17th International Conference on Probabilistic Safety Assessment and Management &
Asian Symposium on Risk Assessment and Management (PSAM17&ASRAM2024)
7-11 October, 2024, Sendai International Center, Sendai, Miyagi, Japan

Optimization of Initial Value Settings for Human Error Probability in the Analysis Process of Improved Probabilistic Risk Assessment Models

Kenichi Kanda[a*], Kenichi Ihara[a], Hiroki Nakamura[a], Yuki Hirai[a], Takahiro Usui[a], Hitoshi Nojima[a], Satoshi Yoneda[a], Kazunobu Noriyasu[a], Yohei Moriya[a], Daichi Shiota[b], Naoki Hirokawa[b]

[a] The Chugoku Electric Power Co.,Inc., Hiroshima, Japan

[b] Hitachi-GE Nuclear Energy, Ltd., Ibaraki, Japan

Abstract: Since the Fukushima Daiichi Nuclear Power Plant accident, the use of probabilistic risk assessment (PRA) has become popular to improve the safety of nuclear power plants. Each Japanese utility is working on activities to refine and improve their PRA model quality and we are also working on improvement of the PRA model for Shimane Unit 2. As PRA models become more sophisticated, the models tend to become more detailed and the number of basic events tends to increase as the range of equipment considered expands. For this reason, PRA models tend to become bigger and the computational costs for analysis tend to increase. The increased calculation cost causes problems such as longer calculation time and the possibility that the truncation value cannot be set low enough, which may affect the analysis accuracy.
Therefore, we investigated a method to reduce calculation costs and perform analysis more efficiently by optimizing the initial value of the human error probability (HEP) when performing analysis. Our PRA model analysis takes several steps to reflect the dependency of human error. In the previous method, first, we set the initial value of the HEP to 1, and cut sets of all combinations are generated. Next, we perform a process of replacing the corresponding human error combinations from the entire cut set with HEPs that take into account dependency analysis. Ideally, it is desirable to set the initial value of the HEP to 1, but the calculation cost increases because the analysis includes cut sets that are sufficiently smaller than the quantification truncation value that does not affect the analysis. We can also set the initial value of the HEP to a value smaller than 1. However, if the initial value of the HEP is too small, in some cases, many HEPs may be multiplied to a value smaller than the quantification truncation value, and as a result, it may not be considered in the analysis, even though HEP considering dependency analysis is relatively large. Conversely, by setting the initial value of the HEP sufficiently large, combinations of human errors can be included in the analysis results without being smaller than the truncation value. By the initial value of the HEP optimizing, it is possible to set the truncation value low, and expected that more precise analysis results can be obtained.

Keywords: PRA, HEP, probabilistic risk assessment, human error probability

1. INTRODUCTION

Since the accident at the Fukushima Daiichi Nuclear Power Plant following the Great East Japan Earthquake, the use of PRA has been promoted in Japan. Until then, PRA had been used to obtain risk information to improve the nuclear power plants safety, but efforts are being made to improve the PRA model and create a more detailed PRA model. For example, under the new regulatory standards for nuclear reactor installation permits that were reviewed after the Fukushima Daiichi Nuclear Power Plant accident, PRA is now being used to analyze the vulnerability of nuclear power plants when considering severe accident (SA) countermeasures. Therefore, risk information from PRA is to be taken into account when selecting accident sequences for evaluating the effectiveness of SA countermeasures during establishment permission process.

Furthermore, nuclear regulatory inspections are being conducted in Japan that are based on the U.S. nuclear reactor oversight process, and the risk information obtained by PRA is also utilized in the significance determination process. For this reason, in Japan, utilities are working together to improve the PRA model, select pilot plants, and share the knowledge gained from improving the PRA model of the pilot plants with other plants. As PRA models become more sophisticated, new knowledge is incorporated and the models become more detailed, so the models generally tend to become more complex and larger. As a result, the computational cost required to quantify PRA tends to increase. We are also working on improving the PRA model for Unit 2 at the Shimane Nuclear Power Plant, but as the PRA model grows larger, the impact of calculation costs is beginning to appear, and the calculation time becomes longer.

Various approaches can be considered to deal with the computational cost in quantification the PRA model, such as updating the computer specs, and reviewing the modeling. We focused on optimizing the initial HEP settings in the quantification process and considered reducing the calculation load by optimizing them. This report describes the status of PRA model improvement, the influence of the initial value of the HEP, the introduction to several optimizing method and the results of optimizing the initial value of the HEP.

2. PRA MODEL IMPROVEMENT

2.1. Status of PRA Model Improvement for Shimane Unit 2

In Japan, each plant is working to improve the PRA model in order to further develop the use of risk information, such as using it for new nuclear regulatory inspections after the plant restarts. At Shimane Unit 2, we are also working to improve the PRA model, to make it compliant with the ASME/ANS PRA standard (ASME/ANS 2013) [1] requirement (Capability Category II), which is the standard for PRA models used for risk information in the United States.

