V.I. Skalozubov, HuiYu Zhou, Yu. A. Komarov

OPTIMIZATION OF STRATEGIES FOR TESTING AND MAINTENANCE OF NUCLEAR POWER PLANT EQUIPMENTS

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V.I. Skalozubov, HuiYu Zhou, Yu. A. Komarov
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The monograph presents of developments for the possibilities of applying a risk-oriented approach to the NPP reliability and safety enhancement problem, optimization of reliability in the modernization of heating equipment, optimisation of tests and repair of safety-related systems of NPP with VVER, optimization of strategies for extending the operation of systems important for the safety of nuclear power plants, revision of nuclear power plants safety systems' routine testing assigned periodicity during the design extension period.

Keywords: risk, safety, efficiency, NPP, probability, significance, repair, monitoring, qualification, strategy, reliability, system, operation, equipment, method

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ABBREVIATIONS LIST

AFWP	–	auxiliary feed water pumps
ALARA	–	As Low As Reasonably Achievable
BRU-A	–	fast acting atmospheric steam dump valve (Russian design)
CDF	–	core damage frequency
DGS	–	diesel generators subsystem
ECCS HP	–	emergency core cooling systems by high-pressure pumps
ECCS LP	–	emergency core cooling systems by low-pressure pumps
ECFS	–	emergency core flooding system
EFWP	–	emergency feed water pumps
ESWS	–	Essential Service Water System
FASIV	–	Fast-acting steam isolating valve
IE	–	initiating event
NNEGC	–	National Nuclear Energy Generating Company
NPP	–	Nuclear power plants
PM	–	preventive maintenance
PS RLMS	–	primary to secondary leak monitoring system
PSA	–	probabilistic safety assessment
RCM	–	reliability centred maintenance
RMS	–	reliability management strategy
ROA	–	Risk-oriented approach
SCV	–	stop and control valve
SPM	–	scheduled preventive maintenance
SRS	–	safety-related systems
SRS NO	–	safety-related systems of normal operation
SS	–	safety systems
TSKP	–	technical state key parameter
VVER	–	water-water energy reactors (Russian design)

INTRODUCTION

One of the basic nuclear power plant (NPP) safety and reliability improvement issues is a methodology support to the supervision program assurance. One of supervision program subtasks of strategies for testing and maintenance of NPP equipment. Special attention is paid to NPP safety-related systems (SRS).

In particular, a deviation from optimum SRS control periodicity can essentially affect operation economy and general safety level of a reactor facility. On the one hand, too rare (in comparison with the optimum one) periodicity of tests / repair results in decreasing the equipment reliability and preparedness to fulfil its functions. This effect is result of the increase in a number of latent failures of SRS within an equipment tests / repair interval. On the other hand, too frequent tests / repair can also decrease an SRS reliability level. The main reason for this is that during tests / repair a system is exposed to some impacts (risks) from which it's defended during routine operation. The optimization of tests / repair periodicity is realised on a base of an availability ratio. The optimum test periodicity corresponds to maximum availability ratio.

Analyzing known researches on optimization of reliability and efficiency of operation of the systems/equipment of thermal and nuclear facilities the authors demonstrate that reliability and costs are the key optimization parameters. The method of forming of reliability management strategy using the key optimization criterion of modernization efficiency is presented. Examples of application of the proposed method are provided.

The original efficiency optimization method of strategy of operation extension of the heat engineering equipment of the safety related systems of nuclear power utilities is developed. The developed method is realized for the pump cases and armature of the safety related systems, as well as for the cases of a spent fuel pool of nuclear power plants with WWER. It is recognized that the reasonable time of operation extension for the pump cases and armature of the safety related systems is 10 years and for the case of a spent fuel pool is 13 years. The critical reliability parameters defining a residual life of the cases of the heat engineering equipment are dynamic metal stresses during beyond design basis earthquakes and the actual quantity of loading cycles during transient and accident operation. Optimization of test periodicity is one of effective approaches to reduce metal degradation/wear rate of the heat engineering equipment cases during the beyond design basis operating period. These questions will be considered in the subsequent publications of authors.

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.

Chapter 1. THE POSSIBILITIES OF APPLYING A RISK-ORIENTED APPROACH TO THE NPP RELIABILITY AND SAFETY ENHANCEMENT PROBLEM

1.1. Concept

Application of a risk-oriented approach (ROA) is one of conditions essential for achieving safer and more efficient operation of the Ukrainian nuclear power plants (NPPs). Traditionally, the essence of the ROA consists in making probabilistic assessments of risk (safety) indicators depending on the conditions under which potentially dangerous events and their consequences may emerge. At present, an ROA is widely used around the world and in the national nuclear power industry. In particular, an ROA is used within the framework of probabilistic safety assessment in elaborating safety analysis reports for determining safety deficits, for licensing the operation and extending the lifetime of power units at the Ukrainian NPPs. In particular, the Ukrainian Nuclear Power Industry Codes and Regulations have specified such probabilistic safety criteria as the permissible core damage frequency (CDF) and the frequency of the maximum accidental release [1]. A long-term State Program for introducing risk┐ oriented approaches has been put in use in the activities performed by the Ukrainian regulatory authorities and NPP operators.

