Study of Detailing Scenarios Leading directly to Core Damage in Seismic PRA(1) Extracting Issues for Introducing Expert Judgement

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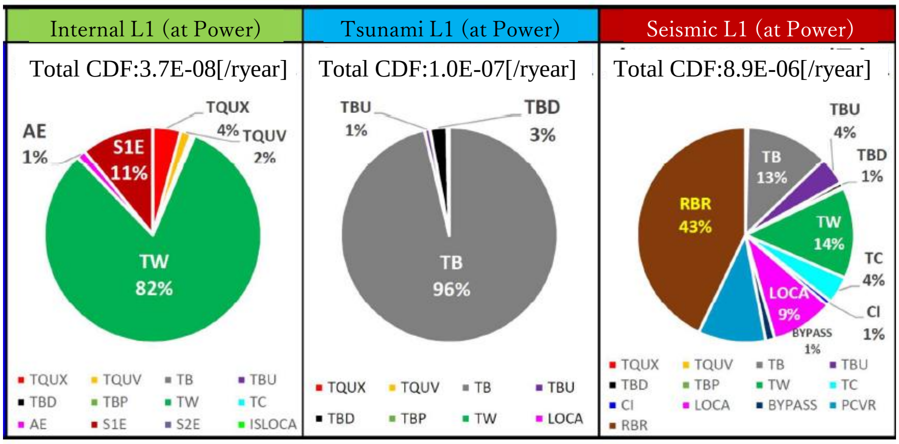
Abstract: In Current Seismic PRA, it is generally assumed that initiating events (such as damage to buildings, containment vessels, reactor pressure vessels, etc.), which are difficult to develop in detail scenario, are conservatively directly leading to core damage. Such conservative assumptions naturally give conservative results. This is why improvement of PRA models is necessary from the viewpoint of Risk-informed decision making (RIDM) such as identifying vulnerabilities of plants. There are several methods for bringing it closer to a realistic scenario, here we will focus on "expert judgment" as a method of efficiently optimizing the risk profile by maximizing the use of existing knowledge, without using conventional assessment by experiment s/analysis, etc. In this paper, as a preliminary examination of the introduction of "expert judgment", the issues in analyzing events directly leading to core damage and in making the "expert judgment" were summarized.

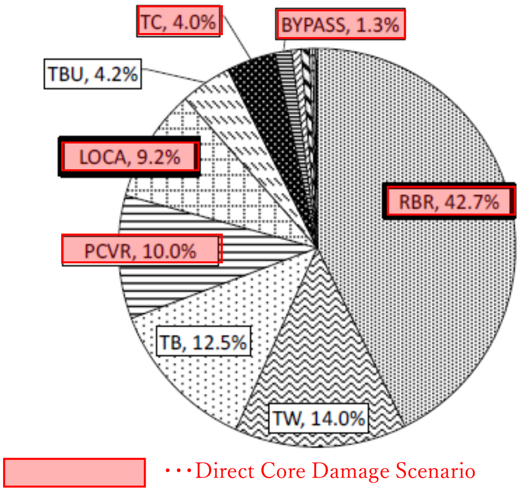
Keywords: Seismic PRA, Expert Judgement, Expert Elicitation, Accident Sequence

1. INTRODUCTION

In the implementation of probabilistic risk assessment (PRA), the impact of external events that should be assumed varies by location. In Japan, as is commonly known, earthquake and tsunami are major factors in external events. For example, Table 1 shows CDFs obtained from TEPCO's KK7 PRA models (as of 2014). CDF in seismic PRA is the largest so the earthquake is a dominant risk factor for KK7 units. The ratio of CDF by core damage sequence in this seismic PRA is as shown in Figure 1, and scenarios leading to direct core damage account for a large percentage of the frequency. Therefore, refinements are required from the viewpoint of RIDM, such as identifying the vulnerability of plants.

