Recent advancements of probabilistic risk assessment methodologies and risk monitoring usages in Japan

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Abstract: The importance of Probabilistic Risk Assessment (PRA) has been highlighted not only for internal events but also for external events following the Fukushima Daiichi NPP accident in Japan. The Standards Committee of Atomic Energy Society of Japan (AESJ) is currently working on the development of the PRA implementation standards concerning the individual external events. At the same time, the Committee is studying on how to assess the combinations of external events, and has started the development of the PRA implementation standards for such hazard combinations. Besides the implementation of PRA as the quantitative risk assessment, we are studying the risk assessment procedures for various types of potential external hazards. This paper describes the Japanese recent advancements on PRA methodologies by focusing on the PRA standards, which are being developed by AESJ.

The Japanese utilities also recognize that the risk information should be used to enhance the rationality and accountability of safety-related activities, and to realize efficient management of NPPs. "Risk Monitoring" is one of the essential applications of PRA and safety-related activities. This paper describes the Japanese current status of "Risk Monitoring" usages especially on "Shutdown risk evaluation for every outage".

Keyword: Probabilistic Risk Assessment (PRA); PRA implementation standard; risk monitoring

1 Introduction

The Probabilistic Risk Assessment (PRA) for nuclear power plants evaluates the safety of nuclear power plants in a comprehensive and quantitative manner using the probabilistic methodology. The PRA focuses on the events which lead to core damage or fuel failure, identifies the accident scenarios which result in failure and development of events following the failure, and estimates the frequencies of each event and its consequence. In Japan, the Standards Committee of the Atomic Energy Society of Japan (AESJ) has been playing the leading role in establishing various PRA implementation standards (hereafter, referred to as the “AESJ Standard”) that describe the PRA methodologies and the approaches to utilize risk information obtained from PRA. There has been growing importance and necessity of the implementation of PRA and introduction of risk-informed approaches since the occurrence of the Fukushima Daiichi NPP accident.

The PRA for nuclear power plants can be roughly classified into two groups according to the characteristics of the initiating events; one for internal events, which result from equipment failure occurring inside of the power generation system and human errors while the other for external events, which result from seismic and fires, etc. The importance of PRA for external events has been highlighted following the Fukushima Daiichi NPP accident. Furthermore, it has been recognized that risk assessments not only for seismic and tsunamis but also for other potential external hazards should be performed in a comprehensive and systematic manner.

The Standards Committee of AESJ is currently working on the development of separate PRA implementation standards for each of the external events. At the same time, the Committee is studying on how to assess the combinations of external events, and has started the development of PRA implementation standards for the combinations of external hazards. In addition, the newly established Japanese regulatory requirements claim design considerations for external hazards associated both with natural phenomena and external human error. Regarding those external hazards, the Risk Technical Committee (RTC) of AESJ has established the implementation standard for the identification of assessment methods of risks associated with external hazards.

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2 Advancements of PRA methodologies

2.1 PRA initiatives in Japan

PRA for NPPs evaluate the safety of a NPP in a comprehensive and quantitative manner applying probabilistic methodology. The PRA focuses on the events which lead to core damage or large amount of fuel failure, identifies the accident scenarios which result in failure and development of events following the failure, and estimates the frequencies of each event and its effects. Efforts have been made worldwide to develop PRA techniques, apply PRA methodology to actual cases, and conduct applied research. As a result, the PRA today is well-recognized as effective means which can support the decision-making process in safety regulations, as well as in the related fields of safety engineering and operation management. In addition, Fukushima Daiichi NPP accident that occurred in March 2011 was caused by loss of multiple important safety functions due to common cause failures induced by tsunami inundation into the reactor building. The PRA is also a very valid method for analyzing the impact of common cause failures of functions important for safety that could severely affect the integrity of the reactor core and the containment.

