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Optimization of the Maintenance Period for WWER Safety Systems with Taking in Account the Maintenance Quality

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Abstract. The specificity of NPP safety systems is that they must be in a state of constant availability, but they are not used and, therefore, are not spend the life of the equipment. Verification of readiness through periodic maintenance or testing can lead to the deterioration of some elements of the system and increases their vulnerability during inspections. Therefore, the maintenance period of security systems should be optimized with taking into account the quality of maintenance.

A methodology for assessing the reliability of safety systems with taking in account their operating modes and quality of maintenance, which was implemented as a computer program, is developed. Operational data on the quality of maintenance of safety equipment of NPPs were used. The results of calculation of the optimal maintenance period for one of WWER safety systems are presented.

Keywords: maintenance, safety systems, maintenance period, reliability, NPP.

1 Introduction

The entire complex of safety systems provides safe operation of nuclear power plants. The performance of their assigned safety functions guarantees the transfer of AEC to a safe state for all design accidents. The specificity of safety systems is that when the unit is operating at power, they are in standby mode. To maintain the performance of safety systems the periodic maintenance are carry out.

Periodic maintenance is paid a lot of attention in regulatory and operational documentation. Considering the large number of elements of equipment related to safety systems and limited access to them when the unit is operating at power, the issues of optimizing its maintenance are topical [1–6]. Moreover, special attention should be paid to the quality of the maintenance taking into account the human factor [7–9].

2 Basic Principles

The state of the single element of safety system, which is in the standby mode and is periodically tested, are described by two typical stages. The first stage is the waiting stage, during which the probability of element failure is accumulates. We are talking about random failures not caused by any degradation processes, which can be predicted such as wear and aging. The second stage is the maintenance, when element is disconnected from the system, it is rendered inoperable. The maintenance allows verifying the operability of the element and ends up by it connecting to the system.

The intensity of the random failure flow λ can be considered as a constant value for this type of equipment. The probability that the element is in an operable state is equal to one immediately after its verification. Then, depending on the waiting time, the probability of failure of the element increases and the probability of element failure in the working state described by the exponential dependence

$$p(t,\lambda) = 1 - \exp(-\lambda t)\,. \tag{1}$$

The change in the probability of failure of an element during periodic maintenance shown in Figure 1(a), if the service performed qualitatively and the element reliability completely restored. The maintenance period and the maintenance duration denoted by T and τ, respectively (see Figure 1). However, there is always a certain probability that the maintenance performed poorly, which can lead to a failure in the future.

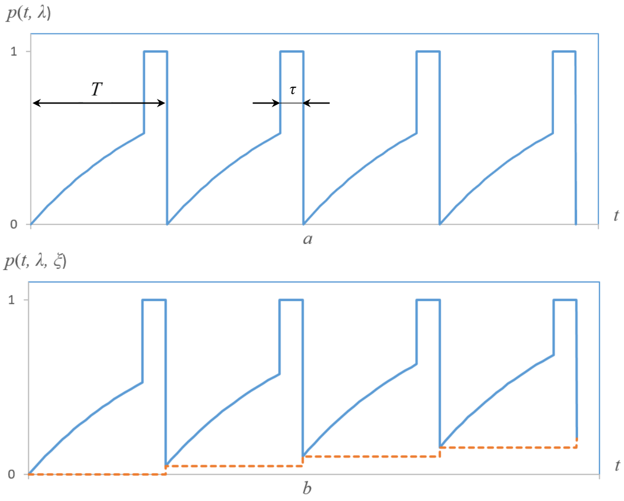


Figure 1. Changing the failure probability of an element during periodic maintenance with quality: (a) perfect; (b) not perfect.

The intensity of the random failure flow related to one service, and due to poor maintenance, will be denoted by ξ. The probability of failure of an element, taking into account the quality of its service described by the dependence:

$$p(t,\lambda,\xi) = 1 - \exp(-\lambda t - \xi n)\,, \tag{2}$$

where $n = t/T$ – an integer number of the maintenance cycles.

Then the probability of failure, due to the quality of service, will constantly accumulate after each time of maintenance and restore the reliability of the element will not be complete. In this case, a complete restoration of the element is possible only after a major repairs or replacement. The change in the probability of element failure during periodic maintenance, taking into account the quality of service is shown in Figure 1(b).

