Resident risk assessment in nuclear power plant accident integrating on-site and off-site information

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Abstract: In case a nuclear power plant (NPP) accident occurs in Japan, residents evacuate according to an evacuation planning established by local authorities based on nuclear emergency response guideline. Emergency action level (EAL) that triggers evacuation is reached in according to the plant condition, but the time from the EAL to the release of radioactive materials varies depending on the accident scenario. Also, the evacuation scenario for residents differs depending on their attributes. Moreover, it differs by the type of disasters such as an NPP-only disaster or a complex disaster where a NPP disaster overlaps with natural disasters. Therefore, it is important to integrate on-site and off-site information against the most important residents' risk assessment. In this paper, radiation effects are analyzed for NPP accident scenarios on typical residents' attribute (cohort) classified by their characteristic evacuation behavior.

Keywords: Level 3 PRA, Complex disaster, Cohort, EAL, Evacuation

1. INTRODUCTION

Probabilistic risk assessment (PRA) study has largely been utilized to evaluate public dose exposure and environmental impact in an accident event of nuclear power plant for enhancement of its safety facilities. In the future, it will be important to utilize the appropriate evaluation results of the PRA in decision-making for ensuring safety. Level 3 PRA evaluates the transport of radioactive materials in the environment, and the health and the economic consequences based on the results of Level 2 PRA.

Figure 1 shows the relation between the evaluation process of Level 2 and Level 3 PRA. Level 2 PRA analyzes the progression of an accident and assesses the amount and the time profile of radioactive material (source term) released from the NPP to the environment. Level 3 PRA assesses the offsite consequences based on the characteristics of the radioactivity release calculated by the Level 2 PRA. In this evaluation, off-site information such as environmental conditions and residents' evacuation behavior will have a large influence on resident's risk. The evacuation behavior for residents differs depending on their attributes and the type of disasters. Also, the timing to start evacuation depends on the accident scenario. Therefore, in the evaluation of offsite consequences, it is important to integrate on-site and off-site information. In this study, we applied Level 3 PRA to assess the residents' risk quantitatively by integrating on-site and off-site information appropriate to the assumed accident scenarios.

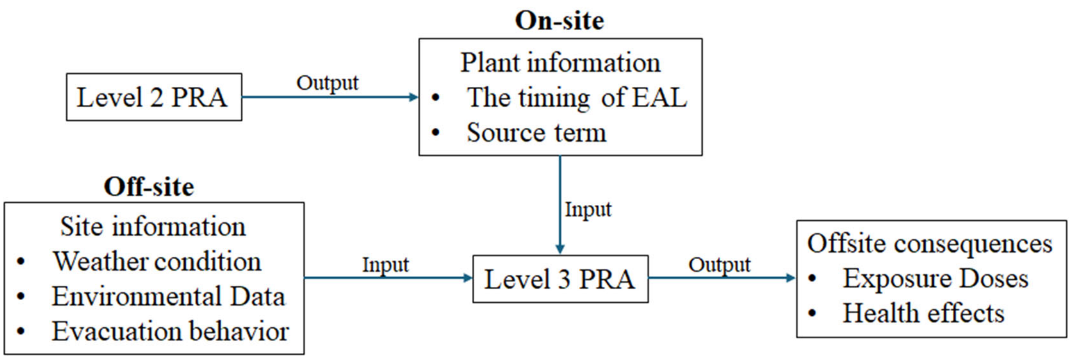


Figure 1. Evaluation process of Level 2 and Level 3 PRA

2. ACCIDENT SCENARIOS

In this paper, we focused on the case of decay heat removal failure causing core damage. In this case, EAL that triggers evacuation, such as site area emergency (SE) and general emergency (GE), are reached in different timing. However, in other cases, such as low pressure make-up failure, high pressure make-up failure & failure of depressurization, loss of coolant accident, etc., SE and GE are reached almost simultaneously. Therefore, decay heat removal failure causing core damage case is expected in which different evacuation behavior will show different effects on risks. The time of reaching EAL and the elapsed time from the EAL to the release of radioactive materials, which are significantly related to offsite consequences, varies depending on the accident scenario. In this study, accident progression scenario cases after core damage were branched depending on the success or failure of the accident response, and eight cases of accident scenarios were extracted. Figure 2 shows the accident progression of each scenario.

