Study on Quantification of the Initiating Event Frequency of Loss of Service Water System in Nuclear Power Plants Via Equipment Reliability Prediction

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Abstract: To provide auxiliary decision-making support for operation and maintenance activities in nuclear power plants (NPPs), the risk monitor is built on the probabilistic safety analysis model of the operation phase, and has been widely used in online risk monitoring. It is an essential type of initiating event from support system represented by the loss of service water system in risk monitors. And the frequency of such events should be modified according to specific external environments, say high temperature or storm surge. However, that modification in risk monitors is based on expert judgment at present and it cannot reflect the risk level of NPPs on time. This paper proposes a novel method, based on the reliability prediction for mechanical equipment, to quantify and modify the frequency of loss of service water systems by selecting the key environmental influencing factors. This method is realized by steps of selecting key environmental factors, determining relationships between those factors and reliability parameters, and modifying these parameters of equipment in the service water system, then the operating state of this system is simulated through Monte Carlo sampling. Compared to expert judgment, this method is more suitable and practical to support for the application of risk monitors.

Keywords: Support System, Initiating Event Frequency, Reliability Parameter Correction, Risk Monitor of Nuclear Power Plant.

1. INTRODUCTION

The risk monitor will use the real-time risk model and the status of equipment in nuclear power plant to evaluate the risk level of the plant on time, and to provide auxiliary information for operation and maintenance activity decision-making [1]. That model is developed based on the probabilistic safety assessment model of the plant, in which the considered equipment failure is usually assumed to be constant. However, the actual state of the equipment will gradually change over time, operating conditions, and environmental factors, resulting in changes in their failure rates. The initiating events that have a direct impact on the actual operation and risk management of the plants will frequently triggered by the failure of certain operating equipment, so the assumption of a constant equipment failure rate is insufficient for the risk assessment of risk monitors. At the same time, in risk monitors, it is necessary to modify the frequency of such initiating events in specific external environments, say high temperature. At present, those modifications in risk monitors are applied mainly according to expert judgment and cannot reflect the actual risk level of nuclear power plants.

The reliability prediction method for mechanical equipment formulates the influence of different environmental factors on the failure rate of various components of mechanical equipment by using reliability testing data [2], which provides a feasible way for the modification of reliability parameters of the equipment. This paper will establish a framework based on that method for modifying equipment failure rates according to key environmental factors, and apply Monte Carlo simulation to estimate the frequency of initiating events, which will also quantify the impact of environmental factors on the frequency of initiating events. Since these initiating events caused by failures of regular operating system have a considerable effect on the safety and economy of nuclear power plants [3], we will focus on the service water system and propose an approach to modify the frequency of initiating events of the loss of service water.

The remaining content of this paper will be organized in the following way. Section 2 proposes an approach framework for modifying the frequency of initiating events based on environmental factors. A typical simplified service water system is provided in Section 3 as an example to apply that approach to modify the frequency of the loss of service water. The last section has the conclusions and a discussion of subsequent research work.

2. THE METHODOLOGY OF MODIFICATION OF INITIATING EVENT FREQUENCY

2.1. Overview of the Framework

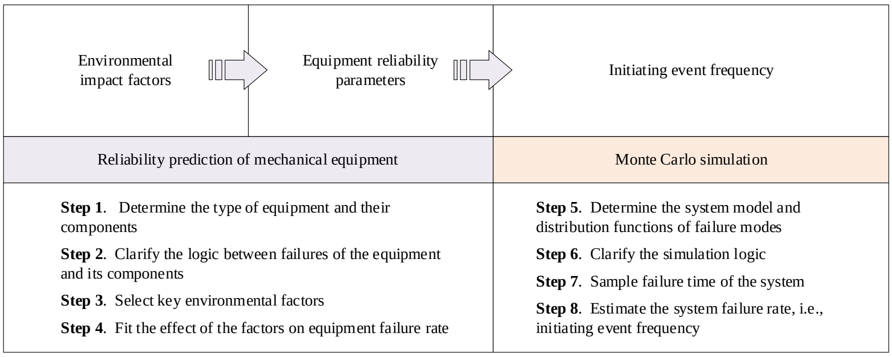

Figure 1. The framework for modifying the initiating event frequency

Having the modification of the initiating event frequency is due to the considerable impact of environmental factors (say temperature and flow) on the failure rate of equipment during operation. Ones have obtained empirical formulas for the failure rates of various components affected by various environmental factors via reliability tests, and thus developed a method to predict the reliability for mechanical equipment. Based on this method, this paper proposes an approach to select key environmental factors suitable for risk monitors to collect for modifying equipment failure rate. Then, the Monte Carlo simulation is used to estimate the frequency of initiating events caused by system failures so that a framework for modifying initiating event frequency is established as shown in Figure 1. The followings in this section will illustrate these steps included in this framework respectively.