At the past in Japan, PRA has been implemented to evaluate the validity of Accident Management strategies and the quantitative safety of NPPs in the Periodic Safety Review (PSR). Furthermore, the Nuclear Safety Commission (NSC) has issued draft safety goals in terms of public risk and determined performance objectives in terms of core damage frequency and containment failure frequency. The NSC and regulators launched discussions for implementing risk informed regulation.

The past initiatives at Japanese utilities are shown in Table 1. We Japanese have the following reflections through the past PRA activities also with in light of the Fukushima Daiichi NPP accident experiences.

- Severe accident (SA) countermeasures based on PRA are not updated since 2002.
- Slow progresses are shown in the assessment of actual plants based on external events PRA.
- There are lack of initiatives for enhancing safety beyond the level required by laws and regulations. That is, we should do more for in-house PRA utilization for the continuous plant safety improvements.

Table 1 Past PRA initiatives at Japanese utilities

PRA Initiatives	
Late 1980s	PRA research
1982	Decision by NSC (Implementation of Accident Management; AM)
1992	Notice by MITI (Future plan of AM)
1994	Utilities' release of the report on AM (PRA overview)
1997 ~	Utilities' release of the internal at-power PRA results in PSR
2001 ~	Utilities' release of the internal shutdown PRA results in PSR
2002	Utilities' release of the report on AM completion (all plants)
2009 ~	Use of PRA in determining maintenance significance
2013 ~	PRA is carrying out to draw out a severe accident scenario according to the New Regulatory Requirements

The current status of PRA in Japan is described as follows:

- All in-service commercial NPPs (BWR/PWR) have been already evaluated internal events CDF and CFF, and utilities should evaluate the risk (*i.e.*, CDF/CFF at operational mode and CDF at shutdown mode) of their own plants in the PSR at least once per 10 years.
- In the new regulatory requirements, utilities are required to conduct "Effectiveness evaluation of SA countermeasures" for both prevention and mitigation, and for this purpose, utilities are also required to conduct "Plant-specific PRA" to select "Risk-significant SA sequence groups" and "Risk-significant Containment vessel failure modes", and conduct deterministic analysis for each.
- In the new regulatory system, it is required to conduct "Plant as-is base" Level 1 and 2 PRA for both internal and external events including hazard re-evaluation periodically and continuously.
- Also, the framework of the new regulatory requirements is to encourage utilities' voluntary initiatives in view of importance of roles to be

played by the utilities in continuous improvements.

- In these voluntary initiatives, utilities take much attention to risk-informed activities such as risk monitoring procedures.
- To support these utilities' activities, many technical standards regarding PRA and risk-informed activities published and preparing under AESJ.

2.2 Development of PRA implementation standard

This subsection describes the efforts made and being made by the Standards Committee of AESJ to establish the PRA implementation standards for external events. The Committee is currently studying on how to address the combinations of external events and has initiated the work to establish the PRA implementation standard for the combinations of external events while working on the development of separate implementation standards for each of external events.

- The following individual PRA implementation standards have been already established.
  - Seismic PRA
  - Tsunami PRA
  - Internal flooding PRA
  - Internal fire PRA
- A revised version of seismic PRA implementation standard is expected to be issued soon after going through the process of discussion over the treatment of the combination of an earthquake and other external events and public hearing.
- Discussion is being held over the revision of the tsunami PRA implementation standard, including the treatment of the combination of a tsunami and an earthquake.
- Regarding the combinations of external events, the priority is given to the combination of an earthquake and accompanying events while efforts are being made to revise the individual external event PRA implementation standards sequentially by including the treatment of the combinations of the concerned external event and others. As mentioned above, the priority is given to the discussion over the revision of Seismic PRA and tsunami PRA standards, which incorporate the combinations of an earthquake/tsunami and other external events. It is planned to hold discussion over the revision of PRA implementation standards concerning internal flooding/internal fire accompanying an earthquake. It is also planned to develop an integrated implementation standard for the combinations of external events after clearly defining the consequential event and the combined event.

