Research on acceptable criteria and calculation method of maintenance rule performance indicator

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Abstract： The current acceptable criteria of maintenance rule Performance indicator is too strict for new nuclear power units with lower benchmark risk, and relatively lenient for old units with higher benchmark risk. The use of classical estimation method for equipment reliability parameters in PSA model overestimates the impact of equipment failure probability with time, and also hinders the optimize of surveillance frequencies. To solve the above problems, this paper sets up an acceptable criterion and calculation method.

Keywords: Maintenance rule; Performance indicator; Acceptable criterion; Configuration risk management

1. INTRODUCTION

The 10 CFR50.65 “Requirements for monitoring the effectiveness of maintenance at nuclear power plants” called “Maintenance Rule” was issued for a trial by Nuclear Regulatory Commission (NRC) of the USA[1] in 1991, and it was formally applied in 1996. The NUMARC 93-01 (Rev. 4C) “Industry guideline for monitoring the effectiveness of maintenance at nuclear power plants”[2] was issued by Nuclear Energy Institute (NEI) of the USA in 2015.

In August 2017, the “Maintenance Rule” (MR) was introduced into China and the "Technical Policy for Improving Maintenance Effectiveness of Nuclear Power Plants (Trial)" [3] (MR Policy) was issued by the National Nuclear Safety Administration (NNSA) of China .the "Technical Policy for Nuclear Power Plant Configuration Risk Management (Trial)" [4] (Configuration Risk Management,CRM) was issued by NNSA in 2019. The law "Safety Regulations for Commissioning and Operation of Nuclear Power Plants" (HAF103)[5] including the application of MR and CRM was revised by NNSA in 2022.

The MR performance indicators in the USA is relatively relaxed and the requirement was enhanced when “Maintenance Rule” introduced into China. For example, there are 10 systems in a Nuclear Power Plant (NPP) and each system has a Maintenance Preventable Functional Failure (MPFF) of “1” that is say each system may has one failure every 2 refueling cycles. The NNSA thought that it is not strict enough and the $\frac{\mathrm{CDF}_1}{\mathrm{CDF}_0} < 10$ (CDF_0 and CDF_1 are the corresponding Core Damage Frequency (CDF) before and after setting performance indicators) was introduced in to control the whole risk of a NPP. As a result, the MPFF of 5 systems may reduced to 0. How to calculate the CDF_1 accurately was discussed in this paper.

2. ANALYSIS OF THE ADVANTAGES AND DISADVANTAGES OF CURRENT ACCEPTABLE CRITERIA

2.1. Current acceptable criteria

The technical requirements of current acceptable criteria of performance indicators in China:

1) When formulating performance indicators, acceptable criteria should be considered, and all performance indicators should not increase the CDF by 10 times after setting, i.e. $\frac{\mathrm{CDF}_1}{\mathrm{CDF}_0} < 10$.

2) When evaluating the overall acceptable criteria for performance indicators, it is advisable to substitute the classical estimated values of equipment reliability and availability parameters represented by performance indicators into the Probabilistic Safety Assessment (PSA) model.

3) When evaluating the acceptable risk of performance indicators, in order to solve the problem of too short running time for the standby equipment, the number of functional failures can be defined as only for startup and not allowed to occur during operation.

2.2. Advantages Analysis

The current acceptable criteria avoids the problem of overly lenient performance indicators, which may not accurately reflect the historical status of equipment and cannot effectively improve the maintenance effectiveness.

The acceptable criteria for performance indicators is to compare the increased CDF value with the benchmark CDF value, reflecting the characteristics of nuclear power units.

2.3. Disadvantage Analysis

The acceptable criteria and calculation methods for current performance indicators have been found to have the following defect after years of application:

1) Determining acceptable criteria only based on ratios is not conducive to nuclear power unit with lower benchmark risk. The comparison between unit A and B, as shown in Table 1, clearly shows that $\triangle \mathrm{CDF}_B$ is much greater than $\triangle \mathrm{CDF}_A$. This method has resulted in stricter requirements for units with relatively high safety compared to units with relatively low safety, and has failed to propose more requirements for improving the effectiveness of maintenance for Unit B.

Table 1 Comparison of Acceptance Criteria for Different Unit

Unit	$\mathbf{CDF_0}$	$\mathbf{CDF_1}$	$\triangle$**CDF**
A	1E-6	1E-5	$\triangle \mathrm{CDF}_A$=9E-6
B	1E-5	1E-4	$\triangle \mathrm{CDF}_B$=9E-5

At the same time, the absolute value is used in the recommended threshold for “configuration risk management in the Technical Policy for Nuclear Power Plant Configuration Risk Management (Trial)” .It’s believed that the acceptable criteria for risk management in nuclear power plants should be basically consistent.

2) When the sample size is small, the classical estimate of reliability parameters is too conservative. The third criterion in Section 2.1 states that the actual operation time for standby equipment is too short, and requires that the number of functional failures be defined as only for startup failures. However, for standby system, it is also a problem of startup time with small sample size. For example, if the surveillance frequency of a certain system in Unit A is once a month, and the maximum MR supervision cycle is only 36 times within 3 years, and the performance indicators allow it to fail once, then the classic estimate of the startup failure probability of the corresponding key equipment in the system is:

$$p_1 = \frac{Number\ of\ allowed\ failure}{Number\ of\ demand} = \frac{1}{36} \approx 0.028 \tag{1}$$

If the surveillance frequency of a system has a optimization of once every four months and a corresponding demand time of only 9 , the classic estimate of the startup failure probability is $\mathrm{p}_4 = \frac{1}{9} \approx 0.11$, when the surveillance frequency is once a year, $\mathrm{p}_{12} = \frac{1}{3} \approx 0.33$. When the sample size of the demand frequency is too small, using classical estimation algorithms overestimates the impact of time, resulting in a large error and not conducive to the optimization work of nuclear power plants.

