Analysis of on-site impact and feasibility of outdoor work under a fission product release at a nuclear power plant.

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ABSTRACT

Studies of multi-unit probabilistic risk assessment (PRA) have conservatively assumed that outdoor work is not feasible after the release of fission products. However, the Fukushima Daiichi Nuclear Power Plant (1F) accident showed that mitigation measures could be implemented during the removal of contaminated debris and the establishment of detours. This study proposes a simple method for evaluating the feasibility of outdoor work during a multi-unit accident. We develop and clarify outdoor work feasibility scenarios by comparing individual and team exposure doses with their respective dose limits. If the expected exposure dose by the completion time—either individual or team—is below the applicable dose limit, outdoor work is considered feasible. Conversely, outdoor work is not feasible if the expected exposure exceeds the dose limit. Since the exposure dose is calculated as the product of the ambient dose rate and the exposure time, we define the feasible work time as the exposure dose limit divided by the ambient dose rate. Work is considered feasible if the required completion time is shorter than the feasible work time. In the case of team-based work, it is assumed that all workers within a team receive the same exposure dose. Based on this assumption, the number of teams required to complete the work can be determined. This study confirms that the feasibility of outdoor work can be evaluated using five parameters: the time required to complete the work, the ambient dose rate, the number of teams, the individual dose limit, and the outdoor work distance. Furthermore, this study demonstrates the preliminary assessment of the feasibility of work after the release of fission products in the 1F accident in terms of the number of teams that could be deemed able to work through a review of available information on the 1F accident.

Keywords: Fukushima Daiichi Nuclear Power Plant accident, individual and team dose limits, Multi-unit PRA, Site risk, Ambient dose rate

Ⅰ.Introduction

Following the Fukushima Daiichi Nuclear Power Plant accident (hereafter referred to as the “1F accident”), increasing attention has been directed toward Multi-Unit Probabilistic Risk Assessment (MUPRA). The accident highlighted critical limitations of traditional Single-Unit Probabilistic Risk Assessment (SUPRA), which is not sufficient to address scenarios involving concurrent damage to multiple reactor units. MUPRA overcomes these limitations by incorporating factors such as inter-unit dependencies, shared systems and resources, and concurrent initiating events—elements that are typically outside the scope of SUPRA [1].

In previous studies, it has often been conservatively assumed that outdoor work is infeasible under conditions involving fission products releases or elevated ambient dose rates [2]. However, during the actual 1F accident, various mitigation efforts—such as the removal or detouring of contaminated debris, the use of personal protective equipment, and continuous dose rate monitoring—were carried out in outdoor environments.

Nevertheless, only limited research has quantitatively assessed the feasibility of conducting outdoor work under realistic radiation conditions. To address this gap, the present study proposes a method to evaluate the feasibility of outdoor work during fission products releases. Based on a literature review of the 1F accident, actual mitigation actions were selected, and the feasibility of work was assessed using the developed method.

II.A Scenario Analysis of Working Conditions during Fission Products Release

Under conditions where fission products have been released, the feasibility of work is determined based on the individual dose limit. If the estimated dose by the end of the work does not exceed the limit, the work is feasible; otherwise, it is not.

Work is assumed to be conducted in teams. Even if an individual's dose exceeds the limit, the work can continue if replacement personnel are available. Conversely, if no substitutes are available and the dose exceeds the individual limit, the work becomes infeasible. Therefore, feasibility is determined by both the individual dose limit and the team dose limit (i.e., the cumulative dose capacity of the teams). Figure 1 illustrates the decision-making scenario for work feasibility. For single-person work, feasibility is governed solely by the individual dose limit. In contrast, team-conducted work may still be feasible even if the individual limit is exceeded, as long as the team dose limit is not. If both the individual and team dose limits are exceeded, work is deemed infeasible.

This study considers both single-person and multi-team work. It is assumed that all team members perform nearly identical work in approximately the same location and therefore receive the same radiation dose regardless of team size. Furthermore, any increase in total working time due to team rotation is not considered.

