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Internal flooding PRA for Kashiwazaki-Kariwa Nuclear Power Plants

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One of the important lessons learned from Fukushima Daiichi Accident is that appropriate and sufficient protection against External hazards like Tsunami is essential for the nuclear safety. Based on this lesson, we have been evaluating risks of external events at Kashiwazaki-Kariwa nuclear power plants and implementing various countermeasures, as one of our continuous activities for nuclear safety improvement.

Regarding internal flooding, we have been implementing countermeasures based on deterministic risk analysis, which is also for meeting new regulatory requirements. Besides, it is necessary to quantify the internal flooding risk and assess the effectiveness of countermeasures by probabilistic risk assessment (PRA).

In this paper, results *of the internal flooding PRA for Kashiwazaki-Kariwa Unit1 (BWR-5) and 7 (ABWR) are shown on the plant condition prior to the implementation of countermeasures against internal flooding. The results show that the most risk-significant flooding source is sea water system in Heat Exchanger Building for Unit1, and fire protection system in Control Building for Unit7, respectively.*

I. Internal Flooding PRA for Kashiwazaki-Kariwa Nuclear Power Plants.

I.A. Introduction

On March 11, 2011, Great East Japan Earthquake and ensuing Tsunami hit Fukushima Dai-ichi Nuclear Power Plants (NPP), which caused Station Black Out and Loss of Ultimate Heat Sink and resulted in core melt and release of radioactive materials from Units 1 to 3. One of the important lessons learned from this accident is that the protection against external hazards like Tsunami is essential for plant safety. Based on this lesson, we have accomplished safety assessment and been installing countermeasures against external events identified at Kashiwazaki-Kariwa NPP. Regarding internal flooding, we have carried out the deterministic risk analysis and implemented countermeasures based on the assessment, which is also for meeting new regulatory requirements. Besides, it is necessary to confirm the submerged risk of internal flooding and assess the effectiveness of these countermeasures quantitatively. Therefore, we have performed internal flooding Probabilistic Risk Assessment (PRA) for Kashiwazaki-Kariwa NPP Unit1, and Unit7.

In this paper, we describe the internal flooding PRA result on the plant condition prior to implementation of countermeasures, and discuss its insights and relation to countermeasures implemented. In the future we will reevaluate this internal flooding PRA with the plant condition after implementing countermeasures to assess the change and benefit.

I.B. Summary of Evaluation Process.

I.B.1. Plant Evaluated.

Kashiwazaki-Kariwa Unit1 and Unit7 are chosen as representatives of BWR5 and ABWR respectively. Here, PRA is performed on the condition that countermeasures are not installed in order to quantitatively evaluate the difference between before and after implementing countermeasures.

I.B.2. Applied Standards and Guidelines.

We applied the following standards.

- ASME/ANS RA-Sa-2009
- Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment [EPRI 1019194]

I.C. Outline of Kashiwazaki-Kariwa Nuclear Power Plants.

Kashiwazaki-Kariwa NPP are located near Kashiwazaki city and Kariwa village in Niigata prefecture, and has 7 units (Unit1~5 : BWR5, Unit6,7 : ABWR, total : 8,212 MWe)

Unit1, target plant of this assessment, mainly consists of Reactor Building, Turbine Building, Heat Exchanger Building, Circulation pump Building and Service Building. The Reactor Building contains an independent main control room. The Unit was originally designed in consideration of internal flood. For example, each ECCS pump is located in isolated rooms surrounded by flood- or fire- barrier walls, and flooding detectors, water draining system and curbs are installed to prevent the flooding propagation.

Unit7 mainly consists of Reactor Building, Turbine Building (including Heat Exchanger area), Control Building (shared with Unit6), Radioactive Waste Treatment Building (shared with Unit6) and Service Building. Main control room is shared with Unit6 and located in the Control Building. This Unit was also originally designed in consideration of internal flood like Unit1. In addintion, water tight doors for each ECCS pump room was installed in Unit7.

