Study on Risk Indicator for Appropriate Plant Maintenance Considering Aging Effect

Akihiro Mano, Akira Yamaguchi and Takashi Takata
Graduate School of Engineering, Osaka University
2-1 Yamada-oka, Suita, Osaka, Japan
mano_a@qe.see.eng.osaka-u.ac.jp, yamaguchi@see.eng.osaka-u.ac.jp
takaka_t@ see.eng.osaka-u.ac.jp

ABSTRACT

Since, nuclear power plants run for a long term and plant component may deteriorate due to aging, plant safety must be maintained through maintenance activities of components. The maintenance will become more important as the number of aged plant increases. In the planning of maintenance, one must select appropriate components and interval. In general, Fussell-Vesely importance (FV) and Risk Achievement Worth (RAW) are used as a risk indicator for the maintenance. A priority order of each component can be evaluated using those risk indicators at a certain condition. However, the influence of aging (time history) on the order cannot be estimated directly.

In the paper, a change of conditional core damage probability (ΔCCDP) and a change of conditional containment failure probability (ΔCCFP) are proposed as additional indicators in which the aging effect is evaluated directly so as to determine the priority order. A simplified level one probabilistic risk assessment (PRA) has been carried out in order to investigate the change of the risk indicators by considering the change of a component failure probability due to aging.

In the analyses, three conditions are assumed; base (original) state, aging state and further aging state without maintenance activities. It is demonstrated that the proposed indicator (ΔCCDP and ΔCCFP) reveals the aging effect of each component, while the change of the FV and RAW represent unrealistic behavior through the states. As a result, it is found that the ΔCCDP and ΔCCFP are superior to the others in terms of the ability to evaluate components appropriately in deteriorated (aging) states and take account of differences of deterioration behavior. It is also found that the priority order of the multiple-components maintenance at the same time can also be evaluated using the ΔCCDP and ΔCCFP. Additionally, a risk informed decision making based on the risk acceptance criteria can be discussed for the maintenance procedure using the proposed indicator.

KEYWORDS

Maintenance, Risk indicators, Probabilistic risk assessment, Deterioration

1. INTRODUCTION

In a nuclear power plant (NPP), one must maintain and progress safety level of the plant so as to keep a radiological risk as low as reasonably achievable. Since NPPs run for a long time and components of the plants will deteriorate due to aging, maintenance activities of components is quite important. Therefore, a priority order of each component and its interval must be selected appropriately. Hence risk indicators will be one of the most significant indexes for determining the maintenance activities.

In the previous studies [1]-[3], Fussell-Vesely importance (FV) [1] and Risk Achievement Worth (RAW) [2] are chosen as the indexes. FV and RAW are defined respectively in the following.

$$FV = \frac{F - F_{A=0}}{F} \tag{1}$$

$$RAW = \frac{F_{A=1}}{F} \tag{2}$$

where F is the risk measures, such as a conditional core damage probability (CCDP) and a containment failure probability (CCFP) that are derived from quantification of Probabilistic Risk Assessment (PRA). Subscript A=0 means the condition in which a risk measure of focusing component A is set to zero (no failure) and A=1 indicates the converse (no success).

As shown in Eq. (1), FV indicates the improvement effect of component A against the risk and thus the priority of the maintenance can be selected. However, FV becomes small when the reliability of the component is high although it is quite important from the view point of safety function. RAW is the proportion of the risk measure the under the loss of function of component A to that in normal condition. Accordingly, the importance against accident can be evaluated using RAW. Consequently, both FV and RAW are used as the indexes. Figure 1 shows an example of the significance map for maintenance using FV and RAW [3]. As seen in Fig.1, high FV and RAW mean a high priority and low FV and RAW reveal a low propriety for the maintenance activities.

A deterioration of component due to aging is one of the key issues in the maintenance activity. A reliability of component will reduce during the interval of the maintenance. Since a relative importance among components of the NPP can be obtained under a certain condition by FV and RAW, an influence of accumulated deterioration (time history of the deterioration) on the importance cannot be evaluated by the indicators.

