Development of methods for evaluating the frequency of accidents related to multiple storage tanks and multiple events at the Rokkasho Reprocessing Plant

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Abstract: Spent fuels of Japanese nuclear power plants will be reprocessed at the Rokkasho Reprocessing Plant. JNFL(Japan Nuclear Fuel Limited) is conducting Probabilistic Risk Assessment (PRA) studies for the Reprocessing Plant with the following aims: (a)Identify vulnerabilities in severe accidents prevention measures, (b)Translating them into specific initiatives for safety improvement and (c)Confirming the extent of risk reduction achieved through measures taken voluntarily. The Japanese regulation for Reprocessing Plants require accident measures to be taken against severe accidents, such as “Loss of cooling function (High Active Liquid Waste(HALW) generated by spent fuel reprocessing have decay heat, and therefore safety cooling water system is used to prevent HALW from boiling in storage tanks.)” and “Loss of Hydrogen Scavenging Function (Hydrogen is generated by radiolysis of the HALW, and therefore, safety compressed air system is used to scavenge hydrogen by supplying compressed air and prevent hydrogen explosions in storage tanks.)” and so on. The loss of cooling function event may involve multiple storage tanks (about 50 tanks) that share safety system equipment. In addition, some safety system facilities are used for both cooling and hydrogen scavenging functions. Therefore, there is a possibility of simultaneous occurrence of severe accidents in multiple storage tanks, as well as simultaneous occurrence of different types of severe accidents. In other words, the PRA model has been developed with focus on accident progression in a single storage tank (representative tank). To identify risk important equipment and operations in terms of risk from severe accidents at the Reprocessing Plant, it is necessary to develop a method that can accurately assess the frequency of severe accidents occurring at multiple storage tanks and with different types of severe accidents (e.g., loss of cooling and loss of hydrogen scavenging). The authors conducted a survey of methods capable of assessing the frequency of simultaneous occurrences involving multiple storage tanks and multiple events. With consideration of the characteristics of the system design and available multi-unit PRA methods, we selected the Multi-unit Event Combinations Approach as a practical evaluation method for the Reprocessing Plant. In addition, the authors are conducting studies to confirm the applicability of the selected method, including trial analyses focusing on the loss of cooling function events in two storage tanks and so on. This paper reports on the progress to date, including the results of the trial analysis.

Keywords: PRA, Multi-Unit, Multi-Event, Reprocessing

1. INTRODUCTION

PRA (Probabilistic Risk Assessment) is an effective method to quantitatively understand the risks associated with nuclear facilities. There are a number of PRA evaluation reports and utilization reports covering nuclear power plants.

On the other hand, there are very few PRA studies focusing on reprocessing plants. The reason could be due to the limited number of reprocessing plants and the differences in facility characteristics between nuclear power plants and reprocessing plants. Examples of the characteristics of reprocessing plants is that risk sources are widely distributed with the facility and consideration of various severe accidents needs to be considered. Therefore, in order to conduct PRAs for reprocessing plants, it is necessary to develop evaluation methods that can take these characteristics into account. In our investigation into PRA methods for reprocessing plants, we examined evaluation methods used for multi-unit nuclear power plants. Various multi-unit PRA methods have been proposed so far, three methods were considered as a candidate method. Among these, we identified Multi-unit Event Combination Approach as the most suitable candidate for PRA evaluation method for reprocessing plants.

In this paper, we report methodology and results of a trial analysis using Multi-unit Event Combination Approach, which we identified as a suitable candidate for the PRA methods for reprocessing plants, and verifide its applicability.

2. Current Status of PRA for Rokkasho Reprocessing Plants

Reprocessing plants handle various types, quantities, and forms of nuclear fuel materials, widely distributed across multiple processes. Consequently, as shown in Figure 1, a wide variety of severe accidents can possibly occur.