The overall reliability of the element estimated by the average integral failure probability for a characteristic period. This index is called the unavailability factor k_U, which is calculated by equation

$$\begin{aligned} k_U &= \frac{1}{T}\int_0^T p(t)dt \\ &= \frac{1}{T}\Big[\int_0^{T-\tau} dt - \int\limits_0^{T-\tau} \exp(-\lambda t)dt + \int\limits_{T-\tau}^{T} dt\Big] \\ &= 1 - \frac{1}{\lambda T}\left[1 - \exp(-\lambda\,[T-\tau])\right] \end{aligned} \tag{3}$$

and availability factor k_A

$$k_A = 1 - k_U = \frac{1}{\lambda T}\left[1 - \exp(-\lambda\,[T-\tau])\right]\,. \tag{4}$$

The element's unavailability factor always has an optimal minimum value, which allows determining the optimal frequency of its maintenance. The minimum value of the inspection period is limited to the duration of one service. When $T = \tau$, the element is permanently in the off state, i.e. completely disabled. The higher the element reliability, the greater the optimal maintenance period (see Figure 2).

It is obvious that the reliability of the system determines the reliability of its single elements. However, the structure of the system is of great importance. To increase the reliability of the system, it is implemented in the form of three or even four independent parallel channels, each of which is capable of performing the function of the system. Servicing of parallel elements and channels of the system is carried out with some uniform shift Δt.

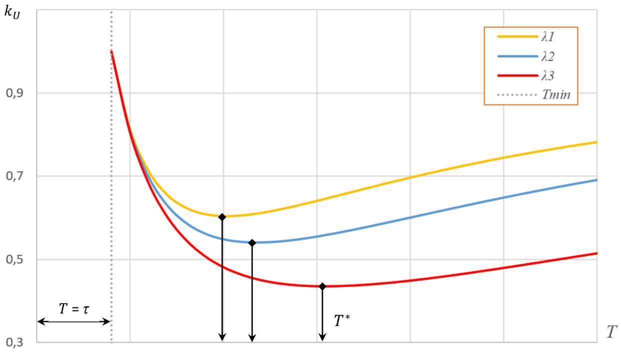


Figure 2. Unavailability factor depending on the maintenance period of the element $\lambda_1 > \lambda_2 > \lambda_3$.

The probability of failure-free operation of the system depends both on the number and on reliability of the elements, and on their logical connection in the system. If you disconnect for maintenance or connect after maintenance any element, the structure of the system changes.

The elements connected sequentially or in parallel can be enlarged to a macro element which repeating their reliability characteristics $p_i\,(t)$. For example, the enlargement of two consecutively connected elements

$$\begin{aligned} p_{12}(t) &= 1 - [1 - p_1(t)][1 - p_2(t)] \\ &= 1 - \exp(-[\lambda_1 + \lambda_2]t) \end{aligned} \tag{5}$$

and the enlargement of two elements connected in parallel

$$\begin{aligned} p_{12}(t) &= p_1(t)p_2(t) \\ &= 1 + \exp(-[\lambda_1 + \lambda_2]t) \\ &\quad - \exp(-\lambda_1 t) - \exp(-\lambda_2 t)\,. \end{aligned} \tag{6}$$

Consistently, the enlargement applied to all elements of the system, which leads to considerable simplification. Moreover, the function obtained for a macro element is the sum of exponentials, which can be easily integrated, which is required to find the unavailability factor (see eq. 3).

3 The Code CXEMA for Optimization of the Maintenance of Systems

To optimize the period of safety systems maintenance, the authors developed a program (calculation code) on Visual Basic for a personal computer with the Windows operating system [10, 11].

The program allows building the structural diagrams of NPP safety systems, consisting of a set of consecutive and parallel elements, to maintain the construction protocol, which allows correcting the structural diagram of the simulated system. It is possible to save the constructed structural diagram and initial data characterizing the reliability and maintenance mode of the system elements. The result of calculation with the application of the program is to find the optimal frequency of maintenance with the required accuracy.