3. DEVELOPMENT OF ACCEPTABLE CRITERIA

3.1. Relationship with Configuration Risk Management Thresholds

The Technical Policy for CRM suggests that the risk management threshold is shown in Table 3, and only the PSA-1 related threshold is listed here. The upper limit of the instantaneous risk CDF green zone at this threshold is a ratio, while the rest are absolute values. Configuration risk management is the risk assessment and management of one or more equipment in a nuclear power plant when they are unavailable (including failures). It should establish a certain connection between the MR reliability performance indicators and the CRM acceptable risk criteria.

Table 3 Configuration Risk Management Risk Thresholds

Risk areas	**CDF**	**ICDP (Incremental Core Damage Probability)**
Risk unacceptable zone	≥1E-3	≥1E-5
Risk management area	≥Double benchmark risk	≥1E-6

Normal control area	＜Double benchmark risk	<1E-6

3.2. Development of acceptable criteria

In order to eliminate the shortcomings described in Section 1.3 (1), a new risk acceptance criterion is established, either:

1) $\frac{\mathrm{CDF_1}}{\mathrm{CDF_0}} < 10$. Or,

2) （$\mathrm{CDF_1} - \mathrm{CDF_0}$）＜t*1E-4. At present, the CDF value of new nuclear power units in China is less than 1E-5. It is more appropriate to take the middle value between the lower limit of the CDF red zone 1E-3 and 1E-5, i.e. 1E-4 level; Nuclear power plants generally use the internal event PSA model for acceptable criterion validation. The risk management threshold in Table 3 is to use the full range PSA model, introduce the internal event contribution ratio t, and calculate it using the following formula. Obtain an acceptable absolute value scheme:<t * 1E-4. For example, the acceptable criterion for Unit A is:<0.3 * 1E-4=3E-5.

$$t_{CDF} = min\ \left(0.5，\frac{CDF_{IE}}{CDF_{IE} + CDF_{FL} + CDF_{FI} + CDF_{SE}}\right) \tag{2}$$

$$t_{LERF} = min\ \left(0.5，\frac{LERF_{IE}}{LERF_{IE} + LERF_{FL} + LERF_{FI} + LERF_{SE}}\right) \tag{3}$$

Among them: $\mathrm{CDF_0}$ and $\mathrm{CDF_1}$ the corresponding core damage frequency before and after performance indicators are set; IE, internal events; FL, internal flooding; FI internal fire; SE, earthquake.

4. CALCULATION METHOD FOR FAILURE PROBABILITY

It is easy to enter a (1) (exceeding the performance indicators)and returning a (2) (not exceeding the performance indicators) due to the too strict or too loose the indicators causing by calculation method of failure probability. It cannot highlight the significance of improving the effectiveness of maintenance.

The probability of equipment failure can be divided into time related and time unrelated parts [6], as shown in the following formula.

$$p = p_d + p_t \tag{4}$$

$$p_t = \frac{1}{2}\lambda T \tag{5}$$

Among them: p is the total failure probability of a certain failure mode of the equipment; p_d is the probability of failure that is time independent; p_t is time related failure probability; λ is the failure rate is independent of time; T is time.

At the same time, in response to the problem of small sample size in classical estimation, the failure probability calculation method is formulated as follows:

1) The failure probability of demand class is selected with a sample size of ≥ 12 times per year to calculate the initial value p of classical estimation. Correspondingly, the frequency of regular testing should not be less than once a month.

2) On the basis of p, the correction only happens on the time related p_t where the sample size is lower than the above requirements .

The case as follows:

A certain system of Unit A is standby, and the MR Performance indicator is allowed to fail once. The startup failure probability is selected to be substituted into the PSA model to verify the acceptance criteria. The typical test cycle for this reactor type is once per month. The initial value of the classic estimate is:

$$p = \frac{Number\ of\ allowed\ failure}{Number\ of\ demand} = \frac{1}{\frac{12\ demand}{year} * 3year} = \frac{1}{36} \approx 2.78E\text{-}2 \tag{6}$$

After optimization, the system has a periodic testing cycle of 1 time per 2 months, with a sample size of 6 times/year<12 times/year. References [7] and [8] provide a ratio of 21:79 between time based failures and demand based failures in the failure data. This ratio may not be 21:79 cause of different component. So, 21% of startup failure probability of the system is divided out and revised based on changes in the periodic testing cycle:

$$p = \frac{1}{36} * 79\% + \frac{1}{36} * 21\% * \left(\frac{2month}{1month}\right) \approx 3.36E - 2 \tag{7}$$

5. SUMMARY

The new acceptable criteria of MR performance indicator and calculation methods are summarized as follows:

1) When formulating performance indicators, acceptable criteria should be considered, $\frac{\mathrm{CDF_1}}{\mathrm{CDF_0}} < 10$ or $(\mathrm{CDF_1} - \mathrm{CDF_0})$ <t * 1E-4, where t is the contribution ratio of internal event PSA.

3) When evaluating the overall acceptable criteria for performance indicators, it is advisable to substitute the classical estimated values of equipment reliability and availability parameters represented by performance indicators into the PSA model for calculation. For reliability parameters, conservative selection of demand or operational failure modes should be made.

3) The failure probability of demand class is selected with a sample size of $\geq$ 12 times per year to calculate the initial value p of classical estimation. On the basis of p, the correction only happens on the time related p_t where the sample size is lower than the above requirements .

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