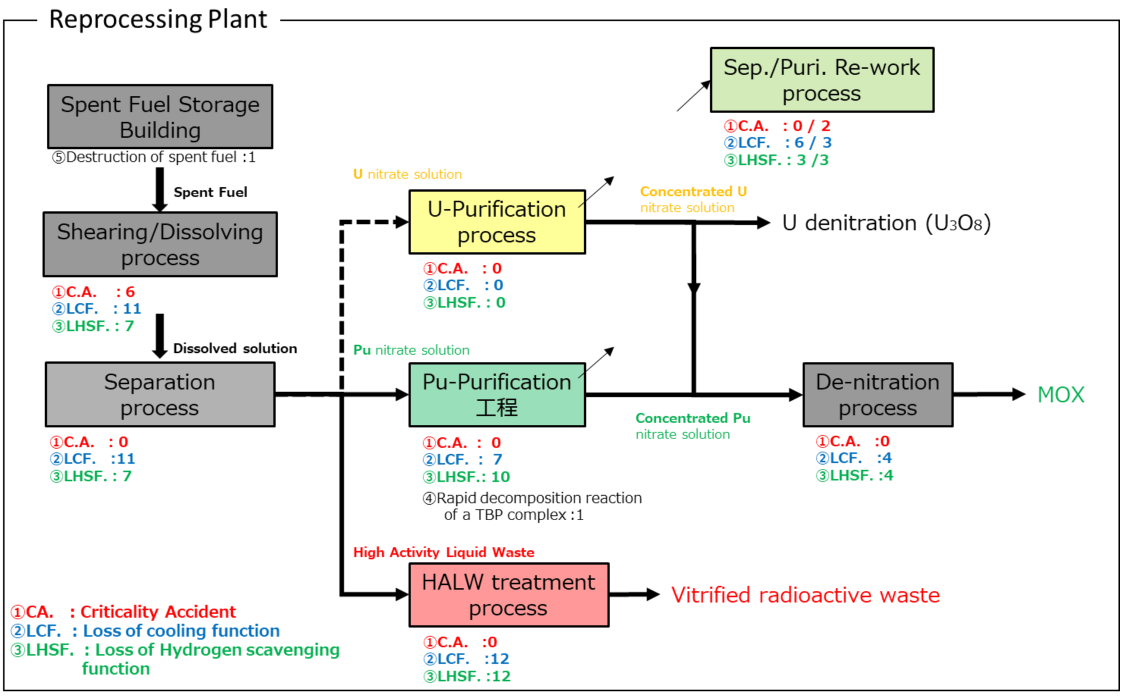

Figure 1. The reprocessing process outline and the number of equipment where severe accidents can occur

We have implemented various safety measures to prevent severe accidents in compliance with regulatory requirements. However, aiming for further safety improvements, we are advancing the development of PRA to identify vulnerabilities related to severe accident countermeasures.

Currently, we are developing internal event PRA models, focusing on severe accidents resulting from the loss of cooling functions and the loss of hydrogen scavenging functions. In this development, we are creating PRA models for each individual tank of which the severe accident can occur. However, since safety equipment related to design basis accidents and severe accidents is shared among multiple tanks, it is necessary to study PRA methods that can evaluate the simultaneous occurrence of multiple severe accidents (multiple events) across multiple tanks.

3. Examination of Evaluation Methods for Multiple tanks and Simultaneous Occurrence of Multiple Severe Accident Events

We investigated the multi-unit PRA methods used in nuclear power plants, and examined which is the most suitable for PRA in reprocessing plants. For multi-unit PRA in nuclear power plants, the following three methods are used as evaluation methods[1].

- Method 1 : Master Event Tree Approach
  This method models accident sequences leading to multiple unit accidents by connecting the event tree of one unit to the end of the event tree of another unit.
- Method 2 : Single Top Fault Tree Approach
  This method converts the accident sequences of each unit into a single fault tree and then combines these fault trees using an AND gate.

- Method 3 : Multi-unit Event Combination Approach
  This method identifies combinations of equipment and so on (multi-unit event) affecting multiple units (multi-unit event scenarios) and calculates the multi-unit accident frequency using the conditional core damage probabilities evaluated from single-unit PRA cutsets. It is a method being developed by Risk Spectrum AB [3,4]. Details of this method are described in section 4.(1).

Figure 2 shows an overview of Method 1 and 2.