2.2. The Method of Reliability Prediction for Mechanical Equipment

The reliability prediction method for mechanical equipment aims to determine the failure modes and unreliable factors in the early design stage of the equipment, and then quantify the reliability and maintainability of it. In order to address the problem of significant deviation in failure rate data from mechanical equipment with their components having clearly similar basic characteristics, this method considers the material characteristics, operating environment, and failure modes, rather than solely relies on the conventional fault statistical data. In fact, mechanical equipment is sensitive to factors such as loading, operating mode, and utilization, so the latter way is not sufficient for predicting the reliability of them.

Specifically, the failure rate λ of a component will be influenced by its material characteristics (say size, roughness) and operating environment (say temperature, fluid pressure). The empirical formula of λ derived through reliability testing is given in the form of the product of the basic failure rate λ_B and the environmental factor a, i.e.,

$$\lambda = \lambda_B \times a = \lambda_B \times \prod_{i=1}^{n} a_i ,$$

where λ_B is mainly determined by the material characteristics (and ones could also use empirical data); a_1, ..., a_n are n environmental modification factors that are related to material properties and operating environment.

For example, the failure rate model of a pump's fluid drive is famulated by

$$\lambda = \lambda_B \times a_{TLF} \times a_{PS} \times a_c .$$

Here λ_B is the basic failure rate which can be obtained by querying the empirical database via the type of pump and the fluid drive mode, say a centrifugal pump with a fluid drive mode of axial flow has the basic failure of 0.2 per million operating hours. The thrust load factor is denoted by a_{TLF}, which is determined by the casing type and the capacity of the pump, say for positive displacement pump,

$$a_{TLF} = 0.80 + 1.1 \times \frac{Q}{Q_{max}} .$$

where Q is the actual working flow, and Q_{max} is the designed maximum flow of the pump in a unit of gallons/min. For the operating speed factor a_{PS}, it could be deduced by the ratio of the actual operating speed V to the maximum allowable speed V_{max}, i.e.,

$$a_{PS} = 5.0 \times \left(\frac{V}{V_{max}}\right)^{1.3}.$$

And the contaminant factor $a_c = 0.6 + 0.05 \times F_{AC}$ where F_{AC} is the size of the filter in a unit of μm.

This method studies the failure rate models of more than 20 types of mechanical components, and involves more than 20 environmental factors. Some of them are listed in the table below.

Table 1. Some of the components and environmental factors involved in the reliability prediction method

Mechanical components			
1	Seals and gaskets	6	Pump
2	Springs	7	Fluid filters
3	Valve assemblies	8	Electric motors
4	Bearings	9	Belt and chain drives
5	Gears and splines	10	Fluid conductors
Environmental factors			
1	Fluid pressure	6	Voltage/current
2	Contact pressure	7	Operating speed
3	Fluid viscosity	8	Vibration
4	Operating temperature	9	Operation and maintenance
5	Contamination sensitivity	10	Shaft displacement

Note that these components involve the common equipment in nuclear power plants, say valves, pumps, and filters, and have good coverage for the equipment modelled in the risk monitor. At the same time, the selection of environmental factors should be suitable for the type and range of measurement points that can be monitored by the risk monitor. Therefore, this paper proposes the following approach for modifying the reliability parameters of equipment.

2.3. Modification of the Reliability Parameters

Based on reliability prediction method for mechanical equipment, we propose the following approach of modification of reliability parameters.

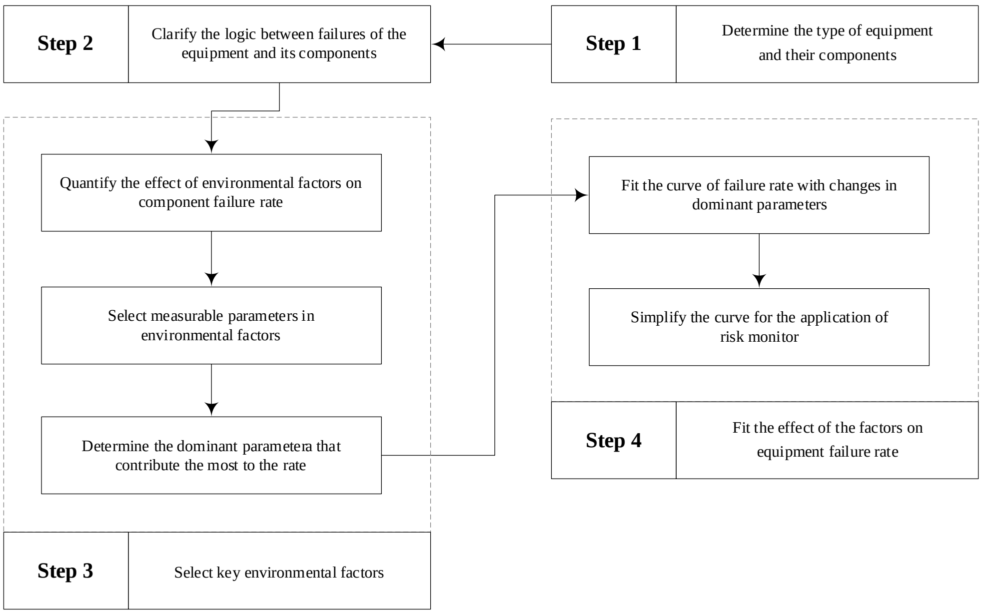

Figure 2. The approach for modifying reliability parameters of equipment

Step 1: Determine the type of equipment and their components. The type of equipment and their process parameters will directly determine the basic failure rate of the component. The reliability prediction method provides more than 20 mechanical components, including those listed in Section 2.2, and we need to choose a corresponding failure model to calculate the failure rate based on the specific component type.

