noted that some events or logics in this fault tree should be eliminated when performing the practical fire PSA. In this postulated fire scenario, we can capture that the motor-driven pump cannot be used to supply fire water due to the LOOP. In addition, the manual actuation for the solenoid valve should be required to open the deluge valve for discharging pressurized fire water when LOOP. As such, it can be found that the use of fault trees provides an opportunity to identify the plant-specific characteristics and dependencies among fire protection systems and fire scenario specific plant damage status (e.g., fire induced LOOP)

4. Conclusions

In this study, we developed the fault trees of typical detection-suppression systems in the reference plant to derive more practical branch probabilities when evaluating the NSP. Consequently, it was confirmed that an approach to constructing fault tree can incorporate various plant-specific features and dependencies into the branch probability and they also provide MCSs that facilitate identification of plant vulnerabilities.

For further studies, efforts should be made to gather reliability data on the relevant fire protection components to quantify the developed fault trees. The quantification results should also be compared with the unreliability shown in Table II.

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