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QUALIFICATION OF STRATEGIES FOR MODERNIZING TEST FREQUENCY OF SAFETY SYSTEMS AT NUCLEAR POWER FACILITIES WITH EXTENDED TIME OF FUEL CAMPAIGNS

В. Скалозубов, Ю. Кацарський, Є. Мазур, В. Кочнєва, І. Вербило. **Кваліфікація стратегій модернізацій періодичності щодо випробувань систем безпеки ядерних енергоустановок підвищеної тривалості паливних кампаній.** Розроблено ризик-орієнтований метод кваліфікації (обґрунтування) стратегій збільшення періодичності випробувань пасивних систем безпеки в режимах підвищення тривалості паливних кампаній ядерних енергоустановок. Критерій кваліфікації – імовірність відмови систем управління аваріями для груп вихідних аварійних подій зі «щільним» та «нещільним» реакторним контуром. Умови кваліфікації – не перевищення ймовірності відмови систем управління аваріями модернізованої стратегії випробувань щодо проектної стратегії випробувань. На базі розробленого методу встановлено, що обґрунтоване збільшення періодичності випробувань пасивних систем безпеки в загальному випадку залежить від модернізації показників надійності та періодичності випробувань активних систем безпеки на потужності реактора. На основі отриманих результатів кваліфікації встановлено, що найбільш обґрунтованою стратегією збільшення періодичності випробувань пасивних систем безпеки є підвищення надійності системи аварійного підживлення парогенераторів. Це може забезпечити аварійний живильний насос з пароприводом від парогенераторів, який надає потрібні для ефективного управління аваріями умови підживлення парогенераторів на всіх етапах аварії при тиску в парогенераторах не менше 0,3 МПа. Розроблений метод кваліфікації стратегій періодичності випробувань пасивних систем безпеки в режимах підвищення тривалості паливних кампаній ядерних енергоустановок може бути реалізовано за допомогою достатніх експлуатаційних даних щодо надійності систем безпеки за повний термін експлуатації.
Ключові слова: періодичність випробувань, система безпеки, паливна кампанія, ядерна енергоустановка

V. Skalozubov, Iu. Katsarskyi, Ye. Mazur, V. Kochnieva, I. Verbylo. **Qualification of strategies for modernizing test frequency of safety systems at nuclear power facilities with extended time of fuel campaigns.** A risk-informed method for qualifying (substantiating) strategies for increasing the test periodicity of passive safety systems in the regimes of increasing the time of fuel campaigns of nuclear power facilities has been developed. The qualification criterion is the probability of failure of accident management systems for groups of initial accident events with a “tight” and “loose” reactor circuit. The qualification conditions are not to exceed the probability of failure of accident management systems of the modernized test strategy as to the design test strategy. Based on the developed method, it was recognized that a reasonable increase in the test periodicity of passive safety systems in the general case depends on the modernization of reliability indicators and the test periodicity of active safety systems at reactor power. Based on the qualification results, it was recognized that to increase the reliability of the emergency feed system of steam generators is the most reasonable strategy for increasing the test periodicity of passive safety systems. This can be provided with an emergency feed pump with a steam drive from the steam generators which get the required conditions for feeding steam generators at all accident stages at a pressure in the steam generators of at least 0.3 MPa. The developed method for qualifying strategies for test periodicity of passive safety systems in modes of increasing the time of fuel campaigns of nuclear power facilities can be implemented using sufficient operational data on the reliability of safety systems over the entire operation life.
Keywords: test periodicity, safety system, fuel campaign, nuclear power facility

Introduction

In general, the following safety systems manage accidents at nuclear power plants (NPPs) with VVERs at the in-vessel stage:

– the active part of the emergency core cooling system using high and low pressure pumps (HP ECCS and LP ECCS);

– a passive system of hydraulic accumulators for supplying boron solution to the coolant in case of leaks in the reactor circuit – YT;

– passive protection system of the 2nd circuit (high-speed shut-off valve) – TX;

– passive steam discharge system of steam generators, which includes a pulse safety device of steam generators, high-speed reducing devices for steam discharge to the atmosphere and a turbine condenser;

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– a passive pressure compensator pulse safety device for pressure control and protection against excessive destructive pressures in the reactor;

– active emergency steam generator feeding system with emergency and auxiliary pumps (EFWP/AFWP);

– passive system for emergency steam and gas removal from the coolant – YR;

– the passive part of the ECCS, consisting of the reactor core cooling water tanks.

