Optimization of Maintenance Periodicity of Complex of NPP Safety Systems

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ABSTRACT

The analysis of the positive and negative aspects connected to maintenance of the safety systems equipment which basically is in a standby state is executed. Tests of systems provide elimination of the latent failures and raise their reliability. Poor quality of carrying out the tests can be a source of the subsequent failures. Therefore excess frequency of tests can result in reducing reliability of safety systems.

The method of optimization of maintenance periodicity of the equipment taking into account factors of its reliability and restoration procedures quality is submitted. The unavailability factor is used as a criterion of optimization of maintenance periodicity. It is offered to use parameters of reliability of the equipment and each of safety systems of NPPs received at developing PSA. And it is offered to carry out the concordance of maintenance periodicity of systems within the NPP maintenance program taking into account a significance factor of the system received on the basis of the contribution of system in CDF.

Basing on the submitted method the small computer code is developed. This code allows to calculate reliability factors of a separate safety system and to determine optimum maintenance periodicity of its equipment. Optimization of maintenance periodicity of a complex of safety systems is stipulated also. As an example results of optimization of maintenance periodicity at Zaporizhzhya NPP are presented.

1 INTRODUCTION

According to working normative documentation [1, 2] safety systems (SS) should be objects of regular maintenance service and tests. The purpose of such scheduled actions is to maintain availability and to confirm design characteristics of systems.

Thus frequency and scope of periodic checks are established by the schedules developed by NPP administration on the basis of design requirements and technological regulations of safe operation (TRSO). These documents are developed on basis of deterministic approaches at the moment of the beginning of operation of the power unit, are based on recommendations of the designer and the manufacturer of the equipment, and therefore contain redundant conservatism.

At the same time, proceeding from recommendations of IAEA [3], it is necessary to make regular reassessment of the established periodicity using operating experience. The urgency of
a problem of optimization of periodicity of maintenance also is endorsed by necessity of its carrying out at prolonging a service life of the NPP equipment [6].

2 PRINCIPLES OF NPP SAFETY ENSURING BY PERIODIC SUPERVISION

To ensure safe operation of the NPP the program of supervision is developed and should be systematically fulfilled. It will provide check of conformity to requirements of safety margins that takes into account random events, errors and malfunctions at operation [3]. The program defines scope, periodicity, the purposes, and the schedule of supervision.

Periodicity and scope of supervision should be sufficient to provide:

- Confidence that plant parameters, including availability of specific systems and elements, correspond to the established operational limits and conditions;
- Detecting incipient failures and revealing necessity for more often carrying out of maintenance service of the equipment;
- Confidence that evolution of any defect does not result in an accident during the period between two subsequent maintenance actions.

Choosing optimum periodicity of supervision the following factors are taken into account:

- A degree of reservation of system of taking into consideration its change at a withdrawal of systems or components from operation for supervision;
- Probable errors during operations and as a result excessive tests that result in unreasonable reduction of operation life of the equipment;
- At scheduling supervision it is necessary to take into account other kinds of activity, such as scheduled maintenance service and shutdowns.

When there is limited experience concerning reliability of systems and components, the originally accepted periodicity of supervision should be based on conservative assumptions (the top limits of estimates). Once sufficient experience is obtained the changes to the maintenance program can be made.

Intervals for inspections covering all elements in the uniformly distributed schedule of checks can be chosen from one to ten years.

At the non-uniform schedule, intervals between inspections are short in the first years, and then they may increase in process of accumulation of experience. However, the information on evolution of defects can also request reduction of intervals between inspections by the end of lifetime of a plant.

For working reactors the types of maintenance service and repair (MSR) and their periodicity are regulated by the technical manual and the information on reactor safety, technological regulations, operating instructions of separate systems of reactor.

Requirements on periodicity of maintenance of safety systems of Ukrainian NPPs are based on conservative deterministic positions as when they have been designing and constructing the probabilistic analysis methods have been insufficiently developed. The fundamental difference of the existing practice to the adaptation of inspection periods with growing experience is that the periodicity of MSR is fixed during the lifetime of a unit for all safety systems. First of all it is caused by that the procedures directed on carrying out of reassessments and making of necessary changes of the established periodicity and scope of MSR till now are not developed and there is no authorized technique of change of periodicity of services and inspections for the whole complex of the safety systems.