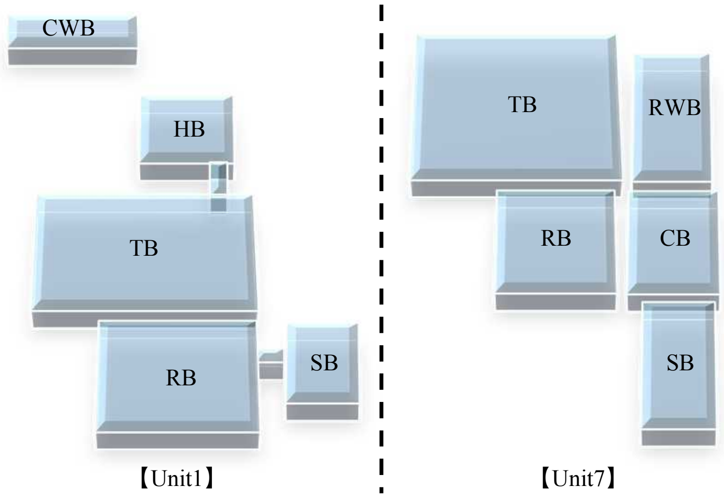

Fig. 1 Arrangement of Unit1 and 7 major buildings

I.D. Internal Flooding PRA Process Flowchart.

Evaluation process flowchart, based on the standards mentioned above, is shown in fig. 2.

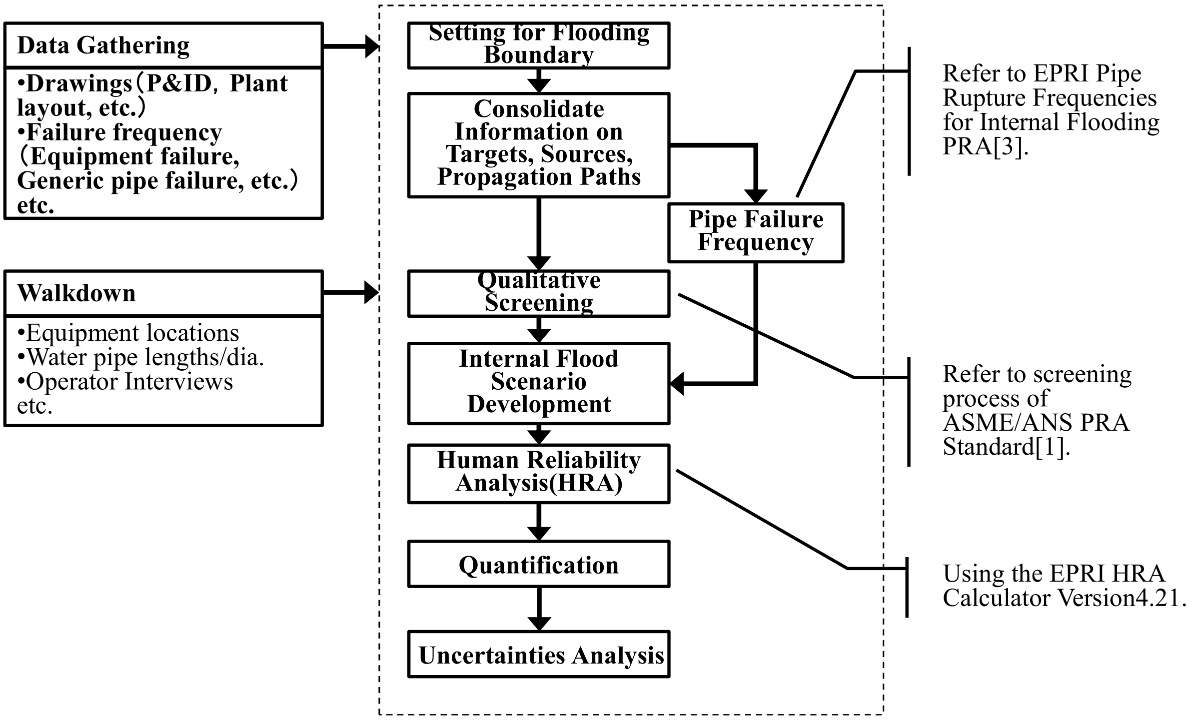

Fig. 2 Internal Flooding PRA Process Flowchart.

