Research on optimal maintenance cycle model of nuclear equipment based on left and right fuzzy sorting method

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Abstract. For the nuclear equipment with high reliability, the optimal maintenance cycle model of nuclear equipments is established by balancing the relationship between working time before component failure and maintenance cost. According to the expert evaluation, the failure of the equipment is analyzed. In the study, the ridge membership function is improved, and the failure probability model is established by using the left and right fuzzy sorting method. It transforms the fuzzy number into the fuzzy probability, so the component fault distribution function is determined. By testing, the model has good applicability and sensitivity. Taking the spent fuel shearing machine as an example, the optimal maintenance cycle of the key parts of the shearing machine is calculated. The results are consistent with the actual conditions, which can provide the basis for the formulation of the nuclear equipment maintenance plan. The results of the study show that the proposed method is of great significance for improving the reliability and maintenance efficiency of nuclear equipment.

1. Introduction
Regular maintenance of nuclear power equipment is an important guarantee for the safe operation of the reactor, and the correct application of maintenance strategy is a powerful guarantee to improve the reliability and economy of reactor operation [1]. For nuclear equipment with high reliability, the strategy of preventive maintenance is usually adopted. Regular maintenance of nuclear-grade equipment is an effective method to reduce the probability of sudden failures [2]. However, most mechanical equipment is composed of several subsystems and components, and the failure rate of each part is different, so the time of failure is also different. The usual maintenance work is to overhaul the whole system regularly, but there are often some parts in the system that have not reached the failure time, or have already been in the fault working state, and so on, which will reduce the maintenance work efficiency and increase the possibility of accidents. Therefore, mastering the pre-fault working time of the components in the system and making the maintenance plan accordingly is of great significance to improve the reliability and maintenance efficiency of the system.

The maintenance cycle model is find out a period that assume the appropriate level of damage (initial or in use) during this period, keep it unrepaired and allow it to grow in the structure, and it should not endanger the safety of the equipment and reduce the performance of the equipment. At present, there are few studies on the optimal maintenance cycle of nuclear equipment. For equipment
outside the nuclear island, Chen Qiqiao et al. [3] proposed an opportunity maintenance control strategy based on the optimal maintenance interval of equipment itself, and the Monte Carlo was adopted to simulate. Zhu Runyan, Onisawa T and other scholars [4-7] also conducted some researches on the maintenance of nuclear equipment, but their models involve many kinds of data and they are hard to obtain on nuclear equipment. Shi J [8] obtained the initial value of the preventive replacement cycle through expert advice, combined with the operating experience of nuclear equipment, and used Bias theory to correct the result. K. Durga Rao et al. [9] presents a solution to test interval optimization problem with uncertain parameters in the model with fuzzy-genetic approach along with a case of application from a safety system of Indian pressurized heavy water reactor (PHWR). Muhammad Zubair et al. [10-12] establish alpha factor mode to estimate system unavailability due to Common Cause Failures, present quantitative and qualitative analyses of safety parameters by using online risk monitor system, and study five years data of Emergency Diesel Generator of Daya Bay Nuclear Power Plant through two classical method and Bayesian method.

As nuclear equipment is in a highly radiation working condition, the reliability data acquisition is difficult. It is generally acquired by simulation analysis or fuzzy theory. Xie Yupeng et al. [13] used Monte Carlo simulation to evaluate the reliability of the feeding system of vertical feeding shears. Purba JH et al. [14] developed a fuzzy probability-based event tree analysis (FPETA) to assess core damage frequency in probabilistic safety assessment of nuclear power plants. The results demonstrate that FPETA could be used as a reasonable alternative for conventional event tree analysis when probability distributions are not available. Fuzzy theory is based on expert experience and has good operability, it is widely used in determining reliability data. Liu Ying et al. [15] established a fuzzy fault tree to analyze the reliability of CNC turret system. Ling Aijuan et al. [16] studied the failure probability calculation method of static equipment in offshore platform by using fuzzy mathematics theory. The left and right fuzzy ranking method is one of the important methods in fuzzy theory, it is proposed by Chen and Hwang that the fuzzy language can be converted into fuzzy probability, which has been widely used in the reliability data acquisition. Zhang Jing et al. [17] used left and right fuzzy sorting methods to study the reliability of oil and gas pipeline leakage.

