Development of a Fault Tree for Fire Protection Systems in Nuclear Power Plants

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Abstract:

In general, it is important to appropriately evaluate the failure probability of fire suppression when assessing the fire-induced risk in nuclear power plants through fire probabilistic safety assessment. Such non-suppression probabilities are closely related to the reliability of fire protection systems and the failure probability of manual fire suppression actions by a fire brigade. While a detection-suppression event tree method was employed to quantify the non-suppression probability logically, not much effort has been made to correctly estimate the failure probability of fire protection systems installed in nuclear power plants. Instead, simple assumptions based on expert judgment, or the generic data provided in NSAC-179L have been used as one of the branch probabilities associated with the system failure in the event tree. Thus, addressing issues such as considering the plant-specific characteristic or understanding the dependencies between fire protection systems has remained a challenge to be resolved. To handle these troublesome issues, this paper performed failure tree analysis on the fire protection systems of the reference nuclear power plants. A comprehensive data investigation for the reference plant was carried out and practical challenges in developing fault trees of fire protection systems were also discussed.

Keywords: Fire PSA, Fire Protection Systems, Non-suppression Probability, Fault Tree Analysis

1. INTRODUCTION

In fire probabilistic safety assessment (PSA), the risk of fire on nuclear power plants (NPPs) can be assessed by evaluating the frequency of fire, fire severity, and the failure probability of fire suppression in a timely manner. According to [1], a detection-suppression event tree (DSET) method has been employed to evaluate the non-suppression probability logically depending on the various fire scenarios that can occur in NPPs.

In the conventional DSET method, the failure probabilities of automatic fire suppression systems, such as sprinklers, are simply based on the system-level data provided in NSAC-179L [2]. Even if the data in [2] is reliable enough, using the system-level failure probabilities as branch probabilities of DSET has several limitations. For example, system-level failure probability cannot capture the dependencies between detection and suppression systems or dependencies resulting from supporting system failure. Furthermore, these generic data do not account for factors such as manual actions by operators or unavailability due to test and maintenance (T&M) and plant-specific configuration [1]. Consequently, it is ultimately unclear whether the general data values in NSAC-179L are sufficiently valid for the NPP being analyzed.

Therefore, in this paper, a study was conducted to identify the characteristics of the fire protection system corresponding to the headings of DSET. More specifically, a fault tree of fire protection system in the reference NPP was developed. A discussion of the overall data investigation process on the fire protection system and difficulties in the development was also discussed in this paper.

2. THE NEED TO DEVELOPE FAULT TREES FOR FIRE PROTECTION SYSTEMS

2.1 Detection-suppression event tree method

In order to determine the non-suppression probability for a given fire scenario, various information such as the reliability of the fire protection system, human error probability, and time to suppress a fire should be comprehensively considered. Since the installation and types of fire protection systems vary for each fire area in NPPs, the variety and complexity of fire scenarios that need to be addressed inevitably increase. For this reason, NUREG/CR-6850 [1] employs a detection-suppression event tree to logically determine fire suppression failure scenarios, rather than assigning a uniform failure probability to all scenarios. DSET is known as a method of depicting the success or failure of fire detection/suppression measures within an event tree so that the non-suppression probability can be evaluated logically and systematically. Figure 1 shows an example of DSET.