As mentioned in the previous report about improving the PRA model for Shimane Unit 2 [2], we are working on expanding the number of initiating events, making the fault tree more detailed, and updating component failure rate data. An overview of Shimane Unit 2 is as follows:
- Reactor type: BWR-5 with Improved Mark I containment
- Rated power output: 820MWe
- Beginning of operation: February 1989

In addition, Shimane Unit 2 has been enhanced with safety measures such as SA countermeasure equipment in order to comply with new regulatory standards, and these are also reflected in the model. Examples of newly installed SA countermeasure are shown in Table 1. Overviews of SA measures are shown in Figure 1.

Table 1. Examples of SA facilities

Function	Facility
Core cooling function	Built-in alternative injection system (high pressure and low pressure)
	Mobile equipment (alternative injection)
Containment vessel heat removal function	Filtered Containment Venting System (FCVS)
	Alternate Containment Spray System (ACSS)
	Alternate Pedestal Flooding System (APFS)
	Residual Heat Alternate Removal system (RHAR)
	Mobile equipment (alternative heat exchanger)
Safety function support functions	Gas turbine generator: Alternate Emergency Power Facility (AEPF)
	Extended DC power supply
	Mobile equipment (AC generator)
Abnormality prevention function	Tsunami protection wall (15m above sea level)
Others	Emergency response facility

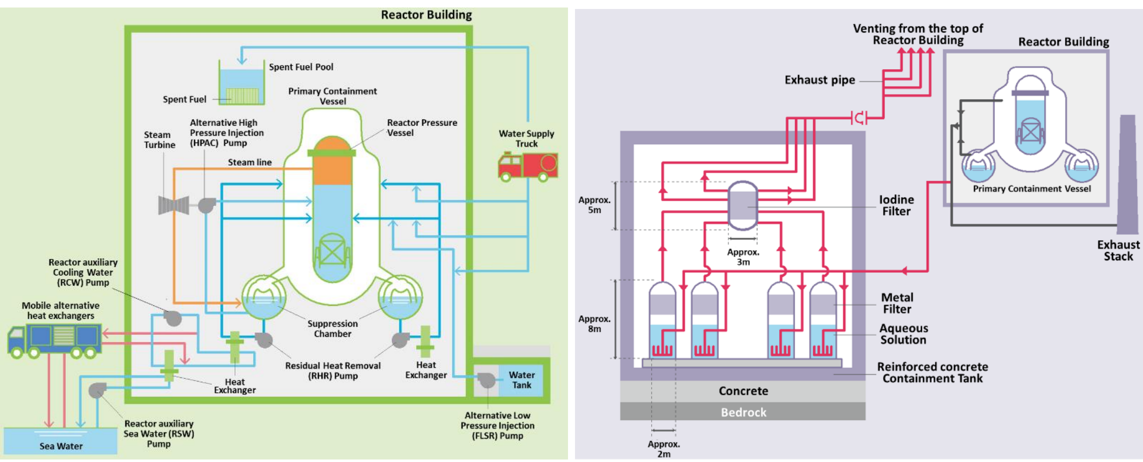

Figure 1. Overviews of SA measures in Shimane Unit 2. Left figure shows an overview of alternative injection systems, and right figure shows FCVS

2.2. PRA Model Overview

The internal event at power PRA model for Shimane Unit 2 is built by using the linking Event Tree (ET) - Fault Tree (FT) method, and the minimal cut set approach is used as the quantification method. ET is a tree diagram that represents the progress of an event in terms of success or failure of mitigation functions. And, FT is a graph in which failures of each mitigation function are set as top gates and are expressed by combinations of basic events that cause the failures. Figure 2 shows images of ET and FT. The linking ET-FT method is a method that gives the failure probability of each branch of an event tree using a linked FT.

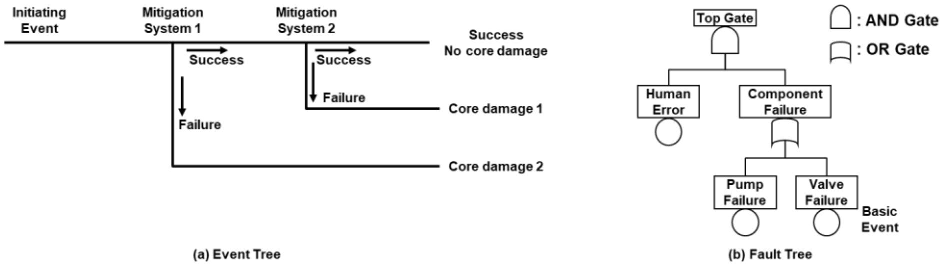

Figure 2. Image of Event Tree and Fault Tree

There are several options for solving the ET-FT, such as the Binary Decision Diagram (BDD) and the minimal cut set method. We have adopted the minimal cut set method, which extracts possible combinations of basic events and applies numerical values to them. Because of this, the number of combinations becomes enormous, and truncation settings are required for the quantification process.

