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QUALIFICATION METHOD TO MODERNIZE STRATEGIES FOR SCHEDULED REPAIRS OF ACTIVE SAFETY SYSTEMS OF NUCLEAR POWER PLANTS WITH WWER

***V.I. Skalozubov*[*,1], *O.M. Vierinov*[1], *A.V. Kanivets*[1], *Ju.O. Komarov*[1], *V.V. Kandieieva*[2]**
[1]Interagency Centre for Fundamental Scientific Research in Energy and Ecology Sector, National Academy of Sciences of Ukraine, Odessa Polytechnic and Ministry of Ecology and Natural Resources of Ukraine, Odessa, Ukraine;
[2]Odessa Polytechnic National University, Odessa, Ukraine
E-mail: valer_nov13@ukr.net

The strategies for scheduled tests and repairs of active safety systems (with pumps) established by the Technological Regulations for the safe operation of NPPs with WWER do not take into account many years of operating experience and the results of numerous tests of active safety systems, current reliability indicators and the residual life of the main equipment and other factors. Modernization/improvement of design strategies for scheduled repairs and tests of active safety systems determines the need to develop appropriate methods for qualification (substantiation) of modernized strategies. There is presented a risk-informed method for qualifying modernizations of strategies for scheduled repairs of active safety systems, taking into account experience in operation, scheduled repairs and tests, as well as the current reliability of the main equipment. The developed method is based on the following provisions. The determining reliability indicator when qualifying strategies for scheduled repairs of active safety systems is the safety unavailability factor, which determines the probability of a critical failure at the current time depending on the critical failure rate established in scheduled tests/repairs over the expired operation life. A critical failure here means a failure to perform safety functions (for example, failure to turn on a pump, forced shutdown of a pump due to a violation of operability conditions, leaks in the circuits of active safety systems, etc.). The qualification criterion to modernize strategies for scheduled repairs of active safety systems is a risk function that determines the ratio of the safety unavailability factors of the design and modernized strategies for scheduled repairs of active safety systems. Condition for successful qualification is the safety unavailability factor of the modernized strategy for scheduled repairs is not greater than the safety unavailability factor of the design strategy for scheduled repairs. Based on the developed method, modernized strategies for scheduled repairs of active safety systems of the WWER-1000 reactor were substantiated and the conditions for the applicability of the modernized strategies were determined.

INTRODUCTION

The relevance of improving/modernizing strategies for scheduled repairs of active safety systems (SRS ASS) is determined by the insufficient validity of the regulated (design) SRS ASS, which does not take into account operating experience, results of scheduled tests and repairs, residual reliability life and other factors.

SRS ASS modernization should be of an optimization nature, since on the one hand, an increase in the number of scheduled tests and repairs increases the probability of detecting "hidden" failures and defects; but on the other hand, an unreasonable increase in the number of scheduled tests and repairs can lead to excessive wear of equipment and a decrease in the residual life for the reliability of safety functions, an increase in the probability of staff errors, an increase in the time of scheduled preventive repairs (SPR) and other negative effects.

To substantiate the modernized SRS ASS for nuclear power plants (NPP), it is necessary to develop appropriate qualification methods that take into account the current reliability of the necessary safety functions, operating experience, the results of previous tests of ASS channels at reactor power/during the SPR process, the number and results of previous repairs, which determines the relevance of the presented work.

ANALYSIS OF LITERATURE AND FORMULATION OF THE PROBLEM

The work [1] analyses the regulated strategy for scheduled ASS tests in reactor operating modes at power at NPPs with WWER. As a result, it was recognized that the design SRS ASS does not take into account the current reliability of the safety functions, experience and test results and other factors. However, the issues of modernization/optimization of SRS ASS were not considered in this work.

The work [2] presents a deterministic analysis of the reliability of SRS ASS pumps during testing in the reactor operating modes at power and SPR for NPPs with WWER. However, the issues of modernization/optimization of SRS ASS were also not considered in this work.

The work [3] analyses the influence of the number of tests of thermal-mechanical equipment on wear and residual reliability life. However, the methods developed in this work are not sufficiently substantiated for the qualification of modernization of SRS ASS of NPP with WWER.

The work [4] presents a risk-informed method for modernizing the leak-tightness testing strategy for the containment of NPP with WWER during SPR based on an analysis of the results of previous tests. However,

this method is also not sufficiently substantiated for the qualification of SRS ASS modernization.

The work [5] presents a risk-informed method for qualifying modernizations of strategies for maintenance, scheduled tests and repair of NPP safety related systems based on the analysis of the results of probabilistic safety analysis of NPP power units. This method assesses the impact of modernizing the frequency of tests/repairs of safety related systems on the integral probabilistic safety indicator of a NPP unit – core damage frequency (CDF).

However, the dominant factors in CDF assessing are the probabilities of common cause failures and staff errors when managing accidents [6]. Therefore, the CDF value may not be "sensitive" to changes in the frequency of tests/repairs of safety related systems.