Step 2: Clarify the logic between failures of the equipment and its components. These logical relationships is the key to link environmental factors and equipment failure, and its rationality determines whether the quantification of failure rate with the change of environmental factors can be formulated correctly or not. The reliability prediction method gives these relationships of the logical OR, that is

$$\lambda = \lambda_1 + \lambda_2 + \cdots + \lambda_n,$$

Where $\lambda_1, \ldots, \lambda_n$ are failure rates of the n components of that equipment respectively.

Step 3: Select key environmental factors. When quantify the effect of environmental factors on the failure rate of a component, the functions of environmental factors with changing in operating parameters should be provided, such as the example listed in Section 2.2.

There are two types of parameters that affect environmental factors: static parameters and dynamic parameters. Static ones include design limits and process parameters of the component, say filter size of fluid drives, while the dynamic ones are parameters that vary with operating conditions and environmental influences, say operating temperature and speed. Since not all parameters of environmental factors, such as fluid viscosity, can be easily monitored on site and considering the feasibility of practical application, it is necessary to integrate parameters that involve in the environmental factors of each component and select the monitorable dynamic ones, especially those that can be monitored by sensors on site.

We evaluate the contribution of these dynamic parameters to the equipment failure rate by calculating the partial derivatives, and choose the dynamic parameter with the largest contribution to the failure rate as the key environmental factor. Note that such a key environmental factor may affect multiple components at the same time. For convenience, the relationship between the failure rate of an equipment and the environmental factors of its two components could be assumed as follows,

$$\lambda = \lambda_1 + \lambda_2 = \lambda_{1,B} \cdot V \cdot T + \lambda_{2,B} \cdot Q \cdot T,$$

where $\lambda_{1,B}, \lambda_{2,B}$ are basic failure rates of these two components, and V, T, Q are three environmental factors with values of V_0, T_0, Q_0 respectively during the normal operating condition. We have the partial derivatives of the failure rate function to these three environmental factors, i.e.,

$$\left.\frac{\partial\lambda}{\partial V}\right|_{T=T_0,\ Q=Q_0} = \lambda_{1,B} \cdot T_0,$$

$$\left.\frac{\partial\lambda}{\partial T}\right|_{V=V_0,\ Q=Q_0} = \lambda_{1,B} \cdot V_0 + \lambda_{2,B} \cdot Q_0,$$

$$\left.\frac{\partial\lambda}{\partial Q}\right|_{V=V_0,\ T=T_0} = \lambda_{2,B} \cdot T_0.$$

Then select the environmental factor with the largest partial derivative as the key environmental factor.

Step 4: Fit the effect of the factors on equipment failure rate. When we have the key environmental factor, the curve of the equipment failure rate changing with that factor could be obtained directly by using the quantification of the environmental factor and the logical relationship (OR) between failures of the equipment and its components. For practical application, the obtained curve can be approximated by a step function in some limited ranges.

2.4. Monte Carlo Simulation for System Failure

The Monte Carlo simulation consists of the system model and the simulation logic. After determining the simulation model, we need to select an appropriate sampling method to sample the failure time and estimate the failure rate of the system. Here we just introduce the main content of each step and more details could be found in reference [4]. We will also provide a specific example in Section 3.

Step 5: Determine the system model and distribution functions of failure modes. Let the system S consist of n parts, denoted by S = $\{z_1, \ldots, z_n\}$. The failure modes of each equipment and their corresponding distribution functions need to be determined for subsequent sampling.

Step 6: Clarify the simulation logic. For a complex system, the fault tree is usually used to represent the simulation logic so as to determine whether the sampling results will cause system failure or not.

Step 7: Sample failure time of the system. There are two types of sampling methods, discrete sampling and continuous sampling, and they could be applied to sample numbers from the distribution of the demand failures and the operation failures of equipment respectively.

It is usually assumed that the lifespan T of an equipment follows an exponential distribution with a parameter of λ, so the cumulative distribution of the operation failure is written as

$$F_T(t) = 1 - e^{-\lambda t}, \quad t \geq 0.$$

According to the inverse transformation sampling,

$$F_T(T) = 1 - e^{-\lambda T} \triangleq Y \sim U[0,1].$$

Then we have

$$t = -\frac{1}{\lambda} ln(1 - y).$$

Thereby, the time t calculated by the formula above after sampling a number y that follows a uniform distribution within the interval of (0,1), could be regarded as a sample from an exponential distribution.

