Development of Approach to Establishment of Risk Informed Accident Management and Management Class in Severe Accident

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Abstract: With the primary purpose of maintaining and improving the accident management capability, Implementation Standard Concerning Preparation Maintenance and Improvement of Severe Accident Management in Nuclear Power Plant which has been developed and approved by AESJ（Atomic Energy Society of Japan）demands strategies, in both hardware and software aspects. The standard requires the effective use of risk-informed activity based on PRA as a tool and the upgrading of hardware, as well as the placement of highly-skilled resident staff at nuclear power plants（NPPs）. The standard also requires the on-going assessment of skills required, including education, enhanced training and development of skills to respond adequately to various scenarios of severe accidents, covering low frequency high consequence events.

The revision of the standard shows that accident management and management class based on vulnerability and latent risk including external events unique to the NPP can be established, the optimized program in accident management can be developed.

Keywords: Severe Accident, Accident Management, PRA, Risk, Management Classification

1. INTRODUCTION

On the basis of specific vulnerability and response capability in NPP_S, the Standard presents the assessment procedure for accident management establishment and management classification to provide the scientific and the rational accident management based on the graded approach including the validity assessment of risk reduction and safety margin holding defense-in-depth.

In the revision of the standard, the assessment procedure for accident management establishment and management classification was developed using deterministic and probabilistic approach, engineering judgment.

2. STRUCTURE OF SEVERE ACCIDENT MANAGEMENT

The Severe Accident Management Standard summarizes the technical requirements regarding the concept for preparing, maintaining, and improving accident management applicable to Japanese nuclear power plants, renovation and/or addition of equipment and the formulation of procedures based on in-depth understanding of the contents and position of IAEA NS-G-2.15 [1] and other relevant guides, which provide the basis for global nuclear safety while taking into account the lessons learned from the Fukushima Daiichi Nuclear Power Plant Accident.

The Severe Accident Management Standard defines the accident management as all the actions to be taken to cope with design extended conditions (including severe accident conditions), which provides the 4th layer of defense-in-depth, and sets the specific objectives of accident management as shown below;

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a) Preventing significant core damage
b) Terminating severe accident progression
c) Maintaining the integrity of the containment
d) Minimizing release of radioactive materials
e) Achieving a long-term stable state

To meet the above objectives, accident management should be established and continuously improved according to the PDCA cycle.

The Severe Accident Management Standard consists of 14 chapters as shown below. The main text in each chapter and its appendix (provision) specify the requirements. Appendices (reference) or explanation are added as necessary to include information which may help the user's understanding of the requirements in the standard.

1. Scope and applicability
2. Citation standards
3. Glossary
4. Principal requirements of the SAM standard
5. Extraction of nuclear power plant vulnerabilities
6. Identification of nuclear power plant capability
7. Developmet of accident management strategy
8. Renovation and/or addition of equipment
9. Accident management guidelines
10. Establishment of emergency response organization
11. Verification and validation
12. Education and training
13. Maintenance and update of accident management strategies
14. Quality assurance

Of the above chapters, specific procedures for evaluating severe accident management measures are described in the chapters from 5 to 13.

The Severe Accident Management Standard incorporates improvements shown below compared with IAEA NS-G-2.15 while taking into account the lessons learned from the Fukushima Daiichi Nuclear Power Plant Accident;

(1) Basic concept

・Only existing plants shall be subject to the accident management.
・Accident management measures shall be established and implemented according to the PDCA cycle to achieve the definite objective of continuous improvement.

(2) Events to be assumed

The Severe Accident Management Standard considers all possible events including those beyond expectation. The events shall be classified into three categories according to risk levels, and accident management measures for each category of events shall be developed considering specific features;

a. Internal events, external events and combination of internal and external events
b. Events leading to significant loss of safety functions
c. Low frequency high consequence events

(3) Attentions to be considered in performing risk assessment

Probabilistic risk Assessment (PRA) approaches are applicable to the above processes, including the selection of accident scenarios. However, in some cases where it is difficult to quantify the parameters to be used in PRA, it is important to utilize deterministic assessment and other methods. It is also important to make use of engineering judgment made by experts having extensive experience.