Thus, an urgent issue is the development of a method for qualifying modernizations of SRS ASS of NPPs with WWER, taking into account the current reliability indicators, operational experience and the results of previous tests/repairs of the ASS equipment, which determines the main purpose of the presented work.

METHOD FOR QUALIFYING MODERNIZATIONS OF STRATEGIES FOR SCHEDULED REPAIRS OF ACTIVE SAFETY SYSTEMS

Basic principles of the method are the followings.

1. The determining reliability indicator when SRS ASS qualifying is the unavailability of the safety function, which determines the probability of a critical failure occurring at the current time t depending on the critical failure λ, detected in scheduled tests/repairs over the expired operation life [7]. A critical failure here means a failure to perform safety functions (for example, failure to turn on a pump, forced shutdown of a pump due to a violation of operability conditions, leaks in the ASS circuits, etc.).

2. Qualification criterion for the SRS ASS modernization is the objective risk function R, which determines the ratio of the safety unavailability factors of the design and modernized SRS ASS.

3. Condition for successful qualification is the safety unavailability factor of the modernized SRS is not greater than the safety unavailability factor of the design SRS.

4. It is assumed that the occurrence of ASS failures/violations in the reactor operating modes at power and/or SPR are random (unintentional) events.

With a normal pattern of distribution of random failures/violations, the CRS safety unavailability at the time of the current operation life T [7]:

$$P(\lambda,T)=\frac{n_R(T)\Delta t}{T}+\frac{n_{ma}(T)\Delta t}{n_0(T)}, \quad (1)$$

where $n_R(t)$, $n_{ma}(t)$ is the number of identified critical failures/violations during ASS testing at reactor power and after repair, accordingly; Δt is frequency of tests in reactor operating modes at power; n_0 is number of ASS repairs over SPR.

Then the condition for successful qualification of SRS modernization:

$$P_m(\lambda,T)\le P_D(\lambda,T), \quad (2)$$

where P_m, P_D is unavailability factor in the modernized and design (regulatory) SRS, accordingly.

After transformation (2) taking into account (1), the condition for successful qualification of the modernization of the reduction of one scheduled ASS repair in the criterial form:

$$K_T\le 1-K_{ma}\left(\frac{1}{n_0}-\frac{1}{n_0+1}\right), \quad (3)$$

where the test efficiency criterion in reactor operating modes at power is

$$K_T=\Delta t_m/\Delta t_0. \quad (4)$$

Quality criterion for maintenance and repair (MRO):

$$K_{ma}=\frac{n_{ma}T}{n_R\Delta t_D}, \quad (5)$$

where Δt_m, Δt_0 is the frequency of ASS tests in reactor operating modes at power for the modernized and design (720 h of one ASS channel) SRS, accordingly.

ANALYSIS OF THE RESULTS OF QUALIFYING MODERNIZATIONS OF STRATEGIES FOR SCHEDULED REPAIRS OF ACTIVE SAFETY SYSTEMS

Based on the developed risk-informed method for qualifying modernizations of SRS ASS, variation calculations of the conditions for a successful (acceptable) SRS ASS were carried out for operation life of 10, 20, and 30 years and MRO quality criteria from 0 to 360.0 (Table). As a result of calculation substantiations, three modernized ASB SPRs were qualified.

SRS-1. Reduction of one repair when the same frequency of tests at power under conditions:

$$K_{ma}\le 10.0;\quad T\le 10 \text{ years}, \quad (6)$$

$$K_{ma}\le 240.0;\quad 10<T\le 20 \text{ years}, \quad (7)$$

$$K_{ma}\le 360.0;\quad 20<T\le 30 \text{ years}. \quad (8)$$

SRS-2. Reducing one repair when reducing the frequency of tests at power by half (360 hours) under conditions:

$$10.0<K_{ma}\le 100.0;\quad T\le 10 \text{ years}. \quad (9)$$

SRS-3. Reducing one repair when reducing the frequency of tests at power by ten times (72 h) under conditions:

$$\frac{\Delta t_m}{\Delta t_D}<<1. \quad (10)$$

The results of conditions for qualifying strategies for scheduled repairs of active safety systems

Operation life T, years	MRO quality criteria K_{ma}	Maximum efficiency criterion for tests at power K_T	Modernization strategy for scheduled repairs and tests
10	0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
10	12.0	0.8	SRS-2. Reducing one repair and reducing the frequency of tests at power by 2 times
10	60.0	0.4	SRS-2. Reducing one repair and reducing the frequency of tests at power by 2 times
10	120.0	≤0.0	SRS-3. Reducing one repair and reducing the frequency of tests at power by 10 times
20	0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
20	24.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
20	120.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
20	240.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
30	0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
30	36.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
30	180.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power
30	360.0	1.0	SRS-1. Reduction of one repair when keeping the design frequency of tests at power

DISCUSSION OF THE RESULTS OBTAINED

The developed risk-informed method allows us to determine the conditions for successful qualification of strategies for reducing scheduled ASS repairs based on operating experience and the results of previous tests and repairs.