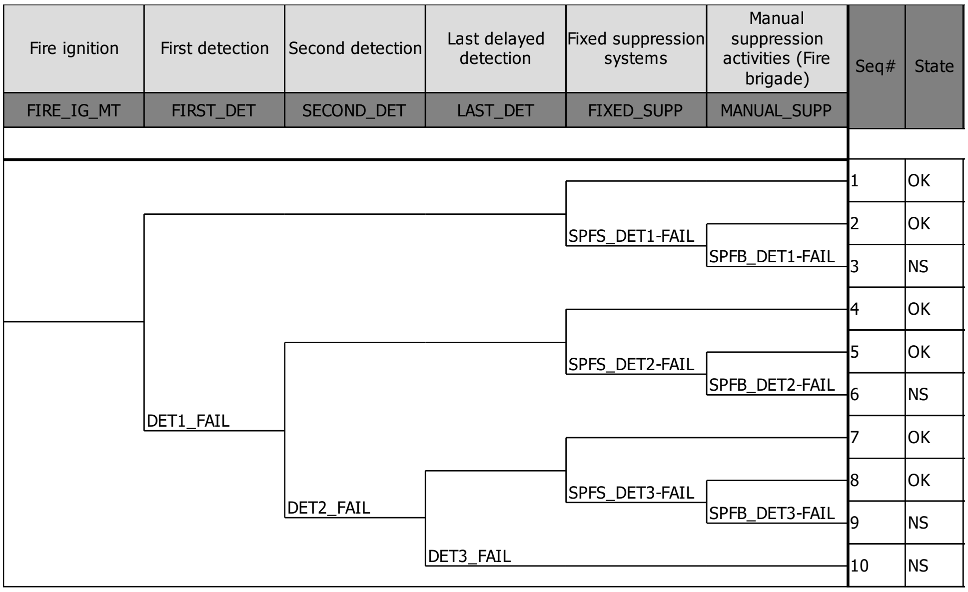

Figure 1. An example DSET for non-suppression probability quantifications

The modelling of each heading of DSET depends on fire scenarios. For example, the heading of *fixed fire suppression* can be eliminated when the fire scenario (or fire area) to be addressed does not have a fixed fire suppression system. The end state of each success or failure path in DSET can be either *OK* state or non-suppression (*NS*) state.

The detection part of the DEST can have three headings. First, in the case of initial heading (*first detection*), the branch probability of this heading can generally be assigned by defining the probability that an operator or worker will be present in the fire area. In NUREG-2230 [3], 22 of the fire incidents reported to FEDB [4] are analyzed as cases that were immediately detected by field operators rather than through automatic fire detection equipment. The second heading (*second detection*) determines the success or failure of the automated fire detection system. The branch probability of this heading can generally be determined through the reliability of the fire detector installed in this fire area. Last delayed detection, which is the last stage of detection in the DSET, is considered only when the manual detection time is smaller than the target damage time. Since a fire within a NPP will be exhausted by all means ultimately, the probability of the last detection failure is not considered in most fire scenarios.

The suppression heading consists of automatic and manual suppression measures. In the case of the automatic suppression, the branch probability can be determined through the failure probability of the fixed fire suppression system. In the conventional fire PSA, the failure probability data in NSAC-179L is used as the branch probability of the corresponding heading. Table 1 summarizes the failure probability data of automatic fixed fire suppression system presented in NSAC-179L. The probability values in Table 1 refer to the probability of failure on demand.

Table 1. Failure probability of automatic fire suppression systems [2]

Automatic fire suppression systems	Failure probability
Wet-pipe sprinkler	0.02
Halon system	0.05
Carbon dioxide system	0.04
Pre-action sprinkler	0.05

Lastly, in the case of the manual suppression action by fire brigade heading of the DSET, once the target damage time and fire detection time are determined through fire simulations, the spare time required for manual action can be calculated based on this result. Consequently, the failure probability of manual suppression can be calculated using non-suppression curves provided in [5].

2.2 Limitations of the conventional branch probability determination methods [1, 6]

The shortcomings of the existing branch probability determination method briefly introduced in Section 2.1 include its reliance on simple assumptions or the system-level data such as provided in NSAC-179L for quantification, despite the complex configuration of fire protection systems. This approach fails to account for dependencies, human errors, and plant-specific information. For example, in fire protection systems where fire detection signals play an important role in initiating fire suppression system, existing DSET frameworks cannot adequately capture such dependencies. Although each NPP has its own design and characteristics for fire protection systems, using generic data uniformly prevents the identification of unique plant-specific features.

Furthermore, even if the data presented in NSAC-179L provides sufficiently reliable failure probabilities for fire suppression systems, applying these values directly to fire PSA requires verifying the evaluation process, assumptions made during assessment, uncertainties inherent in the data. However, to date, such verification efforts have not been appropriately made. Lastly, this approach cannot provide the minimum cut sets (MCSs), which is the key output of PSA. This prevents the identification of vulnerabilities in the fire protection systems of the analyzed NPP through MCSs.

