Maintenance Decision Method for High Temperature Reactor Equipment Group with Expense Ratio Target

Yanpeng Zhang¹, Chen Qing¹, Jianyong Gao¹ and Jie Geng²,*
¹Suzhou Nuclear Power Research Institute, Shenzhen, China
²School of Reliability and Systems Engineering, Beihang University, Beijing, China

*Corresponding author

Abstract. The equipment group of high-temperature gas-cooled reactors has a wide variety and a large number. Reasonable maintenance planning is especially important. An effective maintenance management strategy can reduce the number of shutdowns and reduce maintenance expense during equipment operation. The goal of maintenance strategy optimization is to improve the reliability of system, prevent system from failures, and reduce maintenance expense influenced by degradation, that is, to maintain or restore products to the appropriate system reliability, availability, and safety performance with the lowest possible maintenance expense.

1. Introduction
Maintenance events can be divided into fault maintenance, degraded maintenance and scheduled maintenance. For fault maintenance events, according to influence on task execution and system security after component failure, influence on maintenance expense, maintenance resources, and repair time after failures are retained and associated effects of faulty components on associated components due to fault correlation, fault repair events can be divided into retainable fault maintenance events and non-retainable fault maintenance events. Retainable fault maintenance events refer to after a fault, faulty components have no effect on the system's mission execution, system security, and associated components, or the impact is negligible, then, the fault event can be retained for a period of time. Therefore, the maintenance event has a certain flexibility in time. Therefore, proper reservations can be made without affecting system functions, and there is possibility of combining with other maintenance events for opportunity maintenance. For systems that may have multiple events concurrent, different combinations of events will have different correlation effects on system maintenance expense, maintenance downtime, and maintenance resources. The influence is cumulative when maintenance events are taken separately. But when the maintenance events have associated relationship or the system needs combined maintenance, its influence will change following the difference of combination. First analyse the characteristics of the combined maintenance events, then establish the basic relationship according to the relationship between the events, finally obtain the self-contained components and common components existing in the component combination maintenance, which facilitates the construction of the associated impact model, as shown in figure 1.

![Figure 1. Event combination association impact analysis.](image-url)
2. Maintenance Decision Model Framework with Expense Ratio Target

Which maintenance strategy to select in the maintenance decision needs to comprehensively consider the influencing various factors. Through the system engineering thinking, under the circumstances of fully considering various influencing factors, a scientific and complete maintenance decision-making target system to help choose scientific maintenance strategy. Therefore, the reasonable choice of maintenance decision-making goal is a very important part of the decision-making process. However, when constructing the decision-making target evaluation system, it is meaningless to list all the evaluation indicators, where different systems are under actually different maintenance and use requirement. When solving actual problems, we only need to grasp the main contradictions under the premise of analysing various influencing factors, and construct a maintenance decision-making target evaluation system suitable for specific situation.

The maintenance decision modelling thinking with expense ratio target is shown in figure 2.

Since the various maintenance events has a certain randomness, and the working environment of the system is also under dynamical changing, to achieve dynamic decision-making, this paper adopts the rolling cycle decision method, and the decision cycle is shown in figure 3.

3. Assumptions and Constraints in the Maintenance Decision Model

(1) Suppose n is the number of components in the system, and numbered from 1 to n;
(2) \((\lambda_i^{f}, \lambda_i^{d})\) is the failure rate opportunity maintenance threshold interval after component \(i\) is degraded, and \((T_{p_i}, T_{e_i})\) is the service age opportunity maintenance threshold interval;
(3) \((p_i, h_i, T_{p_i}, T_{e_i})\) is the opportunity maintenance threshold interval for the occurrence of a timed event in component \(i\);
(4) \(t_s\) is the starting time of the decision, \(t_i\) is the time maintenance events \(i\) takes;
(5) \(T_0\) is maintenance decision interval, \(N_0\) is the number of maintenance events that occurred during the cycle \(T_0\);
(6) \(n_1, n_2, n_3\) respectively represent the number of fault repair events, degraded maintenance events, and scheduled maintenance events during the cycle \(T_0\);
(7) \(C_{f}(t, \delta)\) is fault event as a function of retention time;
(8) \(C_{d}(t, \delta)\) is degradation event as a function of retention time. If the maintenance is not taken in time after the occurrence of degradation, the difficulty of maintenance would grows along time, so it is a non-decreasing function;
(9) \(C_{p}\) is maintenance expense for timed events;
(10) \(R_i = \frac{1}{i!} \sum_{k=0}^{i} (-1)^k \binom{i}{k} (i-k)^{n_k}\) is the number of maintenance combinations when the maintenance events are divided into \(i\) blocks;
(11) \( \mathcal{N}_v \) maintenance events are numbered by \( g_{ij} \), the first \( n_1 \) ones are the fault events, the \( n_{i+1} \) to \( n_1+n_2 \) are the degraded events, and the last \( n_3 \) are the timed events, where \( g_{ij} \) shows the part number \( j \) corresponding of \( i \) service event;