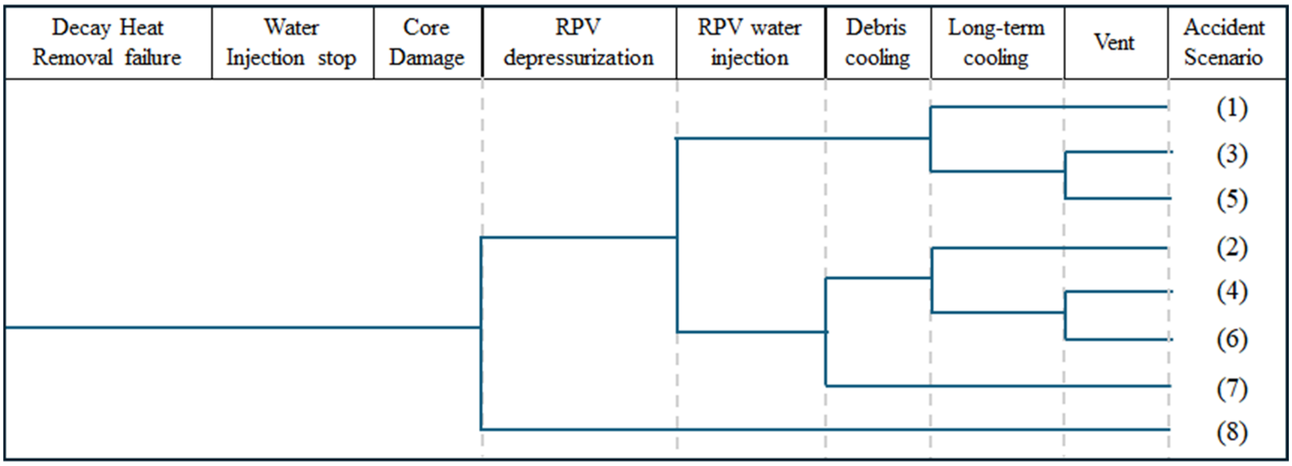


Figure 2. Accident progression of eight accident scenarios in decay heat removal failure case

In this study, ”MAAP” code, which has been developed by Fauske & Associates with support of Electric Power Research Institute, was used as the Level 2 PRA tool. Therefore, event progression for eight cases of accident scenario shown in Figure 2 were evaluated with “MAAP” code and the source term information necessary for Level 3 PRA evaluation was extracted from the output results [1]. Table 1 summarizes the evaluation results of the timing of EAL and fission products (FP) release start timing for each accident scenario. “Small Leak” in the table is due to design leakage, and “Large release” indicates the initiation of FP release due to venting or PCV failure. The rightmost column shows the release path of “Large release”. For all accident scenarios, SE was reached at 0.0 hour and GE at 11.2 hours. Here, the accident occurrence time is set to 0.0 hour, therefore SE reached at the same time as the accident occurs in all accident scenarios shown in Table 1. On the other hand, the initiation of FP large release and the release path differs depending on the accident scenario, so the source terms differ greatly among these accident scenarios.

Table 1. The timing of EAL and FP release start timing for each accident scenario

Scenario No.	Timing of EAL		FP release start timing		FP Large release Path
	SE (hr)	GE (hr)	Small Leak (hr)	Large release (hr)	
(1)	0.0	11.2	13.6	-	-
(2)	0.0	11.2	13.6	-	-
(3)	0.0	11.2	13.6	40.8	Venting
(4)	0.0	11.2	13.6	38.2	Venting
(5)	0.0	11.2	13.6	40.8	PCV Failure
(6)	0.0	11.2	13.6	38.2	PCV Failure
(7)	0.0	11.2	13.6	21.2	PCV Failure
(8)	0.0	11.2	13.6	21.2	PCV Failure

3. RISK ASSESSMENT

Evacuation scenario for residents differs depending on their attributes and the type of disasters. The purpose of this paper is to confirm an effect of difference in evacuation behavior on risk assessment due to their attributes. So, the residents around the NPP site are classified based on their attributes and set up a characteristic evacuation scenario for each. The evacuation scenario differs by the type of disasters such as an NPP-only disaster or a complex disaster where NPP disaster overlaps with natural disasters. Therefore, it is necessary to consider evacuation scenarios depending on the type of disaster. The purpose of this chapter is to confirm how the differences in evacuation scenarios during NPP-only disaster and complex disaster affect the risk assessment.

In this assessment, "WinMACCS", which has been developed by Sandia national Laboratories to support the U.S. Nuclear Regulatory Commission, was used as the Level 3 PRA code. "WinMACCS" can estimate the consequences on residents associated with a release of radioactive materials into the environment. The evacuation zone is the area of 30 km radius from the plant which corresponds to urgent protective action planning zone (UPZ) in the nuclear emergency guidelines [2]. Additionally, circular area within a 5 km of the plant is designated as precautionary action zone (PAZ) and the protective actions are different for each zone. In this evaluation, evacuation is determined to be complete when the position of evacuee exceeds 30 km from the plant, and no further radiation exposure is expected.

This assessment assumed a peninsular region facing the sea, which is a typical geographical feature in Japan. Therefore, residents exist only on the land area, and the terrain was designed to allow evacuation only in the direction of the land. In this study, population distribution on the land area surrounding the NPP is assumed to be uniform at 100 people/km^2. Figure 3 shows an image of the evaluation area assumed in this study. Although the terrain includes rivers, it is assumed that evacuees are able to cross them through bridges. Therefore, it is not intended to be a complicated evaluation route with rivers, and the evacuation cohorts evacuate radially outward from their location on the land.

