Risk-Informed Maintenance Optimization for Safety Systems of NPP

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Abstract. The optimal maintenance of safety systems is one of components, which insure reliable and safe operation of nuclear power plants. The optimal service interval depends on the composition and structure of system and is unique for each safety system. So matching and determination of a common periodicity of safety systems maintenance are required. The method for optimizing the periodicity of safety systems maintenance based on a risk-oriented approach and PSA results is presented. As a criterion of system importance proposed the calculated indicator – interval of risk reduction. An example of implementation of the method is considered and recommendations for its application are given.

Keywords: maintenance, safety systems, service interval, risk-oriented, PSA, NPP.

1 Introduction

In accordance with the current regulatory documentation [1, 2], NPP safety systems should be subject to regular maintenance and testing. The purpose of such planned activities is to maintain the operability and confirm the design characteristics of the systems.

In this case, the frequency and volume of periodic inspections are established by schedules developed by the NPP administration on the basis of design requirements and technological regulations for safe operation (TRSO). These documents are developed on the basis of deterministic approaches at the time of the start of operation of the power unit and therefore contain excessive conservatism, as they rely on the recommendations of the designer and the equipment manufacturer. However, based on the IAEA recommendations [3], it is necessary to produce a regular periodicity established reassessed using operating experience.

2 The Relevance of Issue

The NPP safety is provided by the entire complex of safety systems (SS). Deviation from the optimal maintenance periodicity of SS can significantly affect the economy of operation and the overall safety level of NPP.

Too rare testing leads to a decrease in the reliability and availability of the equipment to perform its functions due to an increase in the number of latent failures in SS equipment during the test interval. Excessive monitoring can also reduce the level of reliability of the SS due to the fact that during the testing period the number of working channels decreases and the system becomes vulnerable to those negative impacts (risks) from which it is protected during normal operation.

Probabilistic methods for estimating reliability and risk for determining the reliability periodicity of maintenance for a particular SS have been developed and applied for analysis of the operation of the WWER-1000 serial unit, taking into account data on equipment reliability and operating experience of Ukrainian NPPs [4]. At the same time, the mean uptime availability of system is used as the determining factor of system reliability.

The authors used MS Visual Basic to develop the CXEMA program for calculating the optimal periodicity of SS maintenance (see Figure 1). The program allows you to model systems of any complexity. First, a structural diagram of system is drawing. Then, for each of the elements, their reliability characteristics are set. All input data is saved, which makes it easy to carry out recalculations when changing some data. The results of the calculation are presented in graphical form and outputted in a file.

The calculated optimal maintenance intervals for SSs are several times higher than the current standard values, and for each SS there is a unique optimal value for the periodicity, which is determined by the reliability of its elements, structure, number of duplicating channels and operating modes. The following VVER1000 safety systems were considered: Containment Spray System, Emergency Core Cooling Systems Low and High Pressure. The optimal maintenance frequency for all SSs exceeds the current standard values by 2-2.5 times (see Table 1).

Under the assumption that each test equally restores the system's operability and all systems that are part of the group are checked simultaneously, the task of harmonizing the periodicity of system maintenance requires the definition of an optimization criterion. To do this, we can use a risk-based approach [5–7]. Then determination of the optimal periodicity of SS maintenance should be carried out taking into account the overall availability of the complex of systems and the importance each SS.
Joint testing, under which several systems are inspected, in fact provide a same for all systems periodicity of maintenance. Since the optimal periodicity of maintenance of each system is unique the periodicity of the joint testing in general does not coincide with the optimal periodicity of the single systems. Therefore, when agreeing and choosing the optimal maintenance intervals for such systems, it is necessary to use a common indicator that assesses the reliability of the entire set of systems taking into account all possible emergency scenarios.

### 3 Criterion of Significance

The risk-informed approach acknowledged in international practice and widely used in nuclear energy. Under risk, in the broad sense of this term, is meant some combination of estimates of the probability of occurrence and the significance of negative consequences. As applied to NPPs, it is customary to use the core damaging frequency ($CDF$) or the frequency of unintended release from the contaminant, as determined by probabilistic analysis (PSA), as an assessment of the consequences.
In Ukraine has been completed the first-level PSA for all NPP pilot units, and its results can serve as a basis for implementing risk-informed approaches.

A number of importance indicators are used in the methodology of the PSA [8]. Birnbaum importance (BI) determines as the change of CDF when the probability of the basic event $x$ varies from 0 to 1:

$$BI(x) = CDF(1) - CDF(0) \quad (1)$$

The Fussell-Vesel importance (FV) determines the relative contribution of the event $x$ to the CDF:

$$FV(x) = \frac{CDF(a) - CDF(0)}{CDF(a)} \quad (2)$$

where $CDF(a)$ is the core damage frequency at the nominal probability of the event $x$ is equal to $a$.

A basic event $x$ is the failure of a single element of the NPP equipment, or the failure of the entire safety system.

