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Estimating the Performance Time of FLEX Implementation Based on Staffing Level Considering Multi-Unit Accidents

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After the Fukushima Daiichi accident, many nuclear power plants have been developing plans for Diverse and Flexible Coping Strategies (FLEX) and preparing portable FLEX equipment to enhance defence-in-depth against beyond-design-basis events. To understand the feasibility and usefulness of the actions related to the use of the portable equipment, attempts have been made to apply human reliability analysis (HRA) methods to the estimation of the failure probabilities of the FLEX implementation actions. In this study, based on the characteristics of multi-unit accidents requiring FLEX actions, we propose to analyse the failure probability due to time insufficiency based on the association between human performance time and staffing level in a given scenario. A mathematical formula is developed for estimating the human performance time for portable equipment use based on staffing levels. Empirical data obtained from a firefighting experiment are then analysed for estimating a key parameter in the equation. Regarding the time-based failure probability, some important issues such as the expected distribution of FLEX actions, key values for calculating the time required, and the initial time of FLEX implementation are also discussed.

Keywords: Human Reliability Analysis, Diverse and Flexible Coping Strategies (FLEX), Multi-unit Accident, Human Performance Time, Nuclear Power Plant, Firefighter Response Time

1. Introduction

Following the Fukushima Daiichi accident, many nuclear power plants are developing Diverse and Flexible Coping Strategies (FLEX). For coping with extreme accidents such as an extended loss of AC power and a loss of ultimate heat sink, portable FLEX equipment is prepared, which can be lined up to alternatively provide cooling water or electricity when the fixed installed facilities are unavailable. The use of these portable systems is expected to enhance plant defence-in-depth against beyond-design-basis events.

To understand the feasibility and usefulness of the actions utilizing the portable equipment, it is beneficial to probabilistically estimate the reliability of the FLEX equipment implementation. In this regard, some researchers have applied human reliability analysis (HRA) methods to the actions utilizing portable equipment and have provided important application guidelines [NEI, 2016; NEI, 2017; NRC, 2020; EPRI, 2018; Suh et al., 2020; Kim et al., 2018; Arigi et al., 2019].

In beyond-design-basis events requiring FLEX equipment, there are several distinctive considerations compared with reliability evaluations of operators in main control rooms under general emergency situations [Kim and Cho, 2020]. Examples of issues that should be addressed during the reliability assessment of FLEX actions are as follows: (1) coordination and collaboration issues including the failure of communication means, (2) decision-making errors related to allocations of authority and roles in related organizations, to description levels of procedures, and to situation awareness, (3) execution errors in operating equipment vehicles, delivering hoses and cables, and connecting hoses and cables, (4) performance time for mobile equipment utilization from the time when personnel arrive on site, and (5) possible lack of staff due to environmental or accessibility issues.

In this study, among these significant concerns, we propose to analyse the failure probability due to time insufficiency for FLEX actions based on the association between human performance time and staffing level in a given scenario. The failure probability due to time insufficiency in this study represents the probability that the human performance time will exceed the available time that makes the actions meaningful to system safety. Staffing level also indicates the adequacy of the workers participating in the tasks of the FLEX event, which results from the number of workers mobilized and their accessibility according to environmental factors, accident severity, organizational decision-making, etc. This paper presents a mathematical formula for estimating the human performance time for portable equipment use based on staffing levels and provides empirical evidence for the equation. This study was conducted considering Korean organizational structures and strategies for FLEX plans.

2. Staffing-Level-Based Performance Time

In this study, as mentioned in the previous section, we defined the failure probability due to time insufficiency as the probability that the time required exceeds the time available. The time available is typically determined with consideration of the thermal-hydraulic characteristics of the plant and the accident. The time available is represented by a probabilistic density function or a conservative value obtained from simulations or expert judgment.

On the other hand, the time required is determined by the performance time of the various tasks to be carried out in the human event. Lacking staffing levels can result in the event being infeasible and also affect the performance time for the tasks. Because FLEX actions often require collaborative behaviours of multiple workers, it is noteworthy that the tasks in some accident cases could actually be performed with less manpower compared to the manpower in regular trainings. Especially in the case of a multi-unit accident, the staffing level can be affected by the following factors:

- Exposure to radiation in the concerned unit or neighbouring units
- Personnel allocation due to simultaneous requests for multiple FLEX responses
- Accessibility degradation due to external hazards (e.g., strong winds, earthquake, or flooding)
- Number of employees summoned and arrived at the plant.