The initial accident events can be conditionally divided into two main groups:

– initial accident events with reactor circuit depressurisation (initial accident events with a “leaky” reactor circuit);

– initial events of an accident with a “tight” reactor circuit.

The group of initial events of an accident with a “leaky” reactor circuit includes reactor circuit leaks into the NPP pressure vessel and into the steam generator, including the maximum design basis accident with instantaneous separation of the main circulation pipeline.

The group of initial events of a “tight” reactor circuit accident includes power outage of power units, jamming/failure of main circulation pumps, failure of reactor emergency protection, external extreme events (earthquakes, hurricanes, tornadoes, flooding of the NPP industrial site, fall of large/explosive objects), etc.

The main mode of operation of safety systems is the “standby” mode of performing safety functions during accident management. Therefore, regulatory and operational documentation regulates periodic operational tests to confirm the performance and reliability of safety systems.

Regulatory and technical documentation provides for the following frequency of operational tests [1, 2]:

– for active safety systems – 720 hours during reactor operation at capacity and annually during scheduled outages;

– annual operational tests for passive safety systems.

When implementing strategies of extended fuel campaign duration that are promising for improving NPP operation efficiency, it is necessary to modernise strategies for testing passive safety systems, which will provide the necessary conditions for reliable accident management of NPPs with VVERs. This determines the relevance of the presented work.

Analysis of known developments on the topic and problem statement

Paper [3] presents a risk-based method for qualifying the frequency of operational tests of the pressure compensator and steam generator pulse safety devices in the mode of extended fuel campaigns of NPPs to bring them into compliance with regulatory requirements – operational tests of the pressure compensator and steam generator pulse safety devices at least once a year. The method is based on the assumption that additional operational tests of the pressure compensator/steam generator pulse safety devices are possible at reactor power.

The condition for acceptability of changing the frequency of operational tests of the pressure compensator/steam generator pulse safety devices [3]:

$$P_{(m)} \le P_{\mathrm{D}} = \begin{cases} 5\cdot 10^{-3},\ P \le 5\cdot 10^{-3}; \\ P,\ \ P > 5\cdot 10^{-3}, \end{cases} \qquad (1)$$

where: $P_{(m)}$ – the probability of failure of the pulse safety devices when changing the frequency of operational tests; P_{D} – the base value of the probability of failure of the pulse safety devices at the scheduled frequency of operational tests, determined by the statistics of failures/violations.

In the general case, the probability of failure of pulse protective devices [3]:

$$P = f(\lambda, t, t_{\mathrm{SPM}}, \alpha_{\mathrm{N}}, \alpha_{\mathrm{SPM}}, n_{\mathrm{OT}}), \qquad (2)$$

where: λ is the parameter of the intensity of the failure flow according to the statistics of failures/violations of impulse safety devices; t is the current time between inspections (4 years for impulse safety devices); t_{SPM} is the time between scheduled preventive maintenance; α_{N}, α_{SPM} is the restoration rate of impulse protective devices as a result of operational tests at capacity and in the process of scheduled preventive maintenance; n_{OT} is the number of operational tests during the period of operation.

Finally, work [3] established the following.

1. Admissibility of operational tests of VVER-1000 pressure compensator pulse safety devices at reactor power without coolant emissions into the pressure vessel (except for Unit 1 of the South Ukrainian NPP due to the lack of technical capability to disconnect the tested channel from the pressure compensator).

2. For technical reasons, it is not possible to conduct full operational tests of steam generator pulse safety devices at reactor power without emissions into the pressure vessel and the environment.

This conclusion is also justified for passive safety systems: the system of steam discharge devices, ECCS of hydraulic vessels, YT, TX.

The following comments can be made regarding the results obtained in [3].