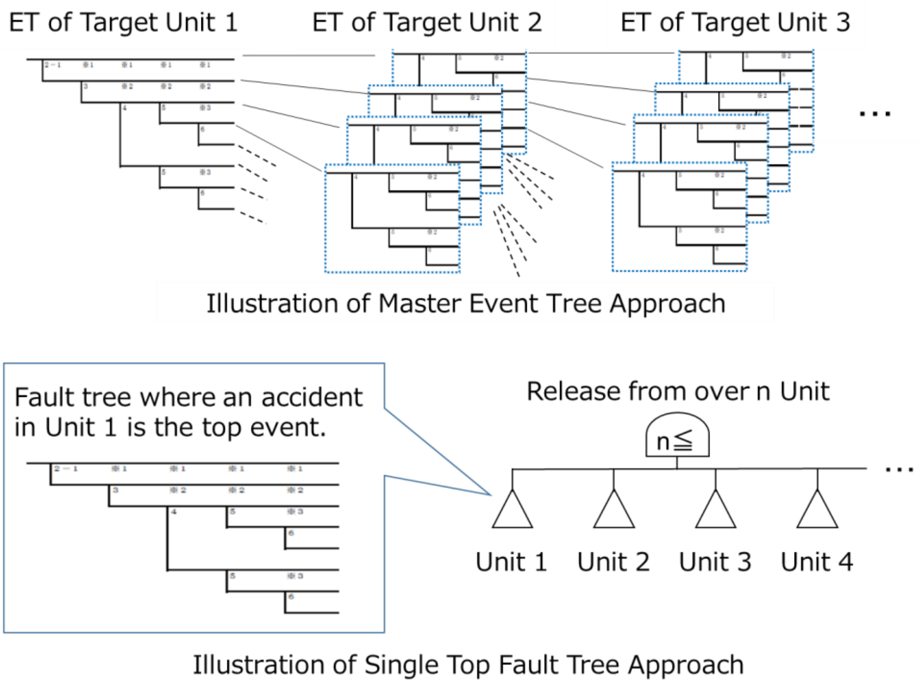

Figure 2. Evaluation Images of Master Event Tree Approach and Single Top Fault Tree Approach

Although, Method 1 and Method 2 have been reported for use in multi-unit nuclear power plants, the following technical issues exist when applying them to multiple tanks and multiple events in reprocessing plants.

Technical issues for method 1 : The number of accident sequences increases exponentially with the increase in the number of tanks and accident events evaluated.

Technical issues for method 2 : The fault tree becomes very large due to the need to connect accident sequence models of each tank as fault trees.

On the other hand, Method 3 does not require the creation or recalculation of event trees and fault trees, and does not require integration of PRA models as in Methods 1 and 2. Therefore, quantification of a large scale integrated model is avoided and the computational load is small. Based on these considerations, we decided to proceed with the examination using Method 3.

4. Overview of Multi-unit Event Combination Approach, application issues for Reprocessing plant and Policy for addressing the issues

(1) Overview of the Evaluation Method

Multi-unit Event Combination Approach is conducted in the following three steps[2]. The calculation image is shown in Figure 3.

- Step 1: Extraction of Multi-unit events Affecting Multiple Tanks and Multiple Events
  Extract multi-unit events from basic events modeled in the PRA, such as failure of external loop pump A shown in Figure 3, is extracted as a multi-unit event because the external loop provides cooling water for two tanks. From the perspective of computational load in quantification, the number of multi-unit events that can be handled is limited.

- Step 2: Identification of Multi-unit event Scenarios from Combinations of Success/Failure of Multi-unit events

  Identify Multi-unit event Scenarios that indicate all possible combinations of multi-unit events and calculate the frequency of each multi-unit event scenario.

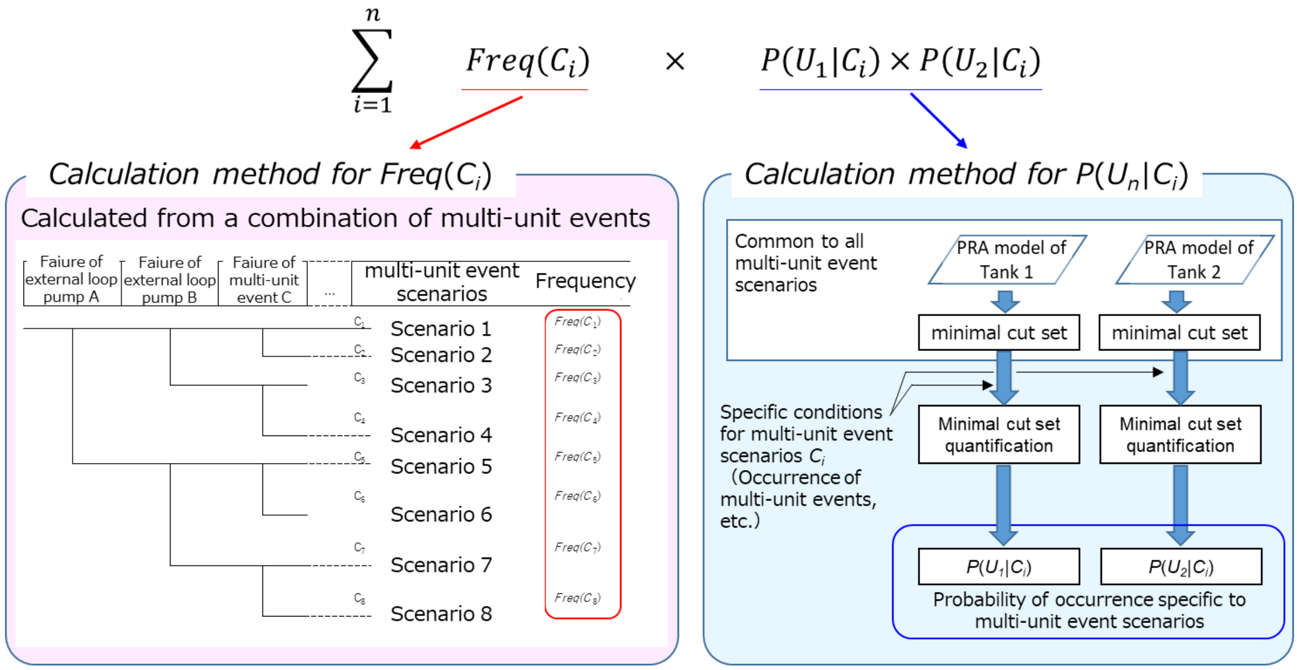

Figure 3. Calculation Image of Step 3 in Multi-unit Event Combination Approach

- Step 3: Quantification of Frequency of simultaneous accidents for Each Multi-unit event Scenario