To address the issues mentioned above, this study has developed fault trees for fire protection systems to be used in DSET. Figure 2 illustrates the differences between the conventional method and the fault tree-based method in the quantification of sequence 9 in the example DSET.

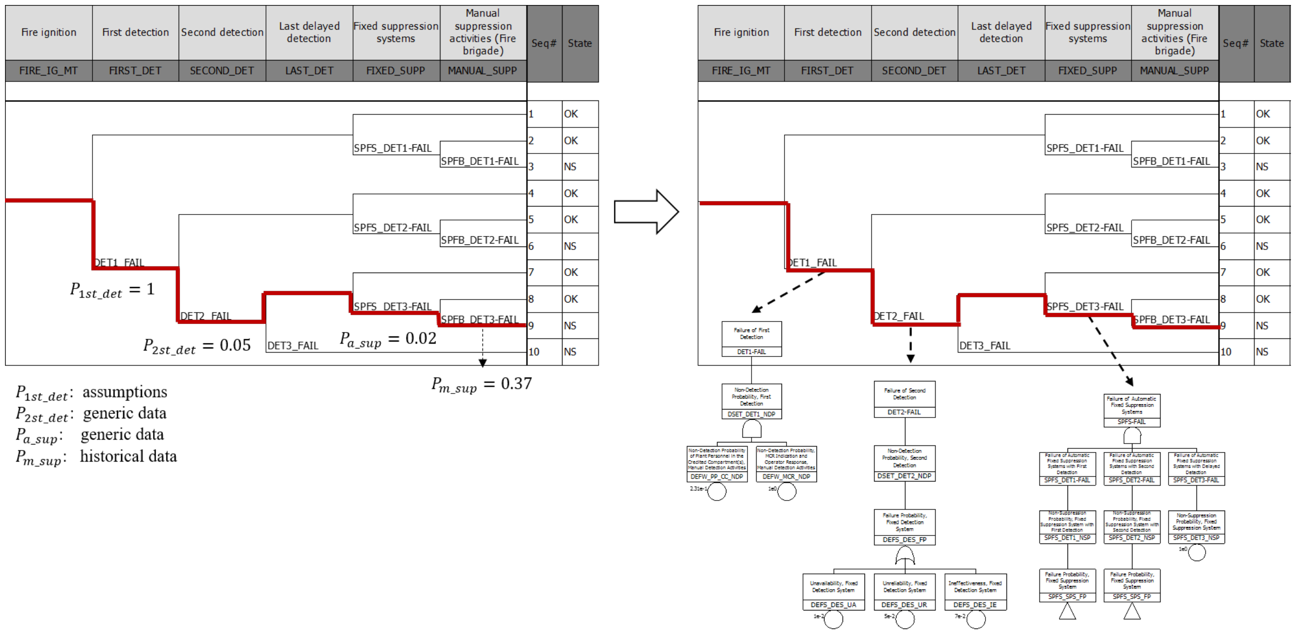

Figure 2. The differences between the conventional and the fault tree-based method in the quantification of sequence 9.

3. AN EXAMPLE FAULT TREE OF AUTOMATIC FIRE SUPPRESSION SYSTEMS IN THE REFERENCE NUCLEAR POWER PLANT

In this paper, a comprehensive literature review on fire protection systems of a reference NPP was conducted to initiate the development of fault trees. Here, we aim to provide a brief overview of water-based fire protection systems among various fire protection systems in the reference NPP.