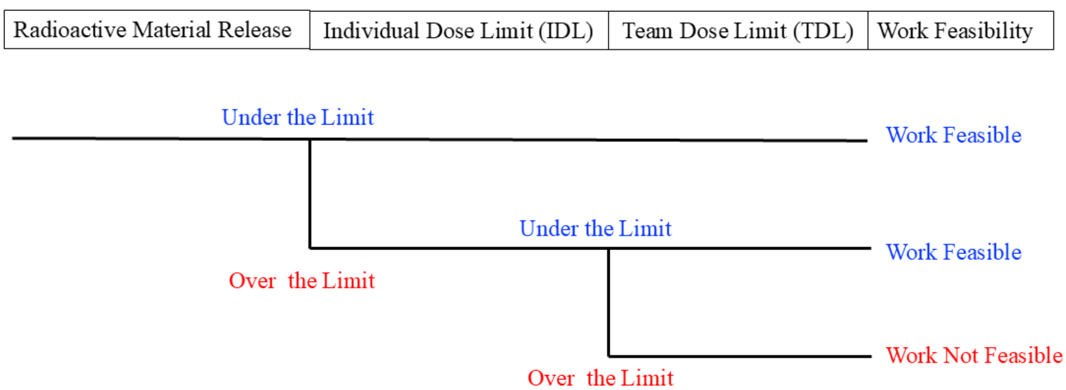

Figure 1 Scenario Definition for Operations during Fission Products Release

II.B Setting of Individual Dose Limits

In Japan, regulations regarding occupational exposure to radiation are governed by the Ordinance on Prevention of Ionizing Radiation Hazards (OPIRH). This ordinance stipulates that, in the event of an accident involving a large-scale release of fission products, the exposure dose limit for workers engaged in emergency operations is set at 100 mSv.

However, a special emergency provision allows the dose limit to be immediately raised to 250 mSv, but only for tasks essential to prevent catastrophic consequences at a nuclear facility [3].

Although 250 mSv is permitted in emergencies, once workers reach this threshold—illustrated in Figure 1—they are no longer allowed to continue working. Since workers typically perform multiple tasks rather than just one, allowing some margin within the individual dose limit is necessary. Furthermore, setting the dose limit to 50 mSv would not provide sufficient time to complete necessary tasks. Therefore, in this study, the individual dose limit is treated as a variable parameter ranging from 100 to 250 mSv.

II.C Evaluation Formula

The radiation dose received by a worker can be calculated by integrating the dose rate (DR) over the working time. Letting T_{fin} represent the time required to complete the work, the individual exposure dose (ID) is given by:

$$ID = \int_0^{T_{\text{fin}}} DR(t)dt \qquad \textbf{(1)}$$

If the dose rate is constant, the exposure dose can be calculated by multiplying the dose rate by the duration of exposure:

$$ID = (T_{\text{fin}} - 0) \times DR \qquad \textbf{(2)}$$

Since ambient dose rates at the work site can fluctuate significantly due to meteorological conditions (e.g., wind direction), this study simplifies the evaluation by using a time-averaged ambient dose rate($\overline{DR}$) over the duration of the work, treating it as a constant.

By dividing the individual dose limit (IDL) by the dose rate, the maximum allowable working time (T) for a single worker can be calculated as:

$$T = {}^{IDL}/_{DR} \qquad \textbf{(3)}$$

The feasibility of work for an individual worker is then evaluated by comparing this allowable working time (T) with the work completion time T_{fin} :

$$Feasible\ : T \leq T_{\text{fin}}$$
$$Not\ feasible\ : T > T_{\text{fin}}$$

Assuming that each worker in a team receives the same radiation dose regardless of the number of team members, the total working time for all teams (T_{N_T}) can be expressed as the product of the allowable working time per team and the number of teams (N_T):

$$T_{N_T} = N_T \times {}^{IDL}/_{DR} \qquad \textbf{(4)}$$

By assuming uniform dose exposure among team members, it is possible to calculate the number of teams required to complete the work within the given dose constraints.