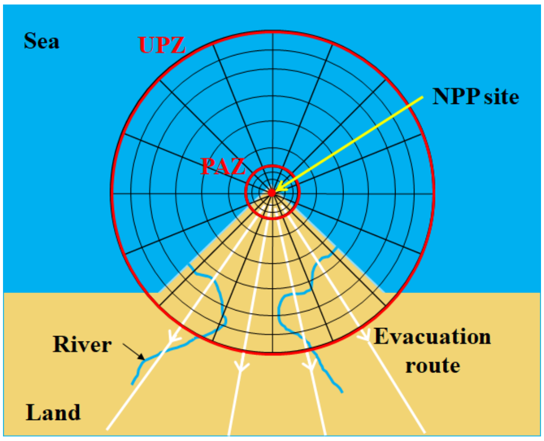


Figure 3. Assumption of evaluation area

3.1. Evacuation Scenarios for NPP-only disaster

In case a NPP accident occurs in Japan, residents evacuate according to an evacuation planning established by local authorities based on nuclear emergency response guideline [2]. Therefore, evacuation scenario for residents differs depending on the area where the residents are present and their attributes. In this assessment, the residents being evaluated were limited within the PAZ and four cohorts are modeled. A cohort is a population group that takes protective action differently from other population groups. Their characteristic evacuation behavior during the NPP-only disaster is based on regional evacuation planning in Japan. In this section, evacuation behavior of each cohort during the NPP-only disaster is set as follows to be used for comparison with the complex disaster [3]. Table 2 summarizes the evacuation scenario for each cohort established for this assessment.

Cohort 1 applies to the general population. Populations within the PAZ basically take the evacuation as protective actions and the sirens to start evacuating for this cohort is sounded at GE. Therefore, 1 hour is assumed for the preparation of evacuation and they start evacuation 1 hour after the GE has been declared. The transportation of evacuation is assumed to be vehicles. Cohort 2 also applies to the general population but have no means of transportation such as vehicles, so the evacuation scenario is somewhat different from cohort 1. This cohort begins preparation of evacuation for 1 hour after the GE has been declared and moves to the primary meeting point, from which they evacuate by bus. This analysis assumed the moving time to the primary meeting point to be 20 minutes and the sheltering periods to wait for the bus at the primary meeting point to be 1 hour. Cohort 3 applies to the population residing at special facilities such as hospitals and nursing homes and evacuate by welfare vehicles. Special facilities population are sounded the sirens to start taking protective actions at SE to evacuate smoothly. They start preparation of evacuation and start evacuation 2 hours after the SE has been declared. On the other hand, some people evacuate spontaneously prior to receiving an evacuation order and they are called shadow evacuees. Cohort 4 applies to shadow evacuees. They start evacuating when the emergency is communicated to the residents, so this analysis assumed that cohort 4 would start evacuation 1 hour after the declaration of SE. Actually, there is a time delay between the time reached to EAL and the time sounded of EAL, but it is included in the evacuation preparation time in this assessment.

These populations exist in a series of concentric circular areas centered around the NPP site. In this evacuation scenarios, all the cohorts evacuate after the declaration of EAL, radially outward from their location by vehicles. Therefore, a baseline evacuation speed for each cohort was set according to the evacuation start time. A baseline evacuation speed of cohort 1 and 2 which start evacuation after the sirens of GE was set assuming that the evacuation would be completed in 10 hours. For cohort 3 and 4 which start evacuation after the sirens of SE, a baseline evacuation speed was set to complete evacuation in 11 hours, considering the vehicle speed, etc.

Table 2. Evacuation scenarios of each cohort

Cohort No.	Attribute	Transport.	Evacuation scenario (NPP-only disaster)
1	General Population	Vehicles	Evacuate 1 hour after GE
2	General Population (via the primary meeting point)	Buses	Start move to primary meeting point 1 hour after GE and moving for 20 minutes. Evacuate 1 hour after shielding in primary meeting point.
3	Special Facilities Population	Welfare vehicles	Evacuate 2 hours after SE
4	Shadow Evacuees	vehicles	Evacuate 1 hour after SE

3.2. Evacuation Scenarios for Complex disasters

This section focuses on a complex disaster where a NPP disaster overlaps with natural disasters. In this evaluation, floods caused by heavy rain were selected as a general disaster that overlaps with a NPP disaster. In recent years, heavy rains have been occurring every year in Japan possibly due to global warming, and flooding has become frequent. When a flood occurs, not all evacuation routes can be used normally, so if this disaster coincides with an NPP disaster, evacuation scenario would be changed from that used for a NPP-only disaster. Therefore, the evacuation scenario for the cohort in the evaluation needs to be changed for the complex disaster. Figure 4 shows the image of evaluation area assumed in the flooding disaster. The river shown in Figure 3 has flooded, creating a flooded area within the evacuation route. This evaluation assumes that if a flooded area occurs, the roadways become unavailable.