  For each multi-unit event scenario identified in Step 2, calculate the conditional probability of release given the multi-unit event scenario using the Minimal Cut Sets developed by the PRA of each individual tank. Then, by multiplying the frequency of each multi-unit event scenario and the conditional probability for each tank, calculate the frequency of simultaneous accidents within tanks is quantified occurrence. For example, in the case of two tanks, the simultaneous occurrence frequency of accidents is calculated using the following formula.

$$\sum_{i=1}^{n} Freq(C_i) \times P(U_1|C_i) \times P(U_2|C_i) \quad (1)$$

Where, Freq(Ci) is the Frequency of multi-unit event scenario Ci; P(U1|Ci) is the conditional probability of accident occurrence in tank 1 under the condition of occurrence of multi-unit event scenario Ci; P(U2|Ci) is the conditional probability of accident occurrence in tank 2 under the condition of occurrence of multi-unit event scenario Ci.

(2) Application issues for Reprocessing plants and Policy for addressing the issues

Although application of Multi-unit Event Combination Approach to reprocessing plants as shown in Figure 1 is considered useful, the following issues must be addressed for practical application.

Issue 1: There is a large number of multi-unit events in reprocessing plants compared to nuclear power plants

In nuclear power plants, equipment used for accident mitigation measures are basically installed for each plant. On the other hand, in reprocessing plants, equipment such as those forming the safety cooling water system for decay heat removal are are shared among multiple tanks, and therefore, there are many multi-unit events.

Issue 2: Large Number of Risk Sources (Tanks) have to be evaluated

In multi-unit PRA for nuclear power plants, a few units are subject to evaluation. However, reprocessing plants have much more units of equipment to be evaluated.

Issue 3: Establishment of a Method to Calculate Importance Considering Radiation Exposure Impact

In PRA for nuclear power plants, risk metrics such as core damage frequency and containment failure frequency are generally used. However, in reprocessing plants, there are multiple risk sources, and the impact of radiation exposure on the public in the event of a severe accident varies depending on the event.

Therefore, it is difficult to identify effective safety improvement measures by evaluating only the frequency of each severe accident.

To address the above issues, we consider the following items:

Item 1: Verification of applicability of Multi-unit Event Combination Approach for reprocessing plants (in the case of two tanks)

Item 2: Extended application of the method to cases with more than three tanks

Item 3: Development of methods to evaluated risk importance taking into consideration of radiation exposure impacts

5. Verification of applicability of Multi-unit Event Combination Approach for reprocessing plants (in the case of two tanks)

We conducted a study on Item 1 of the three items listed in section 4.

(1) Target Events for Evaluation

We focus on the following two severe accidents that have common safety equipment as an accident mitigation measure

(a) Loss of Cooling Function in the Safety Cooling Water System

The cooling function prevents boiling of the radioactive solution in the tank heated by to decay heat. If the cooling function is lost, the temperature of the solution increases. When the solution boils, radioactive materials can be transported with steam and released into the atmosphere. The safety cooling water system consists of an internal loop (including the internal loop pump, intermediate heat exchanger, and connecting pipes) and an external loop (including the external loop pump, cooling tower, and connecting pipes). All tanks share the same external loop from the perspective of accidents in multiple tanks. The related equipment configuration is illustrated in Figure 4.

(b) Loss of Hydrogen scavenging Function in the Safety Compressed Air System

The hydrogen generated by the radiolytic decomposition of the radioactive solution in the tank is scavenged to the ventilation system by compressed air. However, if the scavenging function is lost, the hydrogen concentration within the tank increases and may hydrogen explosion. When it occurs, radioactive materials can be released into the atmosphere. The safety compressed air system consists of hydrogen scavenging pipes and valves, and an air compressor that produces compressed air. The air compressor is cooled by the safety cooling water system. The related equipment configuration is illustrated in Figure 4.