Unfortunately, the available theoretical and scientific potentials have hitherto found little use in risk assessments in nonnuclear industries. There is a well consistent theory of risk in the economic science [2], and there is also a risk concept in the reliability theory [3]. In the nuclear power industry, the term ROA is understood to mean solely a probabilistic safety assessment (PSA). This is because it is exactly this path that was followed by the United States [4] and then also by other countries according to the IAEA recommendations [5, 6]. However, it should be pointed out that there are a lot of problems that cannot be solved using the PSA as a single criterion approach. For solving them, an ROA should be applied with the use of reliability theory, mathematical statistics, etc. In addition, certain methodological problems are intrinsic to the PSA, such as completeness of input data, dimensionality, modeling adequacy, which also limit the PSA application field [7, 8].

The chapter presents some theoretical generalizations and ROA development ways for the nuclear industry that go beyond the confines of a traditional PSA.

1.2. The ROA theoretical basis

There are several definitions of the "risk" concept, because this term is used in different fields of scientific knowledge, such as economy, ecology, engineering, sociology, politics, etc. [2]. But despite the variety of these definitions, they can be generalized and reduced to the following interpretations, which seem at the first glance to be fundamentally different:

(1) risk as damage (financial loss, environment pollution, number of suffered persons, etc.) taking into account the probability of its occurrence;

(2) risk as the probability (possibility) of a dangerous situation to occur (damage, losses, accident, etc.).

It should be noted that risks that are not characterized by numerical variables are usually considered separately. In treating such risks, estimates like "high risk," "acceptable risk," etc. are used, which can be represented as one else individual interpretation (3).

It can be shown with the use of a probabilistic approach and fuzzy sets theory [9-11] that such different definitions and characteristics of risk are in fact different faces of one notion.

Let there is a certain set of unfavorable events $\Theta = \{\theta_1, \theta_2, \ldots, \theta_n\}$. We assume that it has been found from an analysis that a damage (accident, etc.) is resulted not from separate unfavorable events z_i, but certain combinations thereof, $z_i \subset \Theta$. Then, the vector of all combinations of unfavorable events leading to a damage has the form

$$\bar{z} = \{z_1, z_2, \ldots, z_m\}. \tag{1.1}$$

We also assume that the realization probabilities p_i of antithetical events in each combination are known, and that the probability to avoid all combinations of undesired events (the success probability p_{scs}) is such that

$$\sum_{i=1}^{m} p_i(z_i) + p_{scs} = 1. \tag{1.2}$$

If the realization of combinations z_i leads to the known damage q_i, the weighted average damage will make

$$R = \sum_{i=1}^{m} q_i p_i(z_i). \tag{1.3}$$

It is not difficult to notice that the last expression corresponds to the classic risk assessment when risk is treated as damage, taking the probability of such damage into account (formulation 1).

If the damage q_i resulted from realization of undesired events is unknown, or if they are so large that it is sufficient to analyze the very fact of the combination of undesired events to occur, and also if the same damage results from realization of each combination z_i ($q_i = q$, $i = 1, \ldots, n$, due to which it can be taken out from the analysis), the risk assessment is transformed to the form

$$R = \sum_{i=1}^{m} p_i(z_i). \tag{1.4}$$

This expression corresponds to risk assessment as the probability of certain dangerous situation to occur (formulation 2).

The use of fuzzy sets theory allows risk to be assessed in terms of linguistic variables. In this case, risks are stated as the possibility of a combination of negative consequences to occur and do not rest on the theory of random (and, hence, statistically recurrent) combinations of negative events. With such an approach, it becomes possible, in particular, to analyze the risks of rare combinations of z_i, including those that were not realized previously.

The risk value will in the general case depend on a certain level Ψ_j characterizing the possibility of combination z_i to occur and the degree L_k to which this combination affects the risk. The risk influencing degree (the degree of risk) L_k

can be specified as a usual set (in this case, $L_k = q_k$), or it can be a linguistic variable (e.g., with the values "small damage," "medium damage," and "considerable damage").

The fuzzy set model S_L is specified by the fuzzy variable L in certain definitional domain X and by its membership function μ_L:

$$S_L = \{(x, \mu_L(x); x \in X, 0 \le \mu_L(x) \le 1)\}. \tag{1.5}$$

The possibility Ψ_j of combinations z_i to occur can also be specified either as a usual set (in this case, $\Psi_j = p_j$) or as a linguistic variable (e.g., "extremely rare," "rare," "often," "very often") of fuzzy set S_Ψ defined in certain domain Y with the membership function μ_Ψ

$$S_\Psi = \{(x, \mu_\Psi(x); x \in Y, 0 \le \mu_\Psi(x) \le 1)\}. \tag{1.6}$$

The risk assessment will in this case also have the form of fuzzy set obtained as the algebraic sum of fuzzy sets S_L and S_Ψ:

$$\widetilde{R} = \sum_{i=1}^{m} S_L(z_i) S_\Psi(z_i). \tag{1.4}$$

The particular value R from the set $\widetilde{R}$ can be estimated by defuzzification using the method of maximums or the mass center method [11]. With the last expression, it becomes possible to use the mathematical techniques in risk assessments defined according to formulation 3. One interesting particular case appears when there is no uncertainty in the occurrence of combinations z_i, e.g., in analyzing a single combination of undesirable events ($i = 1$). In this case, $\widetilde{R} = S_L$.

Another particular case is when there is no uncertainty in the degree of influence on the risk; in that case, the analysis is aimed only at estimating the possibility of this negative combination z_i to occur; in this case, $\widetilde{R} = S_\Psi$

If there is no uncertainty in the occurrence of combinations z_i and in the risk influencing degree, a deterministic analysis of risk is in fact dealt with; in this case, it is sufficient to prove that the combination z_i leading to negative consequences can indeed be realized (for certain specified conditions).