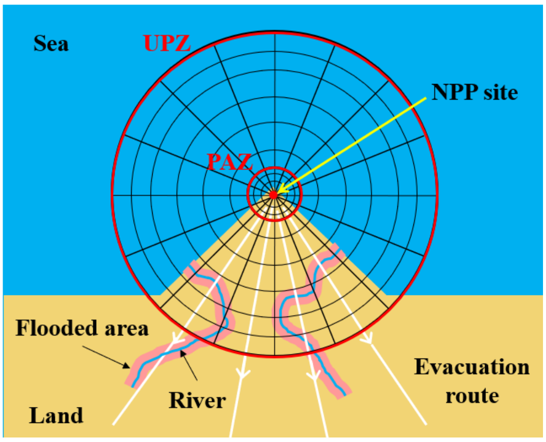


Figure 4. Assumption of evaluation area in the flooding disaster

Cohorts modeled in this analysis is the same as cohorts for the NPP-only disaster described in section 3.1, but the evacuation behavior differs because of flooding. When flooding occurs, roadways crossing the rivers become unavailable. Therefore, it is assumed to be necessary for residents to stay inside the facilities without evacuating to avoid hazard until the flooding has cleared. After the flooding has cleared, the roadway would be available as usual. This assessment assumes that flooding begins at the event time of 0s and lasts for 24 hours. As all the accident scenarios described in chapter 2, the declaration timing of SE is at 0 hour, so flooding begins at the same time of the SE declaration. Therefore, cohort 1, 2, and 3 start evacuation 24 hours after the SE declaration. Behavior to be taken after evacuation begins are the same as described in chapter 3.1 during an NPP-only disaster. Since these cohorts start evacuation at the same time, evacuation speed was set with assuming that evacuation would be completed in 10 hours. On the other hand, cohort 4, shadow evacuees, starts evacuation before the flooding has cleared and evacuates through available roadways. In this evaluation, it is not intended to be a complicated evaluation route with rivers and flooded areas, so cohort 4 evacuates radially outward from their location. Therefore, the influence of unavailable evacuation routes was represented in terms of evacuation speed. Since the available roadways are limited, and the possibility of traffic congestion, the evacuation speed was set at half of the evacuation speed for cohort 4 in chapter 3.1. Therefore, the evacuation speed was set to complete evacuation in 22 hours. Table 3 summarizes the evacuation scenario for each cohort established for this assessment.

Table 3. Evacuation scenarios of each cohort

Cohort NO.	Attribute	Transport.	Evacuation scenario (Complex disasters)
1	General Population	Vehicles	Evacuate 24 hours after SE
2	General Population (via the primary meeting point)	Buses	Evacuate 24 hours after SE
3	Special Facilities Population	Welfare vehicles	Evacuate 24 hours after SE
4	Shadow Evacuees	Vehicles	Evacuate 1 hour after SE

3.3. Consideration of Uncertainty

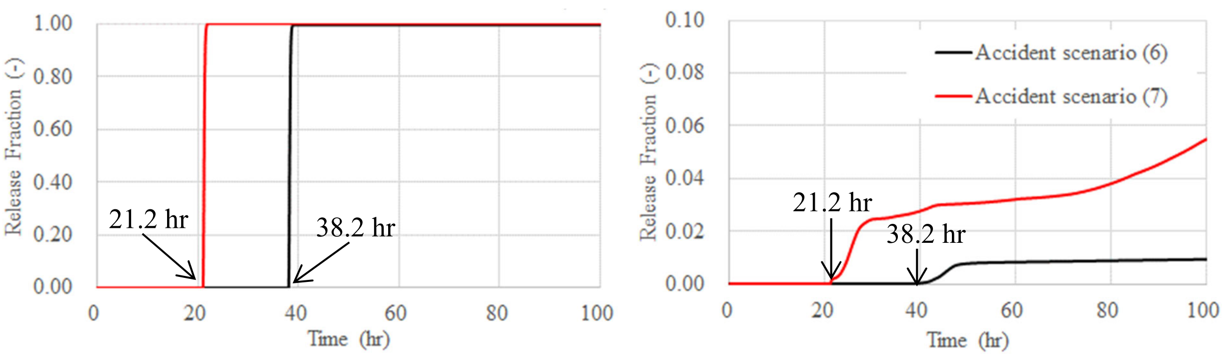
In this study, uncertainty in the parameters was considered in the evaluation. “WinMACCS” uses Latin Hypercube Sampling (LHS) to create realization sets of the uncertain variables with equal probability. In this evaluation, 60 parameter sets were created. The input parameters of “WinMACCS” that take uncertainty into account are those that have a large effect on risk, related to evacuation and the weather. In this evaluation, uncertainty was considered for ten parameters. Five parameters which have a large effect on risks are selected based on the uncertainty analysis of the State-of-the Art Reactor Consequence Analyses Project (SOARCA) results [4]. Specifically, parameters related to deposition, a factor which affects the calculation of latent health effects and dispersion were set. Therefore, the uncertainty distribution for those parameters refers to the SOARCA analysis. Furthermore, uncertainty distributions of two parameters related to the shielding coefficient for evacuation were also set with reference to the SOARCA analysis. As for the weather data, the sample meteorological data file attached to "WinMACCS" is used, which contains hourly data for one year. In this analysis, 8760 cases of meteorological data are all sampled. On the other hand, two parameters related to evacuation such as evacuation start time after the declaration of EAL and evacuation speed must be set based on the analysis conditions of each cohort described in chapter 3.1 and 3.2. In the NPP-only disaster, the uncertainty distribution of evacuation start time after the declaration of EAL was set to the values shown in Table 4. The upper bound was set by referring to the setting method in the SOARCA analysis. As shown in the table, the lower bound was set at 0 hour and the upper bound was set at 4 hours for cohort 1, 2, and 3 who evacuate according to the evacuation order. As for cohort 4, the distribution of the lower bound is set to 0.5 hours with considering the time lag of the emergency communicated to the residents. The upper bound set at 4 hours, same as other cohorts. On the other hand, for cohorts 1, 2, and 3, who evacuate by following the evacuation order in the complex disaster, the uncertainty distribution of evacuation start time was assumed to set the lower and upper bound of flooding duration time as 12 hours and 72 hours. The evacuation speed was assumed to be a normal distribution with a baseline value of 90% evacuation completion for both disasters.