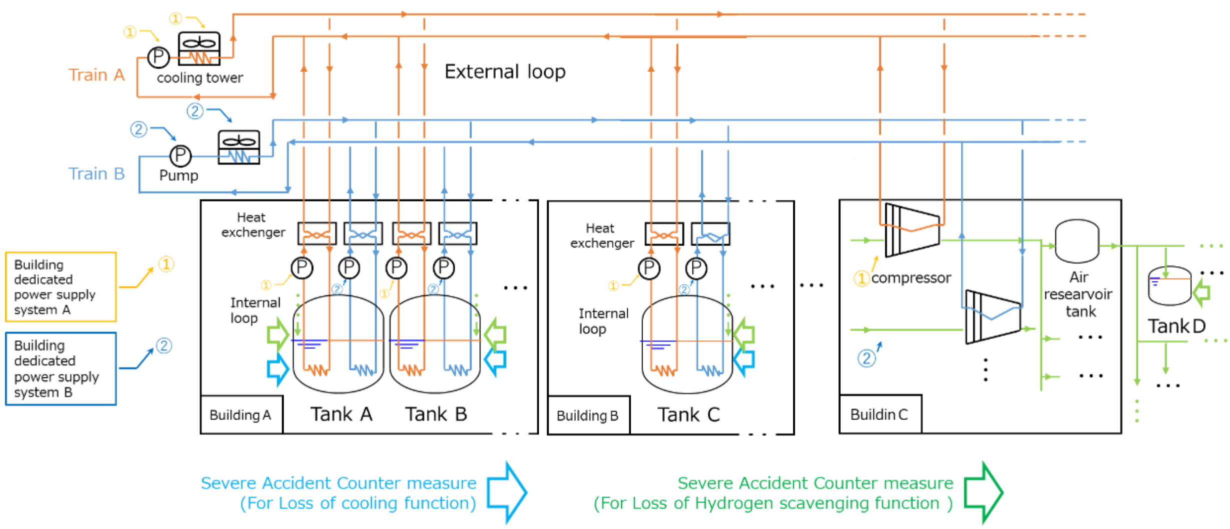

Figure 4. Equipment Related to Loss of Cooling Function and Loss of Hydrogen scavenging Function

(2) Evaluation Cases

To confirm the applicability of the Multi-unit Event Combination Approach to accidents in two tanks, the following two evaluation cases were conducted.

a. Evaluation Case 1

Purpose: To confirm that the frequency simultaneous accident is correctly calculated using the Multi-unit Event Combination Approach.

Event of interest: Loss of cooling function events in the same building (target tanks: Tank A and Tank B in Building A as illustrated in Figure 4.).

b. Evaluation Case 2

Purpose: To understand the sensitivity to the number of multi-unit events.

Event of interest:

Case 2-1: Loss of cooling function events in different buildings (target tanks: Tank A in Building A and Tank C in Building B as illustrated in Figure 4.).

Case 2-2: Loss of cooling function event and loss of hydrogen scavenging function event (target tanks: Tank A (loss of cooling function event) in Building A and Tank C (loss of hydrogen purging function event) in Building B as illustrated in Figure 4.).

(3) Extraction of Multi-unit events

In Multi-unit Event Combination Approach, it is necessary to pre-extract multi-unit events that affect multiple tanks and multiple accident events. In this trial analysis, the following types of multi-unit events were extracted:

- Failure of Common Equipment (e.g. external loop equipment, power supply equipment)
- Common Cause Failures (e.g. internal loop pumps between tanks)
- Dependent Human Error (e.g. refueling operations for portable equipment)

Types of multi-unit events that have been considered for the systems and mitigation measures in Evaluation Case 1 and Evaluation Case 2 are shown in Tables 1 and 2, respectively.

Table 1. Multi-unit event types set for Evaluation Case 1

System or measure*	**Common Equipment**	**Common Cause Failures**	**Dependent Human Error Events**
Internal loop	—	○	—
External loop	○	—	—
Building Power supply system	○	—	—
Severe Accident Countermeasure	○	—	○（complete dependency）

Table 2. Multi-unit event types set for Evaluation Case 2

System or measure*	**Common Equipment**	**Common Cause Failures**	**Dependent Human Error Events**
Internal loop	—	○	—
External loop	○	—	—
Building Power supply system	—	○	—
Severe Accident Countermeasure	—	○	○（partial dependency）

* In practice, extracting multi-unit events is performed at the component failure mode level.

Furthermore, because there is a limit to the number of multi-unit events that can be practically handled using Multi-unit Event Combination Approach, a screening of basic events to be modeled as multi-unit events was conducted through steps in Figure 5. For the criterion of “basic events with relatively high impact” in this flow, “Fussel-Vesely importance (FV) times Risk Achievement Worth (RAW) > 0.01” was used as the final criterion. Details are described in section (6).