The internal flooding analysis general approach involves five basic steps:

1. Obtain pertinent input information
2. Deterministically screen out potential flood zones which could not impact risk
3. Determine potential flood heights, timing of flood effects, and flood consequences on components
4. Using sensitivity studies, quantitatively screen potential flood zones
5. Quantify the flood-induced contribution to the core damage frequency

The first step, information collection, consists of two principal tasks (1) reviewing plant information and documentation, and (2) walking down the plant to confirm and supplement this information.
In the second step, each area is deterministically screened to identify those areas which are susceptible to flooding and flooding-induced failures. This screening is achieved by three approaches:

- Examination of equipment within a compartment
- Examination of potential flood and spray sources that can impact the compartment
- Evaluation of the interface with initiating event potential

The third step assesses the effects of spraying and/or flooding events on the equipment located in each area remaining after the initial screening. Potential flood propagation is also assessed. Where necessary, maximum flood heights are calculated, accounting for potential water sources, barriers (such as watertight doors and curbing), and available drainage. Only those areas identified by this third step as having the potential to significantly impact plant operations are included in the flood model logical and flood-induced core damage frequency quantification. With regard to evaluation of the Human error probabilities, the cognition error is derived using the EPRI Cause Based Method and the ASEP HRA time reliability correlation procedure, and the execution error is derived using Technique for Human Error Rate Prediction (THERP).
The fourth step makes use of sensitivity calculations to demonstrate that certain areas may have such an insignificant quantitative contribution to risk that they can be screened from further consideration.
The last step finalizes the initiating event frequency of flood events. These events are then formally included in the PRA model to determine their contribution to the core damage frequency obtained by multiplying the initial event frequency and the conditional core damage probability.

I.E. Flood Scenario Description.

Identified initiating events are classified by flood area, flooding source (e.g. pipe rupture) and intensity, which is combined by flood propagation scenarios characterized by flood path and extent of condition depending on success of isolation. Example of internal flood scenario is illustrated in Fig. 3. The initiating event of this scenario is the nominal flooding from the flood source X in Area 1. And there are 3 scenarios which have different consequences depending on success of operators' isolation action. Regarding the success or failure of isolation, flooding flow rate is calculated by pipe size and system pressure to know the available time for action. Then, we calculate the human error probability of the isolation depending on the available time using EPRI's HRA calculator. We consider that the flood source X and equipment placed within the range of influence of this scenario are failed, and we select the Event Tree of Transient with PCS.

- Scenario 1 : Succeed in the early isolation, and the range of influence is Area 1.
  Affected equipment : flood source X, pump A, panel A.
- Scenario 2 : Fail in the early isolation, but succeed in the late isolation, and the range of influence is Area 1 and 2.
  Affected equipment : flood source X, pump A, panel A and B.
- Scenario 3 : Fail in the late isolation, and the range of influence is Area 1, 2 and 3.
  Affected equipment : flood source X, pump A, panel A, B and C.

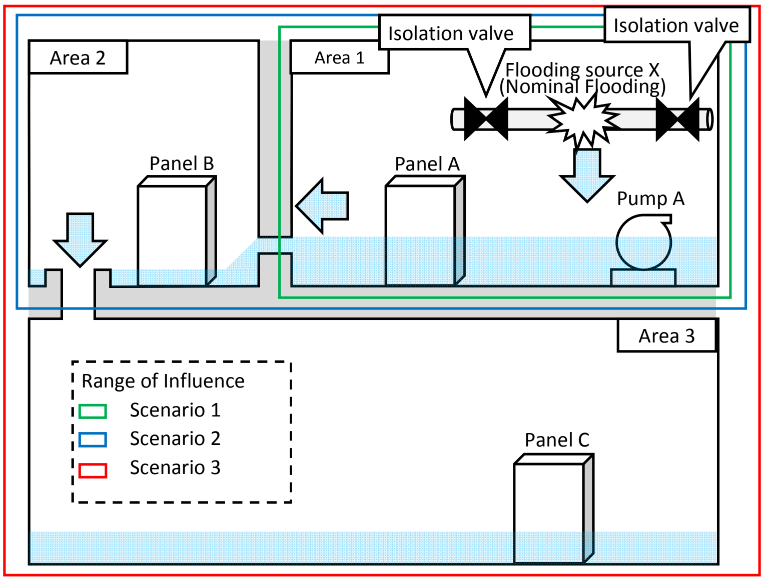

Fig. 3. Illustration of Flooding Scenario

And the nomenclature of each flood scenario is mentioned blow.

$$\underbrace{\text{\%FL-[A]-[B]-[C]-[D]-[E]-}}_{\text{Initiator}}\underbrace{\text{[F]}}_{\text{Operator Intervention}}$$

%FL indicates an internal flood initiator
[A] : the building containing the target equipment
[B] : the system that represents water source
[C] : division A, B, C, or N for non-divisional
[D] : system affected by flood or the floor where flooding occurred
[E] : N for nominal flood M for major flood
[F] : operator intervention, where the following nomenclature is used

INT or P : success of operator in isolation flood or not isolable
ERY or S : failure of operator in isolating flood
LAT or T : failure of operator in isolation flood late

I.F. Result.