Researches on maintenance cycle of ordinary mechanical equipment has been carried out. Lv Libo et al. [18] simulated the equipment maintenance cycle optimization problem by the Monte Carlo, established the relationship between maintenance cycle and average availability over the entire service life of equipment. Li Mingzhe [19] optimized and analyzed the maintenance cycle of coal mining equipment for minimizing equipment maintenance costs. M Bengtsson et al. [20] established a life cycle cost empirical model of processing equipment with dynamic maintenance costs, and analyzed the linear and variable factors in the model. Zhen Xingwei et al. [21] Proposed a multi-objective optimization approach with newly-defined risk, cost criteria and constraints to determine the optimum PM intervals for safety critical barriers on offshore petroleum installations. MP Njeru [22] studied the applicability of the life cycle cost model in the development of construction equipment maintenance policy. Although there have been some optimization calculation methods for maintenance cycle, the parameters involved are difficult to determine in nuclear equipment.

This study establishes the optimal maintenance cycle model of nuclear equipment by balancing the relationship among the cost of detection, fault unit time loss, replacement or maintenance costs and component working time before fault. And the fault function of components is obtained by using left and right fuzzy sorting method. The optimal maintenance cycle of components can be obtained through the model. The model is used to analyze the optimal maintenance cycle of the shearing system of the spent fuel shearing machine, and the validity of the model is verified.

| Nomenclature | Definition |
|--------------|------------|
| $C_t$        | detection fee          |
| $C_r$        | the cost of replacement|
| $T$          | detection interval     |
| $C_d$        | the loss of unit time  |
| $C_g$        | component maintenance cost |
| $S_j$        | the score of expert j  |
2. Optimal detection cycle model

2.1. Model hypothesis

(1) The component failure is random, obeying exponential distribution: $\lambda e^{-\lambda t}$, $t \geq 0$, $(\lambda > 0)$.

(2) Assume the Component failure can only be found by detection, $C_r$ is the detection fee, $T$ is the detection interval, the time for detection is neglected.

(3) If a component failure is found, it can be repaired or replaced. $C_r$ is the component maintenance cost and $C_f$ is the cost of replacement. If the components are intact, let the parts continue to work.

(4) If the component failure is not found in time, the unloss of it time is $C_d$.

(5) Assume that the components after maintenance and replacement are in the accidental failure period of the bathtub curve, and the failure rate is stable.

2.2. Establishment of maintenance cycle model

For nuclear equipment, great losses will be caused in the event of failure. Therefore, preventive maintenance is very important for nuclear equipment. However, the components failure of nuclear equipment usually needs to be detected, if the maintenance cycle is too long, it may cause downtime and lead to accidents; if the maintenance cycle is too short, it will affect the work efficiency and cause unnecessary loss of detection cost. Therefore, selecting a reasonable component maintenance cycle plays an important role in improving equipment management.

The time interval between two adjacent faults is defined as one cycle, denoted as $T$. When the component life time $t$ satisfies the relationship of $nT < t < (n+1)T$, the cycle length is $(n+1)T$.

The expected loss of component replacement in one cycle can be expressed as Equation (1)

$$E = \sum_{n=0}^{(n+1)T} \left[ C_r + C_f / (n+1) + C_d / (n+1)T - t \right] \lambda e^{-\lambda t} dt = C_r + \frac{C_f}{1-e^{-\lambda t}} + C_d (\frac{T}{1-e^{-\lambda t}} - \frac{1}{\lambda})$$

The expected loss of component maintenance in one cycle can be expressed as Equation (2)

$$E = \sum_{n=0}^{(n+1)T} \left[ C_r + C_f / (n+1) + C_d / (n+1)T - t \right] \lambda e^{-\lambda t} dt = C_r + \frac{C_f}{1-e^{-\lambda t}} + C_d (\frac{T}{1-e^{-\lambda t}} - \frac{1}{\lambda})$$

The expected loss per unit time is shown in Equation (3).

$$C(T) = C_r + \frac{C_f + C_f - C_d}{\lambda} (1 - e^{-\lambda t})$$

The $T$ that satisfies Equation (4) is the optimal maintenance cycle.