Table 4. Uncertainty distribution of evacuation start time in NPP-only disaster

Cohort No.	Attribute	EAL	Baseline (hr)	Lower Bound (hr)	Upper Bound (hr)
1	General Population	GE	1.0	0.0	4.0
2	General Population (via the primary meeting point)	GE	2.3	0.0	4.0
3	Special Facilities Population	SE	2.0	0.0	4.0
4	Shadow Evacuees	SE	1.0	0.5	4.0

3.4. Risk Assessment Results

Risk assessment was conducted for accident scenario (6) and (7) shown in Figure 2. The event progression from event occurrence to debris relocation is the same for accident scenario (6) and (7). In accident scenario (7), debris cooling has failed, so there is no FP removal effect, and more FP is released than in accident scenario (6). In both accident scenarios, SE and GE reached 0.0 hour and 11.2 hours respectively, and FP large release occurs due to PCV failure. These cases are selected in terms of FP large release start timing. As shown in Table 1, the start timing of FP large release is 38.2 hours at scenario (6) and 21.2 hours at scenario (7). Therefore, scenario (6) has plenty of time before the start of large release. Comparing of the FP large release timing and the release amount for accident scenario (6) and (7) are shown in Figure 5. The figures show changes in the release fraction over time, about (a)noble gas, and (b)Cesium (Cs) representing particulate radionuclides. For the noble gas in (a), there is a noticeable difference in the release timing, and for Cs in (b), there is a difference in the release amount as well as the release timing. Figures 6 and 7 show a comparison of the FP release start timing for each accident scenario and the timeline for each cohort's evacuation scenario. Figure 6 shows the evacuation scenario of NPP-only disaster and Figure 7 shows the evacuation scenario of the complex disaster. Although uncertainty is considered in this evaluation, the evacuation times for each cohort shown in the figures were calculated using baseline values.



(a) Noble gas (b) Cs

Figure 5. FP large release timing and release amount for accident scenario (6) and (7)