Table 1. Comparison of CDF by PRA model (KK7)





core damage sequence	CDF [/ryear]	ratio
RBR	3. 8E-06	42. 7%
TW	1. 2E-06	14. 0%
TB	1. 1E-06	12. 5%
PCVR	8. 9E-07	10. 0%
LOCA	8. 2E-07	9. 2%
TBU	3. 7E-07	4. 2%
TC	3. 6E-07	4. 0%
BYPASS	1. 2E-07	1. 3%
CI	6. 9E-08	0. 8%
TBD	6. 0E-08	0. 7%
TQUX	2. 3E-08	0. 3%
TBP	2. 0E-08	0. 2%
TQUV	9. 5E-09	0. 1%
合計	8. 9E-06	100. 0%

Figure1. Core Damage Frequency Contribution by Core Damage Sequence in seismic PRA model (KK7)

2. Extraction of Direct Core Damage Scenarios

In order to detail scenarios leading to direct core damage, it is necessary to grasp which scenarios should be developed in detail (or deployable). At the first step, scenarios leading to direct core damage were extracted based on the following.

1) Pilot plant
As a typical Japanese BWR and PWR, the Kashiwazaki-Kariwa Nuclear Power Station Unit 7 (TOKYO ELECTRIC POWER) [1]and Takahama Nuclear Power Station Unit 3 (Kansai Electric Power) [2] are chosen as the pilot plants.

2) Extract scenarios
The PRA models of the pilot plant were analyzed and the candidates of the scenarios for applying expert judgements were extracted. Scenarios to be assessed are those scenarios leading to direct core damage (or loss of containment function) or those scenarios modeled on a fault tree as loss of function in the system that result in core damage (or loss of containment function) due to damage to the relevant SSC. Since then, these scenarios have been described as “direct core damage scenarios”.

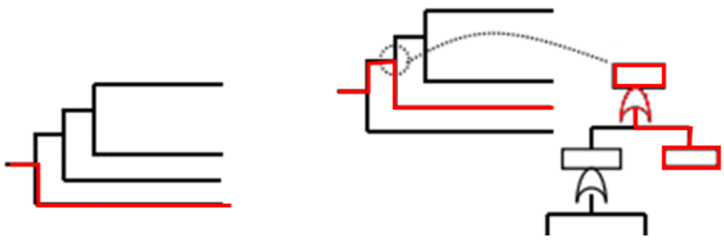


Figure 2. Image of extracting target scenarios

3) Organizing SSC that Causes Direct Core Damage Scenarios
Conservative assumptions in the PRA by organizing extracted SSCs which cause an initiating event or mitigation system failures which are assumed to lead directly to core damage, and assumptions of damaged parts of the SSCs are identified.

2.1. PWR Direct Core Damage Scenarios

Organized direct core damage scenarios are shown in Table 2. In addition, SSC which causes each scenario and the accident scenario when each assessment part is damaged are comprehensively arranged. Table 3 and 4 show examples of SSC, and evaluation target part and assuming accident scenarios including conservative assumptions.

Table 2. PWR Direct Core Damage Scenarios

Scenarios leading directly to core damage	Scenarios leading consequently to core damage
- Reactor Building was damaged - PCV damage - Breakage of heat transfer tube of steam generator (breakage of multiple tubes) - Excessive LOCA	- reactor auxiliary building damaged - Loss of primary coolant flow - Loss of control function of safety system due to damage to control equipment - Loss of function of multiple valves

Table 3. SSC and Assessment Parts (e.g. PCV Damage)

SSC	assessment part
PCV	Containment ring girders, elastic fillers, and connections between the hemispherical and cylindrical sections

Table 4. Assuming Scenario development (e.g. Ring girder)

Scenario	SSC (Assessment Part)	Assuming accident scenario
PCV Damage	PCV (Ring girder)	It is assumed that a large-scale LOCA that cannot be controlled will occur due to damage to the reactor containment vessel, and ECCS injection will also become ineffective, leading to core damage and loss of containment function.