$$(\lambda T \frac{C_f + C_f}{2} - \lambda TC_d + \lambda \frac{C_f + C_f}{2} - C_f) e^{-\lambda T} = C_d - \lambda (\lambda \frac{C_f + C_f}{2} - C_f)$$

2.3. Model discussion

(1) By taking the derivative of Equation (4), we can get that: $-\lambda Te^{-\lambda T} (C_d - \lambda \frac{C_f + C_f}{2})$, because of $-\lambda Te^{-\lambda T} < 0$, this part is strictly monotonically decreasing. When $C_d < \lambda (\lambda \frac{C_f + C_f}{2} - C_f)$, the result of the equation is $\frac{C_d}{T}$, the minimum loss in this case is $C_d$. When $C_d > \lambda (\lambda \frac{C_f + C_f}{2} - C_f)$, the equation has unique solution, which can be solved by numerical method.

(2) Actually, the maintenance cycle is determined by the failure rate of components. For components with low failure rate, the pre-fault working time is longer, so the detection time is longer. While For components with high failure rate, the frequency of failures is greater, its maintenance cycle is short. Therefore, the maintenance cycle is a function related to the component failure rate. The above-mentioned maintenance cycle model is a function related to the failure rate, it shows the model is reasonable to a certain extent.
(3) In general, the value of the failure rate of components is small, and the variation range of the
failure rate between the components is also small, so sometimes the failure rate is selected as the
function of the variable, and the change of its value is not obvious. However, the above-mentioned
optimal maintenance cycle model is exponentially increasing in relation to the parameter failure rate \( \lambda \),
which can ensure that the model has good sensitivity when the component failure rate is small and the
variation range is small.

3. Determination of model parameters \( \lambda \)
According to the model established above, it can be known that the optimal maintenance cycle of the
nuclear equipment is a function of the failure rate \( \lambda \). In fact, nuclear equipment is a high reliability
system. If there is a failure during the operation, it will cause great loss. Therefore, the probability of
accidents is low, and component failure data is difficult to obtain [23]. To solve this problem, the
study proposes a fuzzy theory to determine the failure probability of the component. First, experts
evaluate the failure of each component, then the expert opinion is transformed into fuzzy number by
improved membership function, finally, the fuzzy number is transformed into the failure probability of
components by using the method of sorting the left and right fuzzy numbers.

3.1. Set up evaluation index set
The evaluation index set is a number of indicators for evaluation, usually represented by the set
\( P = \{ p_1, p_2, ..., p_n \} \) [24]. The object of this study is the failure probability of nuclear components, so
establish the following set of evaluation indicators: \( P \) is \{very small, small, relatively small, medium,
relatively large, large, very large\}.

3.2. Using membership function to quantify expert opinion
After the expert uses the evaluation set language to evaluate the failure possibility of component “Xi”
according to the evaluation set, then, fuzzy sets are applied to deal with the uncertain information.
Compared with triangular membership function and trapezoidal membership function, ridge
membership function has better smoothness, and can turn straight line into curve [25-26]. Therefore,
this paper chooses the ridge membership function to quantify the expert opinion.

Generally, the intermediate membership function is only suitable for first-level reviews. In order to
better adapt to the multi-level nature of evaluation language and improve smoothness, the intermediate
ridge membership function has been improved.

The minimum membership function can be expressed as Equation (5).

\[
\mu(x) = \begin{cases} 
1 & 0 < x \leq a \\
\frac{1}{2} \cdot \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( x - \frac{a+b}{2} \right) \right) & a < x < b \\
0 & b \leq x 
\end{cases}
\]

The improved intermediate membership function can be expressed as Equation (6).

