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Dynamic scenario quantification based on continuous Markov Monte Carlo method with meta-model of thermal hydraulics for level 2 PSA

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Abstract

We have established a dynamic scenario quantification method based on the coupling of a Continuous Markov Monte Carlo (CMMC) method and a plant thermal-hydraulics analysis code for level 2 PSA (probabilistic safety assessment). This paper presents meta-analysis coupling model to obtain the dynamic scenario quantification with a reasonable computational cost. The PLOHS (protected-loss-of-heat-sink) accident of a liquid sodium fast reactor is selected as the level 2 PSA scenario in the model. Furthermore, we also discuss categorizing methods of the quantification result because the coupling method differs widely from existing event tree method.

1. Introduction

PSA (probabilistic safety assessment) is a tool to quantify risk for nuclear power plants (NPP). It quantifies event probability and influence in all possible accident scenarios. PSA is classified by phase of assessment into: level 1 PSA (quantification of core damage frequency), level 2 PSA (quantification of source terms), and level 3 PSA (quantification of off-site consequences). In this paper, accident scenario quantification is focused on level 2 PSA.

A PLOHS (protected-loss-of-heat-sink) accident is one of the most severe accidents in Liquid Metal Fast Breeder Reactors (LMFBR). In LMFBR plants (see Fig. 1), Auxiliary Cooling Systems (ACS) have the role of heat removal sources, because LMFBRs have great ability of natural circulation by using high temperature liquid metal as coolant. However, ACSs failure after a scram can lead to a severe accident. A PLOHS severe accident scenario proceeds in the following sequence; 1) heat removal sources are lost after a scram, 2) temperature and pressure increase slowly in fuel and coolant boundary structures, 3) fuel damage and coolant boundary failure(s) occur by high temperature and pressure, 4) fission products (FP) are released into the outside with the leaked coolant. In PLOHS accidents, there are two major FP release scenarios; containment vessel failure (CV-Failure) scenarios and containment vessel bypass (CV-bypass) scenarios. CV-Failure scenarios occur when both primary-loop and containment vessel fail. Especially in LMFBRs, alkali metals such as sodium and lithium, are often used as coolant and they are highly reactive with concrete in containment vessel. Therefore there is a possibility of primary-loop failure and coolant leakage causing containment vessel failure. CV-bypass scenarios occur when both IHX and secondary-loop fail. In the CV-bypass scenarios, radioactive coolant of the primary-loop can leak into the outside of the plant without CV-Failure.

In the level 2 PSA of NPPs, event tree approach is generally used to quantify accident progression scenarios. In a PLOHS accident, the failure probability of each component increases slowly with increase of temperature. Subsequent events are determined probabilistically according to plant status and some events impact on subsequent events. As a result, there are various possible sequences. The high number of sequences leads us to the conclusion that the event tree method has little flexibility to quantify some accidents like a PLOHS accident.

We have proposed a dynamic scenario quantification method based on the coupling of a Continuous Markov Monte Carlo (CMMC) method and a plant thermal-hydraulics analysis code to quantify PLOHS accident scenarios flexibly. In the coupling model, it takes too much time to analyze accident scenarios. Although, it is important to analyze a large number of samples to improve the quantification accuracy, it has a very high computational cost. Furthermore, we have to build other analysis codes into the coupling model to evaluate amount of source terms. Other analysis codes are a coolant leakage analysis code and a liquid metal-concrete reaction analysis code. Therefore, it is necessary to quantify whole accident scenarios with low computational cost to apply the coupling method. We propose a meta-model coupling method to solve these problems.

In addition to proposing a meta-model coupling method, we also consider how to categorize the output data of the coupling model because the coupling method differs widely from existing event tree methods. Output data of the coupling model are collections of accident scenarios and it is difficult to consider individual scenarios, thus plant status is expressed in existing probability at each time step.