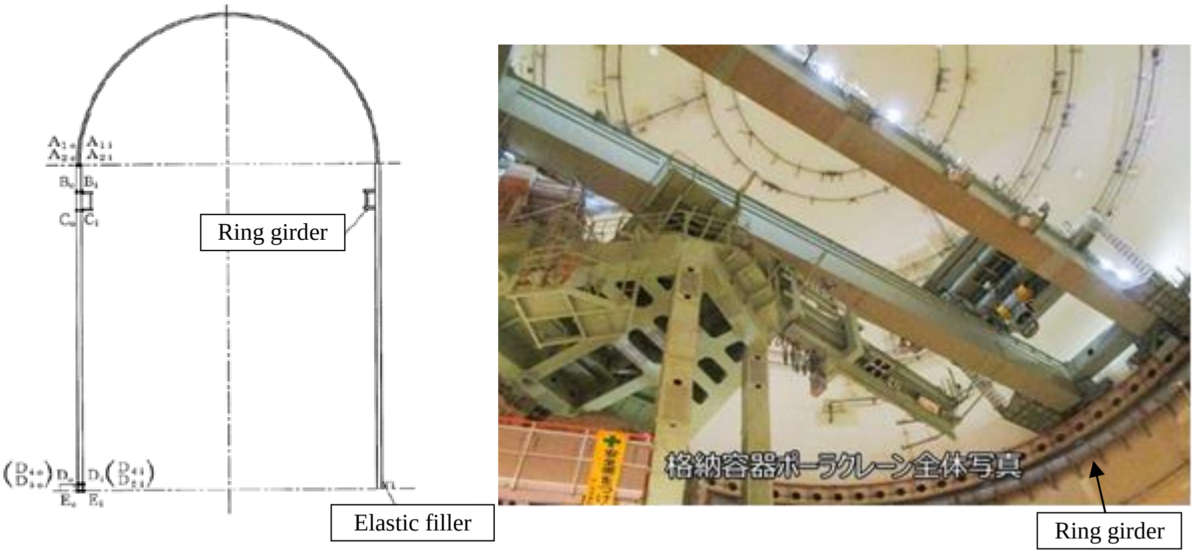


Figure 3. Image of PCV and Ring girder

2.2. BWR Direct Core Damage Scenarios

Organized direct core damage scenarios are shown in Table 5. In addition, SSC which causes each scenario and the accident scenario when each assessment part is damaged are comprehensively arranged. Table 6 and 7 show examples of SSC, and evaluation target part and assuming accident scenarios including conservative assumptions.

Table5. BWR Direct Core Damage Scenarios

Scenarios leading directly to core damage	Scenarios leading consequently to core damage
- Reactor Building damage - PCV/RPV damage - Loss of reactor coolant pressure boundary - Loss of instrumentation and control systems - Loss of DC power supply	-

Table 6. SSC and Assessment Parts (e.g. PCV Damage)

SSC	assessment part
Diaphragm floor	Reinforced concrete slab, shear plate
Reactor shielding wall	General body section, opening concentration section
RPV	Shell plates, foundation bolts, RPV body support skirts
RPV Pedestal	Inner cylinder, outer cylinder, warp rib, concrete, pairing plate, anchor bolt, bracket part, bracket part horizontal plate
Reactor pressure vessel stabilizer	Rod, bracket
Brackets	Steam dryer hold down bracket Steam dryer support bracket Upper/Lower guide rod bracket Water supply sparger bracket Low pressure water injection sparger bracket
Lower head plate	Spherical shell and the connection between the spherical shell and the cone Knuckle Department Joint between the knuckle part and the cylindrical body part
Control rod drive mechanism housing through-hole	Starve tubing Housing Lower plate ligament
Reactor coolant recirculation pump through hole	Casing side root R section RIP Nozzle Weld Connection between the stub and the lower head plate Through-hole stub
RIP motor casing	Casing
Nozzle	Nozzle safe end Nozzle end Thermal Sleep
CRD housing restraint beam	Plate
Steam dryer	Unit support Shear plane of earthquake-resistant block Anti-seismic block bearing surface

Table 7. Assuming Scenario development (e.g. Diaphragm floor)

Scenario	SSC (Assessment Part)	Assuming accident scenario
PCV Damage	Diaphragm floor (Reinforced concrete slab)	Large-scale damage to the SSC can damage the containment support function and cause major damage to components in the reactor containment vessel, reactor pressure vessels, and other structures, which can lead to the following events: - If the reactor vessel is damaged, the reactor cannot be controlled, and ECCS cannot be expected to cool the reactor core, resulting in direct core damage. - Damage to the reactor containment vessel will make the suppression pool water unavailable in the long term, resulting in core damage.
	Diaphragm floor (Shear plate)	Large-scale damage to the SSC may result in the loss of containment support functions, and large-scale damage to structures such as equipment in the reactor containment vessel and the reactor pressure vessel, which may lead to the following events: - If the reactor vessel is damaged, the reactor cannot be controlled, and ECCS cannot be expected to cool the reactor core, resulting in direct core damage.