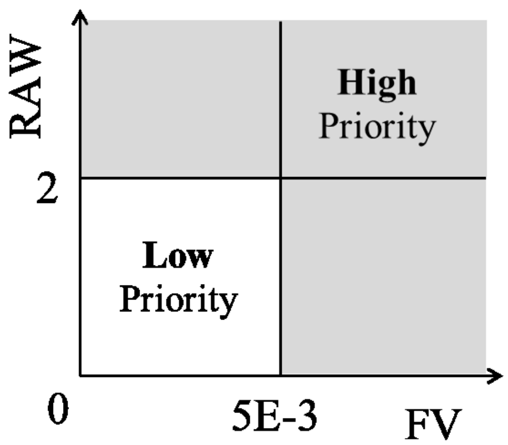

Fig.1 Maintenance Importance [3]

In this paper, a change of conditional core damage probability (ΔCCDP) and a change of conditional containment failure probability (ΔCCFP) are proposed as additional indicators in which the aging effect (deterioration) is evaluated directly so as to determine the priority order. A simplified level 1.5 PRA which assess events to lead to containment failure has been carried out in order to investigate the change of the risk indicators by considering the change of a component failure probability due to aging.

2. A PROPOSED OF RISK INDICATORS

2.1 Indicators of Changing Risks

In a risk informed decision making, a change of core damage frequency (ΔCDF) and a change of containment failure frequency (ΔCFF) are used as an indicator of changing risk. Figures 2 and 3 show the acceptance guideline on the decision making for internal events of PRA issued by the Atomic Energy Society of Japan (AESJ) [4]. Here, CDF and CFF means core damage frequency (CDF) and containment failure probability (CFF) before a safety related activity and ΔCDF and ΔCFF means a risk change involving the safety related activity. A decision making of a proposed safety related activity is carried out based on the maps shown in Figs.2 and 3. In region I, no risk changes are allowed. Therefore, if CDF or ΔCDF exceeds the boundary between region I and region II, it means that the proposed safety related activity is prohibited. In region II, the proposed safety related activity is allowed, but compensatory activities are required to control the risk increase in region II-1 or it is required to consider the compensatory activities in region II-2. In region III, the proposed safety related activity is allowed.

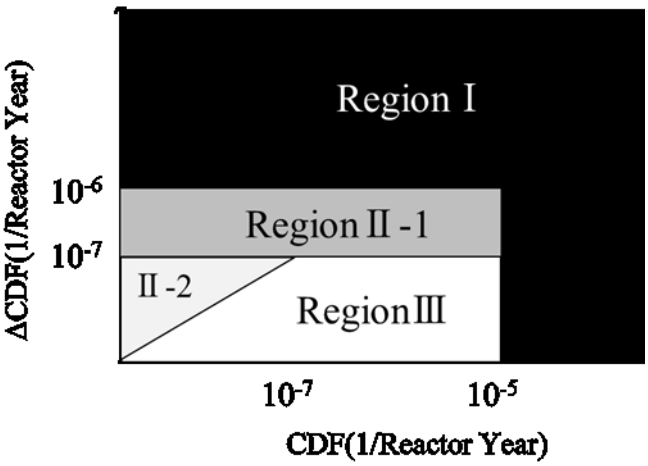

Fig.2 Acceptance Guideline for CDF [4]

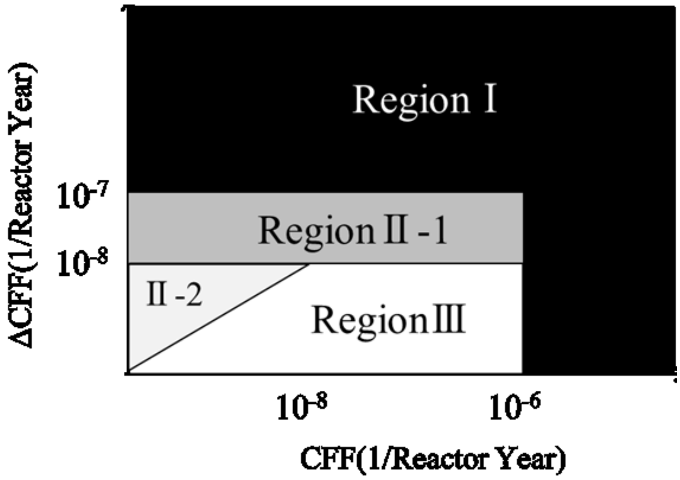

Fig.3 Acceptance Guideline for CFF [4]

In the PRA, an influence of component's deterioration due to aging acts in a manner similar to a change of safety relative activity. Consequently, ΔCDF and ΔCFF have a potential as the indicator of changing risk in a plant maintenance management. CDF and CFF are calculated by multiplying an initiating event frequency by CCDP and CCFP respectively. Therefore, ΔCCDP and ΔCCFP are focused on as the indicator.