3.1 Fire-fighting water supply system and sprinkler systems

The fire protection system of the reference NPP consists of two main systems: a fire-fighting water supply system and a sprinkler system that extinguishes fires by spraying fire-fighting water into specific areas. First, the firefighting water supply system (seismic category I) can be configured as follows:

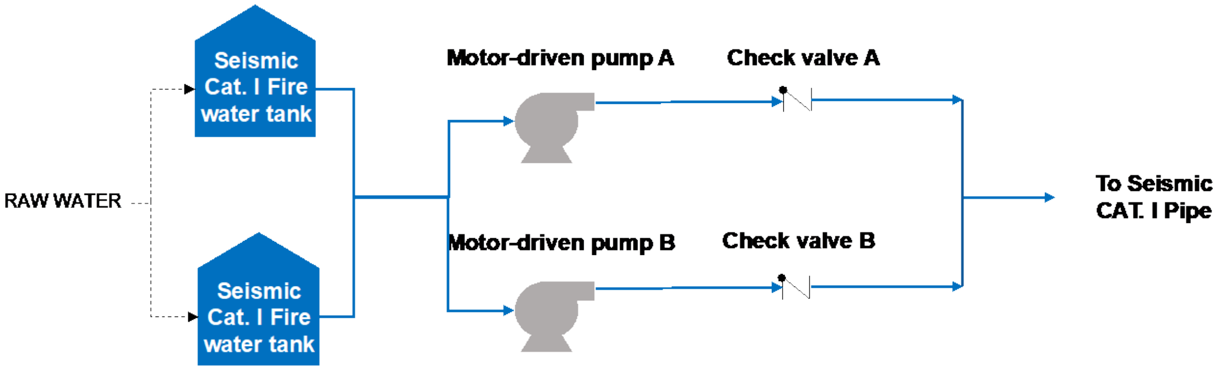

Figure 3. Simplified configuration of the fire-fighting water supply system in the reference NPP

The firefighting water supply system of the reference NPP consists of two fire water tanks that receive water from raw water systems, two 100% capacity motor-driven pumps, and two check valves. Therefore, the success criterion for a fire-fighting water supply system is that fire-fighting water is supplied from at least one of the two trains.
There are three types of sprinklers that extinguish fires by receiving firefighting water from the firefighting water supply system depicted in Figure 3.

- Wet sprinkler system: the wet sprinkler consists of a gate valve, an alarm check valve, and a sprinkler head. Normally, the gate valve is open, so pressurized fire-fighting water is filled up to the front of the sprinkler head. In the event of a fire, the pressurized fire-fighting water is automatically sprayed when the link on the head melts. Figure 4 shows the simplified wet pipe sprinkler system in the reference NPP.