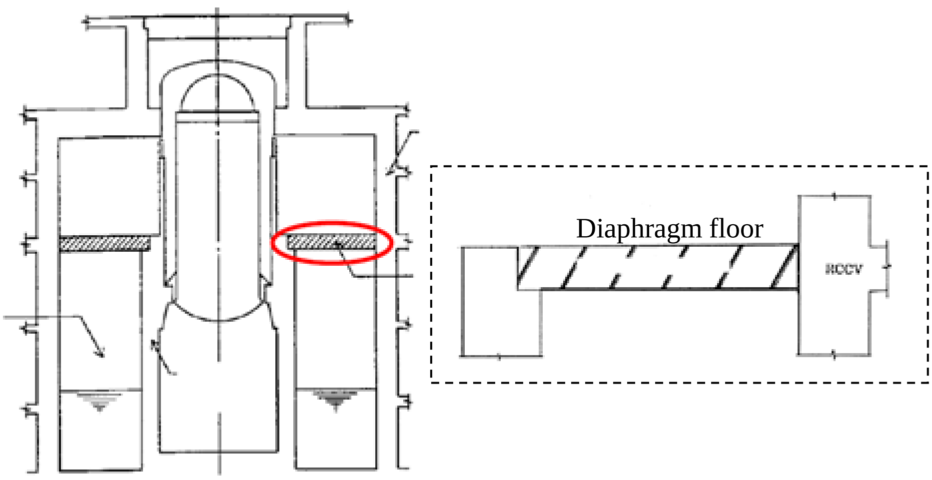


Figure 4. Image of PCV and Diaphragm floor

3. Organize issues for refinement of scenarios

Although the accident scenario arranged in the previous section is considered to be leading directory or consequently to core damage in assessments, but core damage may not occur in some cases depending on the degree of damage to SSC. Issues in reviewing the conservatism of these scenarios were summarized. The following shows the example issues to be addressed for the specific scenarios that have been summarized and the common elements when the overall issues are viewed.

3.1. PWR Scenario-Refinement Issues (e.g. Ring girder)

1) Conservativeness of Assumed Scenarios

Damage to the subject's assessment area is expected to damage PCV boundary and at the same time, a large-scale LOCA due to a decline in the equipment installed inside PCV is assumed. Depending on the extent of the damage, only events such as LOCA which ECCS can mitigate the event, rupture of the secondary cooling system, or damage to some mitigation systems in the containment vessel may occur. Or, PCV boundary may be maintained in the first place and no LOCA may occur.

2) Issues for developing detailed scenarios

a. Degree of damage/damage: The extent of damage at each ground acceleration is unknown

There is a nonlinear analysis method to grasp the displacement of PCV body and each part according to the increase of the input ground acceleration. However, no analytical method has been established to evaluate the impacts of damage to some parts on the overall response and the effects of such damage on the damage to the through piping.

b. Secondary effects: There is no method for evaluating the probability of occurrence.

No analytical method has been established to evaluate the relation between the size of damage to various parts of PCV and the falling/piping breakage of the inner equipment, and the collision/breakage after dropping, including the uncertainty. The possible secondary effects of damage to the assessment site are as follows:

- Falling and damage of equipment and pipes supported on the inner wall of PCV
- Collision and damage of falling objects to other SSCs in PCV