Other importance indicators — Risk Reduction Interval (RRI) and Risk Increase Interval (RII), Risk Reduction Ratio (RRR) and Risk Increase Ratio (RIR):

$$RRI = CDF(a) - CDF(0) ;$$

$$RII = CDF(1) - CDF(a) ;$$

$$RRR = \frac{CDF(a)}{CDF(0)} ;$$

$$RIR = \frac{CDF(1)}{CDF(a)} . \quad (5)$$

Risk Intervals and Risk Ratio can be considered as components of BI and FV importance indicators. In particular, the Birnbaum indicator can be represented as the entire range of risk changes.

$$BI(x) = RRI + RII \quad (4)$$

$$FV(x) = RRR + RIR . \quad (5)$$

Optimization of the periodicity of system maintenance is aimed at increasing the reliability of systems, which ultimately provides a reduction of CDF. Therefore, the importance indicator RRI is most acceptable, which characterizes the risk reduction when the probability of system failure changes from the nominal value to zero. In fact, this indicator provides a quantitative estimate of the reserve to reduce the risk of damage, which can be achieved when the possibility of system failure will be absolutely excluded.

### 4 Optimal Periodicity of Systems Maintenance

It should be taken into account that systems with the same level of failure probability may have different risk reduction intervals. At the equal increasing of the system reliability, system with greater RRI will be more significant for the goal to reduce the overall risk, since it has a larger reserve for risk reduction.

Increasing the system reliability leads to $CDF(x)$ decreases and narrows $RRI$. Suppose that the risk reduction interval decreases proportionally to the change of reliability $R(T)$. When the system reliability varies from $R(T_s)$ to $R(T)$, the value of the risk reduction interval varies from $RRI(T_s)$ to $RRI(T)$. Therefore, the value of the $RRI(T)$ at changed interval $T$ is defined by expression

$$RRI(T) = RRI(T_s) \frac{R(T_s)}{R(T)} , \quad (6)$$

where $RRI(T_s)$ is the risk reduction interval at the standard (current) periodicity of the system maintenance.

This assumption is justified if the measures to improve the system reliability have the same effect on all fault sequences in the accidental event tree of the system. Applied to NPP safety systems this assumption is justified, since a change in the periodicity of maintenance affects the reliability of the entire channel of the system.

The overall reliability of system, which is periodically restored after maintenance, can be estimated by average up-time availability. The mean unavailability is calculated for the period when the system should be available for use (reactor campaign $T_s$). It represents the mean value of the instantaneous availability function $A(t, T)$ over the period $(0, T_s)$ and is given by

$$\bar{A}(T) = \frac{1}{T_s} \int_0^{T_s} A(t, T) \, dt . \quad (7)$$

The mean availability depends not only on the time period, but on the periodicity of maintenance $T$ which changes the function $A(t)$.

Thus, the $RRI$ of system after changing the periodicity of maintenance will be

$$RRI(T) = RRI(T_s) \frac{\bar{A}(T_s)}{\bar{A}(T)} . \quad (8)$$

The cumulative reserve for reducing the risk of core damage of $N$ systems is

$$RI(T) = \sum_{i=1}^{N} [RRI(T_s) \bar{A}(T_s) / \bar{A}(T)]_i , \quad (9)$$

where $N$ is the number of systems involved in complex testing; $T$ — the periodicity of the joint testing of systems. The summation of the risk intervals in the assessment of the total risk interval is acceptable for independent systems. Dependence of systems can be manifested either in the presence of sharing technological equipment, or in the safety functions duplication.

The calculation of $\bar{A}(T_s)$ and $\bar{A}(T)$ for each system was completed using a probabilistic model [9] realized by computer code CXEMA, mentioned above. The calculated dependences $\bar{A}(T)$ for set of safety systems of ZNPP unit 5, are presented in Figure 2.

The risk function $RI(T)$ can be used as a criterion for optimizing the complex testing periodicity of safety systems. The optimal maintenance intervals for safety systems provide maximum using of the existing reserves to reduce the risk of the reactor core damage.


5 Application of Optimization Method

The implementation of the proposed method for optimization the joint testing of systems will be considered on the example for two systems.

The optimal testing interval $T^*$ value at which the value of the total reserve for risk reduction $RI$ is minimal. Figure 3 shows the changing of the mean availability of systems at variation of the testing interval. The values of the risk reduction intervals $RRI_1$ and $RRI_2$ were obtained from the results of PSA. The optimum interval values for both systems $T^*_1$ and $T^*_2$ are indicated in the graph.

After processing the given characteristics of the systems with taking into account their importance the functional dependence of the overall range of risk reduction on the testing interval presented in Figure 4. Then the optimal value of the periodicity of joint testing $T^*$ can be obtained. If many systems are involved in a joint testing and their optimal maintenance intervals are differ significantly, the function $RI(T)$ may have several local minimum. Then, the optimal value of the periodicity of joint testing will correspond to the absolute minimum of the function $RI(T)$.

In cases where there is reason to believe that a change in the periodicity of the system maintenance significantly change its importance indicators, a check should be carried out. If it is necessary the updated estimates of $CDF$s and $RRI_i$ should be obtain by using PSA. If significant deviations of indicators are revealed, then the proposed optimization method should be applied as an iterative process. Due to the low sensitivity of the PSA models to the change in the frequency of maintenance, it can be assumed that one step of the iteration will be sufficient.

Thus, the considered method allows optimizing the periodicity of routine testing of SS on the basis of minimization of the risk function that takes into account the current level of reliability of the components of systems and influence of these systems on $CDF$.

6 Conclusions

1. Optimization of the frequency of maintenance of NPP safety systems is an urgent problem and can be solved on the basis of risk-informed approaches using the results of the PSA.
2. As a criterion for the system importance, it is reasonable to use the calculated indicator – the interval of risk reduction.

3. The presented method allows optimizing the periodicity of joint testing of the safety systems, increasing the safety of nuclear power plants.

References