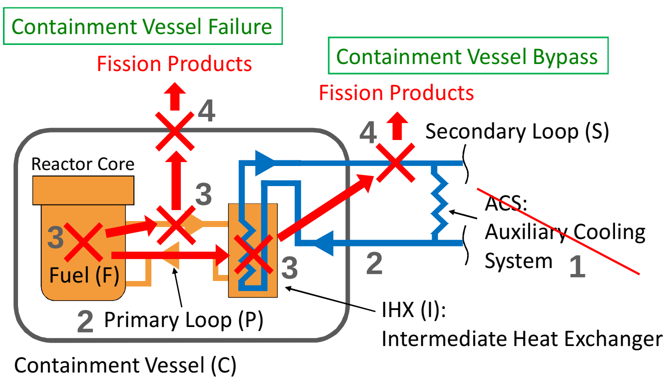

Fig. 1 LMFBR plant in different accident scenarios

2. Coupling method for accident scenario quantification

2.1 Outline of a coupling method

In this section, we explain the coupling method (see Fig. 2). The CMMC method is based on the MCMC (Markov Chain Monte Carlo) method [1] in the coupling method. We consider that the next time plant status depends on the current plant status and the process is a Markov process. Although failure probabilities per unit of time for components depend on the previous records of temperature and pressure, we can treat them as cumulative values of the previous records at each time. Furthermore, to determine the plant status, we compare the state transition probability and a random number at each time (this process is a Monte Carlo method). State transition probability (branch probability) is decided by parameters such as temperature and pressure given for each component from a thermal-hydraulics analysis code in the coupling model. Plant status of next time is decided by the state transition probability. After we repeat these loop processes until the end of the analysis time, we can make a unique accident scenario. In the CMMC method, we have to calculate a large number of unique accident scenarios in the same way to obtain output data as risk information. Each scenario generating process depends on state transition probability and random numbers, therefore the scenarios are different from each other.

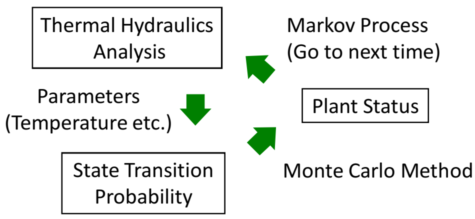

Fig. 2 Coupling method

The coupling method can be applied to not only loop-type LMFBR but tank-type (pool-type) LMFBR. Both types have the potential to occur the CV-bypass scenarios in PLOHS accidents, because the secondary-loops run through outside of the containment vessel. Furthermore, we consider that the coupling method is useful to apply to quantify accident scenarios which have time dependence and interdependence of the events regardless of the type of NPPs.

2.2 Test analysis for a PLOHS accident

In this section, we show a scenario quantification sample for a LMFBR PLOHS accident using the coupling model. The sample analysis has been presented in our published paper [2]. In the coupling model, we use NALAP-II code [3] as the thermal hydraulics analysis code. The NALAP-II code has been developed by JNES, JAPAN and it can analyze thermal hydraulic dynamics of a whole sodium cooled fast reactor plant. The NALAP-II code takes approximately 10 minutes to analyze a PLOHS scenario for approximately 64 hours by using a personal computer. As an example, we show time-temperature histories of primary-loop and secondary-loop which are simulated by the NALAP-II code in a typical PLOHS accident in Fig.

3. In the coupling model, the NALAP-II code analysis gives parameters such as temperature and pressure for each component (primary-loop and secondary-loop), the parameters give the failure probability (state transition probability) for each component. The coupling model determines the next time plant status from failure probability and a random number. If a failure occurs in any component, this component has quasi-leakage of coolant. Fig. 4 shows primary-loop flow rate histories of 100 samples. There are some scenarios which experience a flow rate decrease and this means component failure. The NALAP-II code doesn't have a realistic coolant leakage analysis model, thus the components have quasi-leakage in the coupling model. After we calculate a lot of samples, we can obtain probabilistic information such as shown in Fig. 5. Fig. 5 shows failure probability of each component by an analysis of 1000 samples.