(4) Definition of management classes

In defining the management classes, it is important to give weighting values not only to the hardware provided for accident management but also to the software while considering risks. For the hardware, the management classes shall be mainly established for the purpose of assigning significance in terms of basic safety requirements. And for the software, the management classes shall be established for the purpose of determining the frequency of education/training and their programs as well as the plans of operation and maintenance management.

This version of Severe Accident Management Standard has added following amendments to the original version issued in 2013 taking into account the latest technical knowledge;

① More specifically describing the logic which provides the basis for establishing accident management measures according to the graded approach and the concept of defining the management classes,

② Including more detailed description about technical requirements and enhancing the contents of the appendices to provide a consensus standard for severe accident management, which supplements the Nuclear Regulation Authority requirements, to be utilized by the industry for continuous improvement of their voluntary safety improvement measures,

③ Incorporating most recent findings, including revised IAEA NS-G-2.15, and regulatory developments in the U.S. NRC and other overseas regulators, into the main text and appendices.

④ Showing the reference materials from which most recent findings through verification have been incorporated, and

⑤ Refining the description of technical requirements to more clearly specify its intent.

3. ESTABLISHMENT OF ACCIDENT MANAGEMENT AND MANAGEMENT CLASSIFICATION

3.1 Accident Management Establishment

Based on the result of “Extraction of plant vulnerabilities” and “Identification of plant response capability”, rational accident management should be established. Typical considerations for accident management establishment are as follows.

- Accident management should be established for each NPP.
- Accident management should be established for prevention and mitigation.
- Accident management should be established taking into account the restriction on access root to get to the field, operation time, severe accident environmental condition and etc.;
- Accident management for the external events should be established by choosing where to install and store to retain the effectiveness of accident management.
- The flexible response measures should be established by utilizing all equipment of the enclosure of plant, and neighborhood facilities, materials, and equipment to the events which leads to

significant loss of safety functions.

- To the events made on exception for “Extraction of plant vulnerabilities”, the plan of the education and training for the enhancement in capability which can respond to the events concerned should be formulated.

3.2 Management Classification

Based on the graded approach, management classification should be developed.

In addition to the identification of important accident sequence groups, validity assessment including defense-in-depth, risk reduction and safety margin is performed based on the integrated risk informed decision making process. The approximate assessment procedure is as follows.

Step 1: Perform risk assessment using IPE（Individual Plant Examination）or an alternative method for relevant plant and identify vulnerability in the plant. Extract accident sequence groups that core damage frequency（CDF）is higher than 10^{-6}/reactor year, or is higher than 20% of total CDF and 10^{-7}/reactor year, and classify the sequence groups into three graded significance to optimize risk and cost for management based on the criteria in NEI 91-04[2].

Step 2: Assume the accident management candidate as measures according to each accident sequence group.

Step 3: With regard to the accident management candidate, verify in the point of view of securing defense-in-depth whether they are appropriately assigned to each level, or not.

Step 4: Assess the risk reduction in the case of adopting the accident management candidate quantitatively or qualitatively using PRA or an alternative method. In the standard, the example using NEI method（NEI 16-06）[3] shows that the human error probability in manual operation and the unavailability using portable equipment or permanent equipment can be assessed, in which risk reduction can be semi-quantitatively estimated for the existing dominant sequence.

Step 5: Analyze feasibility and safety margin in the accident management using severe accident（SA）analysis code, and assess validity in the accident management candidate.

Step 6: Determine feasible accident management and management classification using the integrated decision making based on securing defense-in-depth, risk reduction and safety margin.

The management classification flow is shown in Figure 1. Here, it assumes classifying a management class into three steps.