The distribution function of demand failure follows a Bernoulli distribution with parameter p. Denote the normal and the failure state when one calls the equipment by 0 and 1 respectively, then the random variable X of that demand satisfies P{X = 0} = 1 - p, P{X = 1} = p, and its cumulative distribution is written as

$$F_X(x) = \begin{cases} 1 - p, & 0 \leq x < 1 \\ 1, & x \geq 1 \end{cases}.$$

Similarly, when select a number y from a uniform distribution of U(0,1), the probability of y lying in the interval of (0, $F_X(x=0)$) could be calculated by

$$P\{ 0 < R \leq F_X(x=0) \} = \int_0^{F_X(x=0)} dy = F_X(x=0) = 1 - p = P\{ X=0 \}.$$

And the probability of y lying in the interval of $[F_X(x=0), F_X(x=1)]$ could be calculated by

$$P\{ F_X(x=0) \leq R \leq F_X(x=1) \} = \int_{F_X(x=0)}^{F_X(x=1)} dy = p = P\{ X=1 \}.$$

Step 8: Estimate the system failure rate. Assume that the maximum working time of the system is t_{max}, and there are N samples of system failure time of t_1, ..., t_N, after having N times of simulations. If the system have m times of failure in which each sampling $t \leq t_{max}$, then the point estimate of the system failure rate f within t_{max} can be calculated by $f = m$ / N.

3. MODIFICATION FOR THE FREQUENCY OF THE LOSS OF SERVICE WATER

3.1. Service Water System

In nuclear power plants, the service water system (SWS) carries the heat generated during the operation of the relevant systems to the final heat trap through cooling the equipment cooling water system, so SWS is of great important for ensuring the normal operation of plants. The diagram below shows a typical simplified SWS.

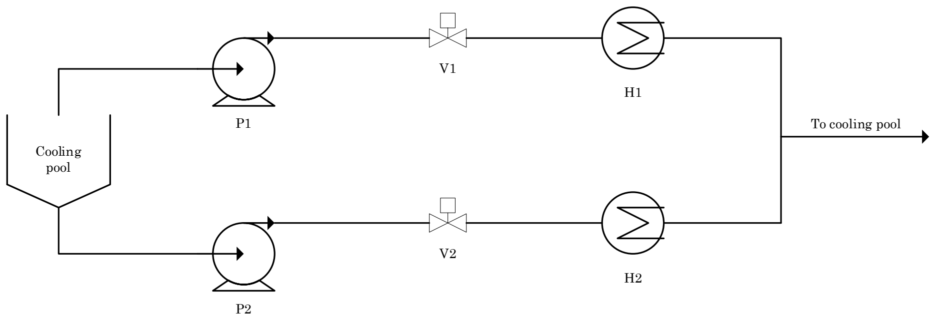

Figure 3. The flow chart of a simplified water system in nuclear power plant

The SWS consists of two trains of feed pumps with 100% capacity, valves, heat exchangers and associated piping, and they share a single cooling pool. Each train includes a pump and a valve that led to a heat exchanger individually. The first train {P1, V1, H1} is under the normal operating state, while the second one {P2, V2, H2} is the standby train.

We have the following assumptions: (1) all the equipment is non-reparable, (2) the failure of the cooling pool is not considered, (3) only the operational failures are considered in the operating train, and the start-up failures will be added to be considered in the standby train, (4) the valve V2 has a normally opened state. For the sake of illustration, we only consider the environmental factors of pumps in this paper.

3.2. Modification of the Failure Rate of Service Water Pump

Step 1: Clarify that the service water pump belongs to the centrifugal pump, which mainly contains 5 components, i.e., the pump casing, fluid drive, pump shaft, bearing and all seals, and their corresponding failure rates are $\lambda_{\text{CA}}, \lambda_{\text{FD}}, \lambda_{\text{SH}}, \lambda_{\text{BE}}, \lambda_{\text{SE}}$ respectively.

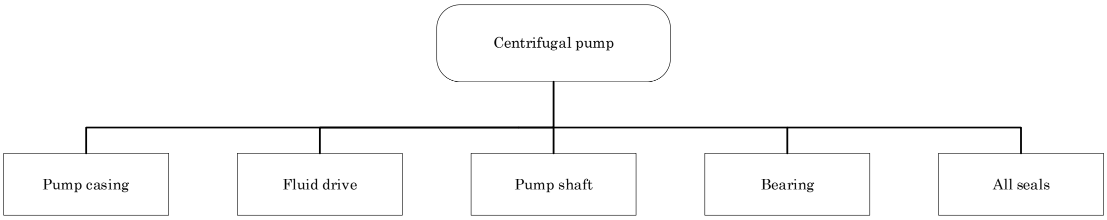

Figure 4. The 5 components of a centrifugal pump

Step 2: The logic between failures of the pump and its component is expressed as

$$\lambda = \lambda_{CA} + \lambda_{FD} + \lambda_{SH} + \lambda_{BE} + \lambda_{SE}.$$

Here the failure rate has a unit of failure times per million operating hours.