For each flood scenario, we evaluate the core damage frequency (CDF) by multiplying the initial event frequency and the conditional core damage probability (CCDP) based on the failure of equipment located in each impacted area

I.F.1. Dominant Flood Scenarios Contribution to CDF.

Table 1 and 2 are the Top-10 lists of the flood scenario which have highest contribution to CDF, and Fig. 4 and 5 show the relative contribution of internal flood scenarios to CDF. Top1 to 3 flood scenarios are described as follows.

a) Unit1.
  - TOP 1 : %FL-HB-SW-N-B1-M-S
    In this scenario, Major flood, resulting from a rupture of Sea Water system, occurred in the first basement floor of Heat exchanger building, early operator response action fails, and this leads to failure of all of the emergency cooling systems located in that building. The human error probability is almost 1 because of the large flooding flow rate that makes the available time very short.

  - TOP 2 : %FL-RB-FP-N-B2-N-S
    Nominal flood, resulting from a rupture of Fire Protection system, occurred in the second basement floor of Reactor Building, early operator response action fails, and this leads to failure of all of the ECCS systems arranged in that building. This scenario has low human error probability due to the long available time based on flooding flow rate and allowable flood volume, but it has high CCDP because of the significant influence if human error were to have occurred.

  - TOP 3 : %FL-RB-FP-N-B2-N-P
    Nominal flood, resulting from a rupture of Fire Protection system, occurred in the second basement floor of Reactor Building, early operator response action succeeds, and this leads to failure of the components located only in the same floor. This scenario has the same initial event with top2, but has a different consequence. In this scenario, operator needs to succeed early isolation, thus it requires shorter available time, which makes HEP high. However this scenario has smaller flood propagation range, and as a result, the CCDP of this scenario is lower than that of top2 scenario.

b) Unit7.
  - TOP 1 : %FL-CB-FPS-N-ACP-N-INT
    Nominal flood, resulting from a rupture of Fire Protection system, occurred at the Control Building, early operator response action succeeds, and this leads to failure of the systems arranged in the same floor of that building. Initial event frequency is relatively high, but there are few affected equipment, for that reason, the CCDP value of this scenario is low.

  - TOP 2 : %FL-CB-FPS-N-DCP-N-ERY
    Nominal flood, resulting from a rupture of Fire Protection system, occurred at the first basement floor in Control Building, early operator response action fails, and this leads to failure of all the emergency DC power arranged in that building. Initial event frequency is low because of the short pipe length arranged in this area, but there are no available DC power if the pipe rupture, thus, the CCDP value of this scenario is 1.

  - TOP 3 : %FL-TB-CWS-N-FWS-M-ERY
    Major flood, resulting from a rupture of Circulating Water system, occurred at the Heat Exchange area in Turbine Building, early operator response action fails, and this leads to failure of all the emergency cooling systems arranged in that area.

TABLE 1 Dominant Flooding Scenario for Unit1

Unit	No	Initiator	Flood Initiator Feq.[/yr]	HEP	Available Time [min]	Scenario Freq. [/yr]	CCDP	CDF [/yr]
1	1	%FL-HB-SW-N-B1-M-S	1.26E-05	9.99E-01	13	1.26E-05	3.81E-03	4.80E-08
	2	%FL-RB-FP-N-B2-N-S	3.08E-04	6.80E-04	563	2.09E-07	1.95E-01	4.08E-08
	3	%FL-RB-FP-N-B2-N-P	3.08E-04	1.62E-03	165	4.99E-07	7.58E-03	3.78E-09
	4	%FL-RB-RIW-N-B1-N-P	1.59E-06	1.00E+00	56	1.59E-06	2.31E-03	3.67E-09
	5	%FL-RB-MUWC-N-B1-N-P	2.12E-07	1.00E+00	82	2.12E-07	1.33E-02	2.82E-09
	6	%FL-RB-MUWP-N-B1-N-P	2.50E-06	1.00E+00	71	2.50E-06	9.79E-04	2.45E-09
	7	%FL-HB-FP-A-B1-N-P	8.74E-05	4.10E-03	110	3.58E-07	5.13E-03	1.84E-09
	8	%FL-HB-FP-B-B1-N-P	8.74E-05	4.10E-03	110	3.58E-07	5.13E-03	1.84E-09
	9	%FL-HB-SW-N-1F-M-T	1.64E-04	2.60E-03	111	4.26E-07	3.81E-03	1.62E-09
	10	%FL-RB-RIW-N-B2-N-P	2.12E-07	1.00E+00	56	2.12E-07	7.58E-03	1.61E-09