4 Optimization of the Maintenance Period of the WWER-1000 Reactor Safety Systems

The optimization of the maintenance intervals for the following safety systems of WWER-1000 reactor carried out [11, 12]:

- Passive Emergency Core Cooling System – Hydroaccumulators (ACC) – YT11
- Containment Spray System (CSS) – TQ11 (21,31)
- Low Pressure Injection System (LPIS) – TQ12 (22, 32)

- High Pressure Injection System (HPIS) – TQ13 (23, 33)
- Full Pressure Injection System (FPIS) – TQ14 (24, 34)
- Emergency Feedwater System (EFS) – TX10 (20, 30) for SG

Under normal operation of NPP, those systems are in standby mode and periodically tested in compliance with the operating procedures.

Consider the sequence of performing the maintenance period optimization using the example of the TQ14 (24, 34) system.

5 Full Pressure Injection System (FPIS) – TQ14 (24, 34)

The system is designed to supply a highly concentrated (not less than 40 g/kg) boric acid solution with a concentration and flow of at least 6 m^3/h at a pressure in the prime circuit of 160 kgf/cm^2. The system consists of three independent identical channels TQ14, 24, 34.

In normal operation, all channels of the system maintained in a ready-to-operate state. In case of violation of the conditions of normal operation in emergency modes, the system switched on to work on the recirculation line and, if necessary, switched to the injection of boric acid solution to the prime circuit at any primary pressure (up to the maximum permitted).

The storage tanks of the concentrated boron solution TQ14 (24, 34) B01 are located at a height of 0.00 m. The tanks maintain a constant volume of 15 m^3 of concentrated boron solution $H_3BO_3 = 40$ g/dm^3, a nominal level of 3100 mm, and a solution temperature of 50°C. The total volume of tanks is 17 m^3.

The main elements of one channel of the system under consideration shown in Figure 3. A valve TQ14S19 and a safety valve TQ14S20 on the pipeline DN16 are installed on the suction line connecting the tank TQ14B01 with the pump TQ14D01. A check valve TQ14S01 installed on the pressure line outside the containment. Inside the containment are fast-acting electric drive valves TQ14S07 and two check valves TQ14S10, 16.

The recirculation line with valves TQ14S03, 04 provides the possibility of testing the pumps and their work in emergencies without injection boric solution into the prime circuit. The pump is actuated automatically upon the signal from the sequential loading program (SLP) or by the operator. The valves on the recirculation and injection lines of boron solution in the first circuit open simultaneously with the pump on. To inject the boron concentrate into the primary circuit, the operator must close the valves on the recirculation line using control switches.

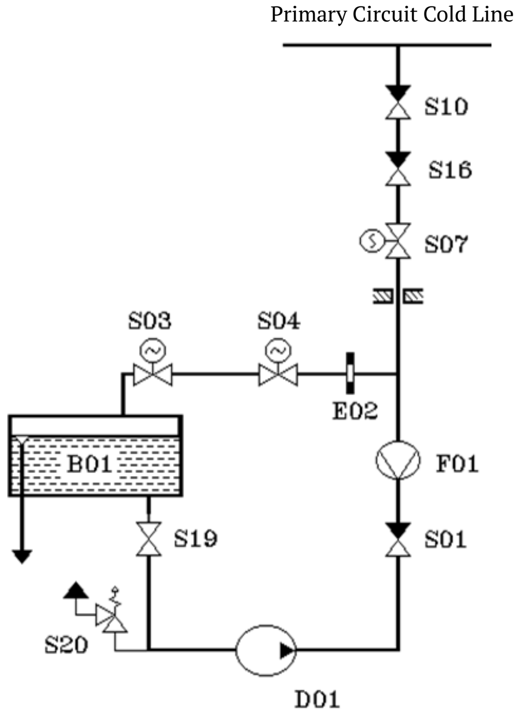


Figure 3. Scheme of FPIS TQ14, 24, 34 (one channel).

6 Modes of Operation and Maintenance of FPIS TQ14 (24, 34)

Logic schemes for analyzing the reliability of the system at an accident on recirculation and injection stages shown in Figure 4 for one channel. Three channels of the system TQ14 (24, 34) are connected in parallel, since each of them can provide the performance of the system functions, and only the failure of all three channels of the system leads to failure in general. Failure of any of the elements of the channel leads to system failure; therefore, all elements of one channel connected in sequence on the logical scheme.

The valves TQ14S03, S04 on logic diagram for injection stage are connected in parallel, since closing of one of them is sufficient to turn off the recirculation line.

