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# A Preliminary Study on Estimating the Failure Probability of Fire Suppression using Scenario-Specific Fire Brigade Response Times with the Agent-Based Model

Kyungho Jin[a], Yong Hun Jung[a]*, Dae Il Kang[a]
[a]*Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*

[*]*Corresponding author: jungyh@kaeri.re.kr*

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## 1. Introduction

In general, the failure probability of manual fire suppression employed in a fire probabilistic safety assessment (PSA) is evaluated by (i) estimating the time required to suppress a fire and (ii) using the historical fire event data such as the fire suppression curve [1, 2, 3], which can be constructed from the EPRI Fire Event DataBase (FEDB).

The available suppression time (denoted by $T_{avail}$) is defined as the difference between the estimated time before target damage and the time to detect a fire (i.e., $T_{avail} = T_{dmg} - T_{det}$). In fact, the time for fire brigades traveling to the ignition source (denoted by $T_{fb}$) was also required to estimate $T_{avail}$, but due to incomplete data records and other limitations (for more details, see [2]), $T_{fb}$ is no longer considered in estimating $T_{avail}$.

These findings also led to a revision of the suppression curve. Previously, the curve was constructed based on the records of *fire suppression time* (when possible) and/or *fire duration* from FEDB, but the suppression curve was later revised to consider only *fire duration* to avoid subtracting $T_{fb}$ from FEDB when estimating $T_{avail}$ [2, 3]. Therefore, it can be said that the current suppression curve contains the industry-average response time of the fire brigade.

According to [2], a simple method called correction factor ($C_s$) was proposed to consider fire scenarios that are significantly different from the average fire brigade response time (i.e., scenario-specific). However, in practice, it is difficult to use because it is tough to obtain data such as industry-average or scenario-specific travel times for calculating $C_s$.

Therefore, this study aimed to collect data for calculating correction factors and discuss a method to support scenario-specific fire brigade response time by introducing an agent-based model (ABM) [5]. The use of an ABM is expected to facilitate a more accurate evaluation of scenario-specific fire brigade travel times, which in turn implies a more realistic assessment of the non-suppression probability (NSP).

## 2. The NSP with Industry-average Response Times

According to [1], the non-suppression probability (NSP) with the industry-average response time, $P_I(t)$, is given by:

$$P_I(t) = P(T_{avail} \geq t) = e^{-\lambda \cdot T_{avail}} \qquad \text{Eq. (1)}$$

where, $\lambda$ is the mean suppression rate for the corresponding fire type. This parameter can be calculated using the *fire duration* records provided in the FEDB. Table I and Fig.1 show the mean suppression rates/time and its curves by time depending on fire types.

Table I: The mean suppression rate(/min) and time(min) depending on fire types [3]

| Types | Mean suppression rate (/min) | Mean suppression time (min) |
|---|---|---|
| **T/G fires** | **0.026** | **38.9** |
| ⋮ | | |
| Flammable gas | 0.034 | 29.3 |
| Oil fires | 0.089 | 11.2 |
| **Cable fires** | **0.138** | **7.3** |
| Electrical fires | 0.098 | 8.8 |
| ⋮ | | |
| All fires | 0.069 | 14.8 |

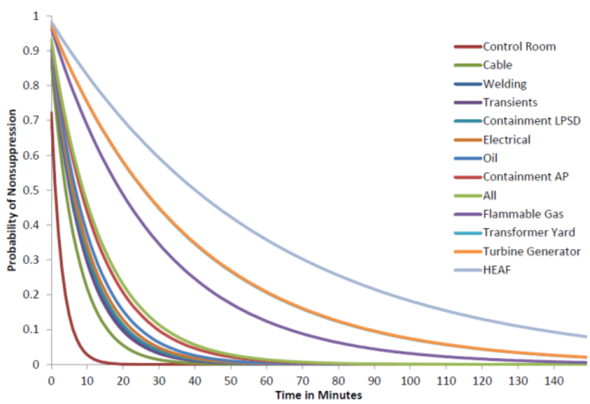


Fig. 1. The suppression curve depending on fire types [3]

As discussed earlier, the parameters shown in Table I are constructed based on the time from fire detection to extinguishment (fire duration), and it includes the response time of the fire brigade. The limitation of using an industry-average response time is that, if the same fire type and $T_{avail}$ are given, the same value of NSP is derived regardless of the fire ignition location or the fire brigade travel time. In other words, in this case there is no ability to discriminate between scenarios.