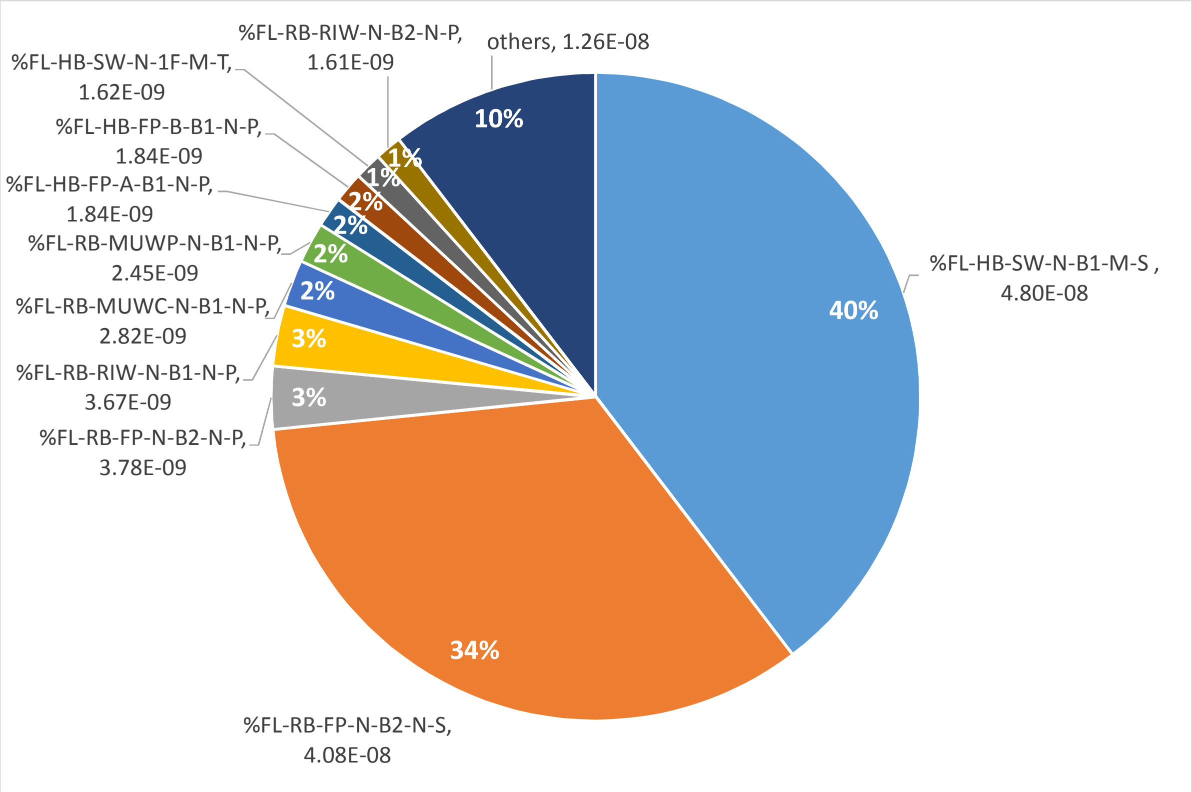

Fig. 4. Internal Flood CDF Contribution By flood scenario (Unit1)

Table 2 Dominant Flooding Scenario for Unit7.

