Application of critical component elimination process and method in a nuclear power plant

Bin Cheng1, Wenchao Yang, Chen Qing and Shuping Che
Suzhou Nuclear Power Research Institute, Suzhou, Jiangsu 215004, China

1 E-mail: cheng.bin@cgnpc.com.cn

Abstract. In order to improve the operation performance of domestic nuclear power plant and promote the application of CCM elimination technology, this paper introduces the process of CCM elimination, expounds in detail the qualitative and quantitative analysis methods to determine the priority of CCM elimination, and takes the Stator Cooling Water System of a nuclear power plant as an application pilot, and shows in detail the specific application process of CCM elimination process and priority identification method. The results show that the process and method are reasonable and efficient, can provide guidance for the popularization application of CCM elimination technology system and process.

1. Introduction
In 2000, Daya Bay Nuclear Power Station took the lead in establishing a reliability management system based on Critical Component Management (CCM), and then the nuclear power plants of China General Nuclear Power Group successively implemented this system, which effectively improved the health status of critical component (also called as CCM) and reduced the unplanned shutdown times [1-3]. However, the system focuses on improving the reliability of CCMs, and does not fundamentally eliminate Single-Point Vulnerability (SPV). On the other hand, compared with the United States, there are more CCMs in domestic nuclear power plants, which makes it difficult for power plants to focus their limited resources on equipment with high risks, which seriously affects the efficiency of equipment reliability management, and further affects the operating performance of units [4-7]. At present, SPV elimination has been widely carried out in many foreign nuclear power and good results have been achieved [8-10], but the research on CCM elimination technologies and methods in domestic nuclear power plants is in its infancy, and no relevant systems and processes have been established.

Under this background, A set of CCM elimination implementation process and priority identification method is developed. Taking the stator cooling water system of a nuclear power plant as an example, the implementation process and priority identification method is elaborated in detail, which lays a foundation for the popularization of CCM elimination in the future.

2. CCM elimination process
The CCM elimination process is shown in Figure 1. Due to the large number of CCMs, it is necessary to analyze if it is necessary to eliminate every CCM. Firstly, the priority of every existing CCM is identified, and whether it should be included in the elimination analysis scope is determined according to the order of priority "high, medium and low". The principles are as follows: ① CCM with priority "high" has a high risk of unplanned shutdown, which should be eliminated; ② CCM with "medium"
priority has moderate risk of unplanned shutdown, which can be selectively eliminated if resources are sufficient; ③ CCM with "low" priority has low risk of unplanned shutdown. If there is no example showing that it is necessary to eliminate these CCMs, CCM elimination may not be carried out.

![Flow diagram of CCM elimination process](image)

**Figure 1.** Flow diagram of CCM elimination process.

For CCM included in the elimination analysis scope, the elimination technology scheme is put forward through collecting related data and analyzing problems, and then the feasibility analysis is carried out from four aspects of safety, reliability, economy and technology. Safety feasibility analysis mainly considers whether it affects nuclear safety and environment; Reliability feasibility analysis mainly considers whether it has negative influence on the function of system and equipment, such as new failure mechanism of equipment and increased failure probability of system function; The economic feasibility analysis mainly considers whether the labor cost, material cost and power generation loss cost consumed by CCM elimination implementation can be significantly lower than the shutdown loss caused by CCM failure. Technical feasibility analysis mainly considers whether there are on-site implementation conditions, implementation risks and implementation difficulties. The feasibility analysis of safety, reliability, economy and technology has all passed, and the relevant personnel have examined and approved it. Finally, it can be implemented. On one hand, if the feasibility analysis fails, the CCM elimination scheme fails, and a new elimination scheme needs to be
put forward before a new round of feasibility analysis. If no suitable elimination scheme can be found at this stage, it is necessary to formulate mitigation strategies.