3.2. PWR Scenario-Refinement Issues (Common Elements)

- Equipments causing direct core damage can be roughly divided into buildings, reactor containment vessels, primary coolant pressure boundary component facilities, reactor internals, electrical panels, and representative valves. Accident scenarios that occur after these facilities are damaged are diverse, and very complex accident scenarios are also included, such as the impacts of simultaneous failure of heat transfer tubes in multiple steam generators, and the effects of damage to the reactor internals and partial inhibition of the cooling channels.
- The results of the arrangement showed that it was necessary to analyze "the extent of damage places/damage (it is unknown how much of the entire facilities will be damaged according to the acceleration)," which is a direct effect at the time of damage common to all facilities. In other words, although the accident scenarios derived after damage are diverse, the starting point where the uncertainty of the scenario occurs is "where and to what extent damage may occur," and this point is a common consideration issue for each facility.
- For some equipment, the indirect effect after damage requires analyses of the "secondary effect (the effect on the surrounding equipment or support components etc. is unknown if the area is damaged)."

3.3. BWR Scenario- Refinement Issues (e.g. Diaphragm floor)

1) Conservativeness of Assumed Scenarios

Depending on the extent of damage, the reactor pressure vessel support function may not be lost, and mitigation functions may not be lost or some mitigation functions may only be lost.

2) Issues for developing detailed scenarios

a. Degree of damage/damage: The extent of damage at each ground acceleration is unknown.

- Concrete slab

  In the current assessment, the fragility evaluation was carried out using the allowable value of reinforced concrete which is the strength member of reinforced concrete slab. Even if a part of the reinforced concrete slab is damaged, if the strength is ensured, no excessive load is generated on the seal plate, and the pressure suppression function is considered to be maintained. However, there is insufficient data to grasp the relationship between the load applied to the reinforced concrete slab and the damage scale.

- Shear plate (RCCV/RPV joints)

  Pressure-suppressing and RPV support functions may be maintained if the reinforced concrete slab is sound and able to bear loads even if RCCV or RPV joints are damaged. However, there is insufficient data on how much load can be borne only by the reinforcement of reinforced concrete slab.

b. Secondary effects: There is no method for evaluating the probability of occurrence.

There is no established method for evaluating the scale of damage to each part of the containment vessel and the relationship between falling and piping breakage of internal equipment, and the collision and breakage after falling, including uncertainty. It is currently difficult to analyze the secondary effects. The secondary effects assumed are as follows.

- Loss of support function for the reactor pressure vessel (damage to the reactor pressure vessel due to the loss of support function)
- Damaged Diaphragm Floor penetration/installation pipes, etc. of S/R valve exhausting pipes, etc.
- Damaged equipment (instrumentation, pipes, strainers, vent pipes, etc.) in S/C

3.4. BWR Scenario-Refinement Issues (Common Elements)

- Equipment causing direct core damages are roughly classified into large reactor internals, RPV support structures, brackets/nozzles, primary coolant pressure boundary component facilities, electric panels and isolation valves. (As the object equipment to which the expert judgment is applied, first, the equipment which has large effort or lack prospect of the approach by the conventional method (evaluation by experiment/analysis, etc.) is appropriate.)
- As a result of classifying the issues in SSCs related to the scenario of direct damage to the core, it can be summarized as "the extent of damage (the extent of damage to which any part of the entire facility will be damaged by each ground acceleration is unknown)" and "secondary effects (the probability of the impact on surrounding facilities and support performance when such assessment part is damaged is unknown)" as consideration factors.

4. Consideration of the application of expert judgment

In the preceding section, we summarized the issues in modeling realistic scenarios. In this section, how the expert judgment can be incorporated in introducing the expert judgment in the future is examined using a concrete scenario as a theme.

4.1. Application to PWR scenarios. (e.g. Ring girder)

<u>a. Degree of damage/damage</u>
Until a methodology has been established to evaluate the effects of damage to some parts of the PCV on the overall response and the effects on penetration pipe by analysis, it is possible to assign a probability of scenario occurrence according to the degree of damage by expert judgment based on the analysis results and qualitative impact analysis that are currently available. It is considered possible to assign probability of damage position and degree of damage by expert judgment with reference to the response and allowable value of each part.

<u>b. Secondary effects</u>
Based on the amount of displacement of the PCV and each part, equipment layout drawings, structural drawings, etc., the possibility of dropping, collision, and breakage can be analyzed, and the probability of secondary impact occurring can be given by expert judgment. It is considered possible to assign the probability of a secondary impact by expert judgment with reference to equipment arrangement diagrams, structural diagrams, etc.