The most suitable for operation is SRS-1, which allows you to reduce one scheduled repair while keeping the design frequency of ASS tests when the reactor is operating at power, and also determines the possibility of qualifying strategies for a reasonable increase in the frequency of scheduled tests at reactor power.

Qualified strategies SPR-2 and SPR-3 are less relevant for operation, since they determine the possibility of reducing the number of scheduled repairs when a decrease in the frequency of tests at power, that can lead to excessive "wear" and a decrease in the residual life of the ASS equipment due to an increase in the frequency of tests.

CONCLUSIONS

1. The strategies for scheduled tests and repairs of active safety systems (with pumps) established by the Technological Regulations for the safe operation of NPPs with WWER do not take into account many years of operating experience and the results of numerous tests of active safety systems, current reliability indicators and the residual life of the main equipment and other factors. Modernization/improvement of design strategies for scheduled repairs and tests of active safety systems determines the need to develop appropriate methods for qualification (substantiation) of modernized strategies.

2. There is presented a risk-informed method for qualifying modernizations of strategies for scheduled repairs of active safety systems, taking into account experience in operation, scheduled repairs and tests, as well as the current reliability of the main equipment.

3. The developed method is based on the following provisions. The determining reliability indicator when qualifying strategies for scheduled repairs of active safety systems is the safety unavailability factor, which determines the probability of a critical failure at the current time depending on the critical failure rate established in scheduled tests/repairs over the expired operation life. A critical failure here means a failure to perform safety functions (for example, failure to turn on a pump, forced shutdown of a pump due to a violation of operability conditions, leaks in the circuits of active safety systems, etc.).

4. The qualification criterion to modernize strategies for scheduled repairs of active safety systems is a risk function that determines the ratio of the safety unavailability factors of the design and modernized strategies for scheduled repairs of active safety systems. Condition for successful qualification is the safety unavailability factor of the modernized strategy for scheduled repairs is not greater than the safety unavailability factor of the design strategy for scheduled repairs.

5. Based on the developed method, modernized strategies for scheduled repairs of active safety systems of the WWER-1000 reactor were substantiated and the conditions for the applicability of the modernized strategies were determined.

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МЕТОД КВАЛІФІКАЦІЇ МОДЕРНІЗАЦІЇ СТРАТЕГІЙ ПЛАНОВИХ РЕМОНТІВ АКТИВНИХ СИСТЕМ БЕЗПЕКИ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК З ВВЕР

В.І. Скалозубов, О.М. Вєрінов, А.В. Канівець, Ю.О. Комаров, В.В. Кандєєва

Встановлені Технологічними регламентами безпечної експлуатації АЕС з ВВЕР стратегії планових випробувань та ремонтів активних систем безпеки (з насосами) не враховують багаторічний досвід експлуатації та результати чисельних випробувань активних систем безпеки, поточні показники надійності та залишковий ресурс основного обладнання та інші фактори. Модернізація/вдосконалення проектних стратегій планових ремонтів та випробувань активних систем безпеки визначають необхідність розроблення відповідних методів кваліфікації (обґрунтування) модернізованих стратегій. Надано ризик-орієнтований метод кваліфікації модернізацій стратегій планових ремонтів активних систем безпеки, що враховує досвід експлуатації, планових ремонтів та випробувань, а також поточну надійність основного обладнання. Розроблений метод ґрунтується на таких положеннях. Визначальний показник надійності при кваліфікації стратегій планових ремонтів активних систем безпеки – коефіцієнт неготовності виконання функції безпеки, що визначає ймовірність виникнення критичної відмови у даний час залежно від параметра інтенсивності потоку критичних відмов, встановлених у планових випробуваннях/ремонтах за термін експлуатації. Під критичною відмовою тут мається на увазі відмова виконання функцій безпеки (наприклад, відмова увімкнення насоса, вимушене відключення насоса внаслідок порушення умов працездатності, течі у контурах активних систем безпеки та інші). Критерій кваліфікації модернізації стратегій планових ремонтів активних систем безпеки – цільова функція ризику, що визначає співвідношення коефіцієнтів неготовності виконання функцій безпеки проектної та модернізованої стратегії планових ремонтів активних систем безпеки. Умови успішної кваліфікації – коефіцієнт неготовності виконання функцій безпеки модернізованої стратегії планових ремонтів не більший за коефіцієнт неготовності проектної стратегії планових ремонтів. На основі розробленого методу обґрунтовано модернізовану стратегію планових ремонтів активної частини систем аварійного охолодження активної зони реактора ВВЕР-1000, а також визначено обмеження застосування модернізованої стратегії.