(12) \( C_{fi} \) is the cost of failure replacement of component \( i \);

(13) \( T_i \) is the working time of component \( i \) before failures before repair at time \( t \);

(14) \( f_i(t|Z(t)) \) is the failure rate density function of component \( i \);

(15) \( R(t) \) is the reliability function of the system at time \( t \) under the influence of age, stage and repair factor.

4. Formal Expression of Decision Model

It can be seen from the assumption that the values of the dummy variables \( \omega_i = \begin{cases} 1, & \text{fault can be retained} \\ 0, & \text{fault can not be retained} \end{cases} \),

\[
\omega_i = \begin{cases} 0, & m_i(t) < M_i(t) \\ 1, & M_i(t) \leq m_i(t) \end{cases}, \quad \omega_{pi} = \begin{cases} 0, & t_i < T_{pi} \\ 1, & t_i \geq T_{pi} \end{cases},
\]

Where, \( M_i(t) = \exp(\beta Z(t)) \) and \( t_i = \gamma Z(t) \).

Available from equations (1), (2), and (3), \( n_1 = \sum_{i=1}^{k} \omega_i, n_2 = \sum_{i=1}^{m} \omega_{pi}, n_3 = \sum_{i=1}^{p} \omega_{pi} \), \( N_0 = n_1+n_2+n_3 \).

\[
B_{R_{i0}} = \begin{bmatrix} B_{i1} & \cdots & B_{i} \\ B_{i2} & \cdots & B_{i} \\ \vdots & \vdots & \vdots \\ B_{R_{i1}} & \cdots & B_{R_{ij}} \end{bmatrix}
\]

is the combination matrix of arbitrarily divided into \( i \) blocks for \( N_0 \)

maintenance events, where \( B_{jk} = \begin{bmatrix} b_{j1}^{k} & \cdots & b_{j}^{k} \end{bmatrix} \) is the sub-combination of the \( k \)-th \((k=1, 2...i)\) block in the \( j \)-th \((j=1, 2, 3...)\) partition combination after the \( N_0 \) maintenance events divided into \( i \) blocks, \( r_{jk} \) is the number of maintenance events in \( A_{kj}, \sum_{k=1}^{i} r_{jk} = N_0 \), The element in \( B_{k} \) is the number of the service event;

\[
\Delta C_{R_{ij}} = \begin{bmatrix} \Delta c_{j1} & \cdots & \Delta c_{ij} \\ \Delta c_{j2} & \cdots & \Delta c_{ij} \\ \vdots & \vdots & \vdots \\ \Delta c_{j1} & \cdots & \Delta c_{ij} \end{bmatrix}
\]

is expense saving matrix, where \( \Delta c_{jk} \) is the expense saved by the \( k \)-th sub-combination of the \( j \)-th combination after the \( N_0 \) maintenance events are divided into \( i \) blocks;

where, \( \Delta c_{jk} = \frac{1}{2} \sum_{w=1}^{t} C_w \). In summary, the expense saved by the \( j \)-th combination after event correlation is as shown in equation (1).

\[
\Delta C_{ij} = \sum_{k=1}^{i} \Delta c_{jk} = \frac{1}{2} \sum_{k=1}^{i} \sum_{w=1}^{t} C_w
\]