As mentioned in 2.1, we are currently improving the PRA model to make it more detailed. As the model becomes more detailed, the number of initiating events and basic events contained in the model increases, and the FT becomes more complex. As a result, it becomes necessary to consider a large number of combinations of initiating event and basic events through the quantification process, which tends to increase calculation steps and required memory capacity. Usually in minimal cut set approach, truncation values are adopted for quantification process and those values are adjusted so that quantification can be performed with the necessary level of detail. If the truncation value is set low, more combinations of initiating event and basic events can be considered and the accuracy of quantification improves, but on the other hand, the computational load increases. The initial value of HEP is one of the condition settings for quantification, and it also affects the accuracy of quantification and calculation load. The details of the quantification process including the extract of the combination of Human Failure Events (HFEs) are described in the next chapter.

3. QUANTIFICATION PROCESS

The minimal cut set method generates a combination of initiating event and basic events called a cut set for the PRA model modeled by ET and FT, substitutes a numerical value such as component failure rate for each basic event and calculates the frequency of occurrence for the cut set. Then, the total core damage frequency is calculated by merging the cut set values.

In ASME/ANS PRA standard, the dependency in HFEs is required to be considered if multiple HFEs affect in the same accident sequence. The quantification of Shimane Unit 2 PRA model takes into account the dependency in human errors in combination. The dependency in human errors is a property in which multiple, related human responses are affected by the success or failure of the previous response. For example, when you carry out a similar response multiple times and the first response fails, it is assumed that the probability of the failure for the subsequent responses will become higher.

The dependency between HFEs in the quantification process is considered in the following two steps. First, the PRA model is quantified and the cut sets are generated as combinations of initiating event and basic events. Next, combination of human errors with dependencies is analyzed and replaced with a certain basic event that has HEP with taking dependencies into account. As a result, for a combination of human errors that have dependencies, the original multiplication of individual HEPs is replaced with one joint HEP (JHEP) that takes dependencies into consideration. The equation below shows how two HEPs with dependencies are replaced with one JHEP that takes dependencies into consideration.

$$HEP1 * HEP2 \rightarrow JHEP\ 1 \tag{1}$$

After that, the frequencies of occurrence for each cut set are added up to obtain the desired result. Regarding the consideration of dependency in combinations of human errors, we separately conducted the dependency analysis. In actual quantification, the quantification model for initial combination identification, such as HFE combination identification and JHEP analysis, and practical quantification for obtaining final results are calculated separately. First, HFE identification and JHEP evaluation are performed using a specific truncation value to construct a dependency rule. In practical quantification, a suitable initial value of HEP is applied to generate a cut set, and a previously constructed dependency rule is applied to obtain the cut set occurrence frequency with HFE dependency taken into account. Figure 3 shows an image of the quantification process.

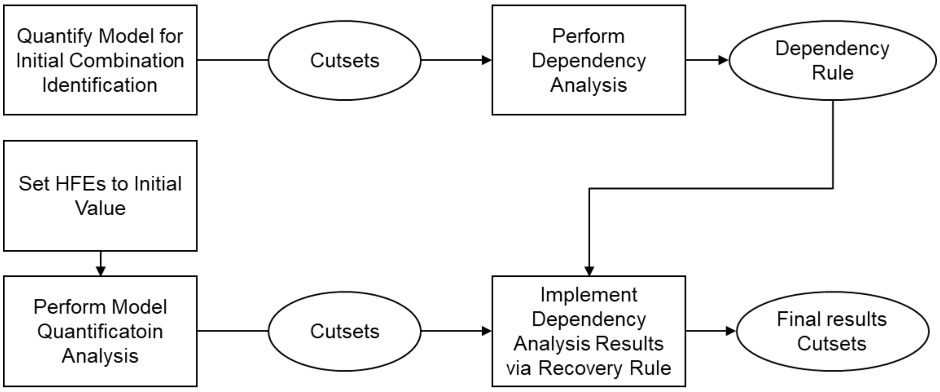

Figure 3. Image of quantification process

In the previous quantification process for the improved PRA model of Shimane Unit 2, the probability of the basic event for human error was set to 1.0 as a initial value of the HEP so that all the combinations in HFEs weren't truncated in the initial quantification. In the quantification process using minimal cut set approach, cut sets which are smaller than the truncation value are excluded and no longer considered in the quantification. In general, JHEP becomes greater than the product of the individual HEPs. The relationship between two HEPs with some dependency level (not individual) and one JHEP is expressed as follows.

$$JHEP1 > HEP1 * HEP2 \tag{2}$$

For example, if each HEP has a probability as HEP1 = 1.0E-3 and HEP2 = 1.0E-4, then if these events are independent, the probability for the combination (JHEP1) is HEP1*HEP2 =1.0E-7. But if there is a dependency between two HFEs, it is assumed that the human error in the earlier step affects the human error in the later step, and JHEP becomes larger than a simple multiplication (i.e. JHEP1 might become larger than 1.0E-7, such as 5.0E-4 in this case). Actually JHEP is calculated with considering the dependency levels between HFEs through the dependency analysis by using HRA Calculator of Electric Power Research Institute (EPRI).

If the individual HEP is set small when performing initial quantification for generating cut sets, cut set values before replacing with JHEP will be smaller than the truncation limit due to the multiplication of HEPs, and some part of the cut sets which should be included in the final quantification result could be excluded. Figure 4 shows an image of excluding cut sets by truncation.