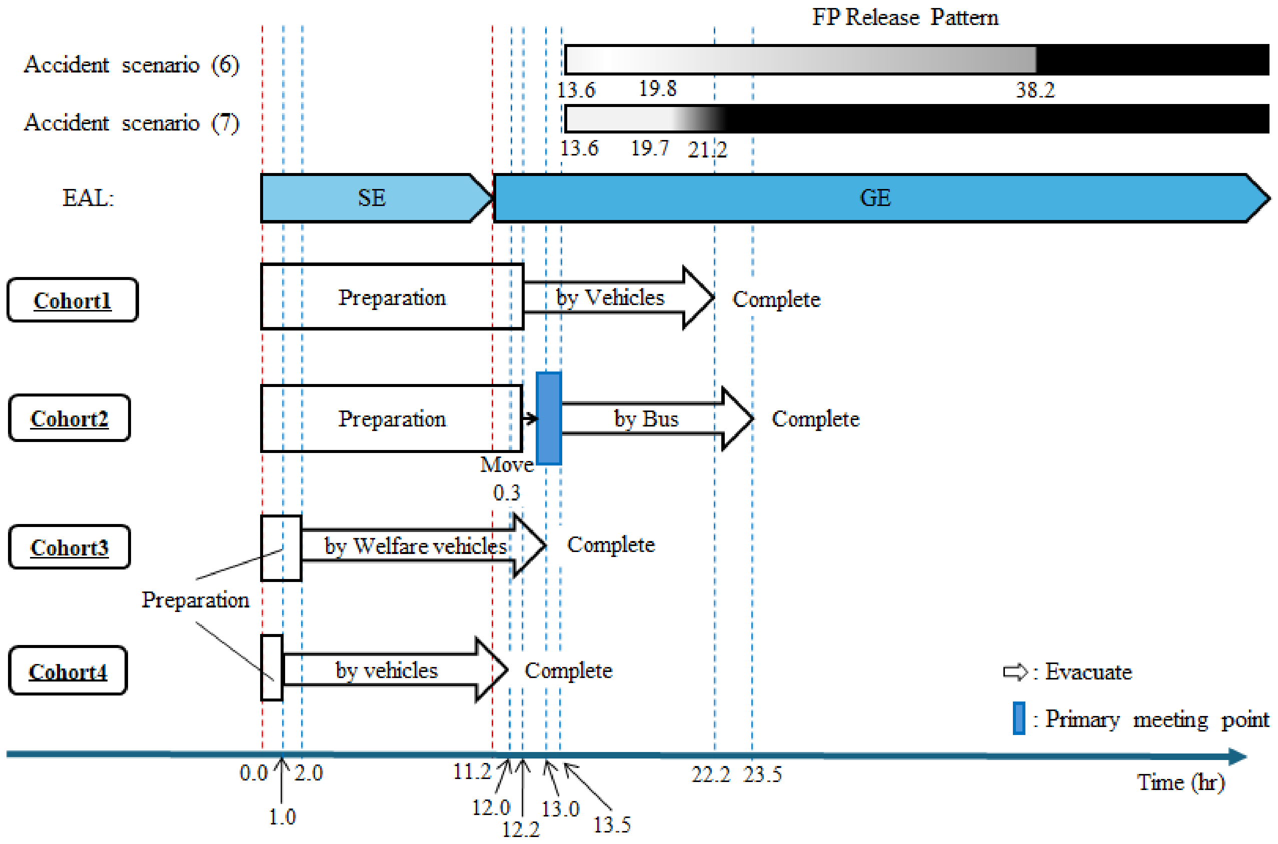


Figure 6. Timeline of NPP-only disaster

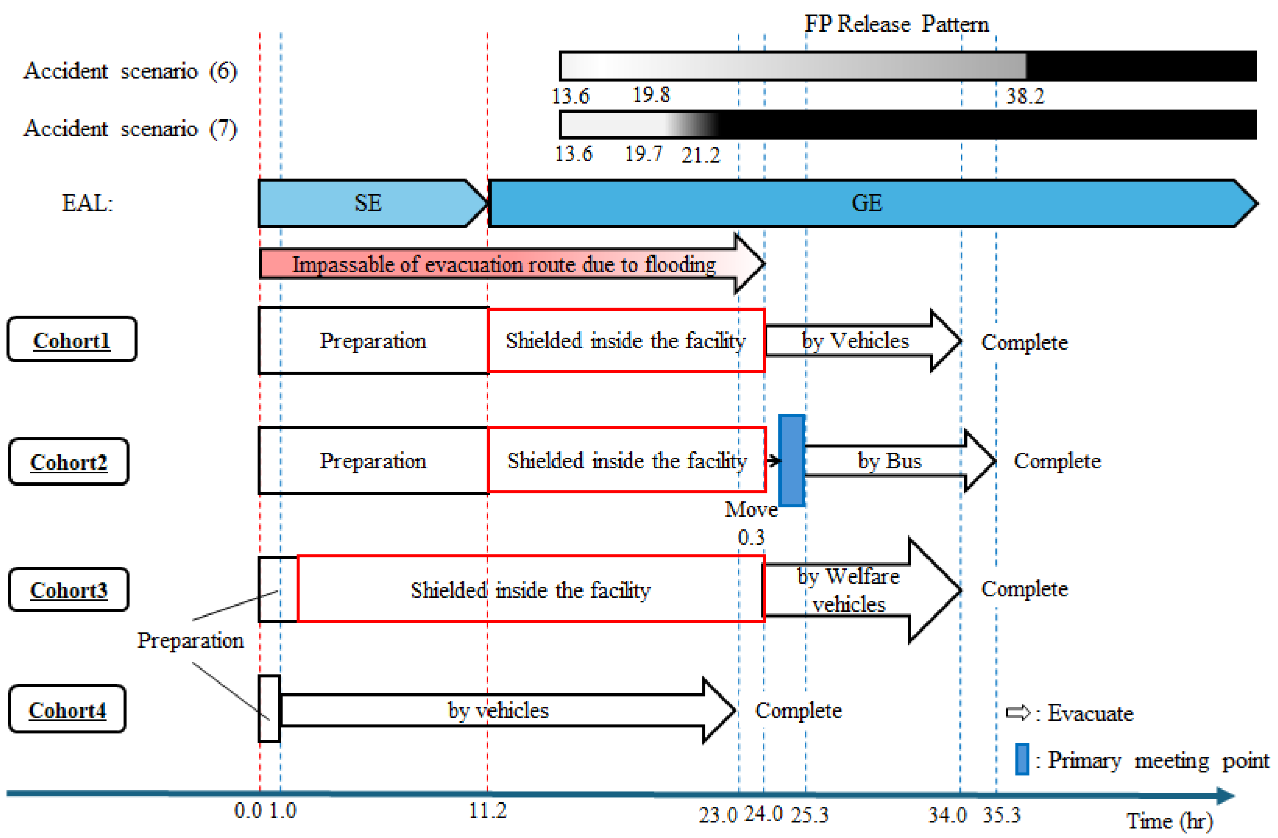


Figure 7. Timeline of complex disaster

As described in section 3.3, 60 cases of evaluations were performed with considering the uncertainty of the parameters in this assessment. Figure 8 shows 60 cases of the assessment results obtained for cohort 1 in the NPP-only disaster for accident scenario (6). It shows the results for health effect risk in the early phase plotted against distance from the NPP site. In these analyses, the early phase is one week from the occurrence of the accident scenario. The health effect risk shown in Figure 8 is obtained by calculating the number of cases of a health effect within a region and dividing by its total population. Therefore, the result includes the population distribution. The nearest residents to the NPP site exist at a distance of 0.5 km from the NPP site, and the health effect risk in the area from 0.5 km to 1.0 km is plotted at a distance of 1.0 km in the figure. A range of uncertainty appears in the assessment results. The results showed that, although there are variations depending on the case, the risk is relatively higher near the NPP site, and the risk tends to decrease slightly as the distance increases.

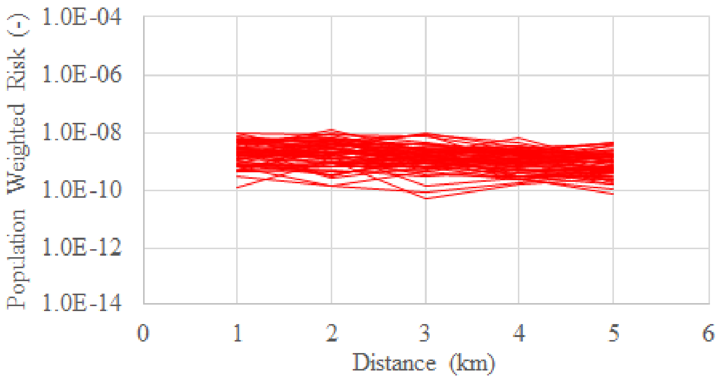


Figure 8. 60 cases of the assessment results of cohort1 in NPP-only disaster for accident scenario (6)

To compare the risks of each cohort for each scenario, Figures 9 and 10 show the results of each cohort in the early phase. Here, figures show the relative risk value based on the health effect risk in cohort 1 of accident scenario (7). Figure 9 shows the result of accident scenario (6), and Figure 10 shows the result of accident scenario (7). In order to confirm the impact on risk of the difference between evacuation scenarios in the NPP-only disaster and in the complex disaster, the relative risk of the NPP-only disaster is shown in blue and the relative risk of the complex disaster is shown in red. In this assessment, cohorts are limited within the PAZ, circular area within a 5 km of the plant. Since the area near the NPP site shows the highest risk, the figure shows the relative risk results for residents within the area from 0.5 km to 1.0 km. Since uncertainty range exists in the assessment