II.D Selection of Work Environment and Derivation of Ambient Dose Rates

In realistic outdoor work scenarios, it is possible to anticipate a sharp increase in ambient dose rates due to venting; however, such an increase is difficult to predict in the case of containment vessel damage. Therefore, this study focuses on two specific scenarios: one assuming containment vessel damage, and the other assuming venting. For each scenario, the ambient dose rate is time-averaged over a selected period and treated as a constant value.

First, based on the measurement data from 1F provided by TEPCO [4], a graph showing the ambient dose rate transition at monitoring post MP4 from March 12 to March 14 was derived as shown in Figure 2. The period from 8:00 to 19:00 on March 13 at MP4 was chosen as the scenario assuming containment vessel damage, and the period from 21:00 on March 12 to 8:00 on March 13 was selected as the scenario assuming venting. The time-averaged ambient dose rates for both cases are shown in Table 1.

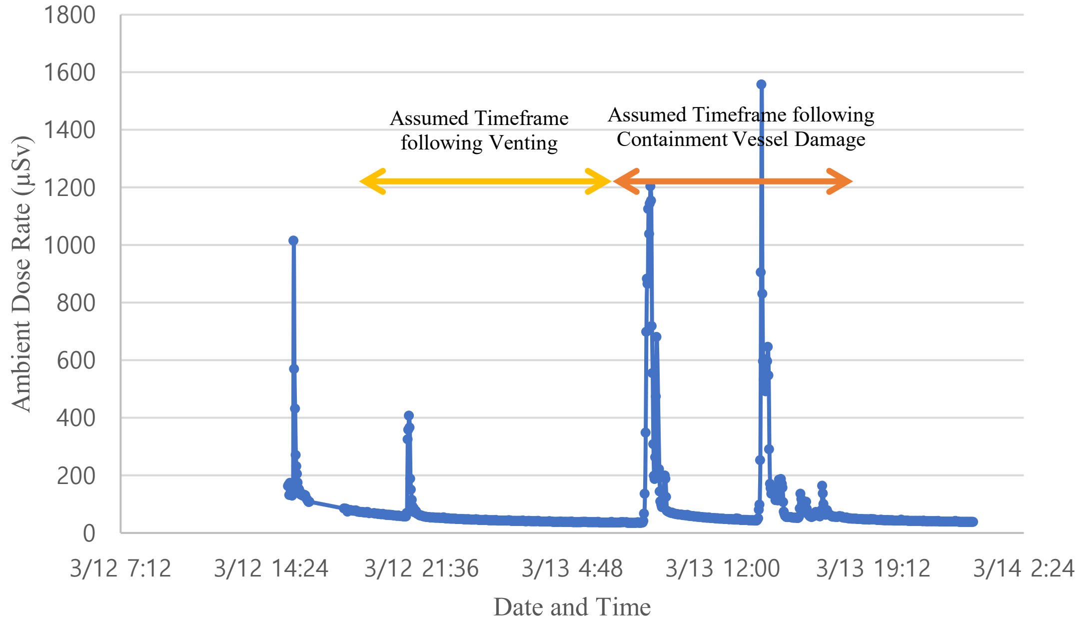

Figure 2 Transition of Ambient Dose Rate and Selected Timeframes at MP4

Table 1 Time-Averaged Ambient Dose Rate under Assumed Conditions of Containment Vessel Damage and Venting

Timeframe	Time-Averaged Ambient Dose Rate (mSv/h)
Assumed Timeframe following Containment Vessel Damage	1.23E-01
Assumed Timeframe following Venting	4.59E-02

II.E Selection of Outdoor Work

As an example of outdoor work, we selected the procedure titled "Natural Convection Cooling of the Containment Vessel Using Mobile High-Capacity Pump Vehicles with A and B Containment Recirculation Units," which is intended to prevent over pressurization and failure of the reactor containment vessel [5].

This procedure consists of five tasks. Two of them can be completed quickly, so the remaining three are selected for evaluation. The task is carried out by six workers over a period of 11 hours, and thus Tfin is set to 11 hours.