1. Operational tests with the disconnection of the pressure compensator's impulse safety devices from the power pressure compensator do not correspond to the actual conditions of accidents with maximum coolant pressure and temperature. In addition, the uncertainty of the recovery parameters is significant.

2. Conducting operational tests of the pressure compensator's pulse safety devices requires reducing the power level and disconnecting one main circulation pump.

3. It is also necessary to develop alternative approaches to modernise the frequency of operational tests of the pressure compensator/steam generator pulse safety devices in modes of extended fuel campaigns.

Papers [4–10] present an analysis of the known risk-based approaches to modernising strategies for operational testing and scheduled maintenance of safety systems based on the results of probabilistic safety analysis to determine the probability of a nuclear (severe) accident – core meltdown frequency. As a result of the analysis carried out in [4–10], the inadmissibility of such approaches was established for the following main reasons.

1. Modernisation of the frequency of operational tests of safety systems is based on an "artificial" reduction of the overall level of nuclear safety.

2. The overall core melting rate may be "insensitive" to the modernisation of the frequency of operational tests of safety systems in modes of extended fuel campaigns.

The analysis of the above developments in the field of modernisation of strategies for operational testing of safety systems in extended fuel campaigns determines the need to develop alternative approaches that eliminate the need for operational testing of passive safety systems at power and do not reduce the overall level of nuclear safety.

The aim of the study is to develop a risk-based method for qualifying the frequency of testing of NPP safety systems under conditions of extended duration of NPP fuel campaigns with VVERs.

Main objectives of the study

1. Analysis of known approaches and methods for qualification of NPP safety system testing strategies.

2. Development of the main provisions of the risk-oriented method for qualification of the safety system testing strategy under conditions of extended fuel campaigns.

3. Analysis of the obtained results and practical recommendations.

Method for qualifying the frequency of operational tests of passive safety systems in modes of extended fuel campaigns

Key provisions and assumptions.

1. Accident management systems are defined by a set of safety systems critical for ensuring the functions of each group of initial accident events.

Critical safety systems for the group of initial accident events with a "loose" reactor circuit are active HP and LP ECCS, passive system of YT hydraulic accumulators, passive ECCS of hydraulic tanks, passive system of steam generator steam discharge devices, passive system of steam generator feeding EFWP/AFWP, passive system of pressure compensator pulse safety devices.

Critical safety systems for the group of initial accident events with a "tight" reactor circuit – steam generator steam discharge system, EFWP/AFWP, TX, pressure compensator pulse safety devices.

2. Qualification criterion – probability of failure of the accident management system for each group of initial accident events.

3. Qualification conditions – the failure probability of the accident management system of the modernised frequency of operational testing of safety systems should not exceed the failure probability of the accident management system in the design strategy of operational testing of safety systems.

4. Necessary operational tests of passive safety systems shall be performed only in the power unit outage mode, and active safety systems shall be performed in reactor operating and outage modes.

In the general case, the probability of failure of the accident management system with a "leaky" reactor circuit:

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$$P_{\mathrm{SA1}} = P_{\mathrm{AH}} P_{\mathrm{PS}} P_{\mathrm{AP}} P_{\mathrm{g}} P_{\mathrm{PR}} P_{\mathrm{ge}} P_{\mathrm{AS}} , \tag{3}$$

where: P_{AH} – the probability of failure of the active part of the HP ECCS; P_{PS} – the probability of failure of the steam generator steam discharge system; P_{AP} – the probability of failure of the emergency feeding systems of the EFWP/AFWP steam generator; P_{g} – the probability of failure of the YT; P_{PR} – the probability of failure of the pressure compensator pulse safety devices; P_{ge} – the probability of failure of the hydraulic reservoirs' ECCS; P_{AS} – the probability of failure of the LP ECCS.

In general, the probability of failure of the accident management system with a "tight" reactor circuit:

$$P_{\mathrm{SA2}} = P_{\mathrm{PS}} P_{\mathrm{AP}} P_{\mathrm{TX}} P_{\mathrm{PR}} , \tag{4}$$

where: P_{TX} is the probability of failure of a high-speed shut-off valve (TX).