After the implementation of CCM elimination, the process is not finished. Next, it is necessary to continuously track the effects of CCM elimination and evaluate whether it achieves the expected effects. If the expected results are not achieved, it is necessary to analyze whether there are other feasible elimination schemes to replace them, and if not, formulate mitigation strategies. If the effects of CCM elimination are expected, prepare the elimination evaluation report, and then the process ends.

3. Identification the priority of CCM elimination

According to the CCM elimination process, the first step is to identify the priority of CCM elimination, which can be identified by qualitative analysis and quantitative analysis.

3.1. Qualitative analysis

The risk of unplanned shutdown caused by CCM failure can be qualitatively evaluated by the following four factors: the possibility of timely discovery after equipment degradation before failure, that is, detectability, the difficulty of timely and effective intervention after equipment degradation, that is, intervenability, the experience feedback frequency of shutdown caused by failure or degradation of similar equipment in history, that is, occurrence frequency, and the effectiveness of equipment failure modes related to unit shutdown managed by preventive maintenance, that is, management effectiveness.

| Evaluation factors   | Value | Evaluation Standards                                      |
|----------------------|-------|----------------------------------------------------------|
| D- detectability     | 1     | Faults can be detected by alarm                           |
|                      | 2     | Faults can be detected by patrol inspection               |
|                      | 3     | Faults can be detected by verification or test            |
|                      | 4     | There is no effective means to detect faults              |
| I- intervenability   | 1     | Equipment can be repaired at full power after degradation |
|                      | 2     | Equipment can be repaired by load reduction after degradation |
|                      | 3     | Equipment can be intervened by operation means after degradation |
|                      | 4     | Equipment cannot be intervened in time after degradation  |
| O- occurrence frequency | 1    | No equipment failure or degradation occurred              |
|                      | 2     | Equipment failure or degradation has occurred once        |
|                      | 3     | Equipment failure or degradation has occurred twice       |
|                      | 4     | Equipment failure or degradation has occurred more than 2 times |
| M- management effectiveness | 1 | Failure modes can be managed by regular replacement |
|                         | 2     | Failure modes can be managed by regular renovation       |
|                         | 3     | Failure modes can be managed by regular tests            |
|                         | 4     | Failure modes cannot be managed by preventive maintenance |

Combining the evaluation results of the above four factors, a dimensionless CCM Elimination Priority Value (EPV) is formed to determine the elimination priority of CCM, namely,

\[ \text{EPV} = D \times I \times O \times M \]  

in which: D——detectability; I——intervenability;
O——occurrence frequency;
M——management effectiveness.

The evaluation standards of D, I, O and M are shown in Table 1.

The EPV of every CCM is analyzed according to Formula (1), and the CCMs are sorted according to EPVs from large to small. For the top 10% of CCMs, the elimination priorities are considered as "high", for the top 10%-20%, the elimination priorities are "medium", and for the rest, the elimination priorities are "low".

3.2. Quantitative analysis

In quantitative analysis, risk can be expressed by the product of failure consequence and failure rate, namely,

\[
\text{Risk} = \text{failure consequence} \times \text{failure rate} \quad (2)
\]

As the consequences of CCM failure eventually lead to shutdown, it can be assumed that the consequences of all CCM failures are the same, and according to the Bathtub Curve, the failure rate of equipment can be considered as a fixed value during normal operation. Therefore, the risk of unplanned shutdown caused by CCM failure can be expressed by specific CCM failure rate. In addition,

\[
\text{Expected failure times} = \text{failure rate} \times \text{remaining life} \quad (3)
\]

In the remaining life of the unit, the acceptable expected failure times should be < 1, which can be assumed to be 0.9 [9], and the target expected failure times should be smaller, which can be assumed to be 0.5. Combined with the remaining life of the unit, the acceptable failure rate and target failure rate of a CCM can be calculated by Formula (3). According to the relationship between actual failure rate, acceptable failure rate and target failure rate, the priority of CCM elimination is determined.