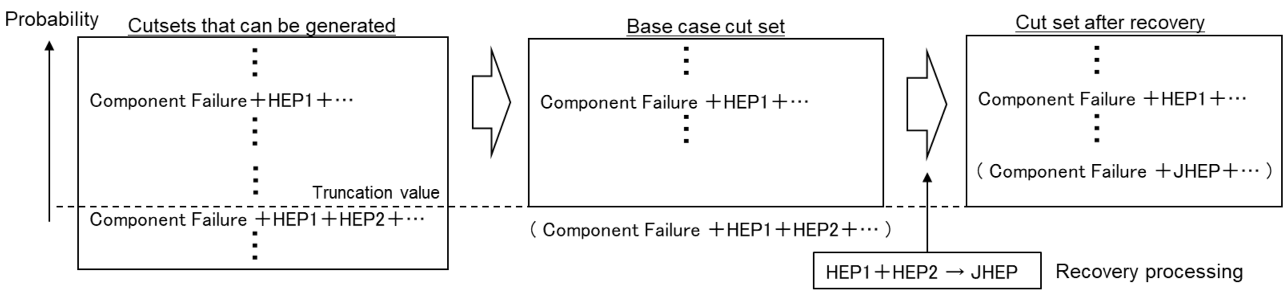

Figure 4. Image of cut set exclusion

Therefore, in the first quantification of the quantification flow shown at the bottom in Figure 3, the HEP is set to 1.0 to ensure that no cut set is excluded in the quantification process. However, in this method, the calculation process is executed with including large number of cut sets that eventually become smaller than the truncation value in the final result (after applying the dependency rule). Those cut sets do not affect the quantification result and do not cause significant increase in the calculation cost. If the initial value for HEP, which is called seed value, can be set as low as possible with an extent that it does not affect the final result, we can reduce the calculation cost.

4. IMPACT OF INITIAL HEP ON QUANTIFICATION

4.1. Initial HEP and Number of Cut Sets

Here we describe the results of confirming the influence of initial values of the HEP on the quantification of the PRA model. Figure 5 shows the number of cut sets when changing the initial value of the dependent HEP using the improved PRA model of Shimane Unit 2.

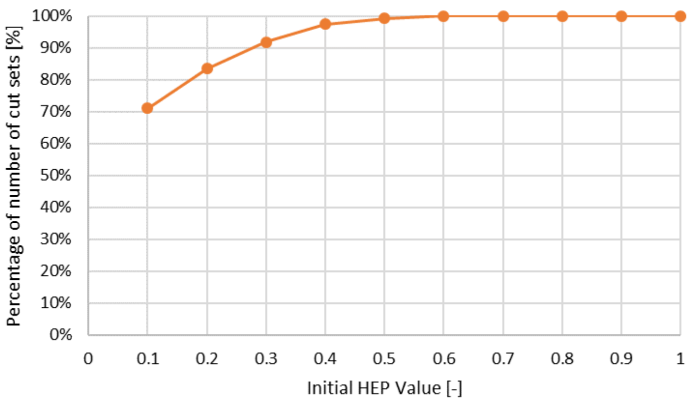

Figure 5. Change in cut set number ratio with respect to change in the initial value of the HEP

Quantification was performed using a laptop PC with a truncation value of 1.0E-11, and the core damage frequency (CDF) is 8.65E-07. The initial HEP was set uniformly for the target human error basic event and varied. The PRA model scope used for quantification is internal event level 1, and the number of basic events is approximately 6500.

In Figure 5, the number of cut sets in the final quantification with setting the initial HEP to 1.0 is as 100%, and the vertical axis shows the ratio of the number of cut sets in the quantification result for each initial value of the HEP as an index. It can be seen that as the initial value of the HEP is decreased, the number of cut sets decreases from a certain value. It was confirmed that the number of cut sets decreased when the initial value of the HEP was set to 0.6, so the number of cut sets equivalent to the final quantification result could be maintained up to 0.7 if we want to have the complete HFE combination without any exclusion.

By reducing the individual HEP, the calculated value of the cut set that includes many human errors becomes smaller than the truncation value in the initial quantification, and is excluded during the quantification process.

4.2. Initial HEP and Calculation Time

Next, Figure 6 shows the changes in calculation time when varying the initial HEP using the improved PRA model of Shimane Unit 2.

Quantification was performed under the same conditions as described in 4.1. The calculation time for the final quantification results when 1.0 is used for the initial HEP is approximately 140 minutes, and it can be confirmed that the calculation time becomes short as the lower initial value of the HEP is used. As shown in the evaluation results in Section 4.1, when the initial value of the HEP is set to 0.7, the same quantification results as when the initial value of the HEP is set to 1.0 can be obtained. Therefore, it was confirmed that by setting the initial value of the HEP to 0.7, the calculation cost could be reduced while maintaining the quality of quantification in this PRA model.