For a characteristic limited number of critical failures/violations of safety systems, a linear approximation of the probability of safety system failure is acceptable [3]:

$$P = \lambda t , \tag{5}$$

where: t is the time interval between operational tests, λ is the intensity of the flow of critical failures/violations:

$$\lambda = n_{\text{к}} / T_{\text{e}} , \tag{6}$$

n_{k} is the number of detected failures/violations during the operating period T_{e}.

Taking into account (3) and (5), the probability of failure of the accident management system with a "leaky" reactor circuit:

$$P_{\mathrm{SA1}} = \lambda_{\mathrm{AH}} \lambda_{\mathrm{PS}} \lambda_{\mathrm{AP}} \lambda_{\mathrm{g}} \lambda_{\mathrm{PR}} \lambda_{\mathrm{ge}} \lambda_{\mathrm{AS}} t_{\mathrm{AH}} t_{\mathrm{PS}} t_{\mathrm{AP}} t_{\mathrm{g}} t_{\mathrm{PR}} t_{\mathrm{ge}} t_{\mathrm{AS}} . \tag{7}$$

Taking into account (4) and (5), the probability of failure of the accident management system with a "dense" reactor circuit:

$$P_{\mathrm{SA2}} = \lambda_{\mathrm{PS}} \lambda_{\mathrm{AP}} \lambda_{\mathrm{TX}} \lambda_{\mathrm{PR}} t_{\mathrm{PS}} t_{\mathrm{AP}} t_{\mathrm{TX}} t_{\mathrm{PR}} . \tag{8}$$

Conditions for qualification of the accident management system when modernising the frequency of operational testing of safety systems:

$$P_{\mathrm{SA1}}(m) \le P_{\mathrm{SA1}}(d) , \tag{9}$$

$$P_{\mathrm{SA2}}(m) \le P_{\mathrm{SA2}}(d) , \tag{10}$$

where m is the modernised strategy, d is the design strategy.

Taking into account the qualification conditions for the accident management system (8) and (9), the qualification conditions for the test frequency for accidents with a "loose" and "tight" reactor circuit:

$$\lambda_{\mathrm{SA1}}(m) t_{\mathrm{SA1}}(m) \le \lambda_{\mathrm{SA1}}(d) t_{\mathrm{SA1}}(d) , \tag{11}$$

$$\lambda_{\mathrm{SA2}}(m) t_{\mathrm{SA2}}(m) \le \lambda_{\mathrm{SA2}}(d) t_{\mathrm{SA2}}(d) , \tag{12}$$

where: $\lambda_{\mathrm{SA1}} = \lambda_{\mathrm{AH}} \lambda_{\mathrm{PS}} \lambda_{\mathrm{AP}} \lambda_{\mathrm{g}} \lambda_{\mathrm{PR}} \lambda_{\mathrm{ge}} \lambda_{\mathrm{AS}}$; $\lambda_{\mathrm{SA2}} = \lambda_{\mathrm{PS}} \lambda_{\mathrm{AP}} \lambda_{\mathrm{TX}} \lambda_{\mathrm{PR}}$; $t_{\mathrm{SA1}} = t_{\mathrm{AH}} t_{\mathrm{PS}} t_{\mathrm{AP}} t_{\mathrm{g}} t_{\mathrm{PR}} t_{\mathrm{ge}} t_{\mathrm{AS}}$; $t_{\mathrm{SA2}} = t_{\mathrm{PS}} t_{\mathrm{AP}} t_{\mathrm{TX}} t_{\mathrm{PR}}$.

In the format of conditional separation of passive and active safety systems, the qualification conditions (11) and (12):

$$\lambda^{\mathrm{P}}_{\mathrm{SA1}}(m) t^{\mathrm{P}}_{\mathrm{SA1}}(m) \lambda^{\mathrm{A}}_{\mathrm{SA1}}(m) t^{\mathrm{A}}_{\mathrm{SA1}}(m) \le \lambda^{\mathrm{P}}_{\mathrm{SA1}}(d) t^{\mathrm{P}}_{\mathrm{SA1}}(d) \lambda^{\mathrm{A}}_{\mathrm{SA1}}(d) t^{\mathrm{A}}_{\mathrm{SA1}}(d) , \tag{13}$$