A deterministic analysis of design basis accidents of NPP power units, for which various failure initiating events (IEs) and sets of equipment failures and human (personnel) errors are specified (in accordance with the single failure criterion), and a conclusion is drawn of whether or not the safe operation limits are violated, can serve as an example of such analysis. In fact, when the safe operation limits are violated, the combination of these IEs, equipment failures, and human errors (i.e., the combination z_i) leads to negative consequences. If the given combination z_i does not lead to violation of safe operation limits, there is no risk. This means that a deterministic analysis can be regarded as a particular case of risk assessments, i.e., a particular case of the risk┐ oriented approach.

The following formulation can be proposed as a generalization of what was said above: risk assessment is evaluation of the probability (the potential possibility) of the occurrence of undesired event combinations with or without taking into account the damage resulting from such realization. It is important to note that for each problem, the vector of parameters to be estimated and the assessment criteria must be substantiated, and the suitable methodical technique must be applied or developed on the basis of probabilistic, deterministic, and/or other methods.

1.3. Applying the ROA for enhancing the NPP reliability and safety

Modernizing the safety related systems (SRS) and sophisticating the control of beyond design basis and severe accidents are the main avenues for enhancing the safety of NPP power units equipped with water cooled water moderated power energy reactors (VVERs).

Increasing the specific (per power unit) production of energy while reducing the operational costs and retaining the design level of reliability and safety is the basic principle of achieving more efficient operation of NPPs. Works on achieving more efficient and safe operation of NPPs were carried out for a number of years. The parameters to be estimated have been substantiated, the assessment criteria have been determined, and the relevant methodical support has been developed.

Works on qualifying the fast acting atmospheric steam dump valve (commonly known in the practice of Russian NPPs as BRU-A) of the 1115-300/350-E and 960-300/350-E Series at the Zaporozh'e NPP have been carried out in the modes with passage of water and steam–water mixture that may take place during accidents involving primary to secondary leak in the reactor plant with a VVER-1000 reactor.

Changes in the CDF and the results from a deterministic analysis of the BRU-A operation modes with passing steam–water mixture are the probabilistic safety criteria. It has been determined that the possibility of BRU-A jamming in passing steam–water mixture corresponds to the possibility of the design basis accident caused by the initiating event involving a medium primary to secondary leak (the T42 IE + human errors) to evolve into a beyond design basis accident (the T42 IE + human errors + BRU-A failure to close). An analysis has shown that the lack of BRU-A qualification for operation with steam–water and water medium is of much significance for the NPP safety. It was recommended to replace the existing BRU-A electric drives by an electric drive of higher capacity [12].

A change in the CDF and indicators pointing to the absence of unstable operating modes of regulators serve as probabilistic and deterministic criteria in estimating the advisability of and conditions for fitting the pressure mains of the emergency core cooling system's active part with additional stop and control valves (SCVs) for different projects of reactor plants with VVER-1000 reactors. It has been found that the use of SCVs is advisable for VVER-1000 based power units equipped with the V-302 and V-338 reactor plants, whereas the use of such valves in similar power units equipped with the V-320 reactor plant may be efficient only in case of making additional adjustments for taking into account the working member's position variation rate [13].

The advisability of and the conditions for putting in use a radiation primary to secondary leak monitoring system (PS RLMS) for improving the control of accidents was analyzed on the basis of probabilistic criteria, such as CDF and the PS RLMS system failure probability according to the developed assessment procedure. It has been found that the use of the PS RLMS system is advisable only provided that a fully automated algorithm for control of medium primary to secondary leaks is implemented and provided that the overall PS RLMS system reliability is at least a factor of 2 higher than that of personnel dominant actions for accidents of this type [14].

A procedural and methodical philosophy of reliability centered maintenance (RCM) for NPP equipment has been developed. The following indicators are analyzed for each type of equipment: Birnbaum importance measure, safety class, electricity underproduction per emergency repair, time margin for carrying out repair and restoration works without changing the reactor plant power output, and time to failure; the values of these indicators are estimated according to the developed procedures. The equipment items have been ranked according to their effect on safety and operation efficiency. The necessary degree of advancement with which an equipment item must be taken out for scheduled preventive maintenance (SPM) has been presented for each rank. For equipment characterized by a strong effect on safety and performance efficiency, the time to failure gamma-percentile margin is 95%; as regards equipment that does not affect safety and performance efficiency, repairs of such equipment can be planned according to mean time between failures. The time to failure is evaluated on the basis of expert estimates or the trend of changes in the key parameters characterizing the technical state of equipment (TSKPs) (assessment of the time taken for the TSKP to reach its limiting value). With the RCM strategy implemented, the duration of power unit outages for SPM can be decreased, and smaller economic expenditures will be required for carrying out SPMs [15].

The possibility of and conditions for reducing the scope of tests to be carried out on the VVER-1000 based reactor plant's sealed containment have been substantiated using the probabilistic methods of analyzing the change of leak from under the containment based on the results of its periodic tightness tests. The system of sealed enclosures is subjected to tests every year on completing the SPM. With this methodology put in use, the time taken to carry out the SPM can be decreased by 1–2.5 days, which will result in a higher power unit capacity utilization factor [16].

A procedure for obtaining probabilistic assessment of measurement validity has been developed for the boron solution concentration monitoring system, which depends on the accuracy and frequency of measurements, and on instrument failure probability. The use of this procedure made it possible to determine the necessary frequency of measurements in shifting from continuous to periodic monitoring. In addition, the possibility of and conditions for discarding the use of a number of expensive means for continuously monitoring boron solution concentration have been determined [17].