If the actual failure rate of a CCM is greater than the acceptable failure rate, the failure rate of the equipment is unacceptable, which is a high-risk CCM and the elimination priority is "high".

If the actual failure rate of a CCM is between the target failure rate and the acceptable failure rate, the risk of the equipment failure is acceptable, but it does not reach the expected target value, which is a medium risk CCM and the elimination priority is "medium".

If the actual failure rate of a CCM is less than the target failure rate, the actual failure rate of the equipment reaches the expected target, which is a low-risk CCM, and the elimination priority is "low".

---

**Figure 2.** Flow diagram of Generator Stator Cooling Water system.
Table 2. The EPV analysis of CCMs in GST system of a nuclear power plant.

| CCMs    | D detectability                                                                 | I intervenability                                                                                     | O occurrence frequency                                                                 | M management effectiveness                                                                 | EPV  |
|---------|---------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-------|
| GST001  | When the probe is short-circuited or open-circuited, there is no alarm and it cannot be detected. | If the probe is short-circuited or open-circuited, it cannot be intervened in time.                  | There has been a load shedding event caused by a probe fault once                          | Random fault of probe cannot be managed by preventive maintenance                          | 128   |
| GST015V | When the control valve is mechanically jammed, there is no alarm and it cannot be detected. | If the regulating valve fails, an alarm will appear, and the operator can intervene manually          | There was an event feedback that the stator cooling water overtemperature was caused by the slow opening of the valve | Internal leakage of valve can be managed through regular renovation                          | 48    |
| GST102V | When the balance valve has internal leakage, there is no alarm and it cannot be detected. | The equipment can be isolated and repaired at full power                                            | no experience feedback event related to failure/degradation of the equipment has occurred | Internal leakage of valve can be managed through regular renovation                          | 8     |
| GST103V | When the balance valve has internal leakage, there is no alarm and it cannot be detected. | The equipment can be isolated and repaired at full power                                            | no experience feedback event related to failure/degradation of the equipment has occurred | Internal leakage of valve can be managed through regular renovation                          | 8     |
| GST104V | When the balance valve has internal leakage, there is no alarm and it cannot be detected. | The equipment can be isolated and repaired at full power                                            | no experience feedback event related to failure/degradation of the equipment has occurred | Internal leakage of valve can be managed through regular renovation                          | 8     |
| GST105V | When the balance valve has internal leakage, there is no alarm and it cannot be detected. | The equipment can be isolated and repaired at full power                                            | no experience feedback event related to failure/degradation of the equipment has occurred | Internal leakage of valve can be managed through regular renovation                          | 8     |
| GST101R | When the heat exchanger fails, it can be detected through patrol inspection.     | After the equipment is degraded, the operator can switch to the standby equipment                   | There was a water leakage incident of GST101RF heat exchanger                              | water leakage can be managed by regularly changing the sealing strip                       | 12    |
| GST201R | When the heat exchanger fails, it can be detected through patrol inspection.     | After the equipment is degraded, the operator can switch to the standby equipment                   | There was a water leakage incident of GST201RF heat exchanger                              | water leakage can be managed by regularly changing the sealing strip                       | 12    |
4. Application of CCM elimination process in a nuclear power plant

4.1. Introduction of Generator Stator Cooling Water System
The flow chart of the Generator Stator Cooling System (GST) of a nuclear power plant is shown in Figure 2. Its function is to take away the heat generated during the operation of the generator stator winding through the circulating flow of desalted water in the rectangular hollow stator winding.

4.2. Priority identification of CCM elimination in GST system
There are eight CCMs in the GST system of the nuclear power plant, including one temperature probe (GST001MT), one three-way regulating valve (GST015VD), four balancing valves (GST1052VD, GST1053VD, GST1054VD, GST1055VD), and two heat exchangers (GST101RF, GST201RF). The EPV of each CCM is evaluated by qualitative analysis, as shown in Table 2.