Unit	No	Initiator	Flood Initiator Feq.[/yr]	HEP	Available Time [min]	Scenario Freq. [/yr]	CCDP	CDF [/yr]
1	1	%FL-CB-FPS-N-ACP-N-INT	8.79E-04	9.46E-01	- (Success)	8.32E-04	1.62E-06	1.35E-09
	2	%FL CB-FPS-B-DCP-N-ERY	2.66E-07	4.60E-03	126	1.22E-09	1.00E+00	1.22E-09
	3	%FL-TB-CWS-N-FWS-M-ERY	1.60E-04	2.50E-03	26	4.00E-07	2.69E-03	1.08E-09
	4	%FL-TB-CWS-N-CDN-M-ERY	1.70E-04	2.32E-03	154	3.94E-07	2.69E-03	1.06E-09
	5	%FL-RB-MUC-N-RB2-M-ERY	9.16E-07	1.90E-02	41.7	8.70E-10	9.88E-01	8.60E-10
	6	%FL-CB-FPS-N-ACP-M-ERY	2.41E-04	1.00E+00	31	2.41E-04	1.62E-06	3.90E-10
	7	%FL-TB-CWS-N-CDN-N-ERY	3.10E-04	4.14E-04	1372	1.28E-07	2.69E-03	3.44E-10
	8	%FL-TB-CWS-N-CDN-N-INT	3.10E-04	1.00E+00	- (Success)	3.10E-04	8.31E-07	2.58E-10
	9	%FL-RB-MUC-N-RB2-N-ERY	5.89E-06	8.70E-04	300	2.56E-10	9.88E-01	2.53E-10
	10	%FL-CB-HEC-N-ACP-N-INT	1.24E-04	1.00E+00	- (Success)	1.24E-04	1.62E-06	2.01E-10

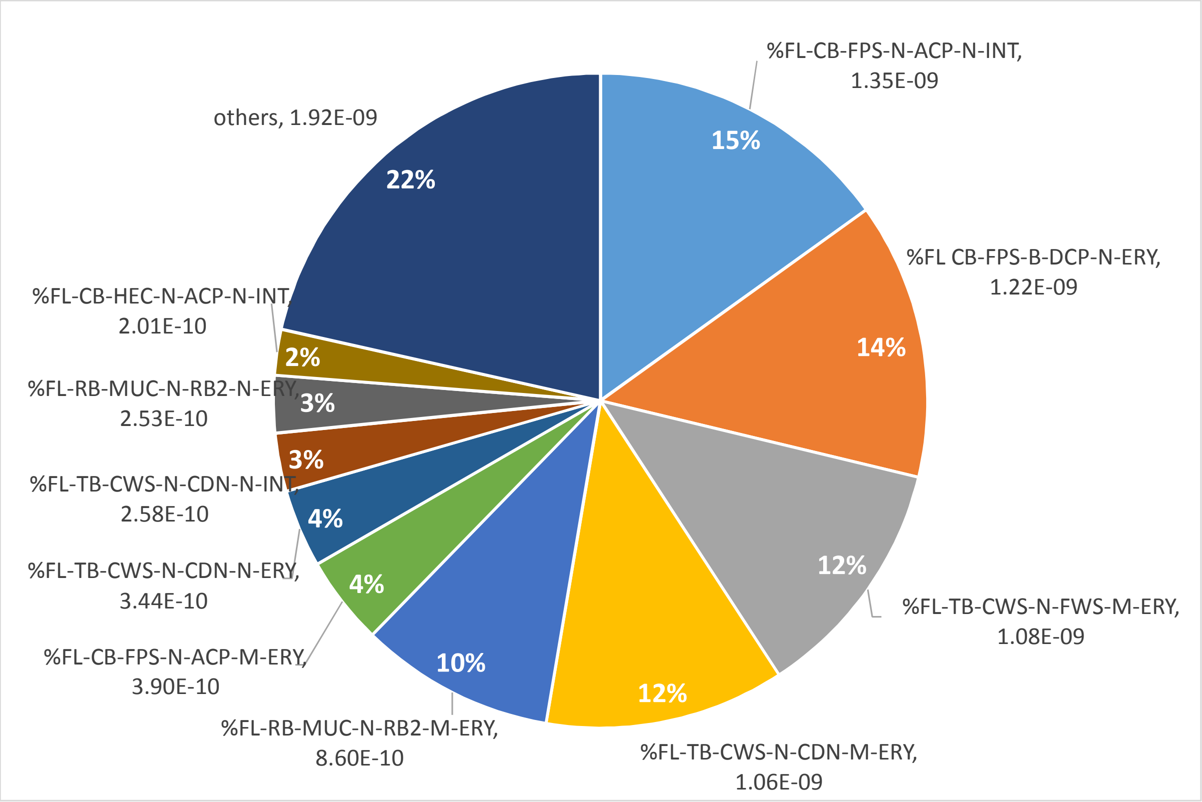

Fig. 5. Internal Flood CDF Contribution By flood scenario (Unit7)

I.F.2. Discussion.

a) Unit1.