To determine the failure rates of single elements of the system, was used the ZNPP database for a period of about 42 reactor-years [13]. As a comparative analysis using a database on similar power units over a period of about

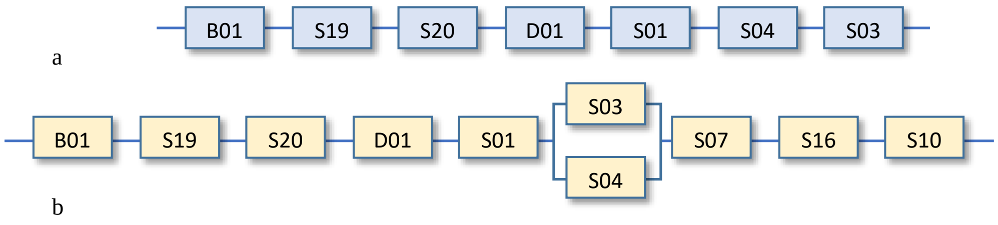


Figure 4. Logic schemes for analyzing the reliability of one channel TQ14: (a) recirculation; (b) injection.

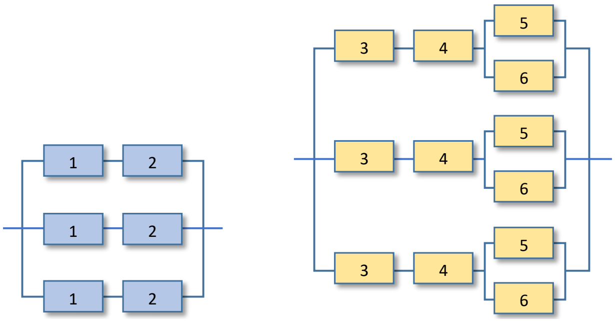
Table 1. Indicators of the elements reliability of FPIS on databases [11–13]

Element	Marking	Periodicity of testing, h	$\lambda \times 10^8$, 1/h	$\xi \times 10^4$, 1/ones
Pump	D01	720	1511.7 / 1200	57.1 / 30.6
Tank	B01	8000	410.5 / 227	— / —
Safety valve	S20	8000	280.6 / —	— / —
Valves	S07	8000	46.8 / 18.93	— / 14.67
	S03	720	51.0 / 115.1	1.94 / 14.23
	S04	720	51.0 / 115.1	1.94 / 14.23
	S19	720	51.0 / 115.1	1.94 / 14.23
Check valves	S10	8000	45.5 / 25.27	— / 19.67
	S16	8000	45.5 / 25.27	— / 19.67
	S01	720	53.4 / 151.3	4.26 / 18.4

30 reactor-years [11]. The failure rate indicators are determined from the upper confidence boundary.

The number of failures due to poor maintenance amounted to $35 \pm 5\%$ of the total number of failures available in the database. Confidence interval is due to incomplete information on particular incidents. Thus, more than a third of failures occur due to poor maintenance. The errors in the calculation of failure rates for the elements of the system are given in Table 1.

Table 2. Composition and intensity of failures of macro elements by databases [11–13]



(a) (b)

Figure 5. Calculation schemes for two stages of FPIS operation: (a) recirculation; (b) injection.

Sequentially connected elements having the same maintenance schedule can be combined into one macro element, characterized by the total failure rate. After the transformations, the calculation schemes were obtained (see Figure 5). The composition of the macro elements of the design schemes at two stages of the system operation and the failure rate for them are given in Table 2.

Macro element number	Composition	$\lambda \times 10^6$, 1/h	$\xi \times 10^2$, 1/ones
1	B01, S20	6.91 / 2.27	—
2	S19, D01, S01, S04, S03	17.18 / 16.97	0.67 / 0.92
3	B01, S20, S07, S16, S10	8.30 / 2.97	—
4	S19, D01, S01	16.16 / 14.66	0.63 / 0.63
5	S03	0.51 / 11.15	0.02 / 0.14
6	S04	0.51 / 11.15	0.02 / 0.14

7 Calculation Results and Analysis

The calculation schemes was applied to optimize the period of maintenance using the CXEMA program. The time for the maintenance varied from 500 to 6500 hours. For both stages of operation of the system TQ14 (24, 34), the optimum values of the availability factor are indicated in Figure 6, the numerical values of the availability factor at two stages of operation with using different databases are given in Table 3. The use of various databases on the reliability of the elements of the system significantly affects the calculated values of the availability factor, but the optimal values of the maintenance period are very close.