2.2 Definition of Proposed Indicators

The evaluation of the risk change due to aging requires definition of starting and end points of the risk change. Three aging conditions of components are assumed so as to define the starting and end points of the risk change as; Base state, Deteriorated state and Further deteriorated state without maintenance activities. All components are assigned failure probabilities at each condition. The failure probabilities are the highest at the further deteriorated state and the lowest at the base state. The definition of proposed indicators for ΔCCDP is specifically described below.

CCDP and ΔCCDP are defined on the assumed conditions as shown in Fig.4.

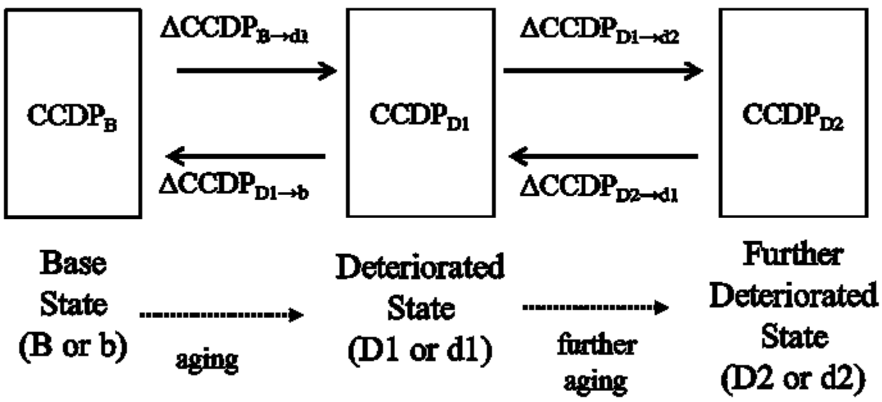

Fig.4 Defined CCDP on the Assumed Aging Conditions

Here, B and b indicate the base state, D1 and d1 indicate the deteriorated state and D2 and d2 indicate the further deteriorated state without maintenance. ΔCCDP is described like in the following.

$$\Delta CCDP^{A}{}_{S1\rightarrow S2} = \left| CCDP_{S1} - CCDP^{A}{}_{S1\rightarrow S2} \right| \quad (3)$$

where subscript S1 means the states in which all components are the same condition and is written in capital B, D1 and D2. Subscript S2 means the states where the aging condition of A is changed from the others and is written in lower case letters b, d1, and d2. For example, $\Delta CCDP_{D1\rightarrow b}$ is defined as shown in Eq. (4).

$$\Delta CCDP^{A}{}_{D1\rightarrow b} = \left| CCDP_{D1} - CCDP^{A}{}_{D1\rightarrow b} \right| \quad (4)$$

where $CCDP_{D1}$ is the CCDP with the all components at the deteriorated state, $CCDP^{A}{}_{D1\rightarrow b}$ is the CCDP with component A at the base state and the component except A staying at the deteriorated state.

In Fig.4, there are two defined ΔCCDP between the same aging states such as $\Delta CCDP_{D1\rightarrow b}$ and $\Delta CCDP_{B\rightarrow d1}$. Maintenance activities would be conducted after some aging thus it is appropriate for plant maintenance management to set the deterioration state (D1) as a reference point. Therefore, $\Delta CCDP_{D1\rightarrow b}$ and $\Delta CCDP_{D1\rightarrow d2}$ are selected as the indicators. $\Delta CCDP_{D1\rightarrow b}$ can evaluate histories of past deterioration of each component and more deteriorated component from the base state to the deteriorated state indicates a component which reduces more overall risk by maintenance. $\Delta CCDP_{D1\rightarrow d2}$ can evaluate predicted deterioration of each component without maintenance and maintaining the components predicted deterioration largely can control forward risks. Both histories of past deterioration and predicted deterioration without maintenance should be considered in the maintenance. Therefore, Eq. (5) is proposed as indicators so as to determine the priority order for maintenance.

$$\Delta CCDP^{A} \equiv \Delta CCDP^{A}{}_{D1\rightarrow b} + \Delta CCDP^{A}{}_{D1\rightarrow d2} \quad (5)$$

ΔCCFP is proposed in the same manner as ΔCCDP described in Eq. (6).