The AESJ Standards Committee is working on the establishment of the PRA implementation standards according to the designated priority while considering the necessity and the maturity of individual methodologies. Table 2 and Fig. 1 show the current status and progress plans related to the PRA implementation standards.

In order to establish the external hazards PRA standards which could be internationally recognized, we have been making efforts by issuing English versions of existing standards and actively participating in international conferences and information exchange opportunities. In addition, in order to contribute to the effective utilization of PRA, lectures on the PRA standards are held on a regular basis so that more people in wider areas can correctly understand PRA. At the same time, we are planning to prepare a text book describing comprehensive PRA procedures.

Table 2 Current status of PRA implementation standards at AESJ

Title of Implementation Standard	The date of Issue
At-power Level 1 PRA (revision 1) [1]	August 2014
At-power Level2 PRA [2]	March 2009
Level3 PRA [3]	March 2009
Shutdown Level1 PRA (revision 1) [4]	October 2011
Estimation of PRA parameter [5]	June 2010
Use of risk information [6]	October 2010
Common Terms and definitions used in the PRA standards [7]	September 2014
Ensuring of PRA quality [8]	March 2014
Seismic PRA [9]	September 2007
	(revision 1) Under discussions
Tsunami PRA [10]	February 2012
	(revision 1) Under

	discussions
Internal flooding PRA [11]	November 2012
Internal fire PRA [12]	June 2014
Risk analysis methodology selection for the external hazards [13]	December 2014

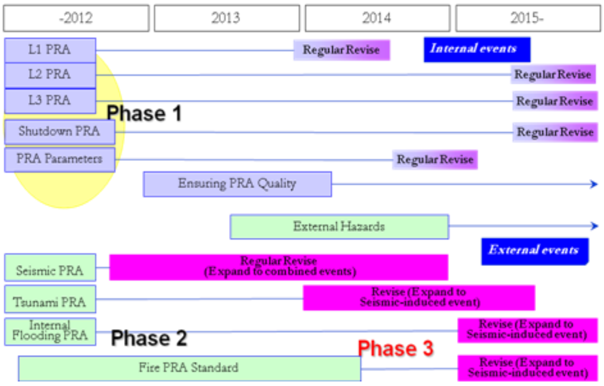

Fig. 1 Current status and progress plans of PRA implementation standards at AESJ.

2.3 Development of the implementation standard for selecting the risk evaluation methodologies for external hazards

The Fukushima Daiichi NPP accident unveiled the fact that design considerations for external hazards were insufficient and related knowledge had not been appropriately improved although risks associated external hazards were considered in the design stage. Since the Fukushima Daiichi NPP accident, the importance of discussion over to what extent other external hazards than earthquakes and tsunamis should be considered in Japan is growing ever more. This is due to the urgent need to secure safety of nuclear power plants against such external hazards that may not be frequent but cause significant effects and the increasing demands for identifying specific events as the Nuclear Regulation Authority has already included in its new safety standards natural events and external man-made events.

Considering such background, the AESJ RTC held discussion over natural phenomena or accidental man-made events aiming at the identification of appropriate risk evaluation methods. The Committee finally published the “Implementation Standard Concerning the Risk Assessment Methodology Selection for the External Hazards” (hereafter, referred to as the “Implementation Standard”) in December 2014.

The Implementation Standard comprehensively identifies external hazards including the ones that were once qualitatively determined to have no significant risk of core damage and establishes a series of assessment processes for selecting appropriate risk assessment methods for the external hazards in terms of their frequency and core damage risks. Since the intent of the risk assessment of these external hazards is not only to identify the scale of risk but mainly to establish the measures against them, not all external hazards necessarily require detailed risk assessments such as PRA. Instead, various risk assessment techniques such as quantitative assessment, hazard analysis (frequency or effect), safety margin evaluation and deterministic core damage frequency evaluation method are also applicable to the evaluation of external hazards. For this purpose, the Implementation Standard identifies the external hazards that may have a risk of core damage at plants and establishes the process for selecting the proper risk assessment technique for each external hazard in terms of its frequency and effects on plants. The establishment of the Implementation Standard is expected to contribute to correctly determining the safety of individual plants against individual external hazard of concern and developing appropriate measures against each of the hazards.