\[
\mu(x) = \begin{cases} 
\frac{1}{2} + \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( x - \frac{b+a+2n_{i-1}}{2n_i} \right) \right) & (a + \frac{n_{i-1}}{n+1} < x \leq b + \frac{n_{i-1}}{n+1}) \\
\frac{1}{2} \cdot \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( x - \frac{b+a+2n_i}{2} \right) \right) & (a + \frac{n_i}{n+1} < x < b + \frac{n_i}{n+1}) \\
\frac{1}{2} + \frac{1}{2} \left( 1 - \frac{2}{b-a} \sin \left( \frac{\pi}{b-a} \left( x - \frac{a+b+2n_i}{2} \right) \right) \right) & x \geq b + \frac{n_i}{n+1}
\end{cases}
\]
In the above equations, the evaluation set is: “very small, small, relatively small, medium, relatively large, large, very large”, “n” represents the number of evaluation grades, “n_i” is the evaluation grade. When i=0, let n_i=i, that is n_0, it means that the evaluation grade is “very small”. When i=1, that is n_1, it means that the evaluation grade is “small”, and so on. When the comment is "very small", it belongs to minimum membership function, when the comment is "very large", it belongs to maximum membership function, the rest of the comments belong to the intermediate membership function.

3.3. The calculation of fuzzy numbers

After establishing the membership function corresponding to the comment set, the fuzzy number of expert opinions will be calculated, and the cut set (δ) of fuzzy sets. The cut set of the Formulas (5), (6), (7) can be expressed as: \( W_0 = (z_1, z_2), \) \( z_1 \) and \( z_2 \) represent the upper and lower limits of the cut set. The cut sets of Formulas (12), (13), (14) are calculated as follows:

1. The cut set of the minimum membership function is \( VS_0 = [vs_1, vs_2] \)

\[
\delta = \frac{1}{2} - \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( vs - \frac{a+b}{2} \right) \right)
\]  

(8)

2. The cut set of the improved intermediate membership function is \( W_0 = [z_1, z_2] \)

\[
\delta_1 = \frac{1}{2} - \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( z - \frac{a+b+2n_{i-1}}{n+1} \right) \right)
\]

(9)

\[
\delta_2 = \frac{1}{2} - \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( z - \frac{a+b}{2} \right) \right)
\]

(10)

3. The cut set of the maximum membership function is \( VL_0 = [vl_1, vl_2] \)

\[
\delta = \frac{1}{2} + \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( vl - \frac{a+b+2n_{i-1}}{n+1} \right) \right)
\]

(11)

Through the above cut set calculation, the fuzzy set of the improved ridge membership function is obtained, which is suitable for the comments of different series. The relation function of fuzzy numbers w corresponding to all kinds of fuzzy languages is derived.

① minimum relation function can be expressed as Equation (12).

\[
f_{\text{min}}(vs) = \begin{cases} 
1 & 0 \leq vs \leq a \\
\frac{1}{2} & a < vs < b \\
0 & \text{others}
\end{cases}
\]

(12)

② the intermediate relation function can be expressed as Equation (13).

\[
f_{\text{int}}(z) = \begin{cases} 
0 & z < a \\
\frac{1}{2} + \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( z - \frac{a+b+2n_{i-1}}{n+1} \right) \right) & a + \frac{n_{i-1}}{n+1} \leq z \leq b + \frac{n_{i-1}}{n+1} \\
\frac{1}{2} & b + \frac{n_{i-1}}{n+1} < z < b + \frac{2n_{i-1}}{n+1} \\
0 & z > b + \frac{2n_{i-1}}{n+1}
\end{cases}
\]

(13)

③ the maximum relation function can be expressed as Equation (14).

\[
f_{\text{max}}(vl) = \begin{cases} 
\frac{1}{2} + \frac{1}{2} \sin \left( \frac{\pi}{b-a} \left( vl - \frac{a+b}{2} \right) \right) & a + \frac{n}{n+1} \leq vl \leq b + \frac{n}{n+1} \\
1 & b + \frac{n}{n+1} \leq x \leq 1 \\
0 & \text{others}
\end{cases}
\]

(14)
3.4. Turn fuzzy numbers into fuzzy probability

Through the calculation of fuzzy number $w$, the expert opinion is transformed into a fuzzy set of $[0, 1]$. To transform the expert opinion into fuzzy probability value of component failure probability, using the left and right fuzzy sort method proposed by Chen and Hwang [26] to convert fuzzy numbers into fuzzy probability value. The method defines the maximum fuzzy set ($f_{\text{max}}$) and the minimum fuzzy set ($f_{\text{min}}$).