$$\Delta CCFP^{A} \equiv \Delta CCFP^{A}{}_{D1\rightarrow b} + \Delta CCFP^{A}{}_{D1\rightarrow d2} \quad (6)$$

3. ANALYSIS OF THE RISK INDICATOR ON PRA

3.1 The Condition of Calculating the Risk Indicators

As a simplified level 1.5 PRA model [5] [6] of a typical boiling water reactor (BWR), Mark I plant, is considered to calculate the proposed indicators and investigate the effectiveness of the indicators. Large loss of coolant accident (LLOCA) initiator event tree (ET) is considered. The frequency of LLOCA is set to 2.20E-5 [1/reactor year] [5] and common cause failure modes are ignored for simplicity in the model. Figure 5 and 6 and Table 1 summarize the present ET. A commercial PRA software, RISKMAN Ver. 14.2.1 is used to calculate the risk indicators.

With regard to the aging deterioration model on the ET analysis, two models are taken into account as in Table 2. One is the constant rate model in which a failure probability of component is proportional to an aging duration. The other is the threshold model where the failure probability increases gradually until a certain time and then increases exponentially. β in Table 2 means the modifier at the further deteriorated state (D2) and is set to 10 considering error factors of the component. In the PRA analyses, the constant rate model is applied to active components whereas the deterioration of passive components follows the threshold model. The deterioration model of each component is also summarized in Table 1.