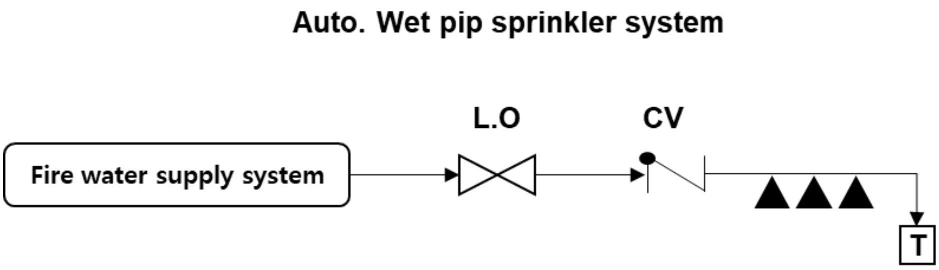

Figure 4. Wet pipe sprinkler system in the reference NPP

- Water spray sprinkler system: the water spray sprinkler consists of a gate valve, solenoid valve, deluge valve, and a sprinkler head. In the event of a fire, this sprinkler starts to extinguish a fire after receiving the signal from the fire detector (from A, B trains, AND logic) or the signal by operators. More specifically, a fire detection signal activates the solenoid valve to open the deluge valve, spraying the pressurized water which is filled up to the front the deluge valve. Figure 5 shows the simplified water spray system in the reference NPP.
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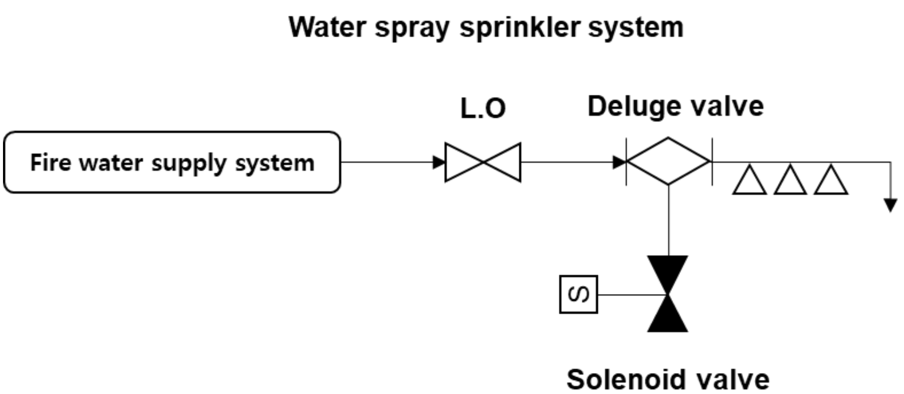

Figure 5. Water spray sprinkler system in the reference NPP

- Pre-action sprinkler system: the pre-action sprinkler consists of a gate valve, alarm check valve, a solenoid valve, deluge valve, and sprinkler head. Similar to water spray sprinkler, it is operated by signal from fire detector or manual operation. It is operated by energizing the solenoid valve to open the deluge valve, thereby spraying pressurized water up to the front of the check valve. The area from the back of the check valve to the head is filled with compressed air, and in the event of a fire, the link of the sprinkler head melts due to heat and pressurized water is sprayed. Figure 6 shows the simplified pre-action sprinkler system in the reference NPP.

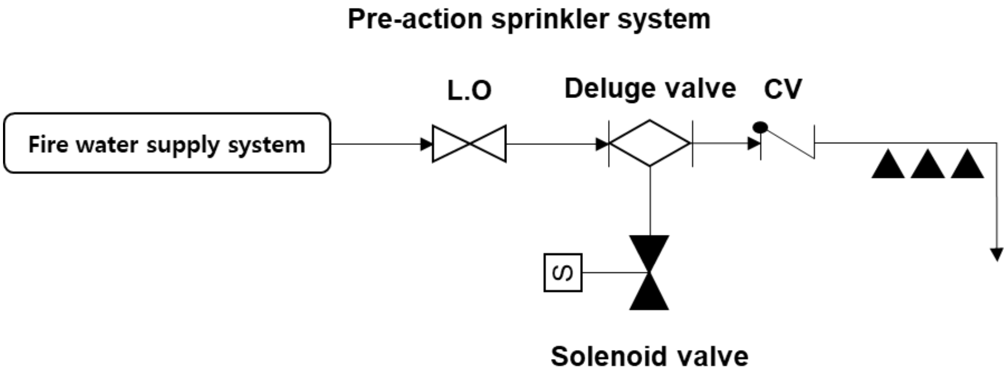

Figure 6. Pre-action sprinkler system in the reference NPP

3.2 An example fault tree of the automatic fire suppression systems

Based on the data investigated in Section 3.1, fault trees for several representative fire protection systems were developed. The top event of this fault tree consists of a failure of firefighting water supply system and a failure of sprinklers. Figure 7 shows the part of the example fault tree of the fire protection system in the reference NPP.

