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REVISION OF NUCLEAR POWER PLANTS SAFETY SYSTEMS' ROUTINE TESTING ASSIGNED PERIODICITY DURING THE DESIGN EXTENTION PERIOD

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When nuclear power plants safety systems' thermal equipment operation extending, a necessary requirement shall rely on revising the scheduled equipment tests frequency to optimize those tests schedule taking into account the equipment's remained lifespan. On the one hand, there exists a need for tests frequency increase to detect "hidden" failures, and on the another, frequent tests cause a premature wear of the equipment. Proposed is an original method for optimizing the frequency of NPPs safety systems' thermal engineering equipment testing. Essential in the proposed method is the optimization criterion chosen: index of security system failure probability non-exceedance during the beyond-design operating period as referred to the failure probability expected considering the equipment residual resource during the design operating period. The developed method implementation when applied to NPPs safety systems operated beyond the design service life at nuclear power plants with WWER-1000 series reactors, allowed to establish that the optimal tests frequency makes half the designed one when the equipment service life is extended by five years and three times less that the designed frequency when subject lifespan extended by 10 years.

INTRODUCTION

The nuclear power plants safety systems (NPP SS) are operated in a mode of readiness to actuate assigned safety functions once the emergency event arisen. To confirm the security function reliable readiness the project design and NPP SS technological regulations for safe operation provide periodic SS tests both during reactor regular operation, and while NPPs power units scheduled repairs [1, 2].

However, the SS planned tests periodicity, established under project design instructions, is determined without sufficient grounds, based mainly on intuitive approaches. The planned frequency of testing established should be optimal: on the one hand, there exists a need for tests frequency increase to detect "hidden" failures or defects, and on the another, the tests excessive frequency cause a premature wear of the SS equipment with corresponding decrease in the safety function reliability.

An analytical review of well-known studies on optimization of tests scheduling, maintenance and repair of systems important for safety during the NPP design lifespan is given in [1, 3].

Below exposed peculiarities in optimizing the SS tests periodicity during the NPPs extended lifespan are as follows [4].

1. Predominantly the operated equipment is already at the beyond-design service life stage. Therefore, measures to extend the operational span include a survey of that equipment technical condition to estimate the remaining service life by its technical condition determining parameters.

2. During the equipment operation period, a considerable experience has been accumulated on the evaluation of SS tests design periodicity effectiveness. In particular, at Ukrainian reactors with WWER-type reactors, a high SS reliability along with practically poor tests efficiency at most cases are established.

Thus, the questions of optimizing the SS tests periodicity when NPPs extended lifespan being of high relevance we enterprised this subject research belo summarized.

MAIN PROVISIONS GROUNDING THE METHOD TO OPTIMIZE THE SS TESTING PERIODICITY WHEN SUBJECT EQUIPMENT SERVICE LIFE EXTENDED

1. The optimisation criteria (condition) adopted: non-exceedance of SS failure probability in the beyond design service period P_1 (failures caused by the assigned security functions degradation /aging processes at standby readiness modes and processes of deterioration during thermal equipment tests) over the probability of failure according to the design lifespan residual resource P_0:

$$P_1 < P_0. \quad (1)$$

2. The optimization parameter here is the periodicity (frequency) of SS scheduled tests when the reactor regular operation at a power f_1 that satisfies the optimization condition (1).

3. The probability of residual resource failure according to the design lifespan is determined by the ratio between the SS equipment loading cycles number during the design lifespan N_0 and the design-permissible number of loading cycles according to technological regulations for the NPPs safe operation N_p [5]:

$$P_0 = \frac{N_0}{N_\text{p}}. \quad (2)$$

For SS in the functional readiness mode, the equipment loading cycles number is determined by the scheduled tests periodicity f_0 within the design service period T_0:

$$N_0 = f_0 T_0 \,. \tag{3}$$

4. The SS failure probability in the beyond design operation period depending onto the time T_1 is caused by aging / degradation and deterioration of equipment during tests and can be defined as

$$P_1 = \int_0^{T_1} \lambda \mathrm{d}t + P_c f_1 T_1, \tag{4}$$

where λ – failure probability per one unit of time (failure due to SS thermal equipment aging/degradation); P_c – probability of failure due to wear during a single test performed; f_1 – tests periodicity in the beyond design operation period which duration is T_1 (optimization parameter).