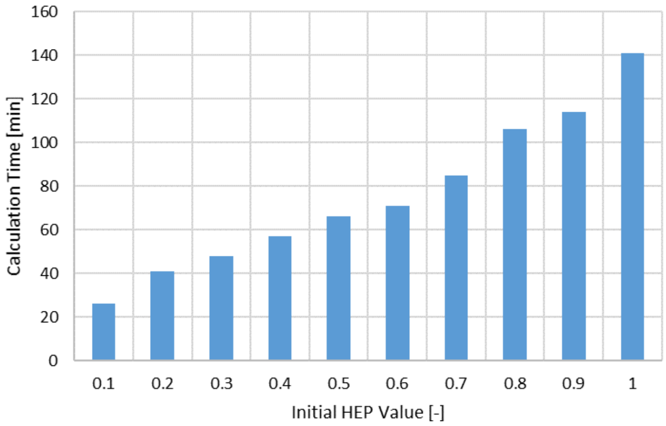

Figure 6. Change in calculation time due to change in the initial value of the HEP

We have shown the evaluation results when initial values of HEP for dependency analysis subject are uniformly changed. In the actual quantification, initial values can be set for each HEP individually, and can be optimized. In other words, some initial HEPs needs to be larger values, and others can be smaller values.

4.3. Reducing Calculation Costs by Optimizing Initial HEP

As shown in the methodology explained earlier and in the previous chapter, here we show the results of optimization without missing cut sets. We individually varied the initial values of the HEP of dependent human errors and confirmed their effects on calculation time. The evaluation results are shown in Figure 7.

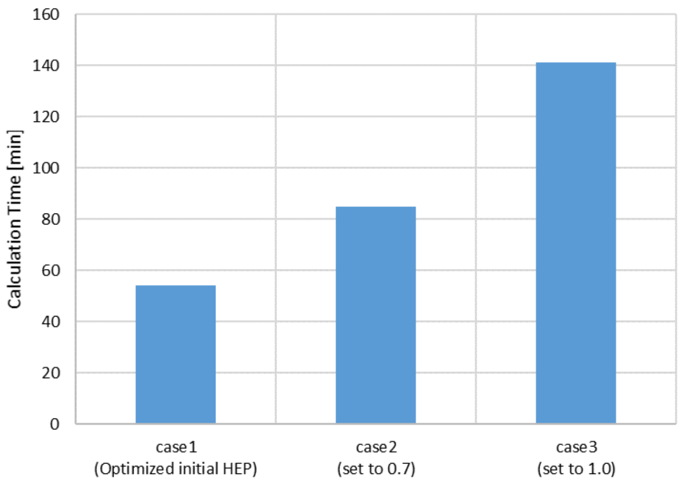

Figure 7. Change in calculation time due to the initial value of the HEP

Quantification was performed under the same conditions as described in 4.1. Figure 7 shows the change in calculation time when the initial value of the HEP is made smaller so that the number of cut sets does not decrease compared to when the initial value of the HEP is set to 1.0. When setting the same value across the board, the initial value of the HEP can be lowered to 0.7, and as the initial value of the HEP is further lowered, the analysis time is also reduced. This is similar to the result shown in Figure 6. Case 1 in Figure 7 means that the initial values of the HEP are optimized individually, and the calculation time can be further reduced while maintaining the number of cut sets.

Here, we will describe the process of manually optimizing the initial values of HEPs. First, the initial value of the HEP is set to 1.0, and the cut set is obtained by quantifying it. Next, the initial value of the HEP is set to 0.95, and quantification is performed to obtain the cut set. Then, compare all cut sets when the initial value of HEP is 1.0 and all cut sets when the initial value of HEP is 0.95. And we check the cut sets that are not included in the quantification results when the initial value of HEP is set to 0.95. Then check whether the dependencies of those cut sets include the combination of human errors considered. If a combination of human errors for which dependency is considered is not included, the initial value of the HEP is set to 0.05 smaller and quantification is performed. If a combination of human errors for which dependency is considered is included, the initial value of the relevant human error is set to the value before change (in this example, it is 1.0), and the other HEPs are set to 0.05 smaller. And, quantification is performed by setting values. Then repeat this until the initial HEP setting becomes smaller. A flow diagram is shown in Figure 8.