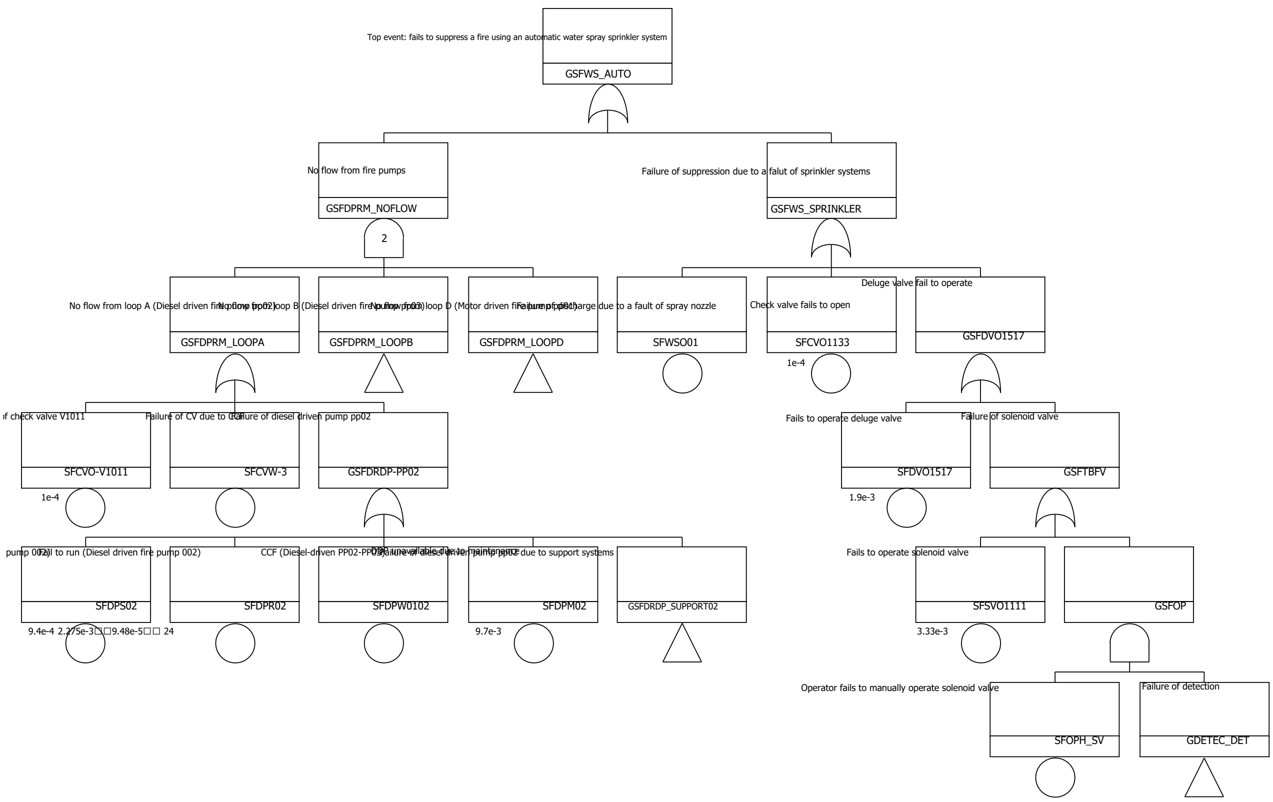

Figure 7. An example fault tree of the fire protection system in the reference NPP

It should be noted that additional research should be conducted based on the fault tree presented in Figure 7, including quantification and integration into the fire PSA model. However, practical challenges are encountered in developing fault trees for fire protection systems, including the collection of reliability data. Section 3.3 discusses the difficulties encountered during this study.

3.3. Difficulties in developing a fault tree of fire protection systems

- Colleting the reliability data for fire protection systems

In order to develop and quantify a fault tree for a fire protection system, reliability data for each component is required to allocate the failure probability to each basic events of the fault tree. In general, data in NUREG/CR-6928 [7] can be utilized as a generic data, but it does not include data applicable to fire protection systems. Therefore, there is a need to additionally collect and analyze reliability data on the fire protection system. For this purpose, research on reliability data of fire protection systems were investigated. Table 2 shows a summary of literature survey on the reliability data of fire protection systems installed in NPPs.

Table 2. Research on the reliability data of fire protection systems operated in NPPs.