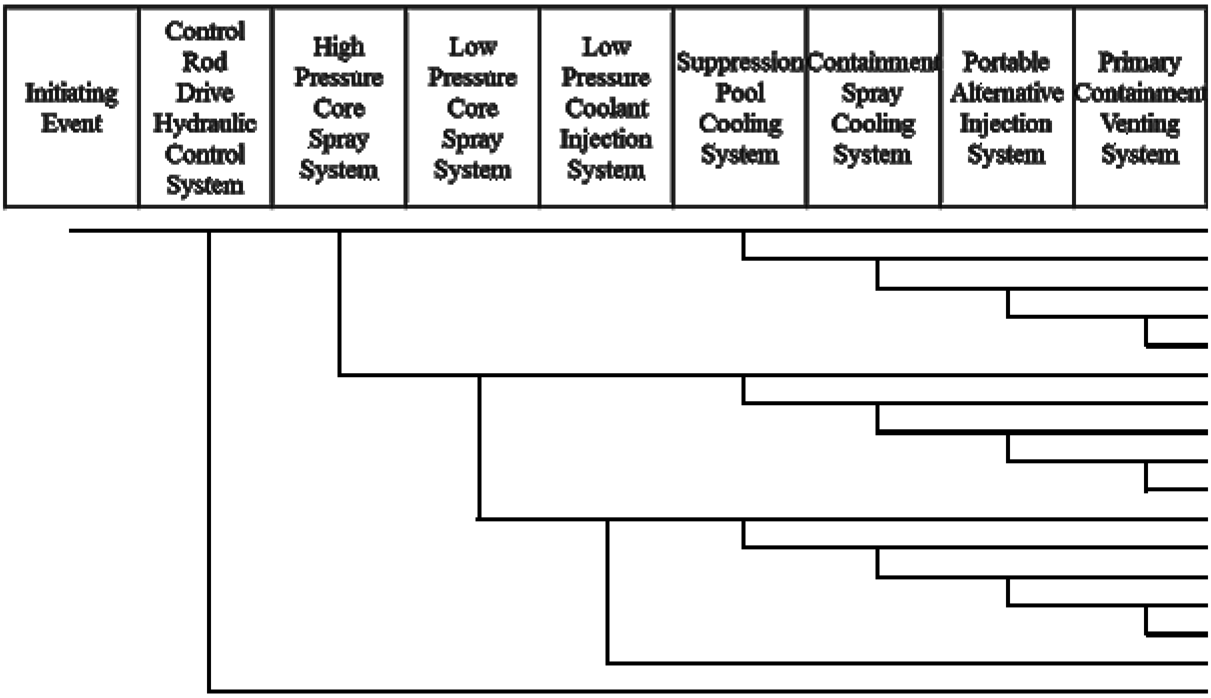

Fig.5 ET for Core Damage

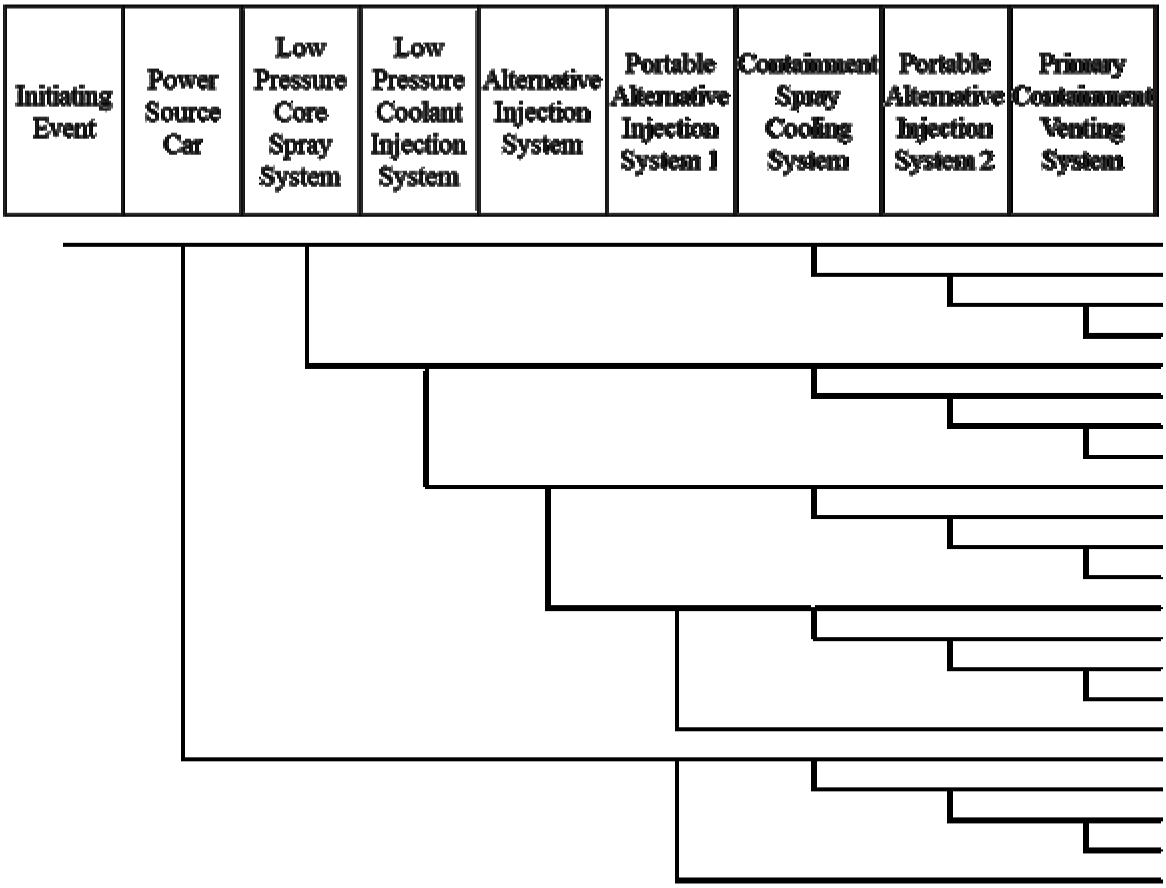

Fig.6 ET for Containment Failure

Table 1. Primary component list

Component	Deterioration model
High Pressure Core Spray System	
Pump	Constant rate
Motor operated valve 1, 2, 3	Constant rate
Strainer	Threshold
Air conditioner	Constant rate
Low Pressure Core Spray System	
Pump	Constant rate
Motor operated valve	Constant rate
Strainer	Threshold
Air conditioner	Constant rate
Low Pressure Coolant Injection System	
Motor operated valve 1, 2, 3	Constant rate
Air conditioner 1, 2, 3	Constant rate
Suppression Pool Cooling System	
Motor operated valve 1, 2	Constant rate
Containment Spray Cooling System	
Motor operated valve 1, 2	Constant rate