$$f_{\text{max}}(x) = \begin{cases} x & 0 < x < 1 \\ 0 & \text{others} \end{cases}$$  \hspace{1cm} (15)

$$f_{\text{min}}(x) = \begin{cases} 1-x & 0 < x < 1 \\ 0 & \text{others} \end{cases}$$  \hspace{1cm} (16)

The left and right fuzzy probability value can be expressed as Equation (19).

$$S\mathcal{R}(w) = \sup_{x} [f_{\text{r}}(x) \wedge f_{\text{max}}(x)]$$  \hspace{1cm} (17)

$$S\mathcal{L}(w) = \sup_{x} [f_{\text{r}}(x) \wedge f_{\text{min}}(x)]$$  \hspace{1cm} (18)

$$S(w) = \frac{[S\mathcal{R}(w) + 1 - S\mathcal{L}(w)]}{2}$$  \hspace{1cm} (19)

Converting fuzzy probability value into fuzzy failure probability, as shown in Equation (20).

$$P = \begin{cases} \frac{1}{10^5} & S \neq 0 \\ 0 & S = 0 \end{cases}$$  \hspace{1cm} (20)

$$k = 2.301 \times \left(\frac{1}{S}\right)^{\frac{1}{3}}$$  \hspace{1cm} (21)

Thus, the optimal maintenance period model for the failure rate of the system components is established, which is suitable for nuclear equipment with high reliability requirements. In view of the fuzziness and uncertainty of component failure rate, fuzzy mathematics and expert scoring method are put forward to calculate fuzzy failure rate. The operation steps of the model are as following Figure 1.

![Figure 1. Optimal maintenance cycle calculation process.](image-url)
4. Model application

Spent fuel post-processing shear is the key equipment for post processing of power reactor spent fuel, which take on the important task of cutting the spent fuel assembly. The spent fuel post-processing shear system is a multi-functional automated system, which is mainly composed of a shearing system, a feeding system, a charging well and other systems. As spent fuel fission products are highly radioactive and highly corrosive, once the spent fuel shearing machine fails, it will bring great difficulties to the maintenance and fault diagnosis of the shearing machine. Studies have shown that tool failure is the most common failure form of shears [13], so this paper takes the shearing system of the spent fuel post-processing shear as an example to calculate the optimal maintenance period of the system.

4.1. Acquisition of expert opinion

(1) Determination of expert weights

An evaluation team was set up to evaluate the failure modes of the spent fuel shears. Due to the different professional backgrounds and working experiences of experts, the differences between these factors will affect the consistency and accuracy of the evaluation results. Therefore, the weight of each expert needs to be determined. The evaluation team is composed of N experts and the weight of each expert is mj. Expert weights can be calculated by Equation (22):

$$m_j = \frac{S_j}{\sum_{j=1}^{n} S_j}$$

where $S_j$ is the score of the expert, reference Table 1 gives each expert a score.

| No. | Personnel | Qualifications | Work experience | Familiarity | Score | Weight |
|-----|-----------|----------------|-----------------|-------------|-------|--------|
| 1   | Designer A| 3 (Intermediate Designer) | 2 (5-9 years) | 3 (familiar) | 8     | 0.151  |
| 2   | Designer B| 2 (General designer) | 1 (Less than 5 years) | 3 (familiar) | 6     | 0.113  |
| 3   | Mechanical engineer | 5 (Senior expert) | 5 (More than 30 years) | 5 (very familiar) | 15 | 0.283 |
| 4   | Electrical engineer | 5 (Senior expert) | 3 (10-19 years) | 5 (very familiar) | 13 | 0.245 |
| 5   | Maintenance specialist | 3 (Intermediate operator) | 3 (10-19 years) | 5 (very familiar) | 11 | 0.208 |
In this evaluation, five experts were invited, including two designers of shearing machine simulation test prototype, one mechanical engineer, one electrical engineer and 1 mechanical maintenance expert. According to the scoring standard of Table 1, the qualification and work experience of five experts are scored, and the weight of each expert is calculated in Table 2.