Therefore, for scenarios that deviate significantly from the average, a method to account for such deviations is required. Chapter 3 describes the approach to correction factors proposed in [2].

## 3. How to Consider Scenario-specific Response Time in an NSP Estimation

### *3.1. Correction factor to adjust $T_{avail}$*

According to [2], a simple adjustment factor was proposed to consider scenario-specific conditions for the fire brigade response. The correction factor ($C_s$) can be estimated as follows:

$$C_s = 1 - \frac{T_{fb\_S} - T_{fb\_I}}{T_{fb\_S} + T_{fb\_I}} \qquad \text{Eq. (2)}$$

where, $T_{fb\_I}$ is the industry-average response time and $T_{fb\_S}$ is the scenario-specific response time. $C_s$ acts as multiplier that effectively controls $T_{avail}$. Therefore, the NSP with the scenario-specific response time, $P_S(t)$ is given by:

$$P_S(t) = e^{-\lambda \cdot T_{avail} \cdot C_s} \qquad \text{Eq. (3)}$$

When $C_s$ is greater than 1, it means that the scenario-specific fire brigade responds faster than the industry-average response time. Consequently, $T_{avail}$ increases, whereas $P_S$ decreases.

### *3.2. Industry-average response time, $T_{fb\_I}$*

Although scenario-specific approaches have been proposed as introduced in *Sec.3.1*, their practical application has been limited due to difficulties in obtaining the necessary data such as $T_{fb\_I}$ and $T_{fb\_S}$.

Therefore, to obtain $T_{fb\_I}$, this paper first estimated the average travel time for cases in which the fire brigade travel time was accurately recorded from the recent FEDB.

Table II shows the fire brigade response times recorded in FEDB [4] and Fig.2 shows their histogram. It was confirmed that the fire brigade response times were recorded for a total of 78 fire events. As a result, the average response time $T_{fb\_I}$ was estimated to be 4 minutes.

Table II: Fire brigade response times in FEDB (2010-2014)

| | Fire ID | Brigade Dispatch | Brigade Arrival | Travel time (min) |
|---|---|---|---|---|
| **1** | 50907 | 19:28 | 19:33 | 0:05 |
| **2** | 50908 | 13:17 | 13:23 | 0:06 |
| **3** | 50909 | 11:28 | 11:31 | 0:03 |
| | | ⋮ | | |
| **76** | 51339 | 15:48 | 15:50 | 0:02 |
| **77** | 51354 | 23:31 | 23:33 | 0:02 |
| **78** | 51366 | 13:47 | 13:50 | 0:03 |

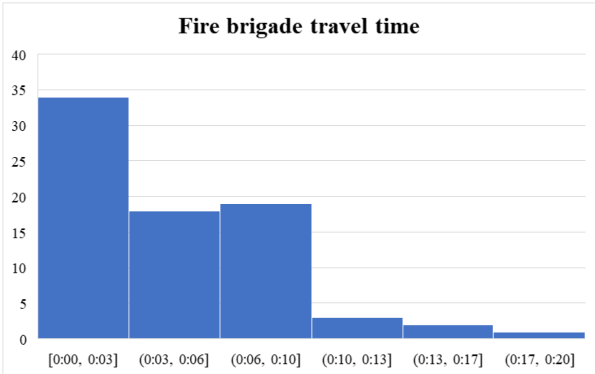

Fig. 2. Histogram of fire brigade travel time from FEDB

### *3.3. Scenario-specific response time, $T_{fb\_S}$*

In general, because the number of fire compartments within a nuclear power plant is substantial, it is very challenging to evaluate the fire brigade travel time for each fire scenario. Therefore, this study proposes a method utilizing an agent-based model (ABM). By realistically representing the nuclear power plant and simulating the movement of agents, travel time data for fire brigade can be established (for more details, see [5]). Fig.3 shows a simple example of estimating fire brigade travel times from main control room (MCR) using ABM.

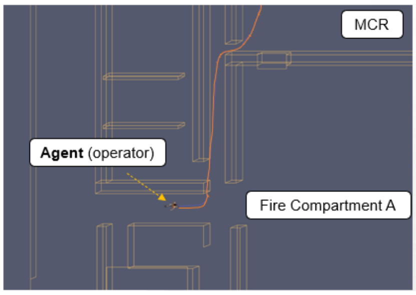

Fig. 3. An example of estimating fire brigade movements using ABM

For example, a fire compartment located near the MCR and another located relatively far from the MCR (e.g., outside the containment building) were selected, and the travel times of agents were measured for each case. The results are presented in Table III.