results as shown in Figure 8, the relative average value of the results including all uncertainties is shown as a symbol such as a red circle or a blue cross, and the maximum value is shown as a bar. As a result, it is confirmed that the health effect risk increases in all cohorts for the complex disaster compared to the NPP-only disaster. In particular, the increase in risk due to the complex disasters for scenario (6) is greater than scenario (7). This paper presents risk results under hypothetical conditions for the purpose of developing an evaluation method and does not represent the results of a specific plant.

Since the FP large release occurs at 38.2 hours in accident scenario (6), it will occur after all cohorts have completed their evacuation in the evacuation scenario of the NPP-only disaster. In using baseline values, even cohort 2 completes evacuation in 23.5 hours, which is the longest time in all cohorts. Therefore, the relative health effect risk in the NPP-only disaster shown in Figure 9 is relatively low due to FP small release. As for cohort3 and 4, a small leak occurs after evacuation when using baseline values as shown in Figure 6. However, when considering the uncertainties, there exists cases which occurs a small leak during the evacuation, therefore the average value of the risk for cohort 3 and 4 in the NPP-only disaster are not zero. On the other hand, in the complex disaster, the evacuation starts later than in the NPP-only disaster except for cohort 4, so in some cases of the 60 parameter sets, FP large release would occur during the evacuation. Therefore, the health effect risks in the complex disasters shown in Figure 9 include not only the effect of FP small release but also the effect of FP large release. As a result, the risk of the complex disasters is significantly higher than that of NPP-only disaster. As for cohort 4, which starts to evacuate earlier than the other cohorts, evacuation is completed before the FP large release even in the evacuation scenario of the complex disaster. However, since the evacuation speed is slower than in the case of the NPP-only disaster, evacuees are exposed to contaminated areas due to FP small release longer than in the case of the NPP-only disaster. Therefore, the risk of cohort 4 shown in Figure 9 also increases during the complex disasters.