The contents of the Implementation Standard are described below from the perspective of the importance of assessing the effects of external hazards on the nuclear safety.

2.3.1 Procedure of selecting the risk assessment methods for each external hazard

Appropriate risk assessment methods for each external hazard will be generally selected according to the following process:
(1) Collection of information
(2) Identification of potential external hazards
(3) Screening of external hazards by characterization
(4) Selection of quantitative risk assessment methods

The flow of selecting risk assessment methods for each external hazard is shown in Figure 2. The details of the individual steps of the flow will be described in Subsection 2.3.2.

2.3.2 Details of individual steps constituting the flow of selecting risk assessment methods

2.3.2.1 Collection of information

Such information as plant design documents, meteorological records of the surrounding area, facility installation status and legal restrictions concerning the aircraft and vessel route that are necessary in performing evaluation on the plant of concern should be collected. Plant walkdowns shall be performed to grasp the current status of facility installation at the plant of concern.

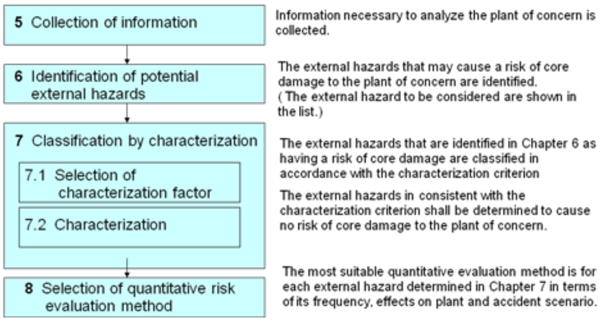

Fig. 2 Flow of selecting risk assessment methods for each external hazard.
(* The number is the chapter in the standard)

2.3.2.2 Identification of potential external hazards

Potential external hazards that may threat the safety of the concerned plant shall be identified in terms of natural hazards and man-made hazards as well as single hazards and combined hazards.

In identifying the potential external hazards, a literature survey is conducted to select several documents that comprehensively describe past natural hazards and man-made hazards occurred in Japan respectively. By sorting out the information described in those documents, a list of external hazards has been developed.

The list of external hazards needs to be updated by adding plant/site-specific external hazards and those assumed to occur considering new findings as necessary.

2.3.2.3 Screening of external events by characterization

(1) Selection of characterization elements

In performing the analysis of an external hazard which was identified in the process described in Subsection 2.3.2.2, one of the following three elements has to be chosen as the focal point:

Element 1: "Occurrence" of an external hazard
Element 2: "Arrival" of an external event
Element 3: "Impact on the plant" of an external hazard

For an external hazard whose characterization seems difficult, this step of selecting an element can be skipped to move to Subsection 2.3.2.4.

For a combination of external hazards, the highest frequency of an external event constituting the combination shall be considered as the frequency of the combined events. Or an element shall be selected through a conservative process that multiplies the impacts of the individual external hazards as the impact of the combined events. Then, the characterization described in item (2) below shall be performed.

(2) Characterization

Each external hazard shall be characterized by comparing with the criterion according to the characterization element described in item (1) above to determine if the external hazard may cause core damage risks to the concerned plant. Individual external hazards shall be qualitatively evaluated by comparing with the characterization criteria to determine if it is apparent that the external hazard will not have any core damage risks. An external hazard that may meets at least one of the criteria shall be determined to have no core damage risks on the concerned plant.