Table 3. Optimal maintenance parameters of FPIS on databases [11–13]

Parameter	Recirculation	Injection
T^*, h	2225 / 2732	2424 / 2427.5
k_A^*	0.999721 / 0.999890	0.999655 / 0.999916

It should be noted that increasing of the maintenance period leads to a significant increase in system reliability. Table 4 shows the ratio of the values of the unavailability factors for the scheduled and optimal value of the maintenance period, which on average is about three. This indicates that the maintenance period should be increased several times.

Table 4. The ratio of the unavailability factors for the regulatory and optimal value of the maintenance period of the system TQ14 (24, 34)

Stages	k_U ($T = 720$ h) /	k_U ($T = 2160$ h)
Recirculation	2,42	4,76
Injection	2.21	3.48
Average value	3.22	

Thus, for the system TQ14 (24, 34) it is possible to recommend a maintenance period $T = 2160$ h closest to the optimal values and which is a multiple of the current regulatory value.

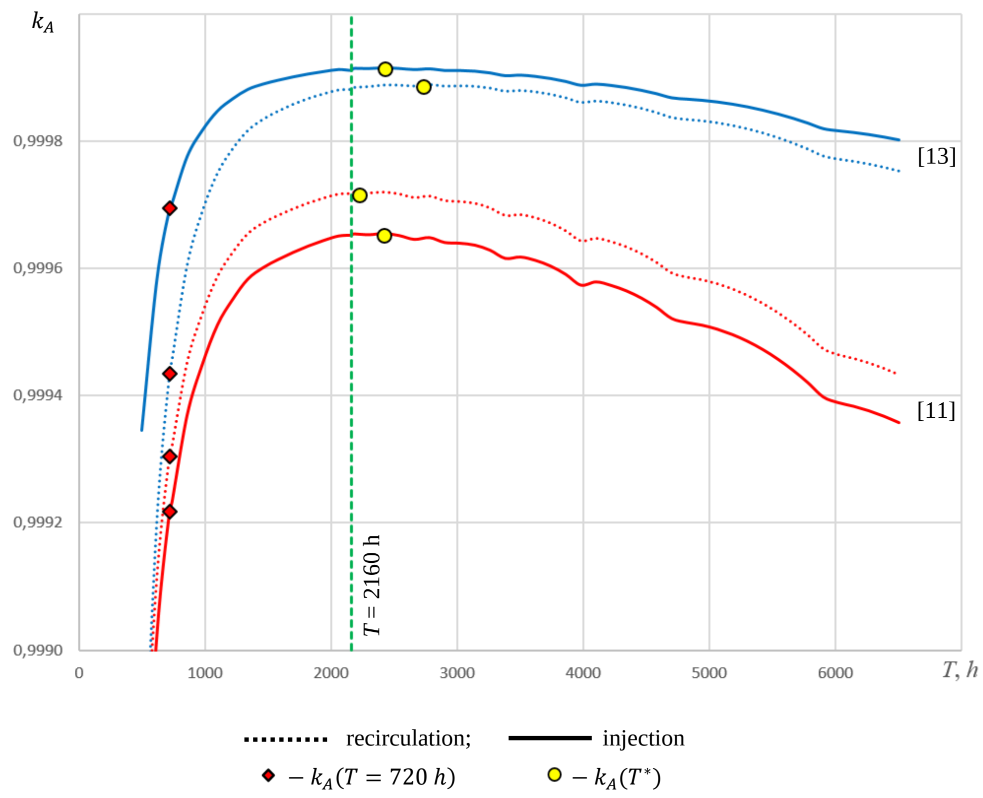


Figure 6. Availability factor of the system TQ14 (24, 34) depending on the maintenance period.

As researched to expect the accounting for the quality of service of the system leads to an increase in the optimal maintenance period. Limiting excessive interference of personnel in a system that is in standby mode reduces the possible negative impact of the human factor.

8 Conclusion

- In order to optimize the maintenance period of system, the program CXEMA has all the necessary features and, in particular, allows taking into account the quality of maintenance.
- The use of various databases on the reliability of elements of NPP safety systems made it possible to establish that the number of failures due to poor service can reach 35% of the total number of failures.
- The maintenance period of FPIS TQ14 (24, 34) can be increased three times as compared to the regulatory value currently in force.

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