II.F Distance from MP4 and Locations of Monitoring Posts

Since the monitoring posts used to observe ambient dose rates are located away from the actual work site, it is necessary to estimate the dose rate at the real work location. As shown in Figure 3, the distance from MP4 to the reactor is approximately 1300 meters [6].

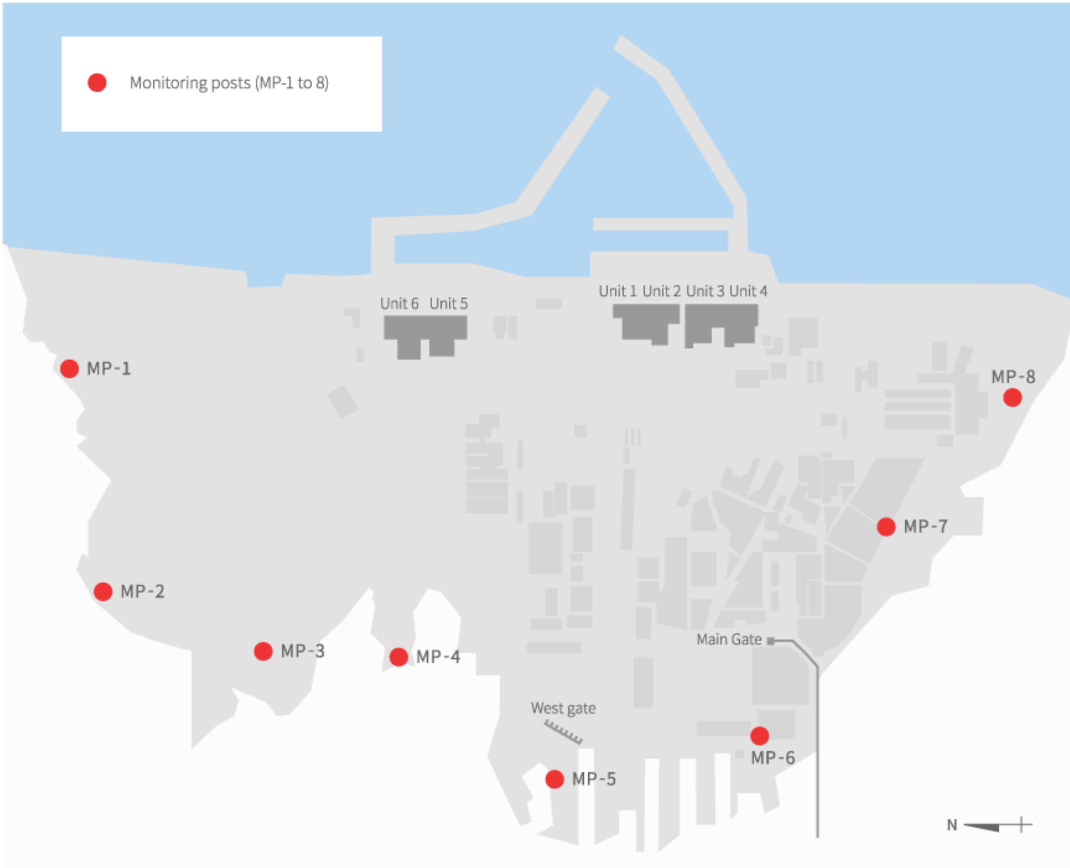

Figure 3 Monitoring points
(Source: Tokyo Electric Power Company, 2020 [4])

II.G Calculation of Dose Rate Based on Distance

Assuming the radiation source is a point source, the dose rate is inversely proportional to the square of the distance. This is expressed in the following formula [7]:

$$I = \frac{k}{r^2} \quad \textbf{(5)}$$

I: dose rate [mSv/h]
r: distance [m]
k: constant [mSv·m²/h]

II.H Outdoor Work Distance and Ambient Dose Rates Within the Range

Since the monitoring posts that observed ambient dose rates were located far from the actual work site, it is necessary to convert the dose rates to reflect the actual work location. In this study, the outdoor work distance is set to range from 30 m to 100 m, based on the area where outdoor work was conducted during the 1F accident. Using Equation (5), the ambient dose rates under the assumptions of containment vessel damage and venting were converted to distances of 30 m, 50 m, and 100 m. The converted values are shown in Tables 2 and 3.