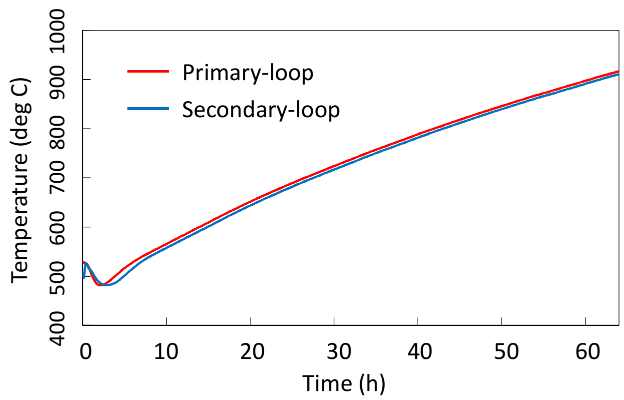

Fig. 3 Temperature in PLOHS accident analysis

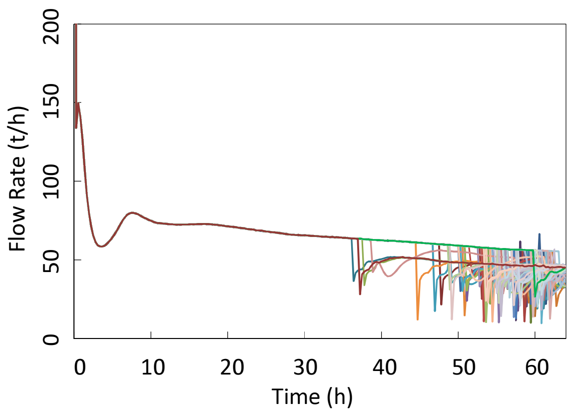

Fig. 4 Primary-loop flow rate in PLOHS accident analysis (100 samples)

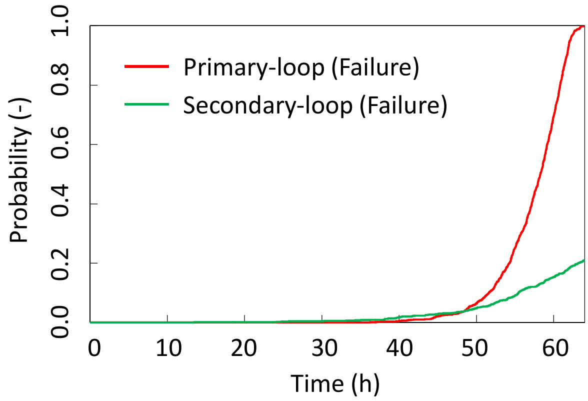

Fig. 5 Failure Probability (1000 samples)

3. Development of meta-coupling model

3.1 What is a meta-model?

We propose a plant thermal-hydraulics meta-analysis model (meta-model) for a NPP to quantify many accident scenarios in realistic time. A meta-model replicates some output parameters of an original analysis code and isn't a simplified analysis model. The meta-model is based on several analysis codes such as a plant thermal-hydraulics code, a concrete-sodium response analysis code and a FP diffusion analysis code. For example, in thermal-hydraulics model, we will solve equations (energy conservation equations and mass conservation equations) and adjust the meta-model to obtain output parameters which are roughly in accordance with that of the original analysis code. When we develop a meta-model, it is necessary to consider the validity of the meta-model. However, output data of the meta-models are based on original analysis codes, therefore validity of the meta-models is ensured automatically if it meets the validity of the original analysis codes. We consider that benchmark evaluations ensure the validity of the meta-model. In this paper, we make a tentative meta-model, because we focus on the categorizing method for the analysis result of the coupling model.

3.2 PLOHS accident analysis by a meta-model

In this section, we show a PLOHS accident analysis in a Fast Breeder Reactors (FBR) plant by a meta-coupling model. The meta-model plant is constituted by five components; fuel (F), primary-loop (P), intermediate heat exchanger (IHX: I), secondary-loop (S) and containment vessel (C). The plant configuration is shown in Fig. 1.