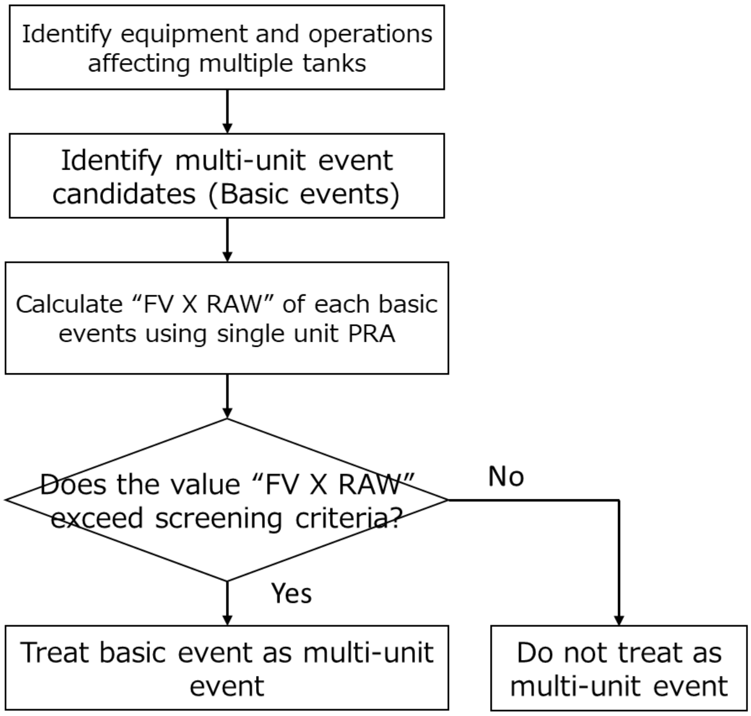

Figure 5. Extraction flow for screening multi-unit basic events

(4) Quantification of Multi-unit event Scenarios

To calculate the frequency of multi-unit event scenarios, it is necessary to set the probabilities of each multi-unit event. The probability of each multi-unit event is calculated as the product of "probability Q of the original basic event used in single unit PRA" and "The dependency parameter β" of the multi-unit event. The concept for setting the probability of each multi-unit event is shown in Table 3.

Table 3. The concept for probability of each multi-unit event

	Q(Probability of the basic event)	**β(The dependency parameter)**
Common Equipment	The probability of the relevant multi-unit event	1
Common Cause Failures	The probability of the relevant multi-unit event	Common Cause Failures parameter （MGL parameters [5]）
Dependent Human Error Events	The human error probability of the relevant multi-unit event	Operation in common building:1 (Treat as complete dependency) Operation in different buildings:0.15 (Treat as partial dependency)

* In this trial analysis, we referred to [6] for establishing common cause failures

(5) Cut Sets used for Conditional Probability evaluation of each tank

To calculate the conditional probability of accident under the occurrence of multi-unit event scenarios for each tank, we used minimal cut sets generated from the individual tank PRA using RiskSpectrum PSA.

(6) Results and Discussion

a. Calculation Results and Discussion for Evaluation Case 1

(a) Calculation Results

The calculation results for Evaluation Case 1 are shown in Table 4.

Table 4. The calculation results for Evaluation Case 1

Consequence	**Ratio to the frequency calculated by RiskSpectrum PSA**
Release from both Tank A and Tank B (simultaneous occurrence)	1.0
Release from Tank A (Tank of concern) [note]	1.0
Release from Tank A (Tank of concern) [note]	1.0

Note: Sum of both single tank failure and multi-tank failure frequencies involving the tank of interest.

(b) Discussion

In this calculation using Multi-unit Event Combination Approach, we were able to calculate the frequency of simultaneous occurrence of two tanks and the frequency of the tank of concern (hereafter, the term " tank of concern" will be used to refer to the specific tank for which the frequency, the sum of multi-tank failure and single tank failure, is calculated using Multi-unit Event Combination Approach) within the range of practical modeling and calculation time.

Furthermore, according to the single tank PRA that we have developed using conventional PRA methods, the dominant cause of the loss of cooling function is the failure of equipment related to the external loop or the equipment. Both equipment is used to maintain cooling function for multiple tanks. This implies that when cooling function to either tank has been lost, it is highly likely that both tanks have lost is cooling function.

Additionally, within multi-unit events extracted by extraction flow (Fig.5), none of the events were related to internal loop (The only difference between Tank A and Tank B). In case 1, all important multi-unit events are related to equipment and operator actions that completely shared, meaning that they rely on the same component or action, between units.

Therefore, in Evaluation Case 1, if the calculated frequency of simultaneous occurrence for two tanks by Multi-unit Event Combination Approach matches the calculated frequency of each individual tank by RiskSpectrum PSA, it can be confirmed that the trial analysis is correct.