4.2. Application to BWR scenarios (e.g. Diaphragm floor)

<u>a. Degree of damage/damage</u>
Check the parts constituting the diaphragm floor and the results of the seismic-resistant evaluation, and identify the locations leading to the total damage to the PCV and the locations leading to partial damage. For this purpose, it is necessary to establish an evaluation method for evaluating the impact of response to the entire PCV and the effect on the penetration part piping when the member concerned is damaged. However, this does not exist at present. It is considered as a means to examine the damage scenario according to the member damaged by the expert judgment and to carry out the identification of the probability of its occurrence. It is considered possible to assign occurrence probability of damage position and degree of damage by expert judgment with reference to the response and allowable value of each part.

<u>b. Secondary effects</u>
Based on the amount of displacement of the PCV and each part, equipment layout drawings, structural drawings, etc., the possibility of dropping, collision, and breakage can be analyzed, and the probability of secondary impact occurring can be given by expert judgment. It is considered possible to assign the probability of a secondary impact by expert judgment with reference to equipment arrangement diagrams, structure diagrams, etc.

5. How the probabilities of damage are derived using expert judgement

The specific process for applying expert judgment and its implementation will be explained in the following presentation, here we present the methodology for applying expert judgment to scenarios directly leading to core damage.

- Based on the identified issues discussed in the previous section, the dataset for the issues will be prepared and a logic tree will be constructed.

- The branching probability in the logic tree will be set based on the results of previous seismic evaluations and the knowledge of other industries.

- The above two elements (logic tree, branching probability) will be determined through expert judgment.

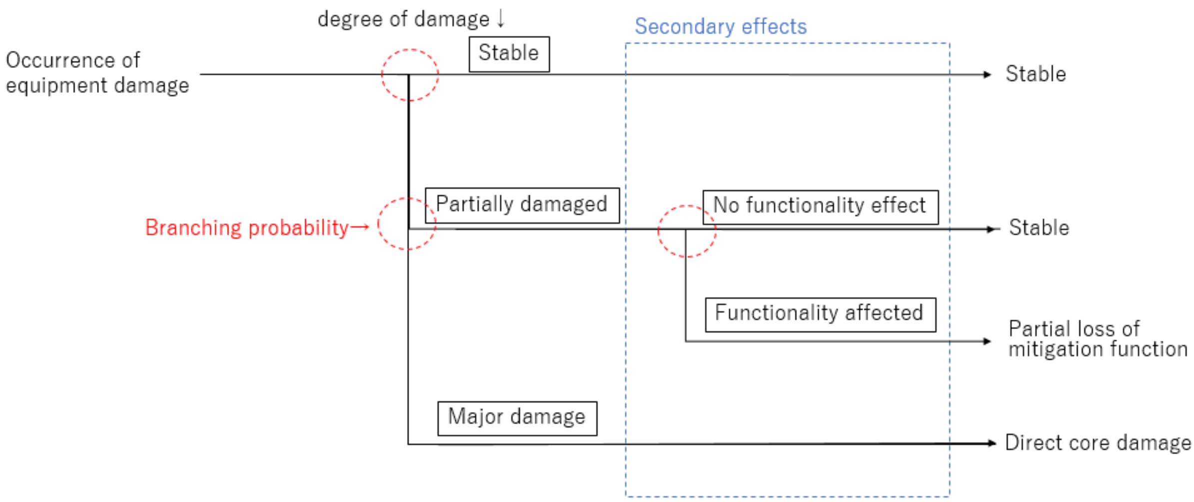


Figure 5. Logic tree image of setting damage probability and damage effect based on expert judgment

6. CONCLUSION

This paper analyzes direct core damage scenarios of seismic PRA and organizes issues for realistic scenario development. By establishing a practical "expert judgment" process that can be applied to detailed direct core damage scenarios based on the results of this time, it is expected that the seismic PRA will be further upgraded and contribute to the development of RIDM in Japan, which is a major earthquake country.

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