(Algorithm)
An algorithm of the coupling meta-model is shown in Fig. 6. The model calculates failure probability per unit of time for each component, leakage amount of coolant and FP leakage amount at each time and in each sample. The failure probability of each component depends on

temperature. Each failure judgment is made by a Monte Carlo method, therefore the model generates many unique scenarios. In the meta-model, the Mersenne Twister (mt19937ar) [4] is used as a random number generator.

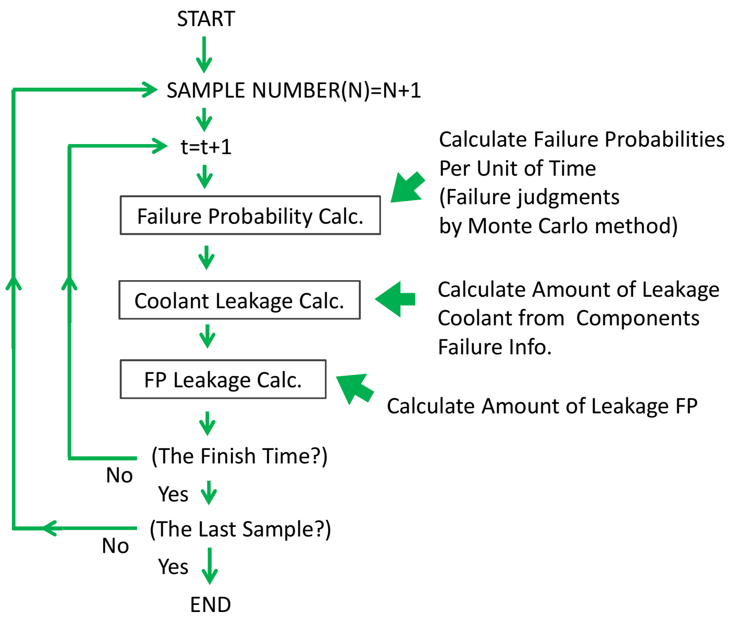

Fig. 6 Meta-model algorithm

(Failure judgments)
Failure probability per unit of time for each component, except for the containment vessel, depends on temperature and can be expressed as follows:

$$\frac{dP_f}{dt} = f(T(t)) \tag{1}$$

where P_f is failure probability per unit of time and $T(t)$ is temperature. Temperature increase depends on time and plant status coefficients (discussed later). Temperature can be expressed as follows:

$$T(t) = T(t-1) + coef \times \frac{dT}{dt} \tag{2}$$

where *coef* is a plant status coefficient. The failure probability per unit of time for the containment vessel depends on leakage coolant amount of the primary-loop.

(Plant status coefficient)
We introduce plant status coefficients so as to reflect plant status to failure probability per unit of time for each component. The coefficients reflect inventory change and influence temperature increasing rate for each component. The plant status coefficients are given in Tab. 1.

Tab. 1 plant status coefficients

Plant status	coef (for the primary-loop)	coef (for the secondary-loop)
Primary-loop inventory is less than 5.0×10^5 (kg)	$\frac{inv_p(0)+inv_s(0)}{inv_p(t)}$	0.0
Primary-loop inventory is greater than 5.0×10^5 (kg)	$\frac{inv_p(0)+inv_s(0)}{inv_p(t)+inv_s(t)}$	$\frac{inv_p(0)+inv_s(0)}{inv_p(t)+inv_s(t)}$

where $inv_p(t)$ and $inv_s(t)$ are coolant inventory in the primary-loop and the secondary-loop

(Coolant leakage and FP release)
After causing a failure of the primary-loop or the secondary-loop, each component has a coolant leakage at a constant rate. If the IHXs fail, the primary-loop and the secondary-loop are connected to each other. If the IHXs and the primary-loop fail, coolant leaks from the secondary-loop via the primary-loop. In the model, the total FP amount is a constant value. If the fuel fails, FP is diffused into the primary-loop at a constant rate and FP is released into the outside of the plant when release passes exist.