Step 3: We use the design data in the reference [5] to quantify the effect of environmental factors on the failure rates of the five components, that is

$$\begin{aligned}
\lambda_{CA} &= 0.001, \\
\lambda_{FD} &= 0.2 * C_{TLF} * C_{PS} * C_c, \\
\lambda_{SH} &= 0.25 * C_f * C_T * C_{DY} * C_{SC}, \\
\lambda_{BE} &= 17.76 * C_v * C_{CW} * C_T * C_{SF}, \\
\lambda_{SE} &= 2.4 * C_Q * C_f * C_v * C_T * C_N * C_{PV}.
\end{aligned}$$

All the environmental factors that affect these components can be found in the table of the Appendix. Four dynamic parameters that can be monitored are selected from the table for the proposed approach, i.e., operating flow, pressure, temperature, and speed. They correspond to the thrust load factor C_{TLF}, fluid pressure factor C_{PV}, operating temperature factor C_T, and operating speed factor C_{PS}, respectively.

(1) The thrust load factor [2]

$$C_{TLF} = \begin{cases} 9.94-0.9*\left(\frac{Q}{Qr}\right)-10.0*\left(\frac{Q}{Qr}\right)^2+1.77*\left(\frac{Q}{Qr}\right)^3, & 0.1 \le Q/Qr \le 1.0 \\ 1.0, & 1.0 \le Q/Qr \le 1.1 \\ -30.6+36*\left(\frac{Q}{Qr}\right)-4.5*\left(\frac{Q}{Qr}\right)^2-2.2*\left(\frac{Q}{Qr}\right)^3, & 1.1 \le Q/Qr \le 1.7 \end{cases}$$

where Q is the operating flow rate in a unit of gpm and Q_r is the maximum allowable flow rate.

(2) The fluid pressure factor [2]

$$C_p = \begin{cases} 0.2 & P_1 - P_2 \le 1500 \text{ pound per square inch} \\ \left(\frac{P_1-P_2}{3000}\right)^2, & P_1 - P_2 > 1500 \text{ pound per square inch} \end{cases}$$

where P_1 and P_2 are the pressures upstream and downstream respectively.

(3) The operating temperature factor [2]

$$C_T = \begin{cases} 2^{-t}, \quad \text{where } t = \frac{T_R - T_o}{18}, & T_R - T_o \le 40℉ \\ 0.21, & T_R - T_o > 40℉ \end{cases}$$

where T_R is the limit of operating temperature and T_o is the current operating temperature.

(4) The operating speed factor [2]

$$C_{ps} = 5 * \left(\frac{Vo}{V_d}\right)^{1.3},$$

where V_o is the running speed in a unit of r/min and V_d is the maximum allowable running speed.

In order to calculate the contribution of these four dynamic parameters to the failure rate of the pump, we have the partial derivatives below according to the step proposed in Section 2.3.

$$coeff(C_{TLF}) = \partial\lambda/\partial C_{TLF} = 0.2 * C_{PS} * C_c,$$
$$coeff(C_{PV}) = \partial\lambda/\partial C_{PV} = 2.4 * C_Q * C_f * C_v * C_T * C_N * C_{PV},$$
$$coeff(C_T) = 0.25 * C_f * C_{DY} * C_{SC} + 17.76 * C_v * C_{CW} * C_{SF} + 2.4 * C_Q * C_f * C_v * C_N * C_{PV},$$
$$coeff(C_{PS}) = 0.2 * C_{TLF} * C_c.$$

All the values of the environmental factor parameters of the pump under the normal state are given in the following: $Cps = 4.9$, $Cc = 1$; $C_Q = 3.8$, $Cf = 2.63$, $Cv = 1.15$, $C_T = 1.0$, $C_N = 4$, $C_{PV} = 0.625$, $C_{DY} = 51$, $Csc = 1.6$; $Ccw = 1.04$, $C_{SF} = 3$; $C_{TLF} = 0.9$. Then we have that coeff(C_{PS}) = 0.18 < coeff(C_{TLF}) = 0.98 < coeff(C_{PV}) = 69.0 < coeff(C_T) = 186.3. Therefore, the operating temperature contributes the most to the failure rate of the pump, and we choose it for curve fitting.

Step 4: The temperature has the dominant effect on the failure rate of the pump and it has impacts on the pump shaft, bearing and dynamic seals at the same time.