Table 2 Ambient Dose Rates Converted for Each Distance under the Assumption of Containment Vessel Damage

Distance (m)	Ambient Dose Rate (mSv/h)
30	2.30E+02
50	8.29E+01
100	2.07E+01

Table 3 Ambient Dose Rates Converted for Each Distance under the Assumption of Venting

Distance (m)	Ambient Dose Rate (mSv/h)
30	8.62E+01
50	3.10E+01
100	7.76E+00

III. Results

Based on the converted ambient dose rates for each distance under the assumptions of containment vessel damage and venting, the number of teams required to make work feasible was calculated for individual dose limits of 100 mSv and 250 mSv. As shown in Tables 4 and 5, the maximum number of teams required decreased from 26 to 10 when comparing the scenarios of containment vessel damage and venting. As expected, the number of required teams is smaller when the individual dose limit is increased from 100 mSv to 250 mSv. Furthermore, the greater the distance from the radiation source, the fewer teams are required to complete the work.

Table 4 Number of Teams Required to Make Work Feasible under the Assumption of Containment Vessel Damage, for Individual Dose Limits of 100 mSv and 250 mSv

Distance (m)	Ambient Dose Rate (mSv/h)	Number of Teams Required	
		For 100 mSv limit	For 250 mSv limit
30	2.30E+02	26	11
50	8.29E+01	10	4
100	2.07E+01	3	1

Table 5 Number of Teams Required to Make Work Feasible under the Assumption of Venting, for Individual Dose Limits of 100 mSv and 250 mSv

Distance (m)	Ambient Dose Rate (mSv/h)	Number of Teams Required	
		For 100 mSv limit	For 250 mSv limit
30	8.62E+01	10	4
50	3.10E+01	4	2
100	7.76E+00	1	1

The above results represent only the number of teams required for limited values of individual dose limits and outdoor working distances; therefore, response surfaces were developed to evaluate the number of teams required to make work feasible under broader conditions. Based on the ambient dose rates under the two assumed scenarios—containment vessel damage and venting (as shown in Table 1)—response surfaces were generated with the individual dose limit and the outdoor working distance from the radiation source as parameters. The range for the individual dose limit was set from 100 mSv to 250 mSv, and the outdoor working distances were set from 30 m to 100 m.

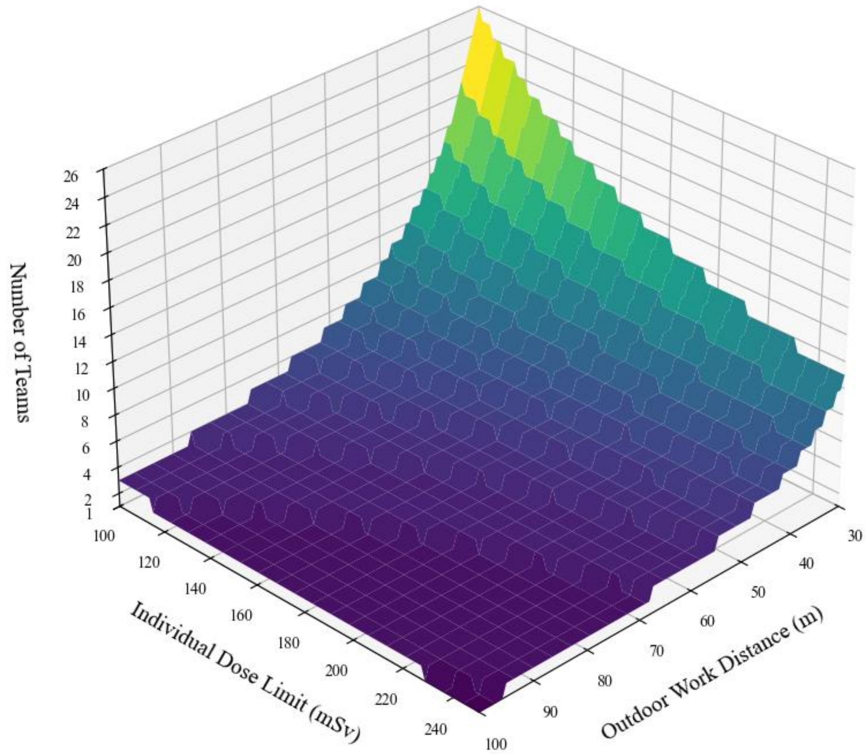

Figure 4 Response Surface of the Number of Teams under the Assumption of Containment Vessel Damage