Therefore, the total maintenance expense of the \( j \)-th combination is shown in equation (2) after the \( N_0 \) maintenance events are divided into \( k \) blocks.

\[
C_{ij}(t_1, t_2, \ldots, t_{N_0}, \delta_1, \delta_2, \ldots, \delta_{N_0}) = \sum_{i=1}^{N_1} C_{ij}(t_1, T_1, \delta_1) + \sum_{i=N_1+1}^{N_1+N_0} C_{ij}(t_2, T_2 \delta_2) + \sum_{i=N_1+N_0+1}^{N_1+N_0+N_0} C_{ij} - \Delta C_{ij}
\]
Where, \( C_p(T_i, T_{R_i}, \delta_i) = (1 - \omega_{p_i}) \cdot C_{pre}(t_i) + \omega_{p_i} \cdot C_{pr}(t_i) \), \( C_{pre}(t_i) = \delta_i (C_{max}(T_p) - C_{min}(T_p)) + H \cdot (t_i - T_p) \)
\( C_{pr}(t_i) = C_{min}(t_i - T_p) + \delta_i (C_{max}(t_i - T_p) - C_{min}(t_i - T_p)) \), \( \omega_{p_i} = \frac{C_{max}(t_i - T_p) - C_{min}(t_i - T_p)}{C_{max}(t_i - T_p) - C_{min}(t_i - T_p)} \)

Considering the impact of the maintenance method and take into account the maintenance costs in the remaining life cycle. After maintenance, the service life of the component is returned to a state before maintenance. If the component is completely maintained, the state after maintenance is as new; if the minimum maintenance is carried out, the failure rate after maintenance is equal to the failure rate at the moment before the failure; if the incomplete maintenance is carried out, the component will return to a state before the maintenance. Therefore, the calculation formula of the influence of the maintenance method on the maintenance expense in the remaining period is as shown in the formula (3).

\[
C = \sum_{i=1}^{n} \left( \int_{t_i + T_0}^{t_i + T_0} f_i(t - \eta_i \cdot \delta_i \cdot T_{i R_i}) | Z(t) dt \right) \cdot C_{pr}
\] (3)

Where, \( \eta_i = \begin{cases} 1, & t_i \leq t_i + T_{0_i} \omega_{i} = 1; \\ 0, & \text{else} \end{cases} \)
indicates whether component \( i \) has been maintained at the time \( t_s + T_0 \)

Where value 1 indicates the maintenance is performed. Value 0 indicates that the maintenance has not been performed. \( T_{i R} \) is the mean value of the remaining life cycle of the system, and its calculation formula is as shown in equation (4).

\[
T_{i R} = \frac{1}{0} \int_{0}^{T_i} f_i(t | Z(t)) \cdot \cdots f_i(t | Z(t)) \cdot f_i(t | Z(t)) dt
\] (4)

To sum up, the decision-making model of multi event opportunity maintenance aiming at minimum expense ratio in the remaining life cycle is shown in equation (5).

\[
\begin{align*}
\min \ S(t_{1}, t_{2} \cdots t_{n_{0}}, \delta_{1}, \delta_{2} \cdots \delta_{n_{0}}) = & \frac{C_{pre}(t_{1}, t_{2} \cdots t_{n_{0}}, \delta_{1}, \delta_{2} \cdots \delta_{n_{0}})}{T_{i R}} \\
\text{s.t.} & t_{1} \leq t_{1} \leq T_{0} \quad (0 < i \leq n_{0}) \\
& t_{1} \leq t_{1} \leq T_{0} \quad (n_{0} < i \leq n_{0} + n_{1}) \\
& t_{1} \leq t_{1} \leq T_{0} \quad (n_{0} + n_{1} < i \leq N_{0}) \\
& \sum_{i=1}^{n} \omega_{i} < N
\end{align*}
\] (5)

5. Case Study

Based on the model above, the data in Table 1 is taken by the equipment 1, 2, 3, 4 in the remaining life cycle when the maintenance cost is 200, 250, 20000, 100, and the maintenance time is 0.3, 0.45, 4, 0.25.