Component	Deterioration model
Residual Heat Removal System	
Strainer 1, 2	Threshold
Pump 1, 2	Constant rate
Motor operated valve 1, 2, 3, 4, 5, 6, 7, 8	Constant rate
Heat exchanger 1,2	Threshold
Makeup Water System Condensated	
Motor operated valve	Constant rate
Primary Containment Venting System	
Motor operated valve 1, 2, 3, 4, 5	Constant rate
Air operated valve 1, 2, 3	Constant rate
Rupture disk	Threshold
Filter 1, 2	Threshold
Fan 1, 2	Constant rate
Alternative Injection System	
Pump 1, 2	Constant rate
High Pressure Core Spray Service Water System	
Heat exchanger	Threshold
Pump 1, 2	Constant rate
Strainer	Threshold
Motor operated valve	Constant rate
Residual Heat Removal Service Water System	
Pump 1, 2, 3, 4, 5, 6, 7, 8, 9, 10	Constant rate
Strain 1, 2	Threshold
Motor operated valve 1, 2, 3, 4	Constant rate
Heat exchanger 1, 2, 3, 4, 5, 6	Threshold
Alternating Current Power Supply System	
Transformer 1, 2	Threshold
Diesel generator 1, 2, 3	Constant rate
Fan 1, 2, 3	Constant rate
Direct Current Power Supply System	
Battery	Threshold

Table 2. Aging deterioration model

Deterioration model	Modifier for failure probability		
	Base state (B)	Deteriorated State (D1)	Further deteriorated state (D2)
Constant rate	×1	×(1+β)/2	×β
Threshold	×1	×1.1	×β

In the investigation of the present indicators, the following four components are selected as a maintenance target from the view point the significance in the PRA analysis as shown Table 3: Residual Heat System Service Water system motor operate valve (A), Primary Containment Venting System air operated valve (B), Residual Heat System Service Water system heat exchanger (C) and High Pressure Core Spray system strainer (D).

Table 3. selected components for evaluation

Component	Assigned symbol	Deterioration model
Residual Heat System Service Water system motor operate valve	A	Constant rate
Primary Containment Venting System air operated valve	B	Constant rate
Residual Heat System Service Water system heat exchanger	C	Threshold
High Pressure Core Spray system strainer	D	Threshold

3.2 Result and Discussion
3.2.1 FV and RAW

The selected components are evaluated by FV and RAW on the three each condition: all components at the base state (B), the deteriorated state (D1) and the further deteriorated state (D2). As shown in Fig.7, arrows represent the direction of aging. Hence the starting points of arrows written in solid line mean the evaluation at the base state and the end points of dotted line mean the evaluation at the further deteriorated state. The criteria of significance for maintenance are written in black solid line in the figure.

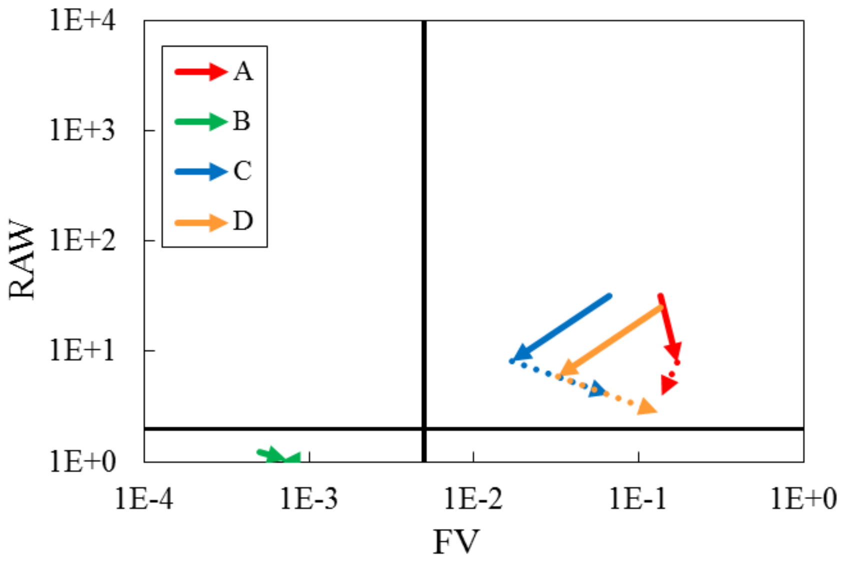

Fig.7 Evaluation by FV and RAW

In Fig.7, the evaluations move on to lower side and indicate decreases in the importance of maintenance with aging as shown by the component A, C and D. FV and RAW are proportion of risk level and evaluate relative priorities at each conditions. Therefore, the evaluations by FV and RAW can be unrealistic with considering aging deterioration and FV and RAW do not seem appropriate indicators for determining the maintenance priorities.

3.2.2 Present indicators

The selected components are also evaluated by the proposed ΔCCDP and ΔCCFP on the assumed condition. The ΔCCDP in each component is shown Fig.8.