	Moelling et al. (1980) [8]		**VTT (2004) [9]**			**B. Forell et al. (2016) [10]**
Component for fire protection	**Failure mode**	**Failure probability**	**Loviisa NPP**	**Olkiluoto NPP**	**Non-nuclear facility**	**Failure rate**
			Failure probability			
Check valve	FTO*	1.00E-04	2.88E-02			
Diesel-driven pump					1.50E-02	
Motor-driven pump					6.20E-03	
Solenoid valve			1.20E-02	6.68E-03		
Storage tank					6.50E-03	
Sprinkler head	FTO	1.00E-06	3.03E-04	4.25E-05	1.80E-04	
Fire detectors	FTS**	2.97E-03				
Deluge valve	FTO	1.90E-03	6.48E-02			
Fire water pump	FTS	1.4E-02	8.64E-02	5.34E-02		4.29E-06
Smoke detector						1.05E-09
Heat detector						3.11E-08
Flame detector						6.19E-08

*FTO: Fail to open
**FTS: Fail to start

Fortunately, several studies have been conducted on the reliability data of fire protection systems, which is installed and operated in NPPs. However, there are still some challenges in directly incorporating these data into fault tree analysis. For example, Moelling et al. [8] provides information on the probability of failure a fire pump, but the description of the type of fire pump (e.g. motor or diesel-driven) is not included. Furthermore, [9] does not provide information on failure mode (e.g. FTO, FTS). Generally, it is important to evaluate common cause failure in redundant systems when assessing system reliability, however no relevant studies on this topic have been made.
Although not introduced in this paper, the reference NPP also have fire suppression systems that utilize CO_2 or INERGEN, in addition to water-based sprinklers. However, reliability data for these fire protection systems are even more difficult to find. Even if data from various studies are selectively used, there remains the issue that the data sources are all different.

- Modelling of manual actuations by an operator

Operator manual actions included in the fault tree analysis of fire protection systems encompass not only the actions where the fire brigade fails to directly extinguish the fire but also the manual activation of the fire suppression system in case the automatic system fails to operate. In the former case, it can be included under the last heading of the DSET in Figure 1, while in the latter case, it can be included within the fault tree under the heading of *fixed suppression system*. Table 3 summarizes the manual actions that can be performed in the event of a failure of the fixed fire suppression system to automatically activate in the reference NPP.

Table 3. Manual actions after the failure of the fixed suppression system to automatically activate

Fixed suppression system	**Manual actions**
Pre-action sprinkler	After confirming that the deluge valve is open, operate the emergency release lever or open the drain valve.
	Manually start the standby fire pump on-site or initiate operation from the main control room.
Water spray sprinkler	After confirming that the deluge valve is open, operate the emergency release lever or open the drain valve.
	Manually start the standby fire pump on-site or initiate operation from the main control room.
CO_2 suppression system	Operate the manual control or the lever of the solenoid valve for manual operation.
	If the ventilation fan is not stopped, manually turn off the ventilation fan.
INERGEN Suppression system	Operate the manual control or the selection and container valve for manual operation.

To model the operator actions in Table 3 within the fault tree, the assessment of the human error probability for each operator action should be conducted. The problem becomes more complicated because it is necessary to understand the dependent relationship between these operator actions in Table 3 and the fire suppression by operators.

- Integration of the developed fault tree into the fire PSA model

Even within a single fire area equipped with fire suppression systems, there exist a lot of fire scenarios. Therefore, it is challenging to individually incorporate developed fault trees of fire protection systems into the fire PSA model. Therefore, for practical application, there is a need to develop automated program that can automatically generate DSET based on fire scenarios and integrate fault tree models suitable for those scenarios.

4. CONCLUSION

In this study, we briefly introduced the DSET method for evaluating non-suppression probabilities and identified potential issues that can arise from the conventional methods of determining branch probabilities. To address the identified issues, fault trees for fire protection systems were developed in this study. To this end, a comprehensive data investigation on the reference NPP was conducted, which is briefly described in Sec. 3. In addition, we discussed the practical challenges encountered during the fault tree development process. Ultimately, it was found that securing reliability data for fire protection systems is of utmost urgency to conclude this research.

On the other hand, we will conduct research on using the developed fault trees to utilize the fire-fighting water supply system as a means for accident mitigation such as water injection to steam generator. Although related studies have been conducted [11], it can be expected that the more detailed fault tree model of the fire protection system developed in this research will enable more precise accident management strategies for the reference NPP.

Acknowledgements

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