・Criterion for Element 1:
  Criterion 1: The frequency of the hazard is extremely low.
・Criteria for Element 2:
  Criterion 2: The hazard does not occur so close to the plant that causes impact on the plant
  Criterion 3: The time scale of hazard progression is sufficiently long compared with the response time at the plant
・Criterion for Element 3:
  Criterion 4: Even if it is assumed that the hazard reaches the plant, it will not result in any initiating events that lead to core damage.

For any hazard determined to have a risk of core damage as a result of the above characterization process, move to Subsection 2.3.2.4.

2.3.2.4 Selection of quantitative risk assessment methods

Any hazard determined to have a risk of core damage as a result of the above characterization process shall move to

For each of the external hazards that were determined to have a risk of core damage in Subsection 2.2.2.3, an appropriate quantitative risk assessment method shall be selected from the following methods depending on its frequency, effects on the plant and accident scenario. Some external hazards accompanying a complicated accident scenario may be subject to more than one risk assessment.

In performing the quantitative evaluations 1) through 3), the decision on whether the concerned external hazard has risks of core damage or not is made according to the established quantitative criteria. When none of these evaluation methods are able to determine the core damage risks, alternative methods will be discussed and further evaluation is performed using such an alternative method if judged applicable. The possibility of simultaneous occurrence of single hazards is also evaluated in the quantitative evaluations 1) through 3). Specifically, for a single hazard that is determined to have core damage risks, a quantitative evaluation shall be performed by combining the single hazard with other single hazards. For an external hazard which is determined to have core damage risks as a result of the quantitative evaluations 1) through 3), detailed risk assessments, such as PRA, should be conducted.

(1) Risk assessment based on the hazard frequency analysis or hazard impact analysis
(2) Safety margin evaluation
(3) Deterministic CDF evaluation
(4) Detailed risk assessment such as PRA

2.3.3 Future plans for evaluation of external hazards

As explained in the above, the Implementation Standard describes the requirements and specific methods for selecting the risk assessment methods. The AESJ RTC will further review and discuss the requirements and specific methods of quantitative risk assessment on a continuous basis.

Improvement of the PRA implementation standards is expected to lead to deeper understanding of the plant safety against all the external hazards and the establishment of appropriate measures against individual hazards.

3 Advancements of risk monitoring usages

3.1 Status of risk monitoring

The results obtained by PRA provide useful risk information that can be utilized in identifying plant vulnerabilities, establishing plant maintenance programs, and revising rules and guidelines. To facilitate the use of PRA, the government and the nuclear industry are actively working on the preparation of regulatory guidelines and industry standards and considering the application of risk-informed approaches to actual plants. It is necessary to continually monitor the risks depending on changing plant conditions, such as core damage, in future risk-informed applications. For this purpose, risk monitoring systems should be developed.

In many countries, risk monitoring has already been instigated for risk-informed applications consistent with PRA models. The status of such applications globally is described in the OECD/NEA report NEA/CSNI/R(2004)20[14].

Consequently, “Risk Monitoring” is the essential item for applying PRA and risk-informed activities, and “At-power risk monitoring in case of On-Line Maintenance” and “Shutdown risk evaluation for every outage” are two key issues for “Risk Monitoring”.

Currently in Japan, many utilities already have risk monitoring systems, or are under consideration for the systems introducing as the effective tools for the continuous plant safety improvements.

3.2 Practical example of shutdown risk evaluation for every outage

The shutdown PRA evaluations are applied as useful risk information for outage scheduling optimization. Specifically, when developing the outage schedule, the risk mitigation measures are identified by analyzing risks to incorporate them into the outage schedule and so reduce risks during outage.

To perform these activities, the risk monitoring system must be used effectively. Also for outage scheduling optimization, the risk criteria are required for decision making.

The following is one practical example of this activity in current Japanese utility.