(Other analysis conditions)
In this analysis, coolant of the primary-loop reaches 900 deg. C. 220000 seconds (approximately 61 hours) after scram. Sodium boils at 880 deg. C. at 1 bar, therefore the analysis time is set to 61 hours for each sample. Total sample number of this analysis is 10000.

3.3 Result of the meta-model analysis

Fig. 7 shows failure probability of each component of 10000 samples and Fig. 8 shows existence probability of combinations of failed components in the 10000 samples analysis. These two figures indicate the coupling model generates many unique accident scenarios. Fig. 9 shows primary-loop temperature histories in 100 samples. In some scenarios, the temperature increases drastically because a primary-loop and (or) a secondary-loop failure causes coolant leakage. The failure probability of the secondary-loop is lower than that of the primary-loop. It is because the secondary-loop temperature is lower than the primary-loop temperature and the temperature of the secondary-loop doesn't increase in some scenarios in which the primary-loop dries out.

The meta-model takes approximately 70 seconds to calculate 10000 samples by using a standard personal computer. It is important to calculate a large number of samples to improve accuracy of results based on a Monte Carlo method. It can be concluded that the computational cost of the coupling model is suitable for practical use.

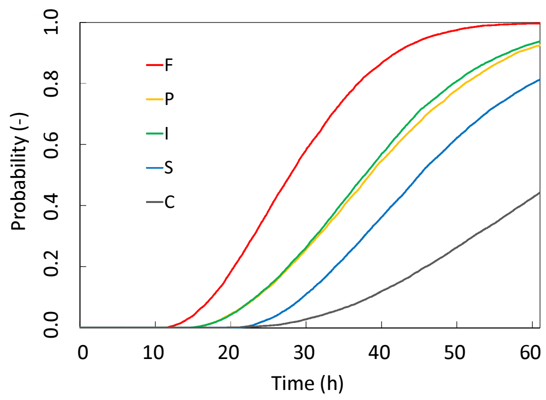

Fig. 7 Failure probability of each component

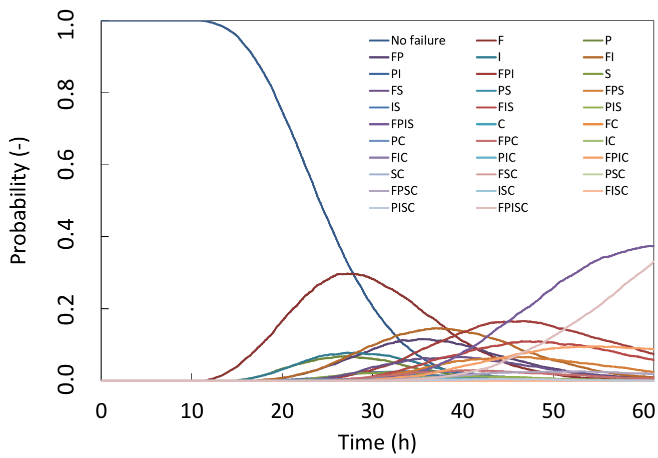

Fig. 8 Combinations of failed components

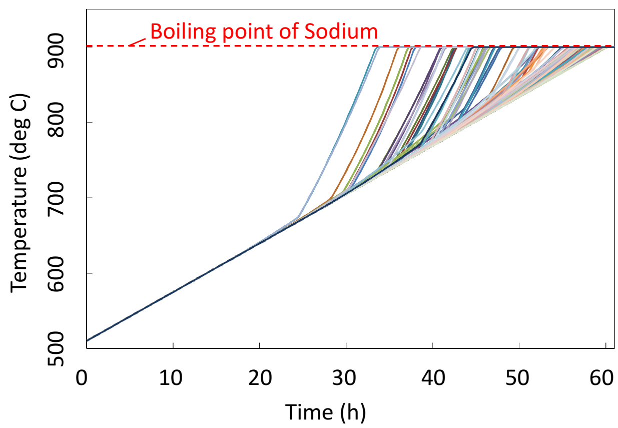

Fig. 9 Primary-loop temperature (100 samples)