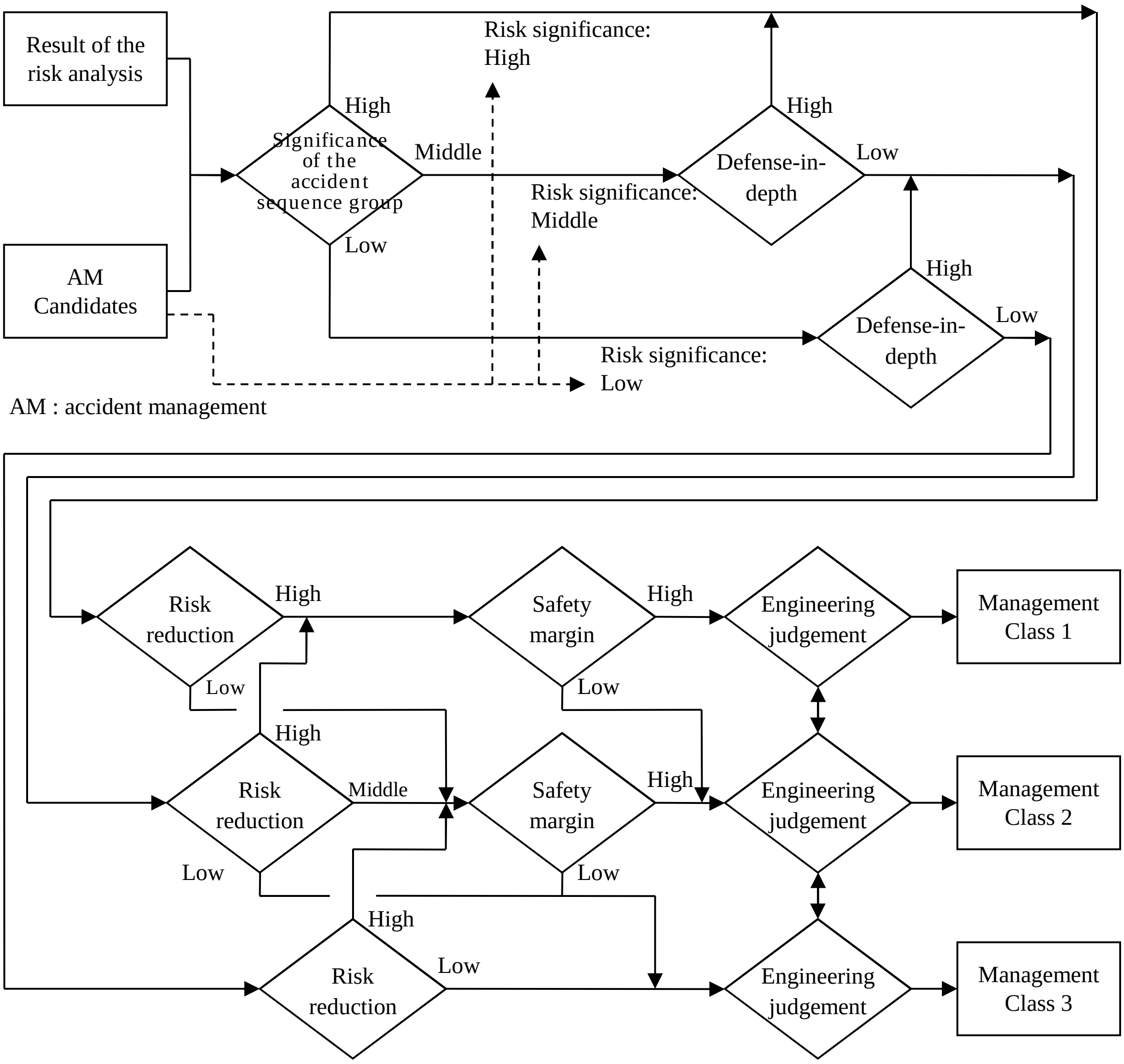

Figure 1 Example of the management classification flow

When quantitative risk assessment results, such as PRA, can be used to the management classification flow, a setup of the quantitative threshold value as a criterion for a classification of the risk significance is effective. For example, in Step-1, the example of a threshold value setup in the case of classifying the significance of the accident sequence group which results in the core damage based on internal level 1PRA result is shown in Figure 2.

Similarly, it is also possible to containment failure frequency (CFF), including occurrence frequency of containment vessel bypass (ISLOCA,SGTR), to set the relative view in a safety goal as reference. (For example, the threshold value to CFF is made into 1/10 of the threshold values of CDF.)

Although the further examination is required to apply to the external PRA, a view is considered that application is possible.