### Table 1. Decision analysis result.

| Number | Combination | Expense ratio | Maintenance time | Maintenance method |
|--------|-------------|---------------|------------------|--------------------|
| 1      | {1,2,3,4}   | 25058.6269    | \( t_1 = t_2 = t_3 = t_4 = 1010 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 2      | {1,3,4} {2} | 58.76488409   | \( t_1 = t_3 = 1010, t_2 = 1000 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 3      | {1,3} {2,4} | 25058.85394   | \( t_1 = t_3 = 1000, t_2 = t_4 = 1010 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 4      | {1,4} {2,3} | 58.84421905   | \( t_1 = t_4 = 1025, t_2 = t_3 = 1000 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 5      | {1} {2,3,4} | 25058.85169   | \( t_1 = 1021, t_2 = t_3 = t_4 = 1010 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 6      | {1,2,4} {3} | 25058.81175   | \( t_1 = t_2 = t_4 = 1010, t_3 = 1000 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 7      | {1,2} {3,4} | 58.73156628   | \( t_1 = t_2 = 1000, t_3 = t_4 = 1010 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
| 8      | {1,2,3} {4} | 58.85056738   | \( t_1 = t_2 = t_3 = 1000, t_4 = 1045 \) | \( \delta_1 = 0, \delta_2 = 0, \delta_3 = 1 \) |
According to the data, the combination of 1, 3, 5, 6, and 10 that does not conform to the actual situation is removed. As the maintenance expense and maintenance downtime taken by component 3 in the remaining life cycle are different, the maintenance methods are also different. If maintenance expense and maintenance downtime take smaller values, it is more economical to take minimum maintenance; if maintenance expense and maintenance downtime take intermediate values, it is more economical to take incomplete maintenance; if maintenance expense and maintenance downtime take larger values, take full maintenance is more economical. The columnar comparison of the data in table 1 is as shown in figure 4.

It can be seen from the figure that these 10 combinations are all available maintenance combinations, and the combination 7 has the lowest expense rate, so it is known from the decision that event 1 and event 2 are maintained at t=1000, event 3 and event 4 are at t=1015 are the optimal maintenance strategy. Considering there is structural correlations between event 1 and event 2, functional correlations between event 3 and event 4, so the decision result conforms to the assumptions, proving that the decision model and the decision algorithm are accurate and usable.

6. Conclusion
In this research, considering the influence of maintenance time, maintenance expense, maintenance impact, fault impact and other factors on system maintenance strategy, a multi-event opportunity maintenance decision-making model is established with the goal of the shortest decision cycle and the lowest expense ratio in the remaining life cycle. In the case study, the maintenance expense ratio of different maintenance combinations is calculated and compared to obtain the best maintenance strategy, which verifies the correctness of the model.

Acknowledgement
The research was financially supported by the Major Project of National Science and Technology-High-temperature Reactor Demonstration Engineering Reliable Operation Technology Research Project, Operation Reliability Key Equipment Support Sub-project (Grant No. 2018ZX06906012).

References
[1] Zhou Shuqiao, Li Duo and Guo Chao 2016 Reliability analysis and availability enhancements for redundant systems with reparable components (International Conference on Nuclear Engineering)

[2] Duffey Romney B. and Saull John W. 2006 The human bathtub: Safety and risk predictions including the dynamic probability of operator errors (International Conference on Nuclear Engineering)
[3] Franklin Lapa Celso M., Pereira, Cláudio M. N. A. and Frutuoso E Melo Paulo F. 2005 Preventive maintenance policy optimization of a nuclear reactor high pressure injection system using a reliability-cost model (IEEE Latin America Transactions) p 159

[4] Moffitt W.C. and Grygiel M.L. 1984 MAINTENANCE VIEWPOINT OF A SUCCESSFUL REACTOR STARTUP PROGRAM. (Transactions of the American Nuclear Society) p 611

[5] Augé L., Capra B., Lasne M., Bernard O., Bénédice P. and Comby R. 2006 Risk management and maintenance optimization of nuclear reactor cooling piping system (Journal De Physique) p 263

[6] Lapa Celso M.F., Pereira Cláudio M.N.A. and Mol Antônio Carlos De A. 2000 Maximization of a nuclear system availability through maintenance scheduling optimization using a genetic algorithm (Nuclear Engineering and Design) p 219