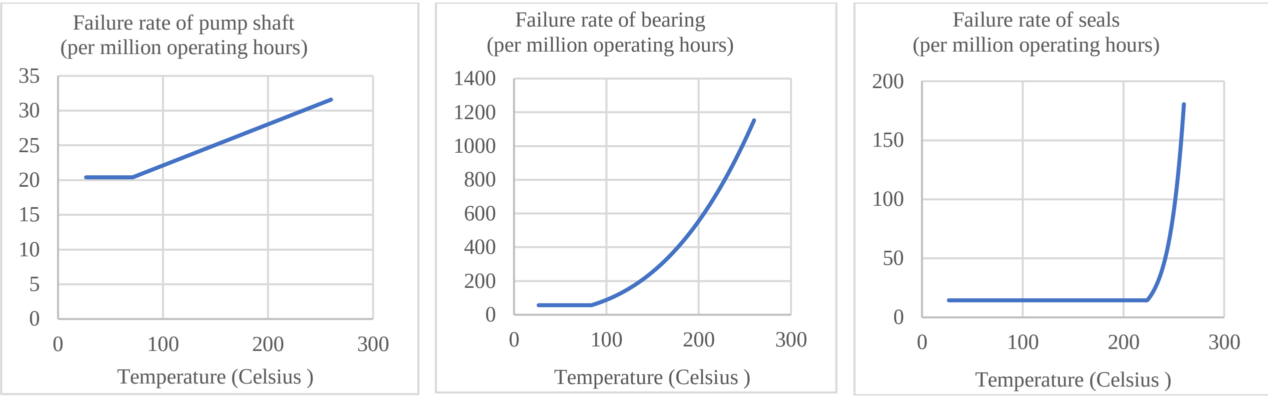

Figure 5. The effect of temperature on the failure rate of pump shaft, bearing, and seals respectively

(1) The influence of temperature on the failure rate of the pump shaft: when the temperature is below 70 °C, it has no effect on the failure rate, but when above 70 °C, it presents a linear influence trend in which the change of every 100 °C will bring about a change of 30% of the failure rate.

(2) The influence of temperature on the failure rate of bearing: It has a significant influence on the failure rate when the temperature T is above 84°C and then increases as a power function of $(T/84)^3$.

(3) The influence of temperature on the failure rate of dynamic seals: It has the most significant influence on the failure rate of dynamic seals when the temperature T exceeds the limit temperature of 246 °C and then increases as an exponential function of $2^{\Delta T/18}$ where $\Delta T = T - 246$.

Then we could fit the curve of the failure rate of the pump with changing in temperature below.

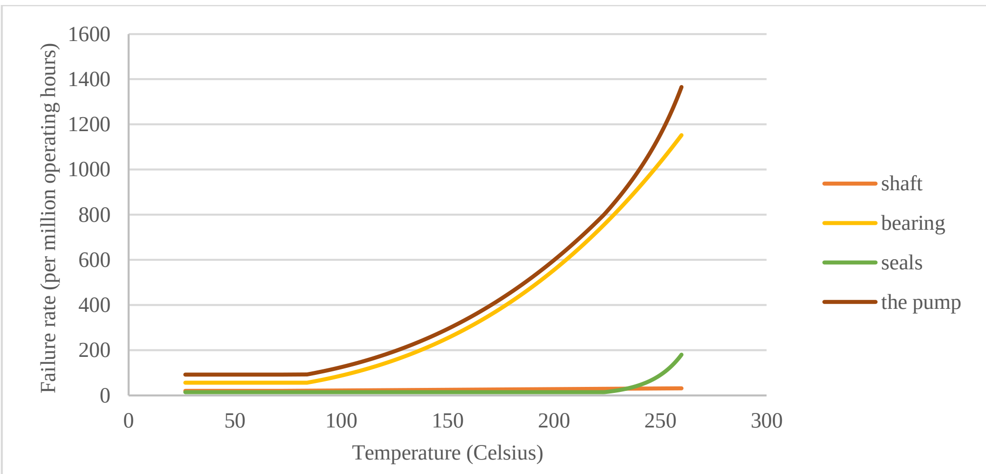

Figure 6. The curve of pump failure rate changing with operating temperature

Through linear fitting, we have a function of the failure rate of pump varying with temperature *T* below.

$$\lambda(T) = \begin{cases} 92.3, & T \leq 80℃ \\ 7.07 * T - 473.6, & T > 80℃ \end{cases}$$

We have that the failure rate of the pump under the normal condition is 92.3 per million operating hours, equal to 9.23E-05/h. And that formula allows the failure rate to be modified in time in response to changes in operating temperature. In order to facilitate the practical application, we could also have the following simplified form of it.

Table 2. The simplified form of the function of pump failure rate

No.	Temperature range	Temp. difference	Pump failure rate	Rate difference
1	0-80℃	80℃	λ	0
2	81-93℃	12℃	2λ	λ
3	94-106℃	12℃	3λ	λ
4	107-119℃	12℃	4λ	λ
5	120-132℃	12℃	5λ	λ

3.3. Monte Carlo Simulation of Service Water System Failure

Step 5: Determine the system model and distribution functions of failure modes. The service water system (SWS) presented in Section 3.1 consists of 6 devices in total, i.e., two pumps {P1, P2}, two valves {V1, V2} and two heat exchangers {H1, H2}. Their failure modes and the corresponding distribution functions are shown in the table below.