The following systems are included in a considered complex of safety systems:

- Emergency Core Flooding System - Hydroaccumulators (ACC) – YT
- Low Pressure Injection System (LPIS) - TQ12/22/32
- High Pressure Injection System (HPIS) - TQ13/23/33
- Full Pressure Injection System (FPIS) - TQ14/24/34
Preventive inspection is performed once per month and more often that provides check of availability of system elements and detecting probable defects. The final stage of routine maintenance and preventive inspection is individual testing of the equipment with the subsequent complex testing of SS according to schedule.

The periodic control of a technical status of the equipment of emergency core flooding system includes the following kinds of the control:

- Visual survey
- Dye penetrant flaw detection or magnaflux inspection
- Hydraulic tests

The active core cooling systems are periodically tested with the purpose to check its good condition during the lifetime. The following kinds of tests are stipulated:

- Tests of pumps and valves by control keys during operation;
- Check of activation of system trains under the automatic start-up sequence program in case of blackout of 6 kV sections;
- Tests with check of operating efficiency of system trains.

The periodic control of most of the controllable elements of each train is made with a periodicity of 720 hours. The trains are tested in a fixed and same distance from each other.

Contrary to the past now there is the necessary operating experience that allows estimating reliability of the NPP equipment, and PSA is carried out for all pilot units of the NPPs. From a safety point of view the optimum periodicity of SS supervision can be determined taking into account all available actual data on reliability of the equipment, and programs of the control of each separate system should be incorporated into the unified optimum program of the control of the whole complex of safety systems.

3 RELIABILITY VARIATION OF RESTORED SYSTEMS ELEMENTS

In consideration of operation of safety systems, it is necessary to note, that the principle of independent trains, that are identical on a set of the equipment and fulfilled functions, is applied to increase of system reliability. The basic condition of SS is a standby mode in which there is no deterioration of the system equipment, but thus occurrence of random failures of system elements also is possible. Thus, reliability of system is constantly reduced in a process of accumulation of uncertainty about the proper condition of system elements, and therefore maintenance of safety systems reliability at a comprehensible level carrying out of the planned control and repairs is necessary.

Carrying out of safety systems repair due to found deficiencies coincides with planned-prophylactic repair/maintenance of the plant conducted every year. According to practice existing now repair of SS includes repair of all safety system trains and their tests after repair. Repair of system provides elimination of all system elements failures arisen up to the moment of repair and, hence, to restore reliability of system completely.

In the between-repairs period, i.e. during unit operating, maintenance of safety systems reliability is provided by periodic controls (tests) of the system train with constant periodicity. Each test affects and is carried out to check only one train, but for the period of repairs cycle all system trains are consistently checked. At tests a train is turned into full or partially non-working condition and is not capable to provide safety functions. As a result of tests probable failures of train elements come to light and shall be eliminated, and its reliability is restored. At the same time other independent trains are capable to carry out the appointed safety functions, but reliability of the whole system for the period of tests is reduced because backup capacity of the whole system is reduced.

For the integrated characteristic of the described operating mode of multitrain system it is possible to use a parameter of reliability - factor of unavailability which evaluates average
reliability of system for some period taking into account its variations. Absence of physical deterioration of systems elements and trains during standby mode allows application the exponential law for time variation of elements failures probability.

The system maintenance is characterized by periodicity of tests of system trains $T$ and by duration of train tests $R$. Character of a single element failure probability variation at periodic restorations is presented in Figure 1a. The failure probability of an element changes with period $T$, and on interval from $T - R$ up to $T$ during tests is equal to one if duplication is absent. Character of dependence of unavailability factor from tests periodicity (see Fig. 1b) specifies presence of optimum value at which there is a minimum of unavailability factor.

![Figure 1: Reliability characteristics of single-element system](image)

Similarly the tests of SS train results in decrease of system reliability during carrying out of tests and at the same time provide restoration of its reliability after end of tests. Therefore under certain conditions there is an optimum periodicity of carrying out of tests corresponding to a minimum of system unavailability factor.

4 THE RESTORATION QUALITY

The character of change of reliability of an element presented above is based on an assumption, that MSR recover an element initial condition when the probability of its failure is equal to zero. So the opportunity of partial restoration of elements or the systems, caused was absolutely excluded by quality of MSR. However even at small probability of poor-quality carrying out MSR procedures due to their big number there is a certain probability of incomplete restoration of an element.