4. Categorizing method for analysis result of the coupling model

In this section, we describe methods to express the output data of the coupling method in the level 2 PSA. The coupling model generates many scenarios. The scenarios are unique in their sequence and events occurring time, therefore as previously discussed, it is difficult to express analysis results of the coupling model in event trees. But, the coupling method can express existing probability of the plant status at each time as shown in Fig. 7 and Fig. 8. Status of each component in each sample is represented by a signal (0/1: no failure/failed) and the entire plant status is represented by a combination of the signals. Therefore existing probability of each plant status in each time can be expressed in a (multidimensional) status matrix (Fig. 10). We consider the matrix is equivalent to a number of event trees which are different in event sequence each other in the ET method. In addition to the expression method by a matrix, we propose some recognizable and reasonable categorizing methods for analysis results of the coupling model by using example analysis data shown in chapter 3.

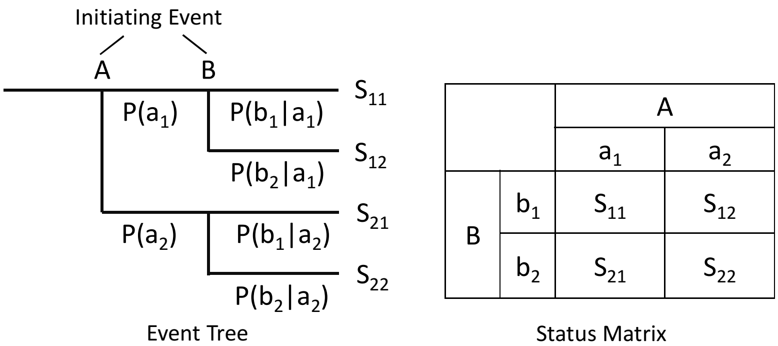

Fig. 10 Event tree and status matrix

4.1 Multi-layer method for risk information categorizing

The IAEA published a guideline on the use of defense-in-depth in NPP design and operation [5]. In the PSA, it is important to show decreasing of FP release probability by several protection barriers. Therefore we propose a categorizing method based on the concept of the defense-in-depth. The method categorizes accident scenarios by several layers. The layers correspond to physical barriers in NPPs. For the results of the coupling model, we set three layers (Fig. 11); containment layer (corresponding to the fuel), transport layer (corresponding to the primary-loop and the IHX) and release layer (corresponding to the secondary-loop and the containment vessel). Combinations of failed components are shown in a Venn diagram or a multidimensional matrix in each layer.

In addition to the categorization method of the accident scenarios in terms of FP release, the multi-layer method can categorize the scenarios from other points of view. In Fig. 12, scenarios are categorized in a perspective of robustness of the containment vessel. It is important to analyze the robustness of the containment vessel because coolant leakages have possibilities to cause liquid metal-concrete reactions in LMFBRs. We can categorize the scenarios in various perspectives because failure histories of components can be recorded in the coupling model.