Table 3. Failure modes and distribution functions considered in service water system

No.	Equip.	Failure modes	Distribution	Parameter	References
1	P1	Operation failure P1-RF	Exponential	λ = 9.23E-05/h	This paper
2	P2	Start-up failure P2-SF	Bernoulli	p = 2.47E-03	NUREG/CR-6928
		Operation failure P2-RF	Exponential	λ = 9.23E-05/h	This paper
3	V1	Unable to keep opening V1-RF	Exponential	λ = 1.22E-07/h	NUREG/CR-6928
4	V2	Unable to keep opening V2-RF	Exponential	λ = 1.22E-07/h	NUREG/CR-6928
5	H1	Operation failure H1-RF	Exponential	λ = 6.40E-07/h	NUREG/CR-6928
6	H2	Operation failure H2-RF	Exponential	λ = 6.40E-07/h	NUREG/CR-6928

Step 6: Clarify the simulation logic. According to system flowchart given in Section 3.1, the following fault tree of SWS can be established. Obviously, it is easy to determine whether the SWS fails or not by the following logical relationship,

SWS = (P1-RF + V1-RF + H1-RF) * (P2-SF + P2-RF + V2-RF + H2-RF).

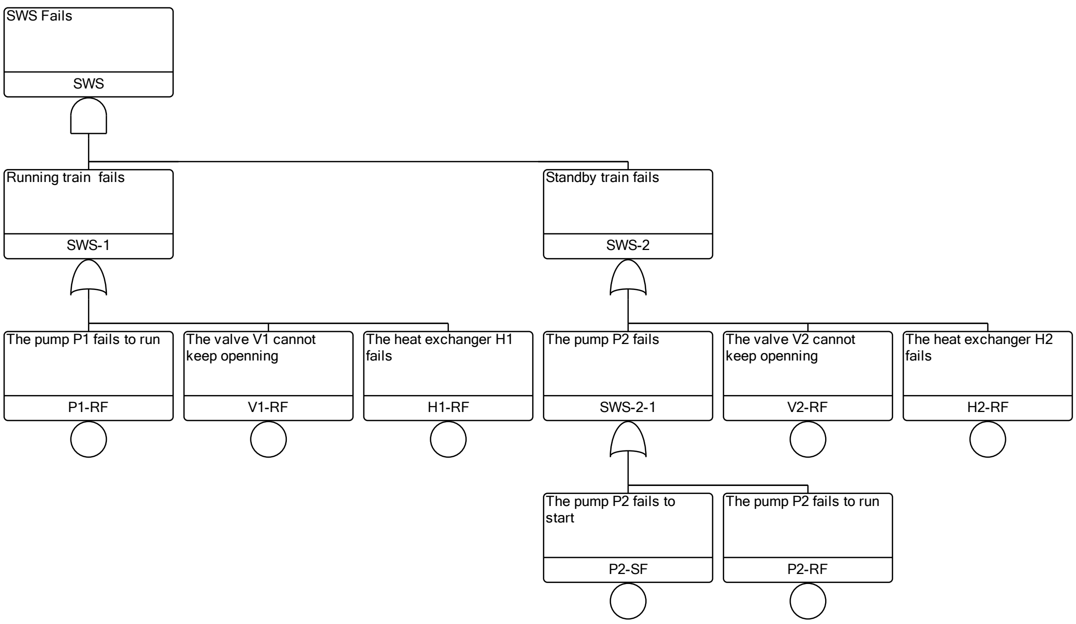

Figure 7. The simulation logic of service water system

Step 7: Sample the failure time of SWS. Let the maximum working time of the system t_{max} be 8760h, and simulation time N = 1.0E+04. We used EXCEL to do the sampling work, and the following table presents the sampling functions for each type of failure mode.

Table 4. The sampling functions and logical values of the failure modes

No.	Failure mode	Sampling function	Logical value
1	P1-RF	*t* = -LN(1-RAND( )) / 9.23E-05	IF(*t* > 8760, 0, 1)
2	V1-RF	*t* = -LN(1-RAND( )) / 1.22E-07	IF(*t* > 8760, 0, 1)
3	H1-RF	*t* = -LN(1-RAND( )) / 6.40E-07	IF(*t* > 8760, 0, 1)
4	P2-SF	*x* = IF(RAND( ) < (1 - 2.47E-03), 0, 1)	*x*
5	P2-RF	*t* = -LN(1-RAND( )) / 9.23E-05	IF(*t* > 8760, 0, 1)
6	V2-RF	*t* = -LN(1-RAND( )) / 1.22E-07	IF(*t* > 8760, 0, 1)
7	H2-RF	*t* = -LN(1-RAND( )) / 6.40E-07	IF(*t* > 8760, 0, 1)
Note that: (1) the function RAND() returns a random number that follows U(0,1); (2) the function LN(*y*) calculates the natural logarithm of *y*; (3) the function IF(*t* > 8760, 0, 1) indicates that when *t* > 8760, it returns 0; otherwise, it returns 1; (4) The failure of SWS is calculated via the logical relationship obtained in Step 6, where SWS > 0 indicates failure, and SWS = 0 corresponds normal.			