The possible strategies for maintenance of systems important to safety have been determined in case of shifting from a 12 to 18 month fuel campaign. The failure probability of each individual equipment item of systems important to safety remaining within the permissible limits under the conditions of increased fuel campaign is the criterion for accepting the new frequency strategy/test scope/repairs of these systems [18].

1.4. Conclusions for chapter

(1) An analysis and some generalizations of approaches to risk assessments are presented. Interconnection between different interpretations of the “risk” notion is shown, and the possibility of applying the fuzzy set theory to risk assessments is demonstrated. A generalized formulation of the risk assessment notion is proposed in applying risk-oriented approaches to the problem of enhancing reliability and safety in nuclear power engineering.

(2) The solution of problems using the developed risk-oriented approaches aimed at achieving more reliable and safe operation of NPPs is demonstrated for:

- BRU-A qualification;
- emergency core cooling system modernisation;
- radiation primary to secondary leak monitoring system modelling;
- reliability centered maintenance;
- containment tests;
- boron solution concentration monitoring system modernisation;
- strategies for SRS maintenance in case of shifting from a 12 to 18 month fuel campaign.

These and others questions will be considered in next chapters of the book.

Chapter 2. OPTIMIZATION OF RELIABILITY IN THE MODERNIZATION OF HEATING EQUIPMENT

2.1. Concept

The main modern directions of development of thermal and nuclear power are associated with improving:

- reliability of systems and the equipment that are priority for safe operation and

- efficiency and competitiveness of electricity generation.

Deep interdependence of practical implementation of these directions can be shown on the example of the solution of two actual problems considered further.

Failure of the long-term emergency power supply need for afterheat cooling of nuclear fuel by emergency pumps was one of the basic technical causes of great accident at the Fukushima-Daiichi NPP in 2011 [19].

Taking into account the Fukushima lessons the operating organization of the Ukrainian NPPs (NNEGC "Energoatom") and the State Nuclear Regulatory Inspectorate of Ukraine required greatly improving reliability of systems of emergency and standby power supply of all power units. To install additional powerful batteries for long-term power supply (more than 72 hours) was one of solutions to this problem. But later it turned out that costs of this modernization of systems of emergency and standby power supply are economically inefficient and need to look for more optimum solutions.

For several decades ALARA is the generally accepted principle in world nuclear power. This principle consists in priority of improving reliability of safety management based on "reasonable sufficiency" [20], i.e. need to make the best (optimum) decisions concerning production safety, reliability and efficiency.

The Fukushima lessons confirmed relevance of the ALARA principle. So, it was two ways to avoid flooding of diesel generators of system of emergency/standby power supply with the catastrophic effects:

1) to install breakwaters with height of more than 15 m above sea level (great costs);

2) to provide tightness of rooms for diesel generators (relatively low costs).

The second typical example of interdependence of reliability and efficiency is associated with a known problem of the NPP operation life extension. Operation life extension (over the design life) is highly effective action as costs of decommissioning and construction of new power units are not comparable to costs of ensuring reliable operation during the beyond design basis period [21]. However operation life extension is inadmissible without sufficient scientific and technical substantiation of ensuring reliable operation of systems and the equipment during the beyond design basis period (especially the safety systems/equipment). The Fukushima-Daiichi can be a characteristic example in this case too. A month before accident Unit 1 operation life was extended and severe accidents with damage of nuclear fuel began at Unit 1.

Given the above, the solution of the problem of improving of operation reliability and efficiency has to be complex and optimization.

Problems of optimization of reliability and efficiency of the systems/equipment of the nuclear power facilities were considered when implementing industry programs for increase of the installed capacity utilization factor (ICUF) and to improvement of production schedules of test periodicity of the safety related systems [22, 23].

ICUF is the main indicator of efficiency of nuclear electric power generation and is defined by the ratio of the actual power of energy releases during the nuclear power facility operation life to the designed power [22]:

$$ICUF = \frac{N_ф}{N_у} \frac{T_э - T_{ППР} - T_a}{T_э} \qquad (2.1)$$

Where $N_ф$, $N_у$ – the actual and rated power of a nuclear reactor, respectively, $T_э$ – the operation period (usually annual), $T_{ППР}$ – time of the scheduled preventive maintenance (SPM), T_a – time of emergency shutdown.

Under normal operating conditions ($N_ф \approx N_у$; $T_a = 0$) ICUF is defined generally by time of the scheduled preventive maintenance: to increase ICUF (i.e.

efficiency) it is required to reduce SPM time as much as possible. On the other hand, the main restrictions for reduction of SPM time are associated with:

- observance of the established safety norms and rules (for example, opening of the reactor vessel upper head no earlier than 72 hours after its shutdown);

- the actions for a state control and tests of systems, the equipment and designs established by maintenance and repair (M&R) regulations (for example, metal control of the equipment and pipelines, leaktightness control of safety related systems, tests for operability of the safety systems, etc.).