(2) Expert evaluation results

Through investigating the common failure modes of the shearing system, three fault modes are selected as an example to calculate. Five experts evaluated the failure mode of the shear system, and the evaluation results are shown in Table 3.

| No. | Failure mode                              | Expert evaluation results |
|-----|-------------------------------------------|---------------------------|
| 1   | Welding crackle of core barrel            | V  VS VS S VS            |
| 2   | Breakage of main knife                    | S  VS S S S             |
| 3   | Deformation of cutting tool fixed baffle  | L  L L L M             |

4.2. Calculation of failure probability

Because the evaluation set language is divided into 7 grades, in order to maintain continuity and smoothness of membership functions, let \( a = 0.125 \), \( b = 0.25 \), \( n = 7 \), \( i = 0,1,2..., 6 \). Therefore, the relation function of the fuzzy number is derived, and the semi ridge type fuzzy number for judging language is in Figure 2.

\[
f_{a}(v_{s}) = \begin{cases} 
0 & 0 \leq v_{s} \leq 0.125 \\
\frac{1}{2} + \frac{1}{2} \sin\left(\frac{\pi}{0.125} (v_{s} - 0.1875)\right) & 0.125 < v_{s} < 0.25 \\
\text{others} & \end{cases} 
\]  

\[
f_{i}(z) = \begin{cases} 
0 & z < 0.125 + \frac{n_{i-1}}{8} \\
\frac{1}{2} + \frac{1}{2} \sin\left(\frac{\pi}{0.125} \left(z - \frac{0.375 + \frac{n_{i-1}}{4}}{2}\right)\right) & 0.125 + \frac{n_{i-1}}{8} \leq z < 0.25 + \frac{n_{i-1}}{8} \\
\frac{1}{2} + \frac{1}{2} \sin\left(\frac{\pi}{0.125} \left(z - \frac{0.375 + \frac{n_{i-1}}{4}}{2}\right)\right) & 0.25 + \frac{n_{i-1}}{8} \leq z < 0.375 + \frac{n_{i-1}}{8} \\
0 & z \geq 0.375 + \frac{n_{i-1}}{8} \\
\text{others} & \end{cases} 
\]  

\[
f_{o}(v_{l}) = \begin{cases} 
\frac{1}{2} + \frac{1}{2} \sin\left(\frac{\pi}{0.125} (v_{l} - 0.8125)\right) & 0.875 \leq v_{l} \leq 1 \\
1 & x > 1 \\
0 & \text{others} 
\end{cases} 
\]

When the evaluation set is "small", \( i = 1 \); when the comment set is "relatively small", \( i = 2 \), and so on.

\[\text{Figure 2. A semi ridge type fuzzy number for judging language.}\]
Judging from the experts, it is known that the evaluation results of the "Welding crackle of core barrel" are "very small". So, the following calculation is carried out:

\[ f_{\text{max}} = 0.2122 \quad (x=0.2122), \quad f_{\text{w}}(x) = \frac{1}{2} - \frac{1}{2} \sin\left(\frac{\pi}{0.125} \times (0.2122 - 0.1857)\right) = 0.2092 \]

\[ f_{\text{min}} = 0.8420 \quad (x=0.1580), \quad f_{\text{w}}(x) = \frac{1}{2} - \frac{1}{2} \sin\left(\frac{\pi}{0.125} \times (0.1580 - 0.1857)\right) = 0.8377 \]

\[ S_{\text{h}}(w) = \sup_x [f_{\text{w}}(x) \wedge f_{\text{max}}(x)] = 0.2092 \]

\[ S_{\text{l}}(w) = \sup_x [f_{\text{w}}(x) \wedge f_{\text{min}}(x)] = 0.8377 \]

\[ S(w) = \frac{[S_{\text{h}}(w) + 1 - S_{\text{l}}(w)]}{2} = 0.1858 \]

\[ k = 2.301 \times \left[\frac{1 - S}{S}\right]^{\frac{1}{3}} = 3.7649 \]

So,

\[ p = \frac{1}{10^4} = 1.72 \times 10^{-4} \]

Similarly, the fuzzy probability values corresponding to different evaluation languages can be obtained by computing other failure modes. The results are shown in Table 4.

### 4.3. Calculation of maintenance cycle

The fuzzy probability of each component is obtained by expert evaluation and left and right fuzzy sorting method, and the probability distribution function of components is determined. Finally, the optimal maintenance period of components is obtained through the maintenance cycle calculation model.