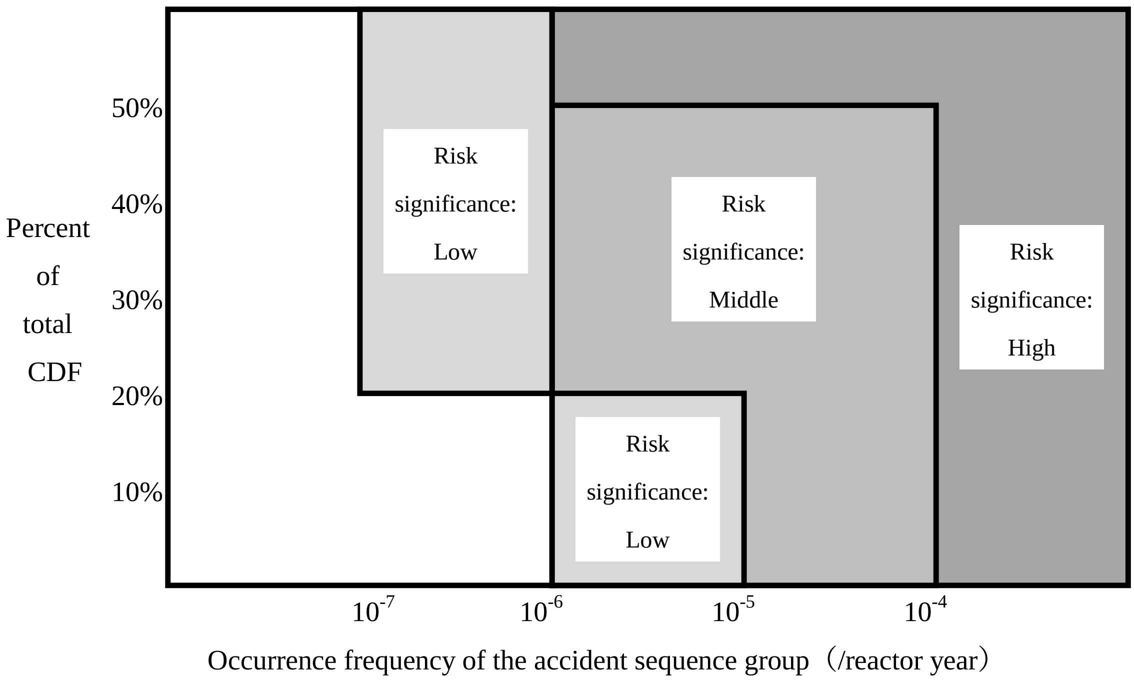

Figure 2 Example of thresholds of the management classification using CDF

According to the management class which classified in this procedure, it sets up as accident management which satisfied the basic requirements for the plant safety (redundancy or diversity, independency, earthquake-proof safety, environmental resistance, flexibility, operability, maintainability, etc.). Thereby, setting optimization of the accident management based on the graded approach can be scientifically and rationally performed.

In addition, the management class set up here should define the existing safety classification independently, and should care about that the management class 1 is not equivalent to the class 1 of the existing safety classification. Moreover, the management class should not be uniformly set up between plants, but it should be set up appropriately for every plant taking into account unique risk characteristics. Furthermore, when accident management has been improved by taking in of most recent knowledge, reexamination of the management class should be also considered.

4. EVALUATION OF RISK REDUCTION BY ACCIDENT MANAGEMENT

In order to confirm effectiveness of certain accident management, risk reduction (and adverse effect, if any) achieved by the strategy should be quantitatively or qualitatively evaluated using PRA or alternative approach. The level of detail depends on aspects such as objective of evaluation, maturity of methodology, and availability of necessary data. Three levels of approach, qualitative, semi-quantitative, and detail evaluation (PRA), would be considered according to the situation. This standard presents semi-quantitative approach as an applicable method.

4.1 Applicability of Semi-quantitative Approach

In order to apply graded approach, it is necessary to evaluate risk reduction effect using the AM candidate. The evaluation should be neither overly conservative nor un-conservative, and has to provide appropriate information for prioritization and classification of accident management.

However, sufficient information about human reliability or equipment failure data might not be acquired, especially for strategy utilizing portable equipment. In order to perform evaluation with limited information and engineering judgement, this standard incorporates semi-quantitative approach [3] that NEI is proposing to NRC as a means taking credit of FLEX equipment in risk-informed activities.

This approach focuses on elements governing reliability of accident management. Main elements are evaluated as influence rate based on AM performance situation including engineering judgment. By making appropriate estimate for these elements considering circumstances of postulated scenario, we can evaluate reasonably the magnitude of risk reduction.