The results of the trial analysis and individual tank results obtained from RiskSpectrum PSA showed agreement, and it has been confirmed that the Multi-unit Event Combination Approach can correctly calculate the frequency of simultaneous occurrence.

In the early stages of the study of Evaluation Case 1, it was found that excessively screening out multi-unit events affected the quantitative results (a few percent difference was observed when the results from Multi-unit Event Combination Approach and Riskspectrum PSA were compared).
Therefore, the following three measures were implemented:

Measure-1: Adjustment the screening Criteria for Multi-unit events (FV times RAW)

The screening criteria for multi-unit events, FV times RAW, was gradually lowered from the initial setting to determine the screening criteria at which the evaluation results converge. In this case, it was confirmed that the results converge with an screening criterion of FV times RAW > 0.01. However, the number of multi-unit events extracted after applying this screening was large, and computational load was high in obtaining the calculation results.

Therefore, the following studies were conducted to reduce the computational load.

Measure -2: Integration of Multi-unit events for External Loop

Since the external loop as a whole is common equipment, it can be integrated into a single multi-unit event. By integrating the multi-unit events of the external loop into a single event, we reduced the apparent number of multi-unit events. The concept for improving the evaluation method is shown in Figure 6.

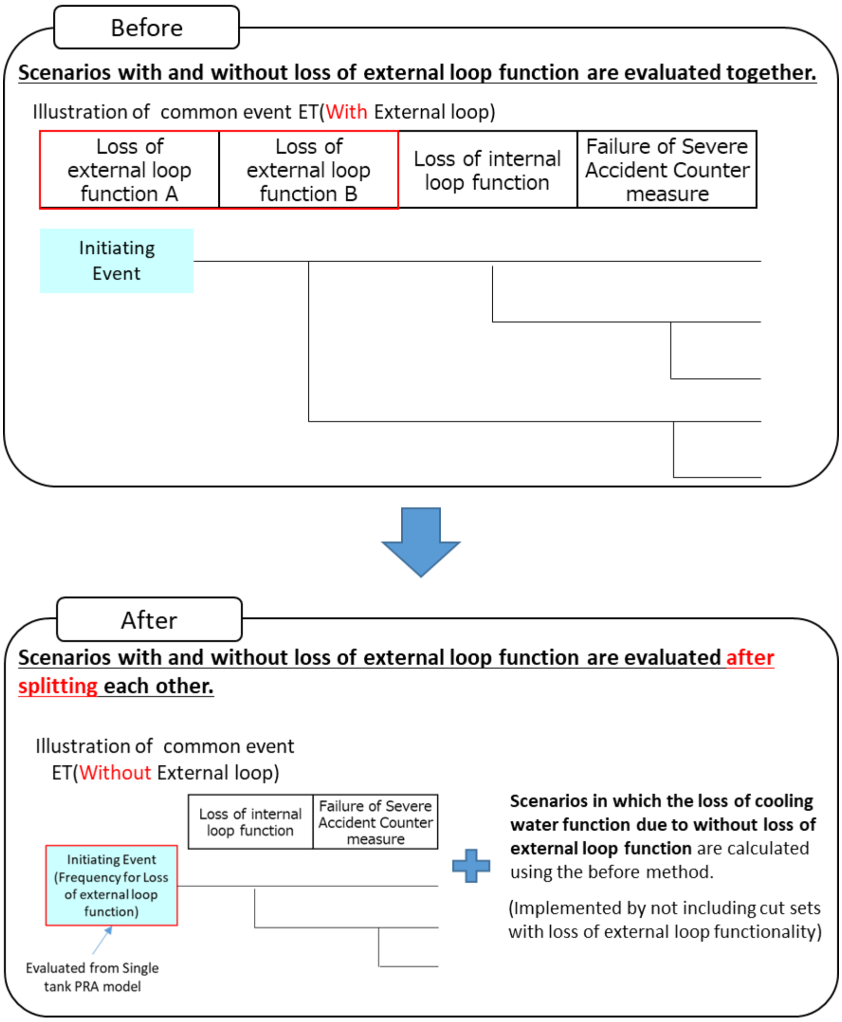

Figure 6. The illustration of integration of Multi-unit events for External Loop

The results of frequency of simultaneous occurrence (after implementing the Measure-1 and Measure-2) are shown in Table 5. As a result, we obtained a value close to that calculated by RiskSpectrum PSA. However, to further improve accuracy, the following measure was implemented:

Table 5. The calculation results for frequency of simultaneous occurrence with changing extraction criterion of FV times RAW

Consequence	**Ratio to the frequency calculated by RiskSpectrum PSA**		
	Screening Criteria for Common Cause Events (FV times RAW)		
	0.1	**0.01**	**0.001**
Release from both Tank A and Tank B (simultaneous occurrence)	0.95	0.99	0.99

Measure-3: Adjustment of the Extraction Criteria for multi-unit event scenarios

In calculating the frequency of multi-unit event scenarios, a certain threshold is used to cut off those scenarios that have a small impact on the overall frequency. As part of further accuracy improvement of the Multi-unit Event Combination Approach, its cut-off value was changed from 1.0E-12 to 1.0E-14. The frequency of simultaneous occurrence with the changed cut-off value is shown in Table 6. As a result, it was confirmed that correct results could be obtained with a threshold value around 1.0E-14.