Taking the failure mode of the Welding crackle of core barrel of spent fuel post-processing shear as an example, the calculation is carried out. The probability of welding crack of the hanging basket is \(1.72 \times 10^{-4}\), so its probability distribution function is \(1.72 \times 10^{-4} e^{-0.000172 t}, \ (t>0)\).

Assuming that the component fails to be replaced in time, it will result in a loss of 30 yuan per unit time, the replacement cost is 50000 yuan, and the maintenance cost is 50000 yuan. The fault needs to be detected, and the detection fee for one time is 10000 yuan.

Thus the parameters of the model are determined: \(\lambda = 0.000172, \ C_d=30, \ C_p=50000, \ C_v=50000, \ C_r=10000\). Put the parameters into the Formula (4):

Obtain that: \(21.4 \times (1 + 0.000172 T) e^{-0.000172 T} = 19.68\)

The result is: \(T=2716\).

Therefore, the maintenance cycle of the internal surface wear of the concave should be less than 2716 hours. Similarly, taking main knife of spent fuel post-processing shear, fixed baffle of tool retract of spent fuel post-processing shear as the examples, the use of other components to determine the maintenance cycle. The result of the calculation is shown in Table 4.

| No. | Failure mode                           | Fuzzy probability | Maintenance cycle / time |
|-----|----------------------------------------|-------------------|-------------------------|
| 1   | Welding crackle of core barrel         | 1.72x10^-4        | 2176                    |
| 2   | Breakage of main knife                 | 3.16x10^-3        | 1844                    |
| 3   | Deformation of cutting tool fixed baffle | 7.1x10^-2         | 870                     |

From the above results, it can be seen that the maintenance cycles of the system components are different, and the results are consistent with the actual situation. In practical work, the components of the same or similar maintenance cycle can be divided into a group as the focus of regular maintenance,
which can reduce the workload of maintenance and improve the efficiency of maintenance and production.

5. Conclusions
In this paper, a failure probability model is established based on fuzzy theory, the ridge membership function is improved, and the left and right fuzzy sorting method is adopted to convert the expert evaluation results into fuzzy probability to determine failure probability the nuclear components.

(1) By balancing the relationship among unit time loss, detection cost, replacement cost and maintenance cost and other factors, the mathematical modeling of the optimal maintenance cycle related to the failure rate is established. The model test shows that the model has good sensitivity and unique finite solution.

(2) For nuclear system equipment, the failure rate and other data are difficult to obtain. In this study, a failure probability model based on event correlation is established. Firstly, the ridge membership function is improved, and the right and left fuzzy sorting method is adopted to convert the result of expert evaluation into fuzzy probability value. Finally, the fault distribution function of the component is determined.

(3) Taking the Spent fuel post-processing shear as an example, the failure probability model is used to calculate the failure probability of three kinds of failure modes: the welding crackle of core barrel, the breakage of main knife and the fixed baffle deformation of tool retract. And the optimal maintenance cycle of the three components is calculated through the optimal maintenance cycle model. The results are consistent with the actual situation, which can provide reference for the maintenance strategy of nuclear class equipment.