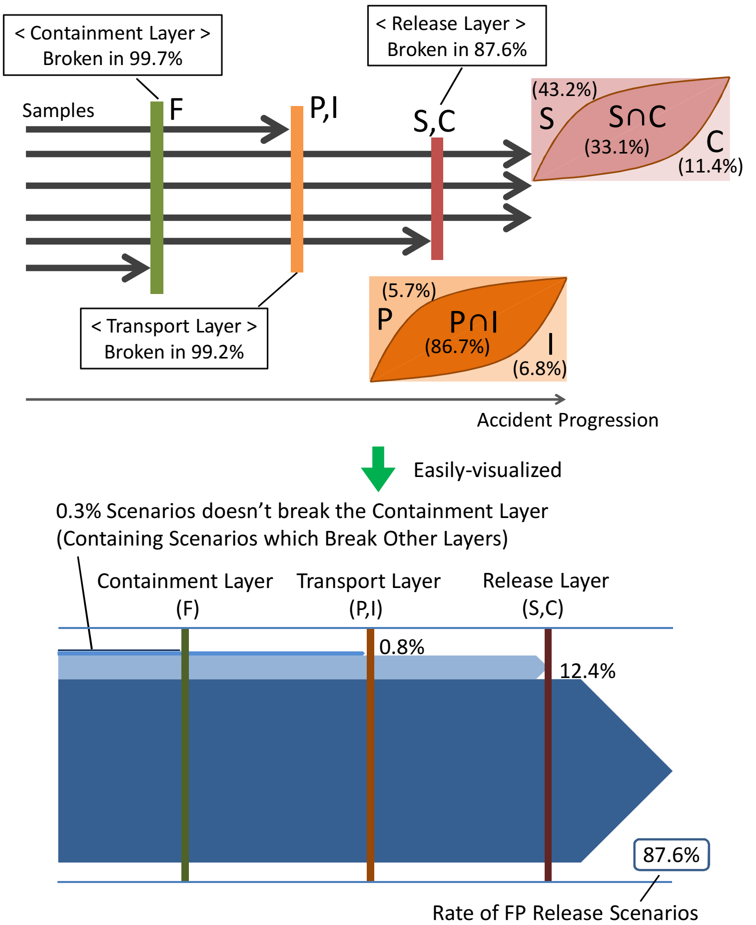

Fig. 11 Three layers and the profiles for FP release

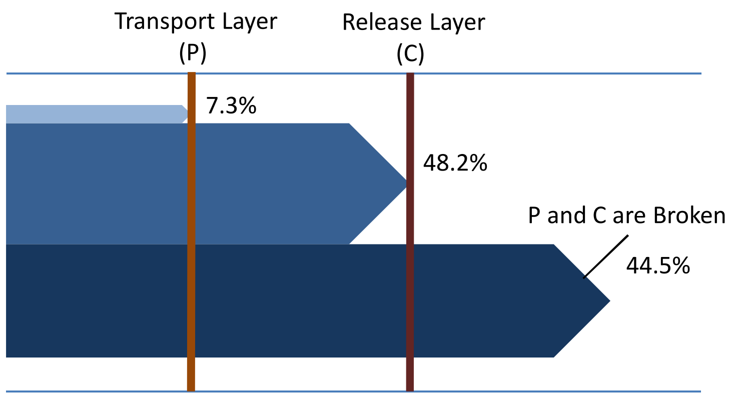

Fig. 12 Two layers for soundness of the containment vessel

4.2 Accident influence categorization

Event probability of FP release accidents is expressed in a risk map. Fig. 13 shows event probability and influence of each accident group at 61 hours after a scram. Each scenario group is indicated by a balloon whose size is equivalent to event probability and whose height is equivalent to influence rate. In the coupling model analysis, uncertainty of failure time is considered by using a Monte Carlo method in failure judgments for each component and the analysis results contain the uncertainty of failure time. But, uncertainty of thermal hydraulics is not considered. If the uncertainty of thermal hydraulics is taken into consideration, it will be expressed in 'peel' of each scenario group (as shown in the 'FPISC' scenario group in Fig. 13).

Fig. 14 shows a FP release histogram at 61 hours after a scram. As shown in the figure, we can categorize the scenarios into several groups of accident level. If we consider the time evolution, the accident scenarios will be expressed in a three-dimensional graph like Fig. 15.