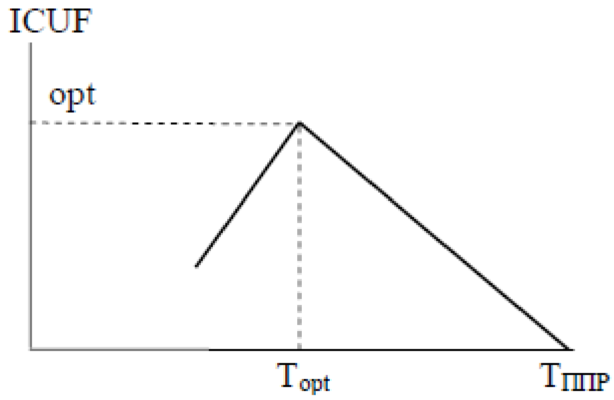
Therefore the program of increasing ICUF is optimization as regards SPM time. On the one hand, reduction of ТППР leads to increase in ICUF, but the unreasonable reduction of $T_{ППР}$ (for example, through inadequate quality of M&R) can lead to increase in emergency reactor shutdown time T_a and, respectively, to decrease in ICUF (Fig. 2.1, *a*). So, the maximum ICUF can be reached at the optimum SPM time T_{opt}.

Thus, the task of increase of ICUF is reduced to achievement of the minimum optimum SPM time T_{opt} that can be provided by:

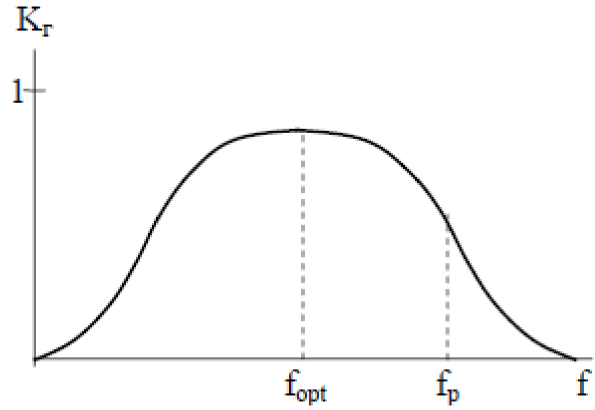
- improvement of technical means of M&R (for example, the modernized nut wrenches to open a reactor vessel upper head, a nuclear refuelling system, technical means of metal control, etc.),

- improvement of M&R scheduling strategy (for example, maximum "parallelism" of separate actions, prevention of downtime during M&R, M&R reasonable technically during the inter-repair period, etc.),

- reduction of inefficient (redundant) actions for a state control and tests of the systems/equipment as regards confirmation of reliability (for example, overpressure leaktightness tests of a containment, redundant tests of pumping equipment, full control of pipe heater of steam generators, etc.).



a) Optimization of ICUF



b) Optimization of test periodicity

Fig. 2.1. Known results of optimization of ICUF and test periodicity of emergency pumps [22, 23]

Thus it is obvious that implementation of last two groups of actions is the most economically preferable. So, for example, the work [22] of the authors demonstrates that implementation of these groups of actions can increase in ICUF by 10–20% without great economic costs[1].

Since scheduled periodicity (normally once a month) is established without sufficient justifications [5] it is required optimization of test periodicity of pumps of safety systems during the inter-repair period (the reactor operation at power). In this case we can use as a criterion for optimization the maximum reliability index (an availability factor of activities of functions K_r) and as parameters for optimization:

[1] By the known estimates, for example, given in [22], the increase in ICUF by 10% over the industry is equivalent to commissioning of the 1000 MW new power unit.

- increase in test periodicity f to detect the "hidden" equipment failures (Φ_1 factor),

Reduction of test periodicity to prevent excessive wear of the equipment (decrease in a resource of operation) and influence of quality of maintenance during tests (the decrease in the general reliability of system as a result of tests of one channel) (Φ_2 factor).

Fig. 2.1, *b* presents known results on optimization of test periodicity of pumps of emergency core cooling systems during the nuclear reactor operation at power [23]. These results show that optimum periodicity at the maximum reliability f_{opt} is twice less than scheduled periodicity f_{p}.

Unlike the above-stated known results reliability and costs of optimization of the systems/equipment of thermal and nuclear power facilities are the key parameters. It determines relevance of this work.

2.2. Basic provisions of optimization of reliability management strategy of thermal and nuclear power plants

1. The reliability management strategy (RMS) is meant as a complex of the organizational and technical actions / modernizations directed on reliability increase depending on their costs.

2. The key RMS parameter as regards reliability is the ratio of integral unavailability factors of activities of functions for the system modernized $K_{\text{н}1}$ and designed $K_{\text{н}0}$:

$$K_{н} = \frac{K_{н1}}{K_{н0}}. \tag{2.2}$$

Where during operation period t [23]

$$K_{н1} = \frac{1}{t}\int_0^t P(\tau)d\tau, \tag{2.3}$$

P(τ) – the current probability of critical failure in the different modes of operation (operating, transient, emergency).

Generally unavailability factors $K_н$ consider wear (aging) of the equipment and quality of maintenance, repair and tests.

Condition of RMS modernization as regards reliability factors:

$$K_н \to \min . \tag{2.4}$$

3. The key RMS parameter as regards modernization costs is the ratio of modernization costs C_1 to the cost of design system C_0:

$$C = \frac{C_1}{C_0} . \tag{2.5}$$

Condition of RMS implementation as regards modernization costs:

$$C \to \min . \tag{2.6}$$

4. The main factor of RMS efficiency is the ratio of increase in reliability level $\Delta K_н$ to the corresponding modernization costs ΔC:

$$K_э = \frac{\Delta K_н}{\Delta C} . \tag{2.7}$$

Conditions of RMS efficiency:

$$K_э < 0; |K_э| \to \max . \tag{2.8}$$

5. Taking into account the above criteria and modernization conditions the key optimization criterion of effective RMS:

$$K_{opt} = \frac{\sum_i K_{эi} \Delta C_i}{\sum_i \Delta C_i} . \tag{2.9}$$

Where the index i corresponds to number of separate modernization in specific RMS.