Therefore, we propose to formulate the expected time required considering staffing level as below:

$$T_{cs} = \begin{cases} T_{rs}\,, \quad N_{cs} \geq N_{rs} \\ T_{rs}\left[1 + (W-1)\cdot\frac{N_{rs}-N_{cs}}{N_{rs}-N_{ms}}\right], N_{ms} \leq N_{cs} < N_{rs}\,, \\ \infty\,, \quad N_{cs} < N_{ms} \end{cases} \tag{1}$$

where T_{cs} is the human performance time for the given event when N_{cs} workers conduct FLEX responses in the current situation, T_{rs} is the expected time for the FLEX tasks when N_{rs} of regular staffs perform them, and T_{ms} means the time required to complete the goal of the given event by the minimum number of employees (i.e., N_{ms}). The parameter W $(=T_{ms} / T_{rs})$ represents the rate of increase in time when the minimum number of workers perform the tasks in an event compared to the regular number of workers, and $W > 1$.

Table 1 shows an example of T_{cs} values according to N_{cs}. In this example, T_{rs} and T_{ms} were assumed to be 1.2 and 2.4 h, respectively. The parameter W thus was 2. N_{rs} and N_{ms} were also assumed to be 10 and 5, respectively.

Table 1. Example of Eq. (1) calculation

N_{cs} (worker #)	T_{cs} (h)
4	∞
5	2.4
6	2.16
7	1.92
8	1.68
9	1.44
10	1.2
11	1.2

For this formula, it is assumed that each plant unit has a general policy that N_{rs} workers are mobilized for the FLEX actions and that this number of workers participates in periodic training for FLEX implementation. In addition, fewer staff than the number participating in training could be deployed in the event of an actual accident. At this time, we assumed that the response time may increase due to such lack of staff, and the time increases linearly up to the minimum required manpower.

To determine the minimum number of employees (N_{ms}), the following points should at least be accounted for. First, the minimum number should be estimated taking into account the weight limit that FLEX workers can lift. For example, the Ministry of Employment and Labour of Korea [2020] stipulates that no worker should lift objects weighing more than 25 kg more than 10 times. Because multiple workers must be mobilized if the weight of a specific device or its auxiliaries exceeds the weight limit, the number of workers required for the weight should be included in the number of minimum workers. Second, the continuous execution time of individual workers should not be excessive, and the response team requires shift rotation every 8 hours. The workable time limit may affect the number of minimum workers. Third, if there are two or more tasks that need to be performed concurrently, the minimum number of workers must be higher than the number of concurrent tasks. Lastly, if the location of the actions can change, and the movement time between two locations has a significant effect on the overall performance time (e.g., greater than 10%), this should be seen as tasks to be performed concurrently.

3. Empirical Data on the Impact of Staffing Level on Performance Time

In Eq. (1), W implies the effect of staffing level on the performance time of FLEX implementations. In this study, existing empirical data were re-analysed to derive a W estimate. Regarding the quantitative relationship between staffing level and performance time, it is difficult to obtain similar data from nuclear power plants. Therefore, we analysed experimental data on fire detection time acquired in an experiment conducted in the Republic of Korea (ROK) [Lim, 2018]. Fire suppression tasks in Seoul are usually completed in 6 min on average from the arrival of firefighters at the site to the extinguishing of the fire [Lim, 2018], which is a very short performance time compared to the expected time of most FLEX actions (usually more than 30 min). Despite the difference in time scale, the firefighting action time—and especially the relative time length at different staffing levels—is worth referring to because firefighting actions have similarities with FLEX actions in that a special vehicle is employed and the task of connecting cables or hoses is involved.

When responding to a fire in the ROK, the fire response team usually consists of six employees, but in some cases, only two firefighters may be deployed. Therefore, Lim [2018] experimented with fire response teams composed of 2, 3, 4, 5, and 6 firefighters and measured the time from the arrival at the building to the discovery of the fire. The experiment was conducted in a training building at the Gyeonggi Fire Service Academy. Each floor of the building has four rooms, and the ignition point was set to a random room on the third floor. Firefighting professionals with more than 5 years of in-field firefighting or instruction experience participated in this experiment. For each response team, three fire detections were observed, and thus 15 data points were acquired. The fire detection scenario consisted of 10 tasks derived based on the basic fire response tasks defined by NIST [2010] as follows.