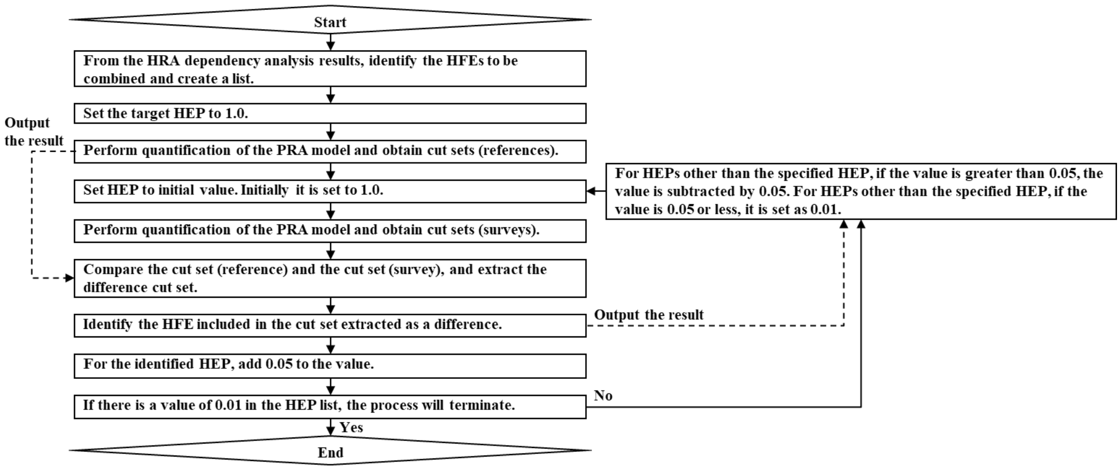

Figure 8. Optimization flow to gradually reduce the initial value of HEP

Figure 9 shows the changes in the time required for quantification and the quantification cut sets yield when the initial value of the HEP is changed uniformly and is changed individually. The graph when the initial value of the HEP is uniformly changed is represented by orange dots and lines.

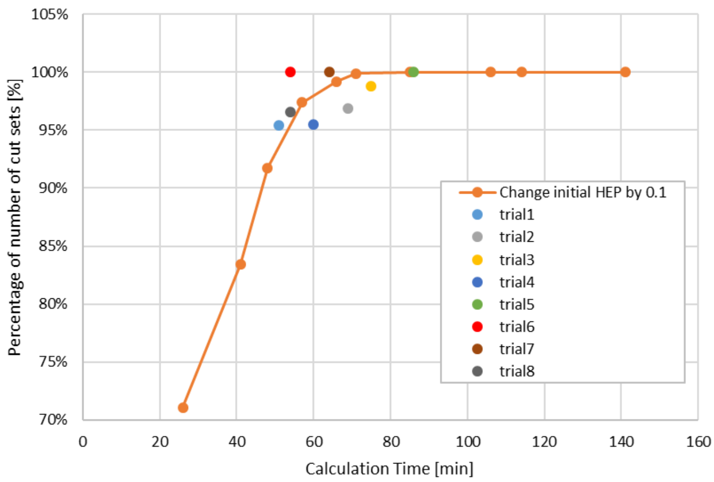

Figure 9. Quantification results when optimizing the initial value of the HEP individually

Among these, there are points located below the orange line and points located above it. This can be interpreted to mean that those at the top are able to obtain more detailed quantification results with less computational cost than when changing values uniformly, and we can say that they are successful in adjusting parameters individually. Here, the red point has the shortest calculation time among them, and the cut set yield is 100%. This is the quantification result when using the initial HEP set obtained as a result of optimization using the flow shown in Figure 8 above, and can be said to be the most successful example of optimization. Also, some points are located below the orange line, which results in longer calculation time and worse cut set yield than if the values were changed uniformly. This indicates the possibility that the quantification results may deteriorate depending on the optimization method.

4.4. Change in Calculation Load

Here, time-series changes in memory usage are shown as the computational load during analysis. Figure 10 shows the change in memory usage when the initial value of HEP was set to 1.0 and 0.7. The analysis tool used to quantify this PRA model has a method to perform parallel processing using multiple processes according to the number of the computer cores, and the analysis is performed with memory utilization almost at its maximum. Although no significant difference was observed in the change in peak value of memory usage due to the setting of the initial value of the HEP, it was confirmed that the calculation load appeared as a difference in the duration of the high load state. We can confirm the difference in load peaks by lowering the truncation value for quantification and using a higher-performance computer.

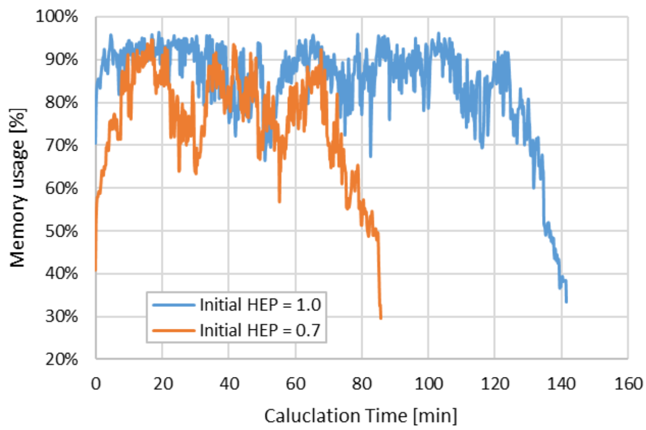

Figure 10. Changes in memory usage

5. CONSIDERATION OF AUTOMATIC OPTIMIZATION

In the analysis in 4.3, the initial values of the HEP were adjusted manually, but we are also considering reading the cut set file using spreadsheet tool and automatically evaluating the initial values of the HEP using automatic processing. Ideas regarding this are discussed in this section.

Note that all of the processes described below are methods that use the results of quantification with HEP set to 1.0 as a reference. If we have the HEP dependency analysis results, it seems possible to algebraically obtain the optimal value from the relationship between the HEP combination and the dependent HEP value. However, in the current quantification process, various factors can be considered, such as recovery processing that replaces values of basic events etc. during the process. Therefore, we think that it is difficult to obtain the optimal values just by solving simple JHEP combinations.