Step 8: Estimate the system failure rate. The number *m* of system failures obtained from sampling is 5523, and then the system failure rate is estimated by 5523 / N / 8760 = 6.30E-05/h, which also equals to the frequency of the loss of service water. Considering the changes of the pump failure rate over different temperature ranges obtained in section 3.2, if repeat the simulation work under these temperature ranges, we obtain the following table of modification of the frequency of that initiating event.

Table 5. Modification results of frequency of the loss of service water under different operating temperatures

No.	temperature range	Failure rate of pump	Frequency of the loss of service water
1	0 - 80℃	λ = 9.23E-05/h	6.30E-05/h
2	80-93℃	2λ	9.12E-05/h
3	93-106℃	3λ	1.05E-04/h
4	106-119℃	4λ	1.10E-04/h
5	119-132℃	5λ	1.12E-04/h

4. CONCLUSION

This paper provides a quantitative approach to have the relationships between operating environment and the frequency of initiating event based on the reliability prediction method and Monte Carlo simulation. It can be used in conjunction with risk monitors to modify the frequency of initiating events in time. The quantification and modification results of the frequency for the loss of service water indicate that the proposed approach can quickly establish the relationships between environmental factors and the initiating event frequency, which could help the operators locate the most critical monitoring parameters that may cause initiating events and provide effective support for real-time risk monitoring.

The application of this approach in real-time risk monitoring could be limited by the monitoring range of on-site operating environment parameters, and it may not be applicable for evaluating the failure rate of a new equipment. We will investigate the followings in the future.

1. Apply more environment factors that have effect on equipment failure. The environmental factors selected in this article for evaluating component failure rates are all dynamic parameters that can be monitored, but some of them may not have measurement points, and the others even are difficult to obtain by using sensors. This may have an impact on the rationality of the selection range of key environmental factors, and the factors that have a greater effect on the failure rates may not have been considered. The key environmental factors could be comprehensively selected through expert judgment or by integrating more information sources.

2. Consider to apply the idea of splitting the failure rate of an equipment into different components, to modify the failure rate of the same type of equipment. In practical applications, the failure rate data of equipment is easy to be obtained, whereas it is difficult to have the basic failure rate data of the components. We can use the proposed approach in this paper to split the equipment failure rate into various components according to existing proportions that have gained from the similar equipment, and then modify the failure rate at the

component level.

3. Consider the common cause failure mode for Monte Carlo Simulation to gain more practical results.

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APPENDIX: ENVIRONMENTAL FACTORS OF THE PUMP

No.	Component	Environmental factor	Parameter	Type
1	Fluid drive	Thrust load factor C_{TLF}	N/A	Static
			Operating flow Q	Dynamic
			Maximum pump specification flow Qr	Static
		Operating speed factor C_{PS}	Operating speed V_O	Dynamic
			Maximum allowable design speed V_D	Static
		Contamination factor C_C	Filter size F_{AC}	Static
2	Pump shaft	Shaft surface finish factor C_f	Finish type	Static
			Tensile strength of material Ts	Static
		Material temperature factor C_T	temperature T_{AT}	Dynamic
		Shaft displacement factor C_{DY}	Fluid radial unbalance force or load weight F	Static
			Modulus of elasticity of shaft material E	Static
			Shaft moment of inertia I	Static
		Stress concentration factor C_{SC}	Radius of fillet r	Static
			Initial shaft diameter D	Static
			Transitioned shaft diameter d	Static
3	Bearing	Lubricant factor C_v	Viscosity of specification lubricant v_O	Static
			Viscosity of lubricant used v_L	Static
		Water contaminant factor C_{CW}	Percentage of water CW	Dynamic
		Temperature factor C_t	Temperature T	Dynamic
		Operating service condition factor C_{SF}	Current operating conditions: Stable without vibration, normal, vibration	Dynamic
			Different applications	Static
4	All seals	Leakage factor C_Q	Allowable leakage Qf	Static
		Surface finish factor C_F	Surface finish *f*	Static
		Fluid viscosity factor C_v	Fluid temperature	Dynamic
			Dynamic viscosity of fluid being used *v*	Dynamic
		Temperature factor C_T	Rated temperature of seal TR	Static
			Operating Temp. of seal To	Dynamic
		Contaminant factor C_N	Empirical quantification	Static
		Pressure-Velocity factor C_{PV}	Operating pressure	Dynamic
			Designed pressure	Static
			Operating velocity	Dynamic
			Designed velocity	Static
5	Pump casing	N/A	A given value	Static