$$\lambda^{\mathrm{P}}_{\mathrm{SA2}}(m) t^{\mathrm{P}}_{\mathrm{SA2}}(m) \lambda^{\mathrm{A}}_{\mathrm{SA2}}(m) t^{\mathrm{A}}_{\mathrm{SA2}}(m) \le \lambda^{\mathrm{P}}_{\mathrm{SA2}}(d) t^{\mathrm{P}}_{\mathrm{SA2}}(d) \lambda^{\mathrm{A}}_{\mathrm{SA2}}(d) t^{\mathrm{A}}_{\mathrm{SA2}}(d) , \tag{14}$$

where:

$$\lambda^{\mathrm{P}}_{\mathrm{SA1}} = \lambda_{\mathrm{PS}} \lambda_{\mathrm{g}} \lambda_{\mathrm{PR}} \lambda_{\mathrm{ge}} , \tag{15}$$

$$\lambda^{\mathrm{A}}_{\mathrm{SA1}} = \lambda_{\mathrm{AH}} \lambda_{\mathrm{AP}} \lambda_{\mathrm{AS}} , \tag{16}$$

$$\lambda^{\mathrm{P}}_{\mathrm{SA2}} = \lambda_{\mathrm{PS}} \lambda_{\mathrm{TX}} \lambda_{\mathrm{PR}} , \tag{17}$$

$$\lambda^{\mathrm{A}}_{\mathrm{SA2}} = \lambda_{\mathrm{AP}} , \tag{18}$$

$$t^{\mathrm{P}}_{\mathrm{SA1}} = t_{\mathrm{PS}} t_{\mathrm{g}} t_{\mathrm{PR}} t_{\mathrm{ge}} , \tag{19}$$

$$t^{\mathrm{A}}_{\mathrm{SA1}} = t_{\mathrm{AH}} t_{\mathrm{AP}} t_{\mathrm{AS}} \tag{20}$$

$$t^{\mathrm{P}}_{\mathrm{SA1}} = t_{\mathrm{PS}} t_{\mathrm{TX}} t_{\mathrm{PR}} , \tag{21}$$

$$t_{\text{SA2}}^{\text{A}} = t_{\text{AP}}\,. \tag{22}$$

After transforming (13)–(22), the conditions for qualifying changes in the frequency of operational tests of passive safety systems:

$$\frac{t_{\text{SA1}}^{\text{P}}(m)}{t_{\text{SA1}}^{\text{P}}(d)} \le \frac{\lambda_{\text{SA1}}^{\text{P}}(d)}{\lambda_{\text{SA1}}^{\text{P}}(m)} \frac{\lambda_{\text{SA1}}^{\text{A}}(d)}{\lambda_{\text{SA1}}^{\text{A}}(m)} \frac{t_{\text{SA1}}^{\text{A}}(d)}{t_{\text{SA1}}^{\text{A}}(m)}, \tag{23}$$

$$\frac{t_{\text{SA2}}^{\text{P}}(\text{m})}{t_{\text{SA2}}^{\text{P}}(\text{d})} \le \frac{\lambda_{\text{SA2}}^{\text{P}}(\text{d})}{\lambda_{\text{SA2}}^{\text{P}}(\text{m})} \frac{\lambda_{\text{SA2}}^{\text{A}}(\text{d})}{\lambda_{\text{SA2}}^{\text{A}}(\text{m})} \frac{t_{\text{SA2}}^{\text{A}}(\text{d})}{t_{\text{SA2}}^{\text{A}}(\text{m})}. \tag{24}$$

Thus, in general, it is necessary to increase the frequency of operational tests of passive safety systems:

$$\frac{t_{\text{SA1}}^{\text{P}}(m)}{t_{\text{SA1}}^{\text{P}}(d)} > 1,\;\; \frac{t_{\text{SA2}}^{\text{P}}(m)}{t_{\text{SA2}}^{\text{P}}(d)} > 1, \tag{25}$$

due to the increased duration of fuel campaigns can be ensured:

– increased reliability of passive safety systems:

$$\left\{ \frac{\lambda_{\text{SA1}}^{\text{P}}(d)}{\lambda_{\text{SA1}}^{\text{P}}(m)} > 1,\;\; \frac{\lambda_{\text{SA2}}^{\text{P}}(d)}{\lambda_{\text{SA2}}^{\text{P}}(m)} > 1 \right\},$$

–and/or increased reliability of active safety systems:

$$\left\{ \frac{\lambda_{\text{SA1}}^{\text{A}}(d)}{\lambda_{\text{SA1}}^{\text{A}}(m)} > 1,\;\; \frac{\lambda_{\text{SA2}}^{\text{A}}(d)}{\lambda_{\text{SA2}}^{\text{A}}(m)} > 1 \right\},$$

– and/or reducing the frequency of operational tests of active safety systems:

$$\left\{ \frac{t_{\text{SA1}}^{\text{A}}(d)}{t_{\text{SA1}}^{\text{A}}(m)} > 1,\;\; \frac{t_{\text{SA2}}^{\text{A}}(d)}{t_{\text{SA2}}^{\text{A}}(m)} > 1 \right\}.$$

Strategy 1: Increase the frequency of operational tests of passive safety systems due to reduction of the frequency of operational tests of active safety systems.

Conditions for implementation of Strategy 1 – unchanged reliability indicators of passive and active safety systems during operation:

$$\frac{\lambda_{\text{SA1}}^{\text{P}}(d)}{\lambda_{\text{SA1}}^{\text{P}}(m)} = \frac{\lambda_{\text{SA2}}^{\text{P}}(d)}{\lambda_{\text{SA2}}^{\text{P}}(m)} = \frac{\lambda_{\text{SA1}}^{\text{A}}(d)}{\lambda_{\text{SA1}}^{\text{A}}(m)} = \frac{\lambda_{\text{SA2}}^{\text{A}}(d)}{\lambda_{\text{SA2}}^{\text{A}}(m)} = 1\,. \tag{26}$$

In this case, the qualification conditions (23) and (24), taking into account (26):

$$\frac{t_{\text{SA1}}^{\text{P}}(m)}{t_{\text{SA1}}^{\text{P}}(d)} \le \frac{t_{\text{SA1}}^{\text{A}}(d)}{t_{\text{SA1}}^{\text{A}}(m)},\;\; \frac{t_{\text{SA2}}^{\text{P}}(m)}{t_{\text{SA2}}^{\text{P}}(d)} \le \frac{t_{\text{SA2}}^{\text{A}}(d)}{t_{\text{SA2}}^{\text{A}}(m)}. \tag{27}$$

Assuming the same periodicity of operational tests for all passive t_{PSS} and all active t_{ASS} safety systems and taking into account (15)–(19), the qualification conditions for strategy 1 follow from (27):

$$\frac{t_{\text{PSS}}(m)}{t_{\text{PSS}}(d)} \le \left[\frac{t_{\text{ASS}}(d)}{t_{\text{ASS}}(m)} \right]^{3/4}, \tag{28}$$

$$\frac{t_{\text{PSS}}(m)}{t_{\text{PSS}}(d)} \le \left[\frac{t_{\text{ASS}}(d)}{t_{\text{ASS}}(m)} \right]^{1/3}. \tag{29}$$

Formulas (28), (29) reflect the required change in the frequency of testing safety systems for two different groups of accidents with different sets of critical safety systems in the accident management system. Based on the results of calculations using formulas (28), (29), a conservative value of the frequency of testing of safety systems is used.

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In particular, the obtained qualification conditions for Strategy 1 (28) and (29) conservatively imply that when switching to an 18-month fuel campaign, the frequency of operational tests of active safety systems should be reduced by three times compared to the design frequency.

Strategy 2. Increase the frequency of operational testing of passive safety systems due to the increase in reliability of active safety systems.