The main objectives of shutdown PRA are to improve efficiency by reducing the outage period, and to reduce the risks during outage. To achieve these objectives, the plant must autonomously develop a low-risk outage schedule. The plant sets the in-house risk criteria as acceptable risk levels to clarify the level of “shutdown safety” for each outage.

In setting the criteria, the plant referred to cases in the US regarding management goals and the CDF values for their own past outages. The in-house risk criteria (total CDF per outage and time based CDF per hour) were determined as shown in Fig. 3.

The criteria shown above were chosen as the risk levels acceptable for the plant. If these were exceeded, the outage schedule should be modified.

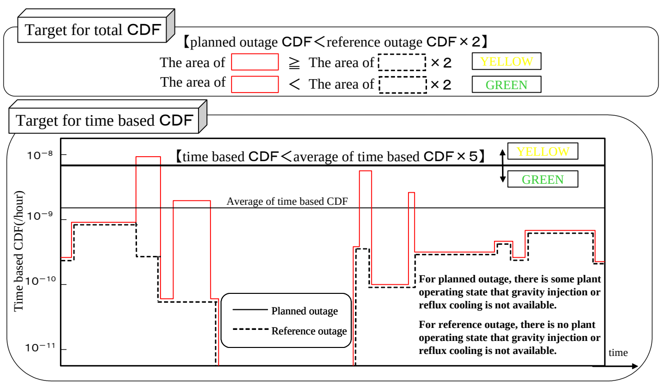

Fig. 3 Example of the in-house risk criteria for the outage scheduling optimization.

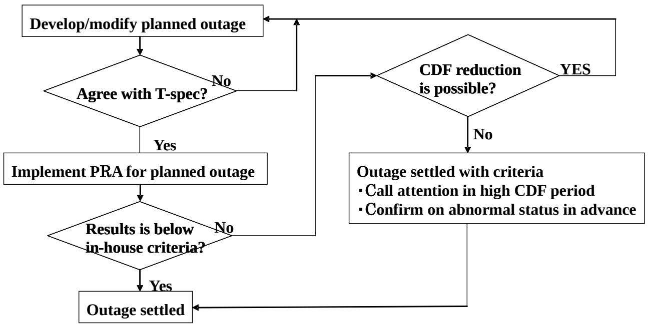

Fig. 4 Example of the flow of outage schedule optimization.

However, to achieve a balance with the other objective of PRA which is to improve efficiency, the outage schedule will be modified within a reasonably achievable range, and not all the risk mitigation measures will be reflected in the outage schedule (shown in Figure 4). If risk exceeds the in-house risk management criteria but the outage schedule cannot be modified within a reasonably achievable range, the risk will be accepted with the following restrictions:

- Greater attention to operation must be paid during the specified period with higher risk level.
- Emergency measures must be confirmed beforehand during a period with higher risk level.

4 Conclusions

The importance of PRA for external events has been highlighted following the Fukushima Daiichi NPP accident. Furthermore, it has been recognized that risk assessments not only for seismic and tsunamis but also for other potential external hazards should be performed in a comprehensive and systematic manner.

The Standards Committee of AESJ has been working on the development of the PRA implementation standards concerning the individual external events. At the same time, the Committee is studying how to assess the combinations of external events, and has started the development of PRA implementation standards for comprehensive external hazards considerations.

With the reflections through our past PRA activities, the utilities are required to conduct "Plant as-is base" PRA, and also to encourage voluntary initiatives in view of importance of roles to be played in the continuous plant safety improvements.

The utilities also recognize that the risk information should be used to enhance the rationality and accountability of safety-related activities, and to realize efficient management of NPPs.

Many utilities have been introduced Risk monitoring tool especially for the shutdown risk evaluation for every outage, and are now using those as the effective tools for the continuous plant safety improvement.
It is our mission to make a continuous effort to further improve the risk assessment methodologies and risk information usages in order to promote risk-informed assessment approaches and furthermore to the enhancement of nuclear safety.

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