5.1. Optimization Method to Gradually Reduce the Initial Value of the HEP

A possible method is to automate optimization using the manually performed optimization process described in 4.3. The optimization process is as shown in the processing flow shown in Figure 8, and the first half of the flow can be automated. Specifically, the steps are loading HFE dependency analysis results, identifying and list HFEs subject to dependency analysis, and setting the initial value of HEP and outputting a text file for HEP settings to be read in quantification. These can be automated using spreadsheet tools. The process as shown in Figure 8 includes quantification iterations, and it may be possible to automate the iteration process by calling up and executing the PRA analysis tool, but there are some issues that need to be resolved, such as converting a cut set output file unique to an analysis tool into a format that can be read by a spreadsheet tool.

5.2. Optimization Method by Analyzing Dependency Analysis Results

If the method described in 4.3 is used, it is necessary to perform quantification multiple times, resulting in a large workload for optimization. Therefore, we considered the following method to optimize the initial value of the HEP by analyzing the dependency analysis results. This optimization process is shown in Figure 11.

(1) Read the HRA dependency analysis results, identify and list the HEPs to be optimized.
(2) Set the HEP to be optimized to 1.0, perform quantification, and obtain a cut set to be used as a reference.
(3) The value Pd for an independent event without consideration of dependency is set in the target HEP.
(4) For the combination of HEPs in the dependency analysis results, calculate the candidate initial HEP value Pc=(JHEP)^(1/n) from the number of HEPs included in the combination (n) and JHEP. Pc is calculated for each HFE combination, and the maximum value is selected for each HEP. The maximum value for each HEP is defined as Pcm. Then, for HEP where Pcm>Pd, the initial value of HEP is set to Pcm.
(5) Quantify using the generated optimized initial values of the HEP and generate a cut set for the survey.
(6) Compare the reference cut set generated with the initial value of the HEP of 1.0 and the survey cut set generated using the optimized initial value of the HEP, and extract the difference cut set.

(7) When the difference cut sets are extracted, extract the combinations of HFEs included in those cut sets, and calculate a revised candidate Pc2 considering the number of HFEs in the extracted cut sets (m) by using the following equation: Pc2=(JHEP)^(1/m). Then among the obtained candidate values, the maximum value satisfying Pc2>Pcm is replaced in the list of initial values of HEP.
(8) Quantify the PRA model using the updated list of the initial value of the HEP, and end the process when there is no difference between the obtained cut set and the reference cut set.

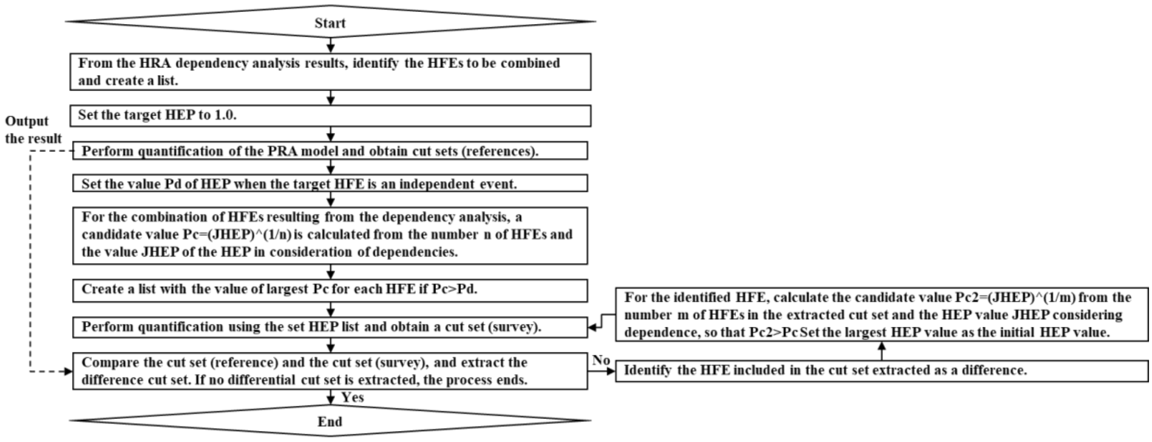

Figure 11. Optimization flow by analyzing dependency analysis results

In this process, first, the value of JHEP that takes into account the dependency included in the result of dependency analysis and the power root obtained from the order of the combination of HEP are set as candidate values for the initial HEP and quantified. With the initial HEP set as this first step, results almost equivalent to the quantification results when the initial HEP is set to 1.0 can be obtained in our PRA model. Comparison with the reference cut set, which is carried out as the next step, is a process of picking out combinations of HEPs that are below the truncation value to check for omissions. The cut set yield is approximately 97% by quantification using the initial HEP settings set as the first step, and the calculation time was approximately 38% of the time when all initial values of HEP were set to 1.0. Therefore, it can be said that the initial HEP settings that obtain almost all the cut sets in the first step of initial HEP optimization have been made. Furthermore, the CDF value was about 99% of that when quantification was performed using the final set of initial HEPs, and results with almost no difference. By going through all the steps including the flow on the right side of Figure 11, the cut set yield was achieved at 100%.