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References
[1] Kuang Ya, Zou Shuliang, Tang Dewen, et al. 2016 Risk assessment of shear device for spent fuel shears based on fuzzy FMEA method[J]. Journal of Safety and Environment 16(5) 15-20
[2] Yang Shuchun 2001 Maintenance strategy and method for reactor operation stage[J]. Nuclear Power Engineering 22(5) 471-474
[3] Chen Yanqiao, Jin Jiashan and Huang Zheng 2009 Research on opportunistic maintenance strategy of nuclear island equipment based on availability[J]. Nuclear Power Engineering 30(6) 108-111
[4] Chen Tong and Yan Fenghe 2014 Demonstration on preventive maintenance cycle adjustment of nuclear power plant [J]. Equipment Management and Maintenance (4) 13-14
[5] Onisawa T 1988 An approach to human reliability in man-machine systems using error possibility[J]. Fuzzy Sets & Systems 27(2) 87-103
[6] Kadir A 2017 A Study about Average Cycle Time in Maintenance of Equipment[J]. International Journal of Advanced Research 5(1) 871-878
[7] Yuan C 2017 Study on the optimal maintenance strategy based on life cycle cost of power equipment[J]. Electronic Test
[8] Shi J 2010 Optimization of preventive maintenance cycle based on experimental feedback in nuclear power plants[J]. Nuclear Power Engineering 31(3) 102-107
[9] K Durga Rao, et al. 2006 Test interval optimization of safety systems of nuclear power plant using fuzzy-genetic approach[J]. Reliability Engineering and System Safety 92(7) 895-901
[10] Muhammad Zubair and Qazi Muhammad Nouman Amjad 2016 Calculation and updating of Common Cause Failure unavailability by using alpha factor model[J]. Annals of Nuclear Energy 90 106-114
[11] Muhammad Zubair, Rizwan Ahmed and Gyunyoung Heo 2014 Quantitative and qualitative analysis of safety parameters in nuclear power plants[J]. *International Journal of Energy Research* **38**(6) 755-764

[12] Muhammad Zubair and Zhang Zhijian 2013 Reliability Data Update Method (RDUM) based on living PSA for emergency diesel generator of Daya Bay nuclear power plant[J]. *Safety Science* **59** 72-77

[13] Xie Yupeng, Zou Shuliang, Tang Dewen, et al. 2016 Reliability evaluation of feeding system for vertical feeding shears based on Monte Carlo method[J]. *Mechanical Design* (1) 70-75

[14] Zhu Honglin 2011 Reliability and safety analysis of nuclear grade butterfly valves based on fuzzy theory[D]. Lanzhou University of Technology

[15] Liu Ying, Chen Zhiheng and Chen Yu 2016 Reliability analysis of CNC turret system based on fuzzy fault tree[J]. *Mechanical Science and Technology* **35**(1) 80-84

[16] Ling Aijun, Wu Qinghong, East Jingbo, et al. 2017 Research on the applicability of failure probability calculation method for offshore platform static equipment[J]. *China Safety Production Science and Technology* **13**(8) 121-125

[17] Zhang Jing, Fan Jianchun, Wen Dong, et al. 2010 Fuzzy reliability evaluation of oil and gas pipeline leakage based on fault tree[J]. *Oil and Gas Storage and Transportation* **29**(6) 401-406

[18] Lv Libo, Gao Qi, Li Youwei, et al. 2011 Modeling and optimization of equipment maintenance cycle based on Monte Carlo simulation[J]. *Computer and Digital Engineering* **39**(4) 47-49

[19] Li Mingzhe 2015 Optimization analysis of maintenance period of fully mechanized mining equipment under cost and cost[J]. *China Science and Technology Expo* (31) 389-389

[20] Bengtsson M and Kurdev M 2016 Machining Equipment Life Cycle Costing Model with Dynamic Maintenance Cost[J]. *Procedia Cirp* **48** 102-107

[21] Zhen Xingwei, Han Yue and Huang Yi 2021 Optimization of preventive maintenance intervals integrating risk and cost for safety critical barriers on offshore petroleum installations[J]. *Process Safety and Environmental Protection* **152** 230-239

[22] Njeru M P 2005 An investigation into the applicability of life cycle costing model in the development of construction equipment maintenance policy[J]. *A Research Project Submitted in Partial Fulfillment for the Award of Bachelor of Arts Degree in Building Economics*

[23] Zou S L, Xie Y P, Wang K, et al. 2014 Reliability Analysis and Experimental Research on Cutting Tool of Vertical Shearing Machine[J]. *Advanced Materials Research* **889-890** 441-449

[24] Xie Jijian and Liu Chengping 2000 Fuzzy mathematics method and its application. 2nd edition[M]. Huazhong University of science and Technology Press

[25] Peng Xingyu, Zhang Peng, Li Zongxin, et al. 2006 Model of risk mitigation for external corrosion maintenance of long-distance oil and gas pipelines[J]. *Technical Supervision of Petroleum Industry* **22**(10) 35-39

[26] Chen S J J and Krelle W 1992 Fuzzy Multiple Attribute Decision Making: Methods and Applications[M]. Springer-Verlag New York, Inc. 220-252