In accident scenario (7), the FP large release occurs at 21.2 hours earlier than scenario (6). Therefore, unlike scenario (6), FP large release starts during the evacuation of some cohorts even in the case of NPP-only disaster. In the evacuation scenario of the NPP-only disaster, cohort 4 completes evacuation before the FP large release, even in consideration of uncertainty of the parameters. Therefore, the risk of cohort 4 in the NPP-only disaster shown in Figure 9 is due to FP small release and there is little difference in the risks between scenario (6) and (7). In the evacuation scenario of the NPP-only disaster for cohort 1, 2, and 3, FP large release starts during evacuation. Cohort 3 starts evacuation relatively earlier than the other cohorts, but they take longer to complete evacuation in consideration of uncertainty of the parameters. Because of the FP small release as well as the FP large release, the health effect risk of the NPP-only disaster of cohort 1, 2, and 3 in scenario (7) has increased significantly in comparison with scenario (6). In the complex disaster, FP large release begins when all cohorts are being evacuated. Cohort 1, 2, and 3 has already begun evacuation before the FP large release, so the risks are extremely high in comparison with scenario (6). The risks in the complex disaster of accident scenario (7) are about two orders larger in cohorts 1 and 2, and about four orders larger in cohort3 than that of scenario (6). This is assumed to be due to the difference in the FP release timing and release amount. Comparing the release amount of Cs, which is shown as a representative particulate radionuclide in Figure 5(b), accident scenario (7) is at most 4 to 5 times as large as accident scenario (6). Therefore, the remaining difference in risks is considered to be due to the effect of FP large release start timing. For cohort 4, FP large release did not occur until the evacuation was completed in the NPP-only disaster, whereas FP large release started during the evacuation in the complex disasters in considering the uncertainties. In the case of complex disaster, the maximum evacuation time for cohort 4 would be approximately 23 hours, taking into account the uncertainties. Therefore, there is a large difference in the risks between these disasters.

As a result, it was confirmed that the health effect risk differs greatly depending on the relation between the FP start timing and the evacuation scenario. Therefore, it is necessary to set evacuation scenarios that consider the type of disaster to evaluate the risk in an accident scenario appropriately.

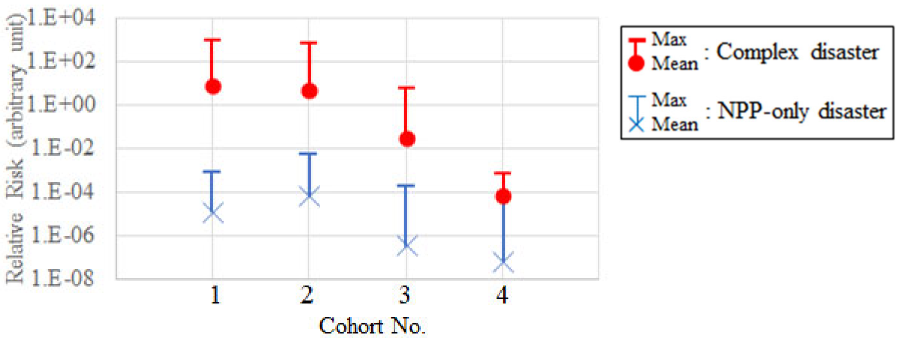


Figure 9. Risk assessment results for NPP-only disaster and complex disaster in accident scenario (6)

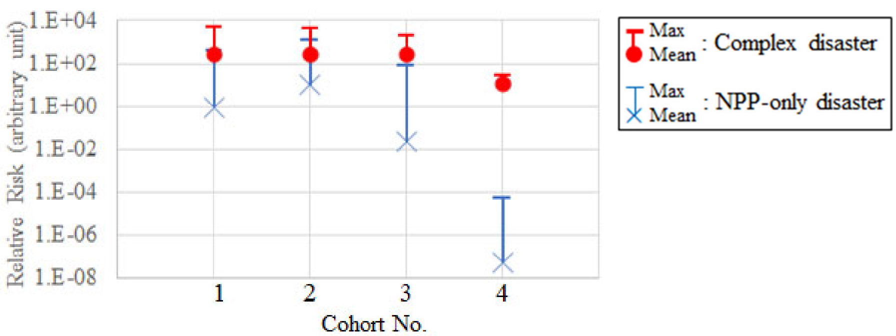


Figure 10. Risk assessment results for NPP-only disaster and complex disaster in accident scenario (7)

4. CONCLUSION

In this study, Level 3 PRA was applied to quantitatively assess residents' risk by integrating on-site and off-site information appropriate to the assumed accident scenarios. As a result, it was confirmed that the residents' risk was greatly depending on their protective actions, and that the risk is also greatly influenced by the accident scenarios. The trigger for residents to initiate protective actions is the EAL, which varies depending on the accident scenarios. For the residents who evacuate, the risk varies greatly depending on the relation between evacuation completion time and FP release start time. In this study, it was confirmed that the risk could remain relatively low if the evacuation completed before the FP large release. Therefore, both the time from the EAL declaration to the FP release and evacuation scenario would greatly affect the residents' risk. Furthermore, in the complex disaster, the evacuation scenario is significantly different from that of the NPP-only disaster, so the risks to evacuees would be significantly different. Therefore, it is important to quantitatively assess the risk to residents by integrating information on both accident scenarios and the environment in which residents exist. The assessment results would provide important information to confirm the appropriateness of residents' evacuation scenarios.

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