Combined with the elimination priority judgment standards of CCM in qualitative analysis and the evaluation results in Table 2, it can be seen that GST001MT is a "high priority" CCM; GST015VD is a "medium priority" CCM; GST1052~1055VD, GST101RF and GST201RF are "low" priority CCMs.

4.3. Establishment of CCM elimination scheme for CCM of GST system
The function of GST001MT probe is to measure the inlet temperature of generator stator cooling water. When the temperature is greater than 50°C, it will trigger an alarm of high inlet stator cooling water temperature. The temperature signal measured by the probe enters the Distributed Control System (DCS) to control the opening of the three-way regulating valve GST015VD, so as to control the generator stator cooling water temperature at about 37°C. In case of the probe failure, the wrong signal of low cooling water temperature is transmitted to GST015VD, which may cause the cooling water side of GST015VD to be completely closed and will increase the generator stator cooling water temperature and eventually lead to the shutdown.

After the analysis, the elimination scheme of adding redundant probes and modifying control logic is selected, and the control of the temperature probe is changed from choosing 1 out of 1 probe (1/1) to choosing 2 out of 3 probes (2/3). The specific elimination technical scheme is as follows:

(1) Add redundant temperature probes
Two other temperature probes GST011MT and GST021MT of the same model as GST001MT are added at the generator stator cooling water inlet. The inlet temperature of generator stator cooling water is measured by three probes and sent to DCS all.

(2) Change the control logic of the three-way regulating valve
Cross-compare the temperatures measured by the three probes in DCS. When the deviation of the comparison between the three probes does not exceed 5% of the range, take the average value of the temperatures measured by the three probes to control GST015VD. When the temperature measured by one probe exceeds 5% of the measuring range compared with the other two probes, the signal of the probe with deviation greater than 5% will be automatically shielded. When any probe has no signal output or the signal output value jumps greatly, the signal of this probe is automatically shielded.

(3) Change the alarm logic
When the temperature measured by two of the three probes is greater than 50°C, the alarm of high inlet stator cooling water temperature is triggered.

(4) Add fault alarm
When the deviation between the measured temperature of one probe and any other two probes exceeds 5% of the measuring range, or any probe has no signal output or the signal output value jumps greatly, a fault alarm will be sent to the main control room.

4.4. Feasibility analysis of CCM elimination scheme in GST system
According to CCM elimination process, feasibility analysis is carried out from four aspects: safety, reliability, economy and technology.
4.4.1. **Safety feasibility analysis.** GST001MT and GST systems have nothing to do with nuclear safety, and the elimination technical scheme is to optimize the reliability of GST system, without changing the functions of the original system, and will not affect nuclear safety and environment. Therefore, safety analysis is feasible.

4.4.2. **Reliability feasibility analysis.** In the original design, there is only one probe to control the three-way regulating valve, so the probability that the three-way valve cannot operate normally due to probe failure is equal to the failure rate of the probe itself, which is 1.02 *10-6/h [11]; In the elimination technical scheme, the control logic of choosing 2 out of 3 probes is adopted, so that the probability that the three-way valve fails to operate normally due to probe failure is the probability that two probes fail at the same time or three probes fail at the same time. Considering the common cause failure, the failure rate calculated by fault tree modeling is 2.04*10-7/h.

Therefore, through the comparison of failure rates, it can be seen that this elimination technical scheme improves the reliability of GST015VD and reduces the risk of unplanned shutdown.

4.4.3. **Economic feasibility analysis.** Only two temperature probes and corresponding accessories need to be added to implement the GST001MT elimination scheme, and the control logic and alarm logic can be directly modified in DCS. The scheme can be implemented during overhaul, and the whole elimination implementation cost including labor cost and material cost can be controlled within 0.4 million yuan.