Taking into account expressions (2)–(4), the optimization condition (1) gets the following form:

$$\frac{f_1}{f_0} < \frac{1}{P_c N_p} \frac{T_0}{T_1} - \frac{1}{P_c f_1 T_1} \int_0^{T_1} \lambda \mathrm{d}t \,. \tag{5}$$

The optimization parameter defining region:

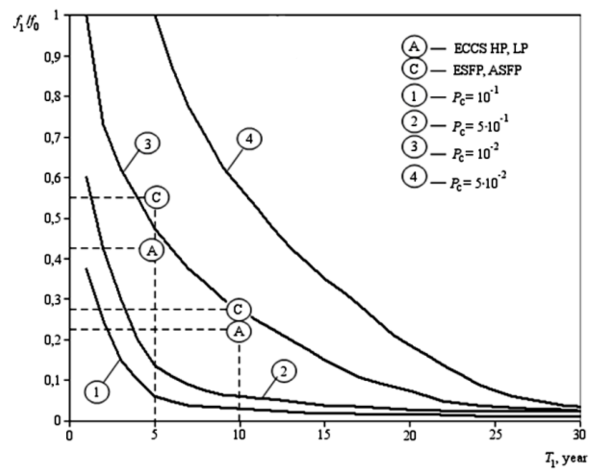
$$0 \le \frac{f_1}{f_0} \le 1 \,. \tag{6}$$

The planned tests periodicity during the design period of operation f_0 and the permissible loading cycles number N_p are determined by the technological regulations for the NPP safe operation (for example, [2]).

The designated operation extension period T_1, thermal equipment failure probability P_c and λ are determined by the operational experience analysis results (including similar equipment), as well as design documentation for SS components (for example, [6]).

ANALYSIS OF CALCULATION RESULTS

The results of optimal values regions calculations for the SS thermal equipment tests periodicity when extended operation periods varying (from 1 up to 30 years) and reliability indicators varied are shown in Figure.



Calculated safety systems tests periodicity optimal values regions when extended operation periods

To determine the probability of failure due to thermal equipment aging/degradation, λ, we used the traditional exponential distribution, such selection being completely justified for heat and power engineering equipment [1–4].

From the results shown in Figure, following conclusions can be drawn:

1. The increase in the extended operation duration at the equipment's certain reliability indicators values leads to a decrease in the SS tests periodicity optimum values during the beyond-design service period.

2. Increasing the reliability (or reducing the probability of failure due to various reasons) leads to the expansion of optimal test periodicity regions.

3. Under probability of failure due to wear during testing less than 10^{-3}, advisable is to maintain the SS tests design-scheduled periodicity.

The developed method was used to extend operational lifespan of NPPs at WWER-1000/V-320 series power units (1st and 2nd units of the Zaporizhzhya NPP) in order to optimize the SS field testing frequency:

Systems of the reactor core emergency cooling by low-pressure pumps (ECCS LP);

Systems of the reactor core emergency cooling by high-pressure pumps (ECCS HP);

Systems of emergency and auxiliary steam generator feeding with power pumps (ESFP, ASFP).

The WWER-1000/V-320 project provides a three-channel redundancy for each ECCS HP, ECCS LP, ESFP and ASFP system. At that, each channel is sufficient to perform the assigned safety functions.

The structure of each channel at the above mentioned SS includes the following thermal equipment: pump, shut-off and control valves, heat exchangers.

Conventinally the reliability indicators were determined by the SS channel's least reliable element, i. e. pumps. The pump failures probability was assessed by the analysis of their operational experience/technical passports/statistical data as to the similar equipment from the "System Analysis" section of the Safety Analysis Reports for WWER-1000/V-320 series power units.

The tests design frequency established under regulatory norm for each SS channel SB is once a month when the reactor is regularly operated.