As an example of RMS optimization we will consider three typical strategies (Fig. 2.2):

RMS1 – strategy with the minimum modernization costs and relatively small increase in reliability,

RMS2 – the strategy using only the maximum effective modernizations, and

RMS3 – strategy to get the maximum reliability.

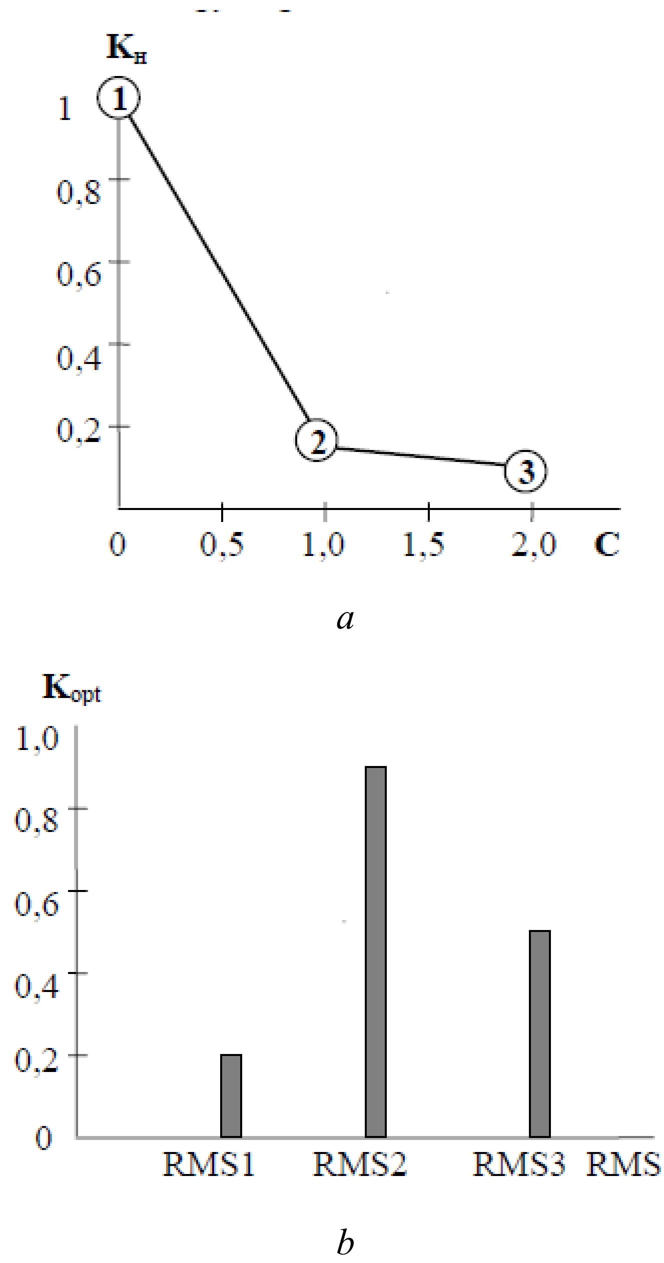


Fig. 2.2. Optimization of reliability management strategies

The typical examples of modernizations of systems of pumping equipment of thermal and nuclear power facilities are the following [24].

1. RMS1 (see Fig. 2.2, *a*) – to set the damping upstream tanks in the pump inlet to reduce amplitude of pressure fluctuations.

Such strategy can be effective for decrease in cyclic hydrodynamic loads and cavitational phenomena in working parts of pumps, but it is ineffective for prevention of critical (as regards the flow capacity of the pressure main) hydroblows in transient and emergency modes.

2. RMS2 (see Fig. 2.2, *a*) – to duplicate channels of system of pumping equipment in parallel. In this case modernization costs are very increased, but reliability of whole system and efficiency of prevention of the critical hydroblows caused by inertia of the pump head and rate are very improved.

3. RMS3 (see Fig. 2.2, *a*) – to set the additional regulating armature in the duplicated channels of emergency core cooling pumps to prevent "thermal shock" to a reactor vessel in emergency modes.

Such modernization demands additional great costs and is ineffective for improving reliability of the nuclear reactor vessel as additional regulators operate after the most critical (for thermal shock) conditions. Besides, [24] demonstrates that the self-oscillatory processes increasing cyclic thermal loads in a reactor vessel can arise under certain conditions of additional flow rate control.

Considering the above strategies RMS2 is optimum as regards criterion (2.9) (see Fig. 2.2, *b*).

2.3. Conclusions for chapter

(1) The analysis of known researches on optimization of reliability and efficiency of operation of the systems/equipment of thermal and nuclear facilities demonstrates that reliability and costs are the key optimization parameters.

(2) The method of forming of reliability management strategy using the key optimization criterion of modernization efficiency is presented. Examples of application of the proposed method are provided.

Chapter 3. OPTIMISATION OF TESTS AND REPAIR OF SAFETY-RELATED SYSTEMS OF NPP WITH VVER

3.1. Concept

The safety-related systems (SRS) are safety systems and systems of normal operation, failures of which can result in failure. The high responsibility of SRS for organization of process of safe operation of NPP determines increased technical requirements to a general level of reliability of these systems.

The planning of periodicity and effort for realization of SRS repairs and tests substantially influences SRS reliability. This chapter considers optimization of planning of repairs and tests of SRS

as determination of periodicity and effort, when performance of SRS design functions has maximal reliability or the number and effort decreases maintaining design parameters of reliability.