4.2 Method Description

The semi-quantitative method evaluates risk reduction based on existing PRA information and estimation of unreliability for relevant accident management. Unreliability consists of failure probability of strategy and unavailability of equipment. Factors affecting the reliability are, time availability and margin, command and control (ex. procedure, staffing, communication), environmental factor (ex. functionality, accessibility), and equipment availability (redundancy such as N+1). Values for these factors are quantitatively assessed, following consideration described below.

a) Failure probability

A typical estimated failure probability is used as a nominal unavailability of the accident management that is considered sufficiently feasible.

b) Time availability and margin (TM)

Starting from nominal failure probability, the value is reduced by factor of two, when expansive (more than twice) time margin exists compared to time for deployment and startup of accident management. In case of inadequate (negative) time margin, the branch is treated as fail. The time margin is the net time available for deployment (transport, connect and initiate) of mitigating equipment. Time required to diagnose and establish accessibility should be separately considered.

c) Command and control (CC)

This branch is treated as fail without sufficient direction, staffing, and equipment required to employ mitigating strategy (such as communication).

d) Environmental factor (EF)

If hazard itself or induced event (such as fire or flood) causes the adverse environmental conditions (temperature, radiation, etc.), and lead to the degradation of accessibility or operability of mitigating equipment, a factor of two increase is applied to failure probability. In case of significant degradation is deemed, the branch is treated as fail.

e) Equipment reliability and availability (EA)

Credit of redundant train/equipment can be taken in case that more than minimum required number (i.e. N+1 or more) is available.

Unreliability (F) of the accident management is calculated by multiplying factors a)～d) described above, and adding unavailability of the equipment.

$$F = \text{Failure probability (typical)} \ast TM \ast CC \ast EF + EA \qquad (1)$$

The total risk reduction is evaluated aggregating ΔCDF (the difference of baseline CDF and mitigated CDF estimated applying factor F) for each accident sequence group that relevant accident management is applicable.

$$\Delta CDF = \Sigma_i \{CDF_{base\ i} - CDF_{base\ i} * F_i\}, \quad i\text{:Accident sequence group} \quad (2)$$

4.3 Remarks for Application

Since the approach is a simplified semi-quantitative method, following features should be noted in case of application.

- Seismic capability is not explicitly considered.
- Since the approach does not cover resultant sequence following success path for accident management of interest, it should be interpreted as the order of risk reduction.

5. EXAMINATION OF SAFETY CLASSIFICATION FOR AM

Safety classification for each AM should be set up based on section 3 "AM development and AM safety classification methodology" and with consideration for following "Items required to be identified for AM". Example of AM safety classification for BWR based on the above and methodology described in section 4 "evaluation method for risk reduction effect of AM" is described as following.

(1) Items required to be identified for AM safety classification

Following items should be identified as background information of engineering and/or qualitative judgement for AM safety classification.

- The safety function(s) to be performed by the AM as mitigation measures and/or related operator actions
- The time following a postulated initiating event at which, or the period for which, the AM will be called upon to perform a safety function such as short term (1 day), middle term (3 days), long term (7 days) or more longer term (months or years)
- The frequency at which the AM will be required to achieve a safety function
- Environmental condition of the AM in severe accident
- Level of difficulty of the AM operation and control

Considering about the time following a postulated initiating event at which, or the period of which, the AM will be called upon to perform a safety function based on above items is particularly important.

In the "short term" phase, since the time margin is short, if it is required to cope with the beyond design basis accident including severe accident by initiating existing safety systems very quickly, those systems should be designed to have automatic initiation functions. Even if those systems can be initiated by only manual operations, those operations have to be able to achieve in the main control room in this phase. In the "middle term" phase, there is enough time to prepare the mobile equipment and to manage responses against the accident by operator in the site. In the "long term" phase, supports from off-site are available and onsite or offsite operators can manage the responses against the accident. In the "more long term" phase, stable cooling of reactor is succeeded and the accident is moving toward safe shutdown state.

Considering the classification by significant accident sequences at each phase described the above makes items required to be identified AM safety classification more clear. Moreover, (environmental) condition where the AM is carried out can be considered at each phase. These improve the reliability of classification for AM.