The averaged design-based justifications results for ECCS HP, ECCS LP, ESFP and ASFP of Zaporizhzhya NPP 1st and 2nd power units are shown in Fig. 1. These results allow concluding that when beyond-design operation period is five years the optimal testing frequency for each SS channel will be one test in two months (half the design periodicity), and when the design lifespan extended for 10 years, it changes into one test per three months (three times less than the tests design periodicity).

MAIN CONCLUSIONS

1. When extending the nuclear power plants safety systems' thermal equipment operational life, necessary is to revise the planned tests periodicity by optimizing schedules taking into account the equipment remaining lifespan. On the one hand, required is to increase tests frequency to detect "hidden" failures, still on the other hand, frequent tests involve the equipment's premature wear.

2. Proposed is the original method for optimizing the nuclear power plants safety systems' thermal equipment tests frequency.

The proposed method relies onto the optimization criterion of the security system failure probability during the beyond-design operation period non-exceedance above the probability of the equipment residual resource failure during the design operation period.

3. As a result of the developed method implementation while WWER-1000 series reactors nuclear power plants' safety systems extended operation, it has been established that the optimum test frequency is half the design-based one when the service life is extended by five years and three times less the design-based when such extension augments to 10 years.

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ПЕРЕНАЗНАЧЕНИЕ ПЕРИОДИЧНОСТИ РЕГЛАМЕНТНЫХ ИСПЫТАНИЙ СИСТЕМ БЕЗОПАСНОСТИ ЯДЕРНЫХ ЭНЕРГЕТИЧЕСКИХ УСТАНОВОК В ЗАПРОЕКТНЫЙ ПЕРИОД ЭКСПЛУАТАЦИИ

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При продлении эксплуатации теплотехнического оборудования систем безопасности ядерных энергетических установок необходимо пересмотреть периодичность плановых испытаний путем их оптимизации с учетом остаточного ресурса оборудования. С одной стороны, необходимо увеличивать частоту испытаний для выявления «скрытых» отказов, а с другой стороны, частые испытания приводят к преждевременному износу оборудования. Предложен оригинальный метод оптимизации периодичности испытаний теплотехнического оборудования систем безопасности ядерных энергетических установок. В предложенном методе критерий оптимизации – непревышение вероятности отказа системы безопасности в запроектный период эксплуатации по отношению к вероятности отказа по остаточному ресурсу оборудования за проектный период эксплуатации. В результате применения разработанного метода при продлении эксплуатации систем безопасности ядерных энергетических установок с серийными реакторами типа ВВЭР-1000 установлено, что оптимальная периодичность испытаний в два раза меньше проектной при продлении срока эксплуатации на пять лет и в три раза меньше – при продлении на 10 лет.

ПЕРЕПРИЗНАЧЕННЯ ПЕРІОДИЧНОСТІ РЕГЛАМЕНТНИХ ВИПРОБУВАНЬ СИСТЕМ БЕЗПЕКИ ЯДЕРНИХ ЕНЕРГЕТИЧНИХ УСТАНОВОК В ПОЗАПРОЕКТНИЙ ПЕРІОД ЕКСПЛУАТАЦІЇ

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При подовженні експлуатації теплотехнічного обладнання систем безпеки ядерних енергетичних установок необхідно переглянути періодичність планових випробувань шляхом їх оптимізації з урахуванням залишкового ресурсу обладнання. З одного боку, необхідно збільшувати частоту випробувань для виявлення «прихованих» відмов, а з іншого боку, часті випробування призводять до передчасного зносу устаткування. Запропоновано оригінальний метод оптимізації періодичності випробувань теплотехнічного обладнання систем безпеки ядерних енергетичних установок. У запропонованому методі критерій оптимізації - неперевищення ймовірності відмови системи безпеки в запроектних період експлуатації по відношенню до ймовірності відмови по залишковому ресурсу обладнання за проектний період експлуатації. В результаті застосування розробленого методу при подовженні експлуатації систем безпеки ядерних енергетичних установок з серійними реакторами типу ВВЕР-1000 встановлено, що оптимальна періодичність випробувань у два рази менша проектної при подовженні терміну експлуатації на п'ять років та в три рази менша - при подовженні на 10 років.