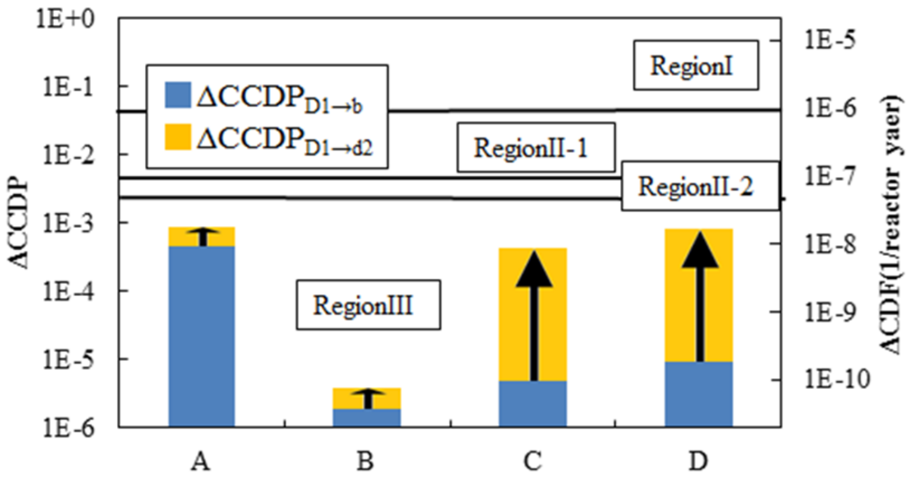

Fig.8 Evaluation by the ΔCCDP

As seen in Fig.8, it is apparent that the aging effect is pictured clearly comparing with Fig.7 and both risk changes from the deteriorated state (D1), history of past deterioration ($\Delta CCDP_{D1\rightarrow b}$) and predicted deterioration without maintenance ($\Delta CCDP_{D1\rightarrow d2}$), are obvious. In components C and D, the threshold type aging is assumed. Consequently, the increase of the risk is significant at the further deterioration state. Hence it is concluded that the summation of the past and future deterioration (Eq. (5)) is important from the viewpoint of the plant safety.

In addition, the proposed ΔCCDP applies to the risk acceptance guideline through multiplying the ΔCCDP by the initiating event frequency. Hence the maintenance activities can be evaluated similarly to the safety related activities by the guideline. The importance for maintenance can be evaluated in terms of systematic safety. Examples of the evaluation for the guideline are also shown in Fig.8. ΔCDF on the right y-axis are calculated through multiplying each ΔCCDP by frequency of LLOCA in the analysis.

Figure 9 shows analytical result of the ΔCCFP. Since component B is important for a protection of the containment vessel failure, the priority of component B is higher than that in case of the ΔCCDP as shown in Fig.9. In the present study, both the ΔCCDP and ΔCCFP are calculated under the condition of LLOCA occurrence. Therefore, the ΔCCFP includes the influence of the core damage probability. From the view of total plant safety, it seems that the ΔCCFP is appropriate rather than the ΔCCDP. In general, CDF and CFF are the indicators for the level 3 and 4 of the defense in depth (DiD) concept [7]. When CCFP is evaluated under the condition of the core damage occurrence instead of the initial event occurrence, the present indicators can be applied as an independent indicator for the effectiveness of level 3 and 4 of the DiD.

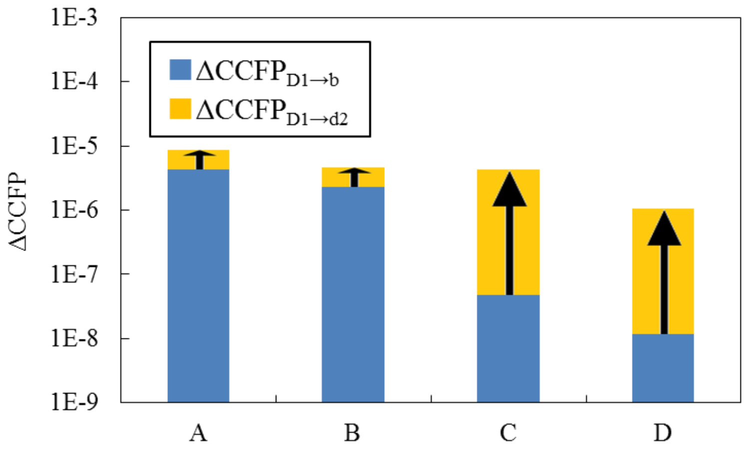

Fig.9 Evaluation by the ΔCCFP

The priority order of combination of multiple components can be evaluated by the proposed indicators as is the case in single component through ET analyses. In addition, the evaluations of combination are broadly applicable. For example, the number of the components conducted maintenance activities can be cut down by comparing the priority between combinations consisted of different numbers of components. The evaluation of combination by the ΔCCDP is shown Fig.10. As seen in combination AD (component A and D) and BCD (component B, C and D) in Fig.10, the both priority orders are similar thus it would be more reasonable to conduct maintenance activity for combination AD than combination BCD.