(i) Installing chocks, connecting the hose to the pump car, and putting on gear

(ii) Entering the building
(iii) Climbing stairs
(iv) Arranging the hose to discharge water
(v) Filling the hose with fire water from the pump car
(vi) Discharging water to the entrance door on the floor of the fire
(vii) Entering the floor of the fire
(viii) Arriving at the first room on the floor
(ix) Searching for the fire in the room
(x) Searching other rooms to detect the fire

The average fire detection times by the staffing level of the fire response team are depicted in Fig. 1. Because a pump car and a tank car are employed for an individual fire event, the minimum number of workers is predicted to be 2 in this data, while the regular number of workers is 6. Therefore, *W* for all firefighting tasks was estimated to be 1.22 (=360/295).

Fig. 1. Average fire detection time (sec) from the entry of the building by number of firefighters.

Among the fire detection tasks, the performance time for the first task (i.e., installing chocks, connecting the hose to the pump car, and putting on gear, also referred to as *installation*) was also compared because the time of the first task is sensitive to the number of firefighters; Fig. 2 shows a bar plot comparing the installation times. Estimating *W* based on the installation task from a conservative viewpoint gives a value of 2.33 (=49/21).

Due to the sample size of the data, it was difficult to conclude statistical significance of the time difference from these data (the p-values of mean difference tests were 0.789 and 0.004 for the whole detection time and installation time, respectively). Nevertheless, this analysis reveals that the performance time differs depending on the staffing levels and also that *W* values can be derived from experimental data.

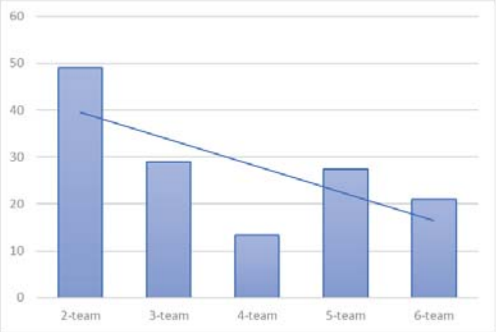

Fig. 2. Average installation time (sec) from the arrival at the building by number of firefighters.

4. Discussion

This paper emphasizes that the staffing level can vary during a multi-unit accident and that the performance time will accordingly change depending on the level. This paper also presents several factors affecting the level of staffing (e.g., accessibility degradation and personnel allocation), which analysts should adequately discuss in terms of how the status of these factors will change according to the progression of the event. In particular, there should be a specific plan for how the decision-making organization allocates staffs during multi-unit accidents. Then based on such a plan, it is necessary to review whether the allocation of the employees is useful in various accident scenarios. We believe that the proposed method can be employed as a tool to verify placement plans by forecasting the risks under various scenarios.

We note that even though the performance time estimation based on staffing level is an important aspect of human reliability, many other issues should be additionally tackled to quantify the failure probability due to time insufficiency.

4.1. Expected distribution of FLEX actions

For the failure probability of a human event due to time insufficiency, it is important to understand the distributions of the time required and the time available. Assuming that the time available can be predicted by the thermal-hydraulic characteristics of the plant and the given accident, the distribution of the time required can be derived through statistical analysis of the time data of response actions. For instance, the Weibull distribution was analysed as the best fit to describe the fire suppression time in domestic residential apartments [Lim, 2018] (Table 2). However, when we analysed 12 time data for mobile power generators in the FLEX response of domestic nuclear power plants, it was found that the lognormal distribution best describes the time information (Fig. 3 shows the diagnostic plots). Table 3 compares the goodness-of-fit values of the statistical distribution candidates. Although the gamma distribution could be a good candidate, it is worth noting that statistical analysis results in various other fields also showed that the repair or maintenance time often follows the lognormal distribution [Kline, 1984; Zapata et al., 2008; Kim, 2021]. Assuming the lognormal distribution (μ, σ), the sigma value was estimated to be 0.179 from the domestic FLEX time data using maximum likelihood estimation. Because the sample size of the data was insufficient, the sigma value was predicted by a Bayesian inference incorporating the data with a weak informative prior. A uniform distribution limited by the upper and lower bounds of the sigma values derived from the operator reliability experiment (ORE) data was employed as the prior [i.e., sigma ~ U (0.26, 0.88)] [EPRI, 1992]. As a result, the sigma value was estimated to be 0.304. Although additional research is required in the future because of the lack of data, these estimates are expected to provide some insights for selecting representative distributions of FLEX action times and forecasting parameter estimates.

Table 2. Statistical fitness values of fire suppression time in domestic events.

Distribution candidate	Akaike information criterion	Bayesian information criterion
Weibull	324.7262	327.2424
Lognormal	327.2744	329.7906
Normal	325.3931	327.9093
Exponential	359.3783	360.6364
Gamma	325.8812	328.3974

(A lower value implies a better fitted distribution.)