The expected shutdown loss due to probe failure in the remaining life of the unit is equal to the expected shutdown times caused by probe failure multiplied by the loss caused by one shutdown. The remaining life of the unit is 52 years, and the failure rate of the probe is 1.02E-6/h, so the expected shutdown times caused by probe failure in the remaining life are 1.02E-6*52*365*24=0.465 times. It takes about 4 hours to replace the failed probe, and about 6 hours to restart the unit to full power. According to the estimated power generation loss of 0.5 million yuan per hour, the power generation loss of one probe failure reaches (4+6)*0.5=5 million yuan. Therefore, the loss of shutdown due to probe failure in the remaining life of the unit is expected to reach 0.465*5=2.33 million. The elimination cost of the CCM is far less than the expected failure loss, so the economic analysis is feasible.

4.4.4. **Technical feasibility analysis.** On-site verification shows that the installation position and mode of existing GST001MT are consistent with the relevant information in the design documents, and adding two probes and corresponding accessories will not change the interface position, interface form and operating parameters of the original systems. On-site installation space is sufficient for reasonable arrangement of newly added equipment. It is also convenient to change control logic, alarm logic and increase alarm in DCS. To sum up, it is judged that this elimination scheme is technically feasible.

5. **Conclusions**

In this paper, the CCM elimination process is established, and the priority identification method of CCM elimination is expounded. Taking the GST system of a nuclear power plant as an example, the necessity of eliminating the high-risk equipment GST001MT is determined through the elimination priority analysis, the elimination technical scheme is put forward through further problem analysis, and the feasibility of eliminating GST001MT is further analyzed through safety feasibility analysis, reliable feasibility analysis, economic feasibility analysis and technical feasibility analysis. GST001MT elimination technology scheme verifies the rationality of CCM elimination process and priority identification method proposed in this paper, and provides technical guidance for the implementation of CCM elimination technology and process in the future.
References

[1] Dai Zhonghua 2012 Establishing Management System of Critical Component[J]. *China Nuclear Industry* (11) 28

[2] Gao Ligang, Wang Zongjun and Dai Zhonghua 2006 Daya Bay Nuclear Power Station equipment reliability management system innovation[J]. *Chinese Journal of Nuclear Science and Engineering* (02) 156-164

[3] Gao Ligang, Wang Zongjun, Dai Zhonghua 2006 Innovation of Equipment Management System in Daya Bay Nuclear Power Station[J]. *Industrial Engineering and Management* (01) 100-103

[4] Lu Wenyue, Li Xiaoming, Han Qinghao, Dai Zhonghua, Hong Zhenmin and Chen Shijun 2005 Exploration & Practice of Reliability Management System for Nuclear Power Station Equipment[J]. *Nuclear Power Engineering* (S1) 65-72

[5] Chen Jie, Qin Kaisheng and Liu Kai 2018 Innovation and Practice of Key Sensitive Equipment Management in Nuclear Power Plants[J]. *Electric Power Equipment Management* (01) 63-66

[6] Tang Qi, Xu Xin and Li Qimin 2017 The Application of Critical Component Management Mode[J]. *China Electric Power Enterprise Management* (30) 54-55

[7] Lin Chuanqing, Shi Yifeng and Hu Wenyong 2016 Practice of Establishing Management System of Critical Component in Nuclear Power Enterprises[J]. *Enterprise Management* (S2) 264-265

[8] INPO Single-Point Vulnerability (SPV) Management Guide[S]. Atlanta, GA: INPO, 2011: 1-30

[9] S Harvey 2015 Single Point Vulnerability (CCM) Process Guide: 3002005419[R]. Palo Alto, California: EPRI, 27-48

[10] Alan Wattling, Luis Yague Munoz, Alessandro Sarich, Ulf Johansson and Sam Harvey 2016 Single Point Vulnerabilities: IERWG Guidance Note[Z]. London: WANO, 3

[11] National Nuclear Safety Administration. Data Report on Equipment Reliability of China's Nuclear Power Plants (2018 Edition)[S]. Beijing: Nuclear Safety Administration, 2019 12