The quality of system elements restoration is determined by a number of factors:
- Quality of carrying out of the operations connected with switch of system from a standby status and returning back after end of MSR (switching, disassembly of examined elements or their dismantling and other changes in a system configuration);
- Quality of carrying out of renewal operations - completeness of detection and removal of the latent failure, including mistakes of the personnel;
- Deterioration of system elements during train tests because non-design conditions arising at work of SS, when connection to the primary circuit is impossible;
- Limitation of depth and completeness of survey and control procedures therefore not covering all elements of the system;
The increased accessibility of system elements during service can lead to appearance of additional factors (risks) leading to system failure. The degree of influence of the listed factors is determined by both number carried out MSR, and their total time.

To describe the change of reliability of an element when its full restoration is absent we shall enter parameter $\xi$ specifying average quantity of failure per one restoration procedure. As against intensity of a random failure flow rate $\lambda$, parameter $\xi$ characterizes only failures induced by poor-quality restoration. The probability of an element failure at partial restoration of reliability after carrying out $k$ MSR will make:

$$P(t, k) = 1 - \exp(-[\lambda t + \xi k])$$  \hspace{1cm} (1)

Dependence in time of an element failure probability is presented in Figure 2.

The unavailability factor of an element on interval which includes $m$ tests (restoration procedures) in view of restoration quality is defined by expression:

$$K_{un} = 1 - \frac{1 - \exp(\lambda[T - R])}{\lambda T} \sum_{k=0}^{m-1} \exp(-\xi k)$$  \hspace{1cm} (2)

Similar approaches can be used to reliability estimation of SS consisting of a many elements and forming a few independent trains. Parameters of the equipment reliability and each of NPP safety systems can be received from developed PSA. The value of parameter $\xi$ for system equipment is defined as result of the analysis of the failures causes. The preliminary analysis of the failures causes with using ZNPP's database has shown that about one third from their quantity are caused by quality of restoration procedures [4].

5  THE PRINCIPLES OF OPTIMIZATION OF MAINTENANCE PERIODICITY OF A SYSTEMS COMPLEX

The problem of the coordination of maintenance periodicity of systems is reduced to definition of the common criterion of optimization. For this purpose risk-oriented approaches, which allow taking into account simultaneously the probability of negative events and the importance of the consequences connected to them, can be used.

Optimization of SS maintenance periodicity is focused on achievement of maximal reliability that finally provides decrease in risk of core damage. Thus the system unavailability
factor characterizes average probability of finding a system in a disabled condition during any moment of the operation period.

The reconciliation of maintenance periodicity of systems within the framework of the NPP's control program can be carried out in view of a parameter of the system importance, dependent on the system contribution in core damage frequency (CDF). Assumed that parameters insignificantly change at maintenance periodicity variation, it is proposed to use as the optimized parameter for a systems complex:

\[
\Delta CDF = \sum_{i=1}^{n} \left[ K_{ua} (T^*) / K_{ua} (T) \right] \cdot RI CDF_i ,
\]

where \( \Delta CDF \) – CDF change at restoration periodicity variation

RI CDF\(_i\) – reduction interval of CDF due to system becomes trouble-free

\( T^*, T \) – changed and actual maintenance periodicity.

Function \( \Delta CDF \) can be used as criterion of optimization of maintenance periodicity of a systems complex. Thus the main point of optimization is to determine the same maintenance periodicity for all systems at which available reserves of CDF reduction is used at most. Generally the systems which are included in a complex have an individual separate optimum of maintenance periodicity and consequently function \( \Delta CDF \) can have some local minima. Optimum value of periodicity for a complex of systems will correspond to an absolute minimum of this function.

If the optimum periodicities found for separate systems essentially differ (for example, more than twice), it is expedient to use multiple periodicity. Thus as a result of optimization the maintenance periodicity is uniform for the majority of systems. But for some systems demanding more often testing the higher maintenance periodicity is defined (2 to 3 times more).