(2) Example of safety classification of AM for BWR

Based on the PRA of representative BWR without consideration of AM, classification for AM during SBO (station blackout) which is one of the significant accident sequences of BWR is considered in this section. Risk reduction effect is quantitatively and qualitatively considered. AM to prevent core damage (e.g., alternative high pressure injection, alternative high voltage power supply) shown in Table 1 are classified.

a) Quantification of risk reduction effect of AM

CDF reduction effect of each AM is evaluated based on the PRA of representative BWR without consideration of AM and methodology described in section 4 “evaluation method for risk reduction effect of AM”. The total CDF summed up the internal and the external event (seismic) PRA is 1.8×10^{-5}/reactor year. CDF reduction effect of each AM is classified by the magnitude of ΔCDF (low, medium, high) as shown in Figure 3. Based on this ΔCDF level, AM shown in Figure 3 can be classified based on the quantification. As shown in Figure 3, the largest ΔCDF values are provided by mobile power sources, alternative high voltage AC power sources and alternative mobile injection which are effective against long term SBO due to the earthquake (loss of off-site power due to the earthquake, loss of EDG, outage of RCIC due to the loss of power source after 8 hours operation) in the SBO sequence. The second largest ΔCDF values are provided by alternative high pressure injection, black-start and alternative DC power source which are effective against short term SBO. Since power sources from neighboring plant using tie line is effective against only SBO caused by internal event, CDF reduction is limited. Alternative low pressure injection has limited risk reduction efficiency since it is not credited for the seismic event because of utilization of existing system which is not seismically classified.

b) Qualitative consideration of risk reduction effect of AM

Since some items required to be identified to AM cannot be quantitatively considered, qualitative consideration to prioritize AM is conducted. Also, the class of AM which cannot be quantitatively considered is qualitatively determined. The following is example of classification for AM during the middle term.

<u>Middle term</u>

To manage the accident to safe shutdown state, alternative AC power source, depressurization of reactor and heat removal by RHR are prioritized. When the AC power source cannot be available, management of supply of DC power source to maintain RCIC function and injecting water to the reactor by alternative injection after depressurization of the reactor are important. Containment venting is also required to avoid increasing the PCV pressure. When the AC power source cannot be available, it is difficult to access the close area to suppression chamber due to severe environmental condition (i.e., the water temperature of the suppression pool in the PCV increases over 100℃).

[Prioritization of AM classification]

・For water injection, alternative mobile injection is classified as class 1 since it has a large risk reduction effect. Alternative low pressure injection is classified as class 2 considering the diversity of injection measure.
・For enhancement of depressurization system, the air tank and battery for air-operated valve are classified as class 1 due to the importance of depressurization. Air compressing facility is classified as class 2 since it generates air source of various systems.
・For heat removal, since containment venting continues while AC power source is not available, containment venting facility (including enhancement of component such as PCV vent valve and air tank for air-operated valve) is classified as class 1.
・Enhancement of battery capacity is classified as class 1 since continuous operation of RCIC is required.

Table 1 shows that safety classification for AM based on the qualitative consideration as described above at each phase.

Table 1 Safety classifications for AM based on the quantification and qualitative consideration (Core damage prevention)

	Short term (～8 hours)	Middle term (8 hours～72 hours)	Long term (72 hours～7 days)	More longer term (7days～)
Class 1	･Alternative high voltage AC power source	･Alternative high voltage power source ･Alternative mobile injection ･Enhancement of reactor depressurization system (air tank and battery capacity for air-operated valve) * ･Mobile power sources ･Enhancement of component of containment venting system) (Containment venting valve, air tank for air-operated valve) *	･Recovery of off-site power*	—
Class 2	･Alternative high pressure injection ･Black start (Manual initiating of RCIC) ･Enhancement of battery capacity	･Alternative low pressure injection* ･Enhancement of reactor depressurization system (SRV, air compressing facility) * ･Enhancement of battery capacity*	—	—
Class 3	･Low voltage AC power Sources from neighboring plant using tie line by adjacent unit	･Low voltage AC power sources from neighboring plant using tie line ･High voltage AC power sources from neighboring plant using tie line	—	—

[grey shading] : The class of this AM becomes higher due to considering not only quantitative but also qualitatively.

* : The class of this AM determined qualitatively.