In such a way that, two basic criteria of optimization are used - maximal reliability criterion of performance of design functions and / or criterion of maintaining a design level of reliability.

Optimization of planning of SRS repairs and tests should take into account conditions of realization of these measures and design and technical limitation. So, for some SRS (for example, emergency core cooling system) the design provides for monthly tests power operation of NPP and annual scheduled repair with post repair tests after shutdown of power unit for preventive maintenance (PM). For others SRS that cannot be completely checked / tested under power operation of NPP for technical reasons (for example, containment, safety valves of steam generator), a complete set of tests and repair-and-renewal operations is stipulated only during PM. Thus, techniques of optimization of planning of repairs and tests for SRS having a various condition and the rules of tests and repair-and-renewal operations are generally various.

The important directions connected to optimization of SRS planning of repairs and tests are the perspective transfer for VVERs to the enlarged fuel campaign and increasing of the between-repairs period of reactor installation. Transfer to the enlarged fuel campaign (more than year) results in necessity of reconsideration and additional substantiation of many design and regulation requirements to periodicity, volumes and sequences of procedures on planning SRS repairs and tests.

3.2. Optimization of periodicity of tests of safety-related systems under full reactor operation

The general provisions and assumptions of an optimization technique of planning of tests (for power operation of NPP) of auxiliary SRS of NPP and some results of calculations are submitted.

3.2.1. General provisions of a technique

Object of consideration is the SRS equipment operated in a complex mode, which includes:

- mode of run (specified safety functions operated),
- standby mode,
- mode of checks (scheduled and unscheduled) and functional tests under power operation of NPP, and
- mode of unscheduled (under failure) repair-and-renewal operations.

Periodicity of tests is meant as time (or lifelength) between the given kind of tests and the following same kind of tests of one channel of system.

SRS are subdivided into safety systems (SS) and safety-related systems of normal operation (SRS NO). SS are characterized by the absence of run mode, such systems actuate only during tests of system channels. SRS NO are characterized by time of continuous run when the channel functions, and then there is a scheduled switching to one of reserve channels, and other reserve channels are tested. Thus, for SRS NO the periodicity of scheduled switching is explicitly connected to periodicity of scheduled tests.

Methodical basis of optimization of strategy of scheduled SRS tests is the risk-informed approach [25]. In frameworks of the risk-informed approach for optimization of strategy of scheduled SRS tests, criterion function of risk R is accepted:

$$R = R\left(K_{г_i}, Y_i\right) \tag{3.1}$$

where: Y_i - probabilistic measures of the specific contribution of system i to an estimation of safety criteria of power unit,

$K_г$ - integral availability factor of performance of project safety functions over considered time t:

$$K_г = 1 - \frac{1}{t}\int_0^t P(x)dx\,. \tag{3.2}$$

$P(x)$ - probability of system failure at the current moment x.

Optimization criteria of strategy of scheduled SRS tests are:

$$K_г(T^*) = \max K_г(T) \tag{3.3}$$

$$R(T^*) = \min R(K_{гi}, Y_i), \tag{3.4}$$

where: T^* - optimum periodicity of SRS tests.

For independent SRS (from the point of view of an opportunity of realization of a complete complex of tests), the minimization of criterion function of risk is come to an estimation of conditions of maximum $K_г$.

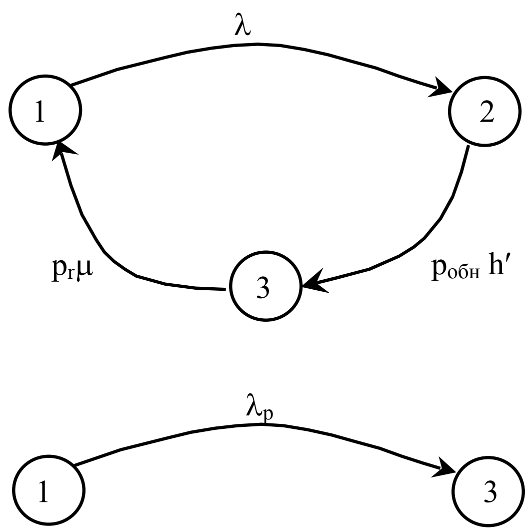
To find optimum periodicity of complex tests for the group of systems the analysis of impact of a reliability level of each system on a safety level of NPP is necessary. This task is solved by estimating factors of the significance of systems (for example, from probabilistic safety analysis) and common impact of group of systems on risk factors.

3.2.2. State graphs

When SRS are modelling, it is important to reflect a completely complex schedule of operation.

The state of system components changes because of the accidental causes (failure, emergency demand, test after damage repairs), and the condition of components can change according to schedule, i.e. deterministically. For example, scheduled tests and scheduled switching are deterministic (switching is the transfer of a component of system from mode of run to a standby or back).

For SRS elements operating cyclically between tests / switching, the mathematical model is illustrated by two Markovian graphs (fig. 3.1).



1 - state of operability of a standby / run mode (incorporated),

2 - state of the latent failure,

3 - state of detectable failure with damage repair

Fig. 3.1: Complex of State Graphs for Modelling of SRS Channel

$\lambda = 1/l$ - failure rate in standby mode, where: l - Average time between failures in standby mode,

$\lambda p = 1/lp$ - failure rate in operation mode, where: lp - Average time between failures in run mode,

$\mu = 1/\tau$ - frequency of damage repairs, where: τ - average time of damage repair,

$h' = 1/\vartheta$ - frequency of scheduled inspections, where: ϑ - average time between inspections of SRS (usually ϑ=8 hours),

p_r - probability of qualitative realization of damage repair (per one repair),

$p_{обн}$ - probability of detection of failure during inspection (per one inspection).