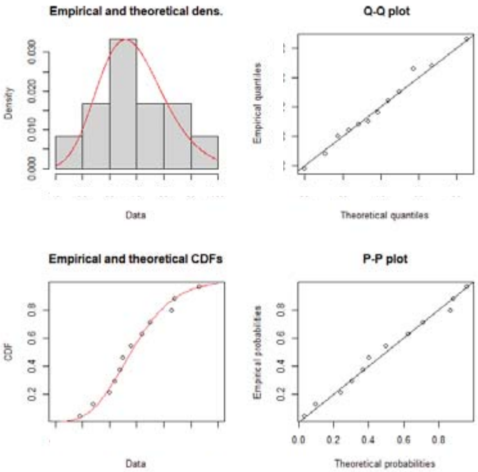

Fig. 3. Diagnostic plots of lognormal distribution for describing time data to implement mobile generators.

Table 3. Statistical fitness values of the distributions of FLEX time data.

Distribution candidate	Akaike information criterion	Bayesian information criterion
Weibull	99.154	100.124
Lognormal	98.067	99.036
Normal	98.439	99.409
Exponential	127.648	128.132
Gamma	98.095	99.065

(A lower value implies a better fitted distribution.)

4.2. Key values for calculating time required

FLEX implementations usually consist of a set of tasks that are expected to have different completion times or execution times depending on the context. The effects of the context on the time for key tasks should thus be analysed.

Declaration time to FLEX implementation—To initiate a FLEX strategy, it is necessary to recognize when it is not possible to use fixed installed facilities in the power plant and accordingly declare the need for mobile equipment based on the inoperability of the fixed systems. Because there are procedures guiding FLEX-related decisions, it is important to estimate the time to reach these procedure steps. For example, Kim et al. [2019] estimated the duration of procedure progressions. Based on the progression time to reach a FLEX step and the time to present the relevant plant information, it is possible to forecast the declaration time. In addition, in the case of a multi-unit accident, because several organizations may be involved in the FLEX-related decision-making, the declaration authority between related organizations and how the decision information is delivered should be considered.

Time for employees to arrive at the task location—The time for the personnel who are required for the FLEX actions to arrive at the plant site and move to the required task location should be calculated. When moving from the outside to the inside of the site, the travel time should be predicted based on the traffic conditions based on geographical road conditions, meteorological conditions, demographic characteristics, and effects of external events. For example, during an earthquake of extreme intensity, plant personnel may have to enter the plant on foot. If some roads are flooded due to heavy rain, delays caused by route detours should also be accounted for. Studies on evacuation speeds might provide a useful insight to estimate the convocation time of employees [Kim and Lim, 2016; Bernardini et al., 2016].

Travel time for the FLEX equipment—It is necessary to calculate the moving time of the mobile equipment from on-site or off-site storage to the power plant connection point. In the case of extreme external events or harsh external conditions, it is important to estimate the time to remove any debris and appropriately include this estimate in the time analysis.

Connection time of mobile equipment to plant systems—Connecting hoses and cables is often carried out simultaneously by multiple workers. As in this study, the time for this should be estimated considering the staffing level, for which it is necessary to secure data on the transportation and operation time regarding cables and hoses.

4.3. Initial cue time of FLEX implementation

Regarding the distribution comparison of time required and time available for calculating time-based failure probabilities, a concern has been raised about reliability estimations based on the lognormal distribution [EPRI, 2018]. This is because, in the case of some long-term operations, the difference between the time when the cue is initially recognized and the time to use the FLEX equipment may be significantly large. Therefore, in order to calculate the time-based failure probability of FLEX actions, the initial cue time should be carefully determined as the point in time when the critical need for action is recognized. For example, Kim et al. [2021] developed an algorithm to determine the initial time by comparing the procedure cue time and instrumentation cue time. This algorithm allows the instrumentation cue time to be selected as the initial cue time if the instrumentation cue occurs significantly later than the procedure cue.

5. Conclusion and Future Work

In this study, an equation was presented to deal with the influence of staffing level on the estimation of human performance time. In addition, by analysing experimental data on fire detection time in relation to staffing level, estimate candidates for a key parameter were suggested. We also discussed considerations for estimating time-related human reliability. Staffing level is a critical factor in estimating the reliability of FLEX actions in multi-unit accidents and is particularly meaningful in dynamically predicting human reliability.

In the future, we plan to develop a method to quantify the failure probability due to time insufficiency that includes the formula developed in this paper. Methods for determining the probabilities of communication errors, decision failures, and installation and/or operation errors of mobile FLEX equipment, which were addressed in the Introduction of this work, will also be developed.

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