Table 6. The calculation results for frequency of simultaneous occurrence with changing cut-off value for multi-unit event scenarios

Cut-off value for multi-unit event scenarios	Ratio to the frequency calculated by RiskSpectrum PSA
1.0E-12	0.994
1.0E-13	0.998
1.0E-14	0.999
1.0E-15	0.999

b. Calculation Results and Discussion for Evaluation Case 2

Evaluation case 2 was calculated under the same conditions as evaluation case 1. The evaluation results are shown in Figure 7 together with evaluation case 1.

The ratio of the frequency of simultaneous occurrence decreased in the order of evaluation case 1 and evaluation case 2 (in evaluation case 2, Case 2-1 and Case 2-2), which is considered to reflect the type of accidents occurred depending on the degree of shared mitigation measures.
As a result, we were able to understand the sensitivity to the number of multi-unit events.

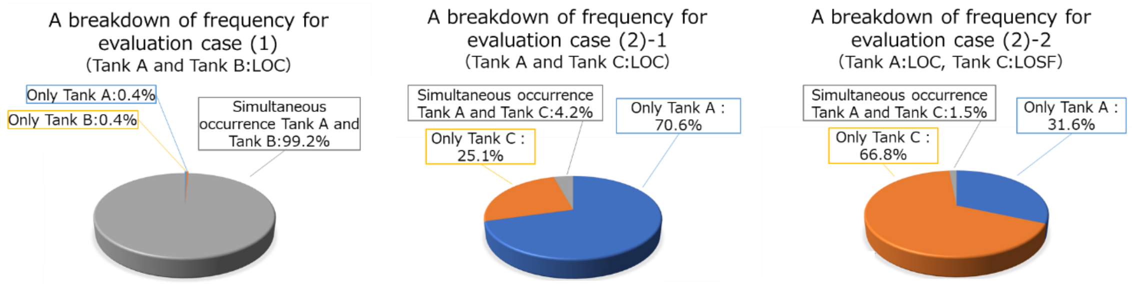

Figure 7. The ratio of the frequency of simultaneous occurrence Evaluation Case 1 and Evaluation Case 2

6. CONCLUSION

In this paper, we investigated the multi-unit PRA methods used in nuclear power plants, and considered the evaluation method most suitable for PRA in reprocessing plants.As a result, we selected Multi-unit Event Combination Approach for PRA in reprocessing plants. In the evaluation using Multi-unit Event Combination Approach, we were able to calculate the frequency of simultaneous occurrence for two tanks with practical amount of modeling effort and calculation time.

Additionally, through the comparison between the evaluation results obtained using Multi-unit Event Combination Approach and RiskSpectrum PSA, it was quantitatively confirmed that Multi-unit Event Combination Approach can accurately evaluate the frequency.Furthermore, the result of Evaluation Case 2 allowed us to understand the sensitivity to the number of multi-unit events.

Moving forward, we will extend the evaluation to three or more tanks and consider the evaluation methods including the risk importance of radiation exposure.

References

[1] IAEA. IAEA Safety Reports series No.110. Multi - unit Probabilistic Safety Assessment, Vienna, 2023.
[2] Jan-Erik Holmberg, Stefan Authén, Kim Björkman, Ola Bäckström, Xuhong He, Salvatore Massaiu, Tero Tyrväinen, NKS-419 Site risk analysis for nuclear installations, Roskilde, Denmark (2019).
[3] O. Bäckström, P. Krcal, X. He, “Use of PSA for small modular reactors”, Proceedings of PSAM 16, Honolulu, USA (2022).
[4] Futoshi Tanaka, Yuki Nakano , Akihiko Endo , Ola Bäckström , Pavel Krcal5, “APPROACH FOR MULTI-UNIT PRA WITH DEPENDENCIES AND ITS APPLICATION TO SEISMIC RISK EVALUATION”, Proceedings of ASRAM2022, Daejeon, Korea (2022).
[5] U.S. Nuclear Regulatory Commission, CCF Parameter Estimations, 2015 Update, (2016).
[6] IAEA. IAEA Safety Reports series No.96. Technical Approach to Probabilistic Safety Assessment for Multiple Reactor Units, Vienna, 2019.