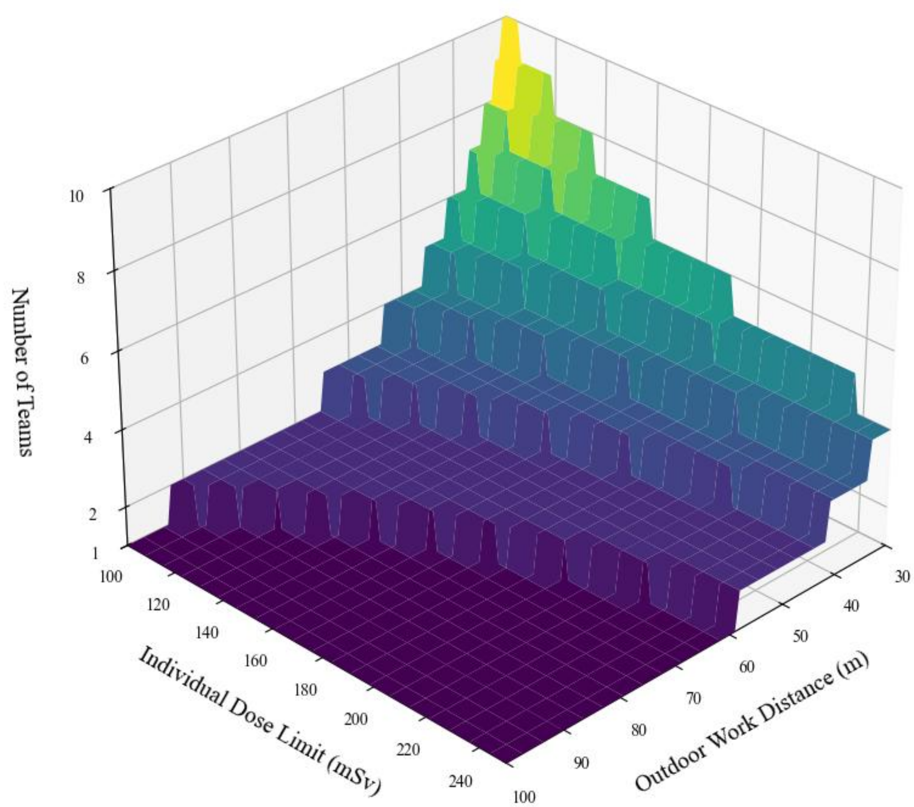

Figure 5 Response Surface of the Number of Teams under the Assumption of Venting

In the scenario assuming containment vessel damage, the number of teams required ranged from a minimum of 1 to a maximum of 26. In the scenario assuming venting, the number of teams required ranged from a minimum of 1 to a maximum of 10 in all cases.

IV. CONCLUSIONS

This study proposed a methodology for evaluating the feasibility of outdoor work during multi-unit nuclear accidents, taking into account realistic impact areas.

Feasibility was evaluated from the perspective of the number of required teams, using the Fukushima Daiichi Nuclear Power Plant accident as a case study. The evaluation demonstrated that the feasibility of conducting outdoor work can be assessed using five parameters: required work completion time (T_{fin}), ambient dose rate (DR), number of teams (N_T), individual dose limit (IDL:100-250 mSv), and outdoor working distance (r:30-100 m).

As a result, it was found that under the assumption of containment vessel damage, between 1 and 26 teams would be required to complete the work, while under the assumption of venting, between 1 and 10 teams would be sufficient.

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