Table III: An example of the estimated response time depending on fire compartments using ABM

| Compartment | $T_{fb\_S}$ using ABM |
|---|---|
| **(a) Close to MCR** | 20 sec |
| **(b) Far from MCR** | 372 sec |

Based on Table III, the values of $C_S$ and $P_S(t)$ were derived and are organized in Table IV. In this case, $T_{avail}$ is simply assumed to be 7 min.

Table IV: $P_I$ and $P_S$ for cable fires using Table III

| | $P(t = 7\ min)$ |
|---|---|
| **Industry-average $P_I$** | 0.452 |
| (a) **Scenario-specific $P_S$** | 0.231 |
| (b) **Scenario-specific $P_S$** | 0.537 |

As shown in Table IV, fire scenarios that deviate significantly from the average value (4 minutes) result in notable differences in the NSP results.

For fires with relatively short suppression times, such as the cable fire presented in Table I, the impact of the fire brigade's travel time becomes more pronounced [2]. Therefore, in Section 3.4, a sensitivity analysis was conducted for two representative cases: a T/G fire and a cable fire.

*3.4. Sensitivity analysis by fire type*

In particular, for T/G fires where the average suppression time is relatively long, the influence of $T_{fb\_S}$ tends to be relatively small. In contrast, for cable fires, which are characterized by shorter average suppression times, differences in $T_{fb\_S}$ can exert a relatively larger impact.

Fig. 4 and 5 illustrate the values of ΔP as a function of $T_{avail}$, for the cases where $T_{fb\_S}$ is increased by +1 minute (i.e., 4+1min) and +5 minutes (4+5min), respectively. Where ΔP is defined as $P_S - P_I$.

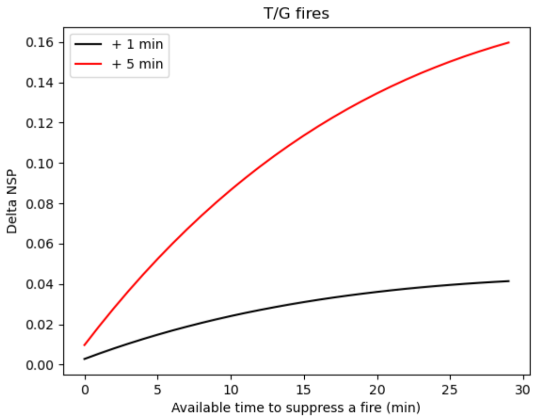


Fig.4. ΔP for T/G fires depending on $T_{avail}$

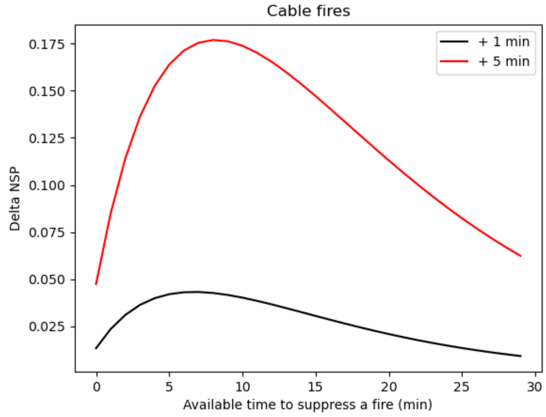


Fig.5. ΔP for cable fires depending on $T_{avail}$

As a result, it was observed that cable fires are more sensitive to $T_{fb\_S}$ when $T_{avail}$ is less than 10 minutes. In contrast, for T/G fires, the influence of $T_{fb\_S}$ increases as time progresses.

In the case of T/G fires, since their ignition locations are fixed, the actual influence of $T_{fb\_S}$ may not be significant. However, for cable fires, which can occur in most fire compartments, it appears necessary to carefully consider scenario-specific conditions, particularly when $T_{avail}$ is less than 10 minutes.

## 4. Conclusions

Although scenario-specific approaches have been proposed, their practical application has been limited due to difficulties in obtaining the necessary data. In this study, to address this issue, the industry-average fire brigade travel time was evaluated using FEDB, and a method to estimate scenario-specific travel times based on an agent-based model was proposed.

Through various case studies, the effectiveness of incorporating scenario-specific conditions was confirmed, and the potential use of an agent-based model to support this approach was also examined. Future work should focus on developing a more sophisticated ABM to enable its application in actual fire PSA analyses.

## ACKNOWLEDGEMENTS

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