5.3. Results of Automatic Optimization Processing

This time, we used a spreadsheet tool to implement the automation of the process in 5.2. However, what was targeted for automation was the splitting and optimization of HEP parameters using a spreadsheet tool, output as a text file, etc., and the quantification of the PRA model was performed as a separate task using a other PRA analysis tool. The time required to automate HEP optimization using a spreadsheet tool was only a few minutes. In Table 2, the initial value of HEP after optimization by automated processing explained in Section 5.2 were shown, with the initial value HEP obtained in process 5.1 as a reference.

Table 2. Example of optimization results for initial values of HEP

HFE	Independent probability	5.1 Process	5.2 Process
Failure to manually depressurize reactor and ensure/initiate subsequent low pressure injection short term	8.83E-03	0.5	0.47
Failure to feeding water to CST	1.00E-01	0.05	0.22
Failure to feeding water to hotwell	1.00E-01	0.5	0.48
Failure to manually bypass turbine exhaust pressure high trip signal for RCIC continuous operation in SBO	1.00E-01	0.01	0.16
Failure to switch water source from CST to S/P	1.00E-01	0.01	0.1

From the results in the table, the initial value of the HEP is updated to a value different from the independent probability value in both processes 5.1 and 5.2. We confirmed which HEPs should be set larger than the independent probability and which HEPs can be set smaller. It can also be confirmed that there are differences in the values reached by each process. In addition, in the process shown in 5.1, it is necessary to quantify the PRA model every time the initial value of the HEP candidates are updated and compare them with the reference. In the process shown in 5.2, optimization is possible with at most one quantification, so there is an advantage that optimization can be performed in a shorter time with low calculation cost overall.

5.4. Optimization of Truncation Values in Quantification

There is a trade-off relationship between the initial value of HEP and the quantification truncation value in terms of computational cost. Therefore, if the initial value of HEP can be optimized, the truncation value can be further lowered and more detailed analysis results can be obtained under the same computing environment.

For example, when quantifying a highly sophisticated and large-scale PRA model using the laptop PC in this time, with an initial HEP of 1.0, the lower limit of the quantification truncation value was 1.0E-12. When the truncation value was set to 1.0E-13, it could not be calculated due to a processing error. However, by optimizing the initial HEP, it may be possible to perform quantification with a further lower truncation value with the same laptop PC without any cut set drop off. Until now, it was necessary to procure a high-performance computer to further reduce the truncation value, but by adjusting the initial HEP settings, there is an option to eliminate the need to replace the computer. This method can contribute to the appropriate computer performance selection for quantification, procurement costs reduction, and cost optimization.

Recently, as the modeling scope has expanded and the failure rate has decreased due to technological developments, it has become necessary to handle a large number of cut sets with small value in the quantification of PRA models. From this perspective, initial HEP optimization will be an effective technique.

6. CONCLUSION

In this report, we focused on the initial value of the dependent HEP in the quantification of the improved PRA model, evaluated its influence on the quantification and confirmed the results. If the initial HEPs are set large, the values of the intermediate cut sets can be made larger than the truncation value of quantification, and we can ensure a large number of cut sets resulting from the final quantification. On the other hand, we confirmed that because the number of cut sets handled in the quantification process increases, the computational cost required for quantification, such as computational time, increases. We also demonstrated a method for individually optimizing the initial value of the HEP, and confirmed that optimization can reduce computational costs to quantify it. We also described a method for automatically optimizing the initial value of the dependent HEP using a spreadsheet tool. A future topic for consideration is a method to perform optimization without using the results with an initial value of the HEP of 1.0. Currently, in order to optimize the initial value of HEP so that no cut set is dropped at a certain truncation value, a cut sets generated with HEP=1.0 is required. In the future, we would like to consider how to apply this initial value of HEP optimization process to the quantification at low truncation values where a cut set cannot be obtained with initial HEP = 1.0. In addition to that, we also would like to consider the method to identify undefined HFE combinations by applying this process. Furthermore, there are various existing related studies [3] [4], and we would like to conduct comparative studies in future research.

References

[1] The American Society of Mechanical Engineers/American Nuclear Society. Addenda to ASME/ANS RA-S-2008 Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-Sb-2013, 2013.

[2] Y.Moriya et.al. Development of advanced PRA model for Shimane Unit 2 internal event at-power, Mechanical Engineering Journal/Volume 11 (2024) Issue 2, 2024.

[3] Zhiping Li et.al. Insights and Lessons Learned in HRA Dependency Analysis with RISKMAN PRA Model, 18th International Probabilistic Safety Assessment and Analysis (PSA 2023), Pages 470-474, July 15-20, 2023

[4] Jung, W. S. et.al. How to incorporate human failure event recovery into minimal cut set generation stage for efficient probabilistic safety assessments of nuclear power plants, Nuclear Engineering and Technology, 54(1), 110-116, 2022