- The total internal flooding CDF of Unit1 is equal to 1.21E-07, and that value is not so large. In addition, internal event CDF of Unit1 is the order of E-06, so that the internal flooding CDF is an order of magnitude smaller than that of internal event. This means that the internal flooding CDF is relatively small compared to other internal events.

- Top 1 and 2 scenarios account for almost 70% of total CDF, and these are dominant scenario compared to others. Because of this, we can reduce total CDF effectively by reducing CDF of these two scenarios. It is thought that an improvement in detection performance by installing new detectors, or an extension of available time by installing water-tight measures are effective in order to reduce HEP of top1 scenario, and as a result, we can reduce top1 CDF. Regarding top2, if we install the water-tight measures for each ECCS pump rooms in order to prevent simultaneous failures of these pumps, we can reduce CCDP and CDF effectively.

- Top1, 7, 8 and 9 scenario have the same location of initial event, and these have large contribution for total CDF. It is thought that this is because the incompleteness of separation of each safety divisions. Because of this, big effect can be expected from thoroughly separating these safety divisions.

b) Unit7.

- The total internal flooding CDF of Unit7 is equal to 8.93E-09, and that value is quite small. In addition, internal event CDF of Unit7 is equal to about E-07, so that the internal flooding CDF is an order of magnitude smaller than that of internal event as with Unit1. This means that the internal flooding CDF is relatively small compared to other internal events.

- The sum of the CDF by totaling each top1 to 10 flood scenario occupied almost 75% of total CDF. But in the case of Unit7, unlike Unit1, there are no large difference between each top1 to 10 flood scenarios.

- On the other hand, we can find some dominant contributing factors by separating these top1 to 10 scenarios from the point of view of the initial flood occurrence point. For example, top1,2 and 6 scenarios have similar initial flood, occurrence point is at the Control Building, flood source is Fire Protection system. And top3,4,7 and 8 scenarios have also similar initial flood, occurrence point is at the Turbine Building, flood source is Circulating Water system. Because of this, CDF reduction can be expected by installing countermeasures for these scenarios.

I.F.3. Deterministic Safety Analysis and Countermeasure after Fukushima Daiichi Accident.

a) Unit1.

Unit1 is going to install several countermeasures, based on the result of deterministic safety analysis, as typified by the separation of safety divisions at the Heat Exchanger Building and at the Reactor Building or the like, in addition to the external flood countermeasures against for Tsunami based on the Fukushima Daiichi accident. These countermeasures, which are designed with the flooding at the Heat Exchanger Building or Reactor Building, can limit the range of influence, and extend the available time to isolate. Because of this, we can expect reduction effect of HEP. Also, we can expect reduction effect of CCDP by preventing simultaneous failure of several safety divisions.

b) Unit7.

Unit7, as with Unit1, is going to install countermeasures based on the result of deterministic safety analysis. For example, we improve reliability of DC power by installing an alternative which provides separation between existing trains in the Control Building in order not to fail them simultaneously. And also, we improve reliability of isolation operation by installing new flooding detectors in Turbine Building to be able to find the flood event early, resulting from the rupture of CW pipe. Because of this, we can expect reduction in HEP and CCDP values.

II. CONCLUSIONS

We carried out internal flood PRA for Kashiwazaki-Kariwa NPP. After a review of the results, we found that the total internal flood CDF is relatively small, and we were able to identify the dominant scenarios. Thus, we could estimate plans to more effectively further reduce the CDF. And, if we consider the internal flood countermeasures based on the result of deterministic safety analysis, we can expect the big effect of reducing the internal flood risk based on these countermeasures including the effective way to reduce CDF for the dominant scenario identified by PRA. For future planning, we will carry out re-evaluation of the plant condition that includes installation of these countermeasures, and quantify the effect of these measures, and as a result, achieve the desired continuous improvement of plant safety.

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