Multi-equipment maintenance decision-making method for high temperature reactor based on maintenance event correlation

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Abstract. The composition of the high temperature reactor system is complex, effective maintenance management strategy can reduce the number of shutdowns and reduce maintenance costs during the operation of the equipment and caused by deterioration, improve system reliability, and also avoid system failures, maintain or restore the system to the most appropriate standard of reliability, availability and safety. This paper proposes a methodology on maintenance decision making with target of minimal downtime by analyse the associated relationships of different maintenance activities to realize merge maintenance.

1. Introduction
The composition of the high temperature reactor system is complex. The degradation process of each component is different, and the time of failure occurrence is different [1]. At the same time, the correlation between component maintenance, which leads to the uncertainty of maintenance activities, needs to be analysed to make informed decisions [2].

For maintenance time, maintenance downtime can be mainly divided into two categories: the first is maintenance time, including preventive maintenance time (maintenance time and inspection time) and failure maintenance time (preparation time, troubleshooting time, approach and reorganization time, replacement time, adjustment time, inspection time); the second is delay time, including the supply delay time and administrative delay time.

Generally, maintenance events can be divided into fault maintenance events, degraded maintenance events, and scheduled maintenance events. Fault maintenance events refer to the conditions that components need to be repaired. It is generally divided into retainable faults events and non-retainable fault events. When the system has redundant spare parts not on operation, or the reliability is higher than the minimum acceptable value, the fault event can be retained. Degraded maintenance events refer to when components have performance degradation, preventive maintenance is required. System components would undergo a degradation phase before failure. When reach the warning limit, the components begin to degrade. After pushing the dangerous limit, the components would fail. When the components reach the warning limit and danger limit, components need to be maintained. Scheduled maintenance events refer to maintenance stipulated by technical requirements, etc., where the maintenance time and maintenance work need to be determined in advance [3-5].
Through the retention of fault events and the advancement of timed events, maintenance events of different maintenance timings can be combined [6]. Besides, the timing of maintenance of degradation events is also uncertain, and can be reasonably incorporated into other maintenance groups to save maintenance costs, reduce downtime, improve efficiency, etc. So, there are ways to find the right time to combine as many maintenance events as possible.

Treat maintenance events of high temperature reactors as timed events, when the equipment is running to the lowest acceptable value of reliability, it must be maintained, however, maintenance can also be carried out before this moment. This paper is to find the most appropriate time for multi-equipment maintenance based on this requirement.

2. Analysis of the correlation of maintenance time [7]
For systems with concurrent multiple events, different combinations of events will have different correlation influence on system maintenance costs, maintenance downtime and other aspects. When maintenance events are taken separately, the influence is simple and cumulative; when the maintenance events are combined to take, its influence will vary with the combination.

There are individual and common ingredients in the combination maintenance of components. Thus, repair time can be divided into individual maintenance time and common maintenance time. Individual maintenance time is completely determined by the design of the component itself, and cannot be reduced during maintenance activities, such as installation time, training time, etc.; while during maintenance activities, there are some maintenance activities can be carried out at the same time, the time spent on this type of events is called common maintenance time, such as preparation time, spare parts access time, etc. Through the combination of maintenance events, the maintenance time of different maintenance events will be changed from the superposition of the respective maintenance time to the superposition of each component's individual maintenance time and a separate common maintenance time, which is equivalent to reducing the total maintenance time during individual maintenance. And it is the same for maintenance costs, which can also be saved through combined maintenance.

Common maintenance time includes structural related and function related repair time, set to $\Delta T^1_{ij}(t)$, $\Delta T^2_{ij}(t)$. Combined maintenance events can combine some common maintenance activities to reduce maintenance downtime. Therefore, it is possible to obtain structural related common maintenance time by loop traversal according to a given maintenance step and its standard time [8]. When there are several components in the system that need to be maintained, if there are similar functions between the faulty components, the common components can be found between several components during maintenance to reduce the logistics delay time (mainly due to the delay of the transportation process) and obtain functionally related common maintenance time.

The two parts are superimposed to get the reduced common maintenance time $\Delta T_{ij}(t)$:

$$\Delta T_{ij}(t)=\Delta T^1_{ij}(t)+\Delta T^2_{ij}(t)$$

Half of the maintenance time reduced by all combinations is the total reduced maintenance time (calculated twice for each combination), shows:

$$\Delta T(t)=\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\Delta T_{ij}(t)$$

3. Maintenance decision making process
For most systems of the high temperature reactor, the selection of maintenance time has influence on operation, thus, the making process can be widely used on maintenance work arrange of reactors [9]. Based on the analysis result of the correlation of maintenance time, the logical process of decision making can be concluded as follows [10].

First, classify the maintenance events to form a maintenance event store; then analyze the relationship between the events. According to the need of the project, the influence on downtime should be analyzed. Further, establish the associated influence model $\Delta T_{ij}(t)$ based on the analysis result, then the choice of
maintenance time should be selected as the constraint condition, and the reliability of maintenance should not be lower than the minimum acceptable threshold. Then select reduced maintenance downtime $\Delta T_\nu(t)$ as the evaluation criteria to maximize; According to the associated influence model, decision variables, decision objectives and the decision model can be constructed. Finally, the best maintenance time can be obtained from calculation result.