Conditions for implementation of Strategy 2:

$$\frac{\lambda^{\mathrm{P}}_{\mathrm{SA1}}(d)}{\lambda^{\mathrm{P}}_{\mathrm{SA1}}(m)}=\frac{\lambda^{\mathrm{P}}_{\mathrm{SA2}}(d)}{\lambda^{\mathrm{P}}_{\mathrm{SA2}}(m)}=\frac{t^{\mathrm{A}}_{\mathrm{SA1}}(d)}{t^{\mathrm{A}}_{\mathrm{SA1}}(m)}=\frac{t^{\mathrm{A}}_{\mathrm{SA2}}(d)}{t^{\mathrm{A}}_{\mathrm{SA2}}(m)}=1\,. \tag{30}$$

In this case, the qualification conditions (23) and (24), taking into account (15)–(19):

$$\frac{t_{\mathrm{PSS}}(m)}{t_{\mathrm{PSS}}(d)}\le\left[\frac{\lambda_{\mathrm{ASS}}(d)}{\lambda_{\mathrm{ASS}}(m)}\right]^{3/4}, \tag{31}$$

$$\frac{t_{\mathrm{PSS}}(m)}{t_{\mathrm{PSS}}(d)}\le\left[\frac{\lambda_{\mathrm{ASS}}(d)}{\lambda_{\mathrm{ASS}}(m)}\right]^{1/3}. \tag{32}$$

In particular, the obtained qualification conditions for strategy 2 (31) and (32) conservatively imply that the reliability of active safety systems should be increased threefold when switching to an 18-month fuel campaign.

Analysis of the results

1. The strategy of increasing the frequency of operational testing of passive safety systems due to an increase in the frequency of operational testing of active safety systems at reactor power can be qualified (justified) at long design stages of power unit operation under the condition of quasi-constant reliability indicators of safety systems. However, the increased frequency of operational tests of active safety systems may lead to premature wear/degradation/reduction of the residual service life of active safety system equipment.

At the end of the design life and during the extension of the service life, such a strategy of operational testing of passive safety systems is not justified, since the reliability indicators of active safety system equipment may significantly depend on the residual life.

2. The strategy of increasing the frequency of operational testing of passive safety systems by increasing the reliability of active safety systems is qualified for any stages of design and post-design life.

This strategy can be implemented by increasing the reliability of the emergency feeding system of the steam generator for the following reasons.

1. The emergency steam generator feeding system is the only active safety system for the groups of initial accident events with a “tight” reactor circuit, as well as one of the critical systems for the groups of initial accident events with a “loose” reactor circuit.

2. The deterministic analysis of the initial accident event “Complete long-term power unit outage” (analogous to the initial accident event at Fukushima NPP) for NPPs with VVERs established that a nuclear accident (with damage to nuclear fuel) may result in failure of the emergency steam generator feeding system during the accident [6].

Paper [6] presents the qualification of the modernisation of the emergency steam supply system of a VVER steam generator by an alternative emergency pump with a steam drive from the steam generator. It is established that the pressure-flow characteristic of the emergency pump with a steam generator drive can be similar to the pressure-flow characteristic of the turbo feed pump of a NPP with a VVER and provides the necessary steam generator feed to a pressure in the steam generator volume not lower than 0.3 MPa.

In addition, the emergency pump system with steam drive from the steam generator eliminates the need to trigger the steam discharge system in the course of any accident and ensures nuclear safety conditions in the conditions of the initial accident event “Total Long Duration Blackout”.

Conclusions

1. A risk-based method for qualifying (justifying) strategies for increasing the frequency of testing passive safety systems in modes of increasing the duration of fuel campaigns of nuclear power plants has been developed.

The qualification criterion is the probability of failure of accident management systems for groups of initial accident events with a "tight" and "loose" reactor circuit. Qualification conditions – not exceeding the probability of failure of the accident management systems of the upgraded test strategy relative to the design test strategy.

2. Based on the developed method, it was established that a reasonable increase in the frequency of testing of passive safety systems in general depends on the modernisation of reliability indicators and frequency of testing of active safety systems at reactor power.

3. Based on the obtained qualification results, it was established that the most reasonable strategy for increasing the frequency of testing of passive safety systems is to improve the reliability of the emergency steam generator feeding system.

4. The necessary increase in the reliability of the emergency feeding system for steam generators can be provided by an emergency feed pump with a steam drive from steam generators.

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