6 THE RESULTS OF MAINTENANCE PERIODICITY OPTIMIZATION OF THE SAFETY SYSTEM COMPLEX

The considered principles of maintenance periodicity optimization of SS have been realized by development of the computer code for calculation of reliability parameters. The small computer code which allows to obtain the reliability parameters, in particular \( K_{ua}(T) \), for a separate safety system is developed and allows to define optimum maintenance periodicity. The detailed description of a calculation algorithm is presented in [4].

As calculation for each safety system has shown there is an optimum value of periodicity which is defined by reliability of its elements, its structure (including number of duplicating trains) and operating modes. Optimum periodicity of maintenance for all safety system exceeds present values by 2-3 times (see Tab. 1 and Fig. 3).

<table>
<thead>
<tr>
<th>Name of SS</th>
<th>Actual maintenance periodicity ( T^* ), h</th>
<th>Optimal maintenance periodicity ( T_o ), h</th>
<th>( K_{ua} (T^*) / K_{ua} (T_o) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC – TQ11(21,31)</td>
<td>720</td>
<td>1603</td>
<td>1.32</td>
</tr>
<tr>
<td>LPIS – TQ12(22,32)</td>
<td>720</td>
<td>1876</td>
<td>2.15</td>
</tr>
<tr>
<td>HPIS – TQ13(23,33)</td>
<td>720</td>
<td>1405</td>
<td>1.25</td>
</tr>
<tr>
<td>FPIS – TQ14(24,34)</td>
<td>720</td>
<td>2027</td>
<td>2.36</td>
</tr>
</tbody>
</table>
As a first approximation the importance of systems can be estimated on the importance of the basic safety functions which they should carry out according to their purpose. PSA contain the analysis of influence of safety functions on CDF, including definition of all accident sequences, which include failure of considered function and the percentage specific contribution of each safety function in value of total CDF. The system importance for considered systems is submitted in Table 2 [5].

Table 2: Specific contribution of safety functions in CDF

<table>
<thead>
<tr>
<th>Safety system</th>
<th>Safety function</th>
<th>Frequency, 1/year</th>
<th>The specific contribution in CDF, %</th>
<th>IR CDF, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TQ12(22,32)</td>
<td>F1. Primary cooling down and decay heat removal by planned cooldown line</td>
<td>1.14E-06</td>
<td>2.41</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>F2. Primary cooling down and decay heat removal by LPIS from sump</td>
<td>1.79E-07</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D4. Primary coolant inventory control by LPIS</td>
<td>1.79E-07</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>TQ13(23,33)</td>
<td>B2. Boron injection in the primary circuit from HIPS</td>
<td>5.98E-07</td>
<td>1.27</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>D2. Primary coolant inventory control by HPIS</td>
<td>5.98E-07</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>TQ14(24,34)</td>
<td>B3. Boron injection in the primary circuit from FPIS</td>
<td>6.30E-08</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Note: the safety functions of selected SS which specific contributions in CDF 0.03 % above are taken into account only.
Taking into account the values of the systems importance parameter the dependence $\Delta CDF$ from maintenance periodicity is received (see Fig. 4). Base value of the optimized parameter at actual maintenance periodicity for a complex of systems equals to $\Delta CDF = 5.84\%$. Optimum value of maintenance periodicity equal to 1720 hours is received at $\Delta CDF = 3.43\%$.

![Figure 4: Dependence of optimization parameter on maintenance periodicity](image)

The proposed way of optimization can be considered as iterative process. As a first approximation optimum periodicity for a systems complex is with use of a reduction interval of CDF – $RI \ CDF_i$ received at current maintenance periodicity for each system. Because of an assumption that change of reduction interval of CDF is proportional to system failure probability the found optimum has an uncertainty. Therefore in the following step of iteration it is necessary to obtain more precise $RI \ CDF_i$ at the changed maintenance periodicity. For this purpose PSA models for corresponding systems [5] can be used. Thus it is necessary to have in view that PSA models are insufficiently sensitive to change of periodicity and quality of maintenance [7].

**CONCLUSIONS**

1. Optimization of maintenance periodicity of NPP safety systems is a present problem and can be solved by using the risk-informed approaches in combination with PSA results.
2. As criterion of the system importance it is appropriate to use the parameter calculated on the basis of a reduction interval of CDF.
3. The submitted method allows to optimize maintenance periodicity of a systems complex and to raise safety of NPP.
REFERENCES