The decision-making process is shown in Figure 1:

![Decision-making process diagram](image)

**Figure 1.** Decision-making process.

4. Case verification
Take control rod system of high temperature reactor for example. The control rod system is used for controlling the operation mode of reactor and emergent shutdown where accident occurs.

Selected maintenance events include inner rod, outer rod, control rod assembly, thin-walled shell buffer, upper sealing barrel, shielded sealing barrel, steering piece, rod position indicator, disc spring shock absorber, diaphragm coupling, eddy current limiter, limit device, final drive, stepper motor, chain.

The probability-life curve of the above equipment as follows in Figure 2:
Based on the analysis above, the decision-making model targeting the minimum downtime is as follows:

\[
\begin{align*}
\text{max} \quad \Delta T(t) &= \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Delta T_{ij}(t) \\
\text{s.t.} \quad Pr_{Li} \leq Pr_t \leq Pr_{Ui} & \quad \text{where } 1 \leq i \leq N
\end{align*}
\]

Where, \( \Delta T(t) \) is cumulative reduced maintenance downtime. To achieve the minimal downtime, the cumulative reduced maintenance downtime should be maximized. \( \Delta T_{ij}(t) \) is the reduced maintenance downtime of a combination, the expression is given below:

\[
\Delta T_{ij}(t) = \Delta T_{ij}(t) + \Delta T_{ij}^2(t)
\]

\( Pr \) is the reliability of the component, \( Pr_{Li} \) is the minimum acceptable value of reliability, \( Pr_{Ui} \) is the maximum acceptable value of reliability.

To prove the feasibility of the method, we need to make the assumption of maintenance downtime expression:

The reduced maintenance downtime expression for thin-walled shell buffers and limiters is:

\[
\Delta T_{4,12}(t_1) = -8.8459* t_1^2 + 20.6929* t_1 - 16.5326 \quad \text{(where } t_1 = N*10^{-5})
\]

The reduced maintenance downtime expression for control rod assembly and disc spring shock absorber is:

\[
\Delta T_{3,9}(t_2) = -4.4023* t_2^2 + 5.8551* t_2 - 2.5476 \quad \text{(where } t_2 = N*10^{-6})
\]

The reduced maintenance downtime expression for inner rod and shielded sealed barrel is:

\[
\Delta T_{1,6}(t_3) = -5.0822* t_3^2 + 3.8573* t_3 - 6.5479 \quad \text{(where } t_3 = N*10^{-8})
\]

get:

\[
\Delta T(t) = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \Delta T_{ij}(t)
\]

\[
= \frac{1}{2} \left[ \Delta T_{4,12}(t_1) + \Delta T_{2,4}(t_1) + \Delta T_{3,9}(t_2) + \Delta T_{3,9}(t_2) + \Delta T_{1,6}(t_3) + \Delta T_{1,6}(t_3) \right]
\]

\[
= \Delta T_{4,12}(t_1) + \Delta T_{2,4}(t_1) + \Delta T_{3,9}(t_2) + \Delta T_{1,6}(t_3)
\]

\[
= -8.8459* t_1^2 - 4.4023* t_2^2 - 5.0822* t_3^2 + 20.6929* t_1 + 5.8551* t_2 + 3.8573* t_3 - 25.6281
\]
When the target is the minimum downtime, we need to solve $t_1, t_2, t_3$:

$$\max \Delta T(t) = -8.8459*t_1^2 - 4.4023*t_2^2 - 5.0822*t_3^2 + 20.6929*t_1 + 5.8551*t_2 + 3.8573*t_3 - 25.6281$$

$$s.t. \quad \Pr_{t_1} \leq 0.96557406$$
$$s.t. \quad \Pr_{t_2} \leq 0.98002804$$
$$s.t. \quad \Pr_{t_3} \leq 0.94853756$$
$$s.t. \quad \Pr_{t_4} \leq 0.98491293$$
$$s.t. \quad \Pr_{t_5} \leq 0.99594924$$
$$s.t. \quad \Pr_{t_6} \leq 0.99157355$$

The particle swarm optimization algorithm is used to solve the problem [11, 12], when the time is $t_1=1.16963211, t_2=0.66500466, t_3=0.37949121$, the cumulative maintenance downtime reaches the maximum, and the maximum value is 10.8478.

Based on the results, when performing maintenance with minimum downtime, propose the following three suggestions:

(1) Combine maintenance of the limit device and the thin-walled shell buffer when running to 116963 times;
(2) Combine maintenance of control rod assembly and disc spring damper when running to 665004 times;
(3) Combine maintenance of inner rod and shielded sealed barrel when running to 37949121 times.

5. Conclusions

This paper proposes a methodology on maintenance decision making with target of minimal downtime by taking combined maintenance based on the analysis result of associated relationship and the calculation result of mathematical model. The case of control rod system shows the validity and availability of the methodology. With the correlation of maintenance activities analysed in advance and fatigue life of components under given reliability level known, the maintenance of components of control rod system can be combined in pairs at specific time to obtain minimal maintenance downtime.

However, in actual scenario, mathematical expressions of combined maintenance downtime and fatigue life changes with reliability changes are not easy to establish. Besides, for commercial considerations, minimal maintenance costs may be more important than minimal maintenance downtime.

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