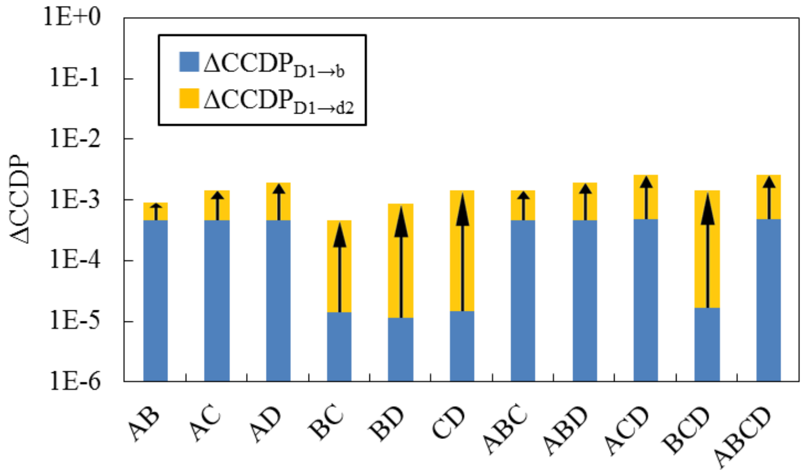

Fig.10 Evaluation of combination by the ΔCCDP

The components which do not cause risk change due to aging cannot be evaluated by the proposed indicators although the components are important from the view of the safety function. Such components can be evaluated by RAW. Since the evaluation by RAW degrade due to decrease of overall reliability with deterioration as shown in Fig.7, the RAW with the aging condition of all components at the base state is appropriate for evaluation of the components. Because the proposed ΔCCDP and ΔCCFP are effective for the components which cause large risk changes and the RAW are effective for the critical components against accident regardless of its reliability, the proposed indicators should be used for the evaluation of the priority order for repairs or replacements and the RAW should be used for the evaluation of the priority order for inspections. Therefore, the combination of the proposed ΔCCDP, ΔCCFP and the RAW is effective for plant maintenance management if the failure probabilities at the aging conditions are available.

4. CONCLUSION

In the paper, the ΔCCDP and ΔCCFP are proposed as the additional indicators by which the deterioration is evaluated directly so as to determine the priority order of component for maintenance. It is because that the influence of deterioration (time history) on the order cannot be evaluated directly by FV and RAW which are generally used as indicators for maintenance although the influence is key issue. Among the assumed three aging conditions (Base state, Deteriorated stated and Further deteriorated state without maintenance), the ΔCCDP and ΔCCFP are defined to evaluate both histories of past deterioration and predicted deterioration without maintenance of each component at the reference point.

In order to investigate the effectiveness of the indicators, a simplified level 1.5 PRA is carried out. FV, RAW, the ΔCCDP and the ΔCCFP are calculated through the assessment. As for the aging model, two deterioration types (constant rate type and threshold type) are assumed in the each failure probability of component. The analyses of evaluations by FV, RAW, the ΔCCDP and the ΔCCFP show some insights about the priority order and methodology of the maintenance as described below.

The ΔCCDP and ΔCCFP show the aging effects of each component more clearly than FV and RAW and importance of both past and predicted deterioration in the maintenance. The ΔCCDP and ΔCCFP are appropriate to the indicators for maintenance such as repairs and replacements. In terms of overall risks, the ΔCCFP is effective for the evaluation. Meanwhile, the ΔCCFP under the condition of occurrence of core damage and ΔCCDP are effective form the view point of defense in depth. The evaluations of the components can be compared with the risk acceptance guideline and the guideline can apply to the planning maintenance. The priority order of combination of multiple components can be evaluated by the proposed indicators in the same way as single component. Besides, the RAW with the aging condition of all components at the base state is used for the evaluation of the priority order for inspections.

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