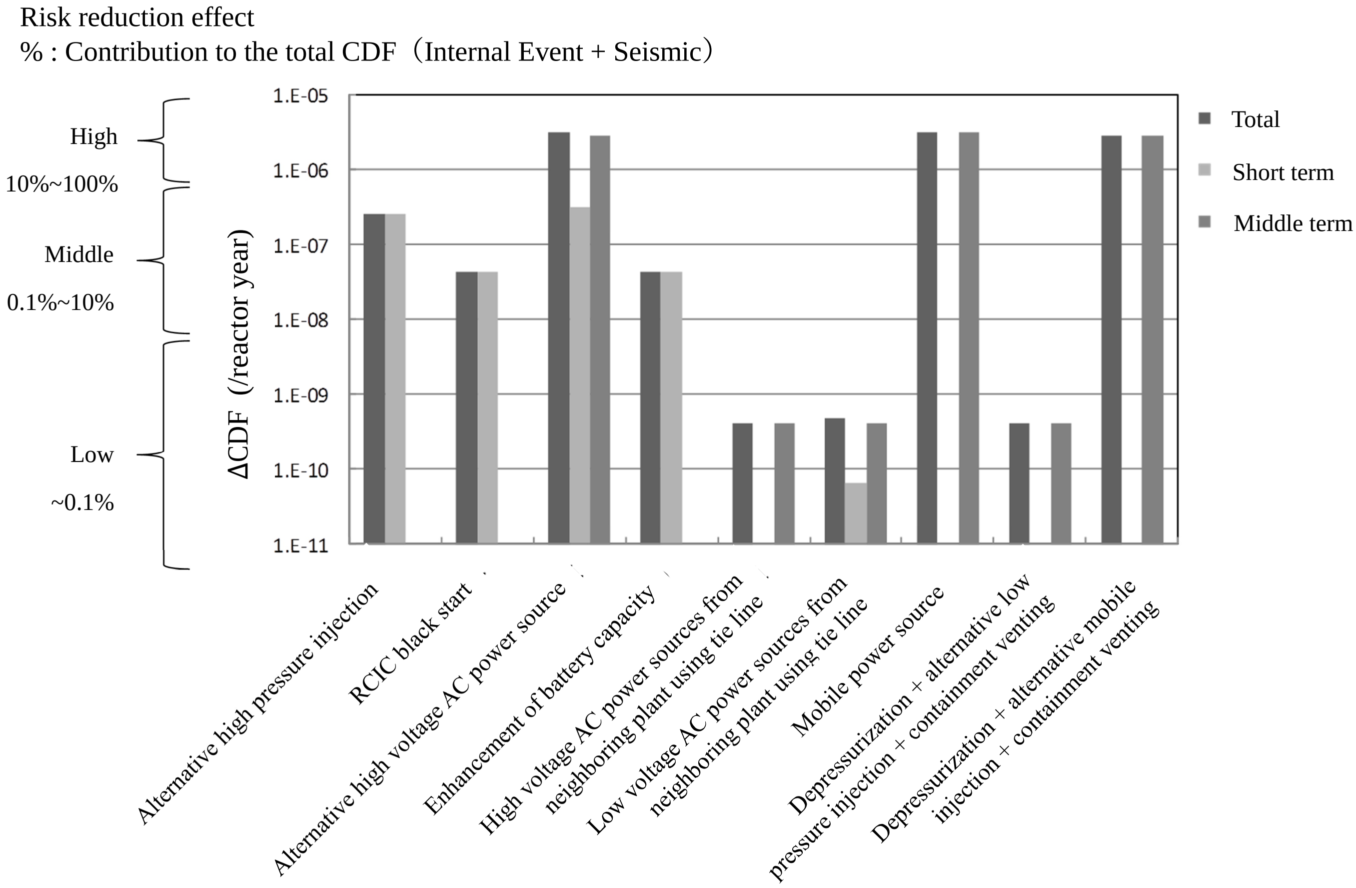

Figure 3 Comparison of ΔCDF of each AM

6. CONCLUSION

The trial assessment using the procedure for accident management establishment and management classification shows that accident management and management class based on vulnerability and latent risk including external events unique to each NPP can be established, and that the optimized program in accident management can be developed.

In the revision, NEI reliability assessment method for management using FLEX component is applied during severe accident. It is shown that the risk reduction effect can be simply calculated, and that the method can be alternative to PRA with complicated human error model in accident management.

It is significant to assign resources to optimized operation on the basis of class for system modification, addition, maintenance, procedures and training in order to embody management classification to the accident management.

In near future, it is recommended that the pilot studies will be performed in the existing plant, the feasibility and optimization of the accident management will be verified with checking the applicability.

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Reference

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