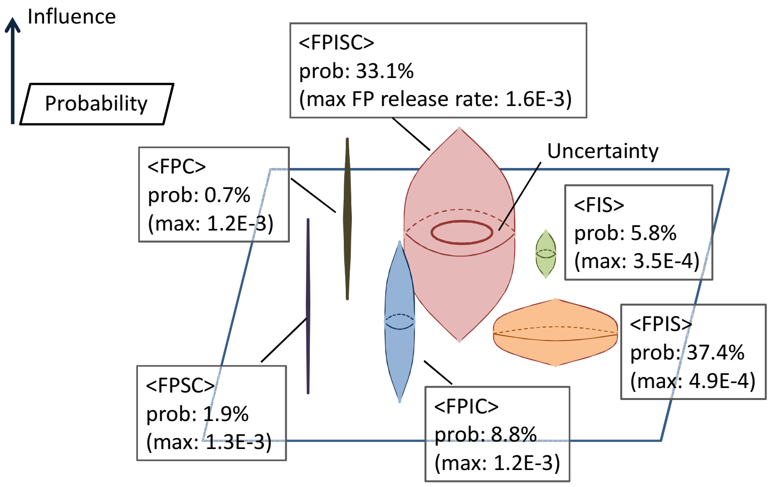

Fig. 13 Risk map

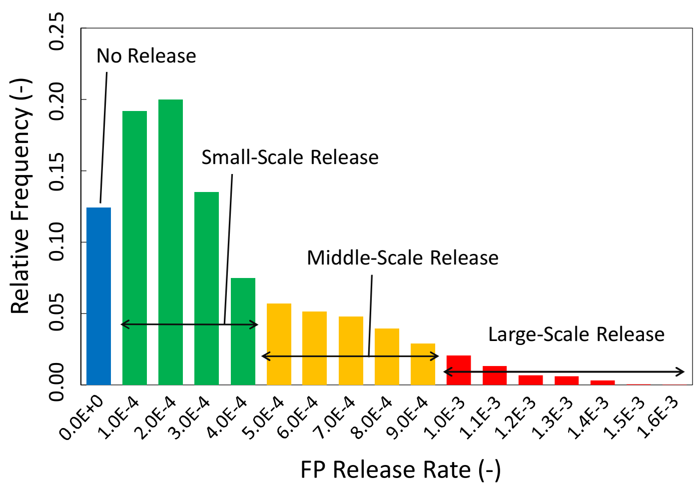

Fig. 14 FP release histogram (at 61 hours after a scram)

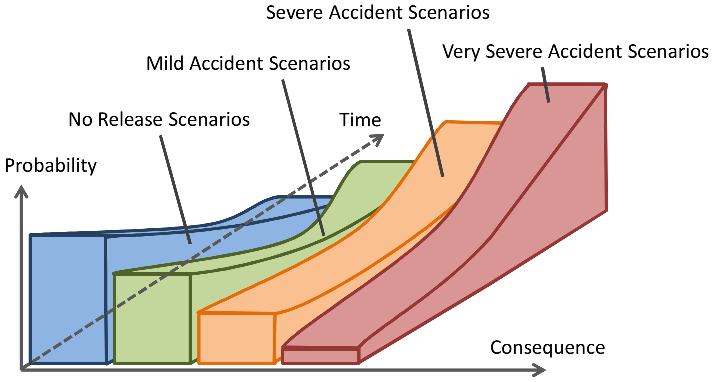

Fig. 15 FP release histogram (considering time evolution)

5. Conclusion

We have proposed a scenario quantification method based on a coupling of a CMMC method and a thermal-hydraulics meta-model in the level 2 PSA for FBRs. The coupling method can quantify a PLOHS accident in FBRs flexibly and the method can quantify not only FP release scenarios but general accident scenarios such as a sodium leakage accident by coupling other analysis models. Especially, the meta-coupling model is suitable for practical use with low computational cost. Additionally, we have proposed some categorizing methods for analysis of results of the coupling method. Quantified accident scenarios are categorized from the point of view of defense-in-depth and influence rate. These categorizing methods improve explicitness of the results in the level 2 PSA. Especially, the categorizing methods have a possibility to express time evolution easily. It is important for the level 3 PSA to quantify FP amounts at each time. Therefore, these categorizing methods can improve extensibility for the level 3 PSA.

6. References

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