The first graph of a complex describes behaviour in a standby mode. The second graph simulates unavailability because of channel start (during tests for SS or during scheduled operation for SRS NO).

For the first graph the system of Kholmogorov's linear differential equations is:

$$\left.\begin{aligned} P_1'(t) &= p_r \mu P_3(t) - \lambda P_1(t) \\ P_2'(t) &= \lambda P_1(t) - h' p_{обн} P_2(t) \\ P_3'(t) &= h' p_{обн} P_2(t) - p_r \mu P_3(t) \end{aligned}\right\} \qquad (3.5)$$

Pointwise availability: $K_г(t) = P_1(t)$.

3.2.3. Estimation of initial conditions

The model for estimating initial conditions is submitted for SS channels. During periodic scheduled (and unscheduled - because of failure in the tested channel) tests there is a jump change of probabilities of condition.

The notations of channels (Fig. 3.2):

A - channel, which only has passed scheduled tests,

B - channel, which should pass tests according to schedule after the channel **A**,

C - channel, which should pass tests according to schedule after the channel **B**.

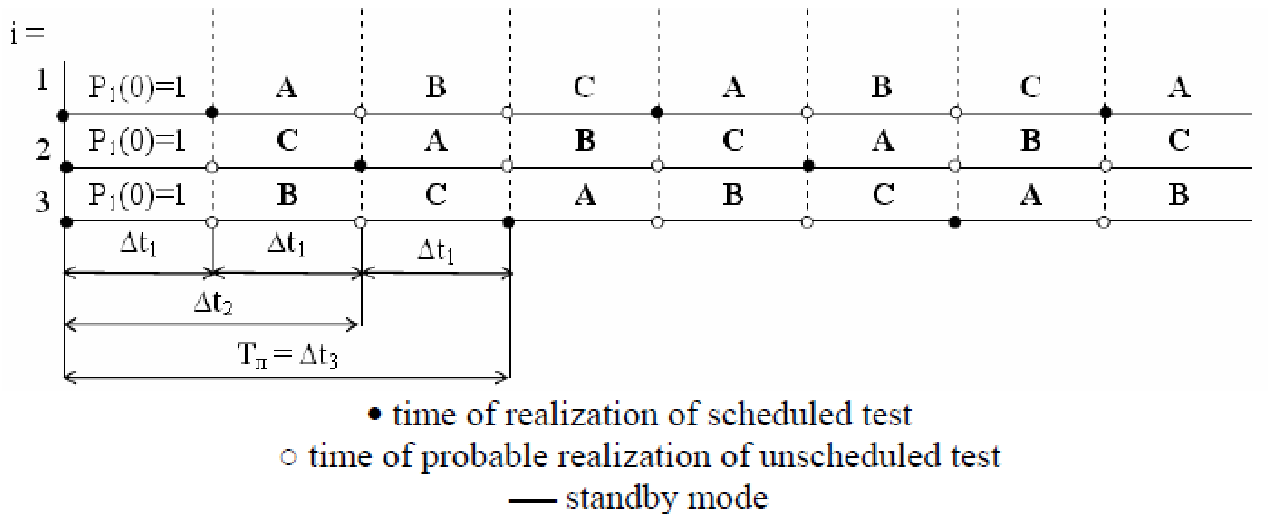


Fig. 3.2: Diagram of functioning of three-channel SS

After scheduled test, the state probability of the latent failure 2 is zeroize, and state probability of the repair 3 increases by the state probability of the latent failure. Failure rate during tests (run) and during standby can considerably differ. Probability of non-failure during tests is:

$$P_p = \exp(-\lambda_p \tau_{пл}), \tag{3.6}$$

where: λ_p - failure rate during operation, 1/h; $\tau_{пл}$ - test time, h.

After scheduled test the value P_p is deducted from the probability of operability state *1*, and this value is add to the probability of the damage repair state *3*.

Taking into calculation above, for the channel **A** the initial conditions (at the moment $t=0$) are:

$$\left.\begin{array}{l} P_1^A(0) = P_1^A(\Delta t) P_p \\ P_2^A(0) = 0 \\ P_3^A(0) = 1 - P_1^A(0) \end{array}\right\}, \tag{3.7}$$

where: Δt - time between the nearest tests in the neighbouring channels of system ($\Delta t = \Delta t_1 = T_n/3$), h.

For channels **B** and **C** also there is a jump change of probabilities of condition at the end of scheduled tests of the channel **A**. If in the channel **A** is fault and the channel **A** is transferred to the repair state then channels **B** and **C** must be tested for confirming their operability state.

$$\left.\begin{array}{l} P_1^{BC}(0) = 1 - \left(1 - P_1^{BC}(\Delta t)\right)\left(1 - P_3^A(0)\right)\left(1 - P_3^{BC}(\Delta t) P_3^A(0)\right) \\ P_2^{BC}(0) = 1 - P_1^{BC}(0) - P_3^{BC}(0) \\ P_3^{BC}(0) = P_3^{BC}(\Delta t)\left(1 - P_3^A(0)\right) \end{array}\right\}, \tag{3.8}$$

The initial conditions in each next time interval (in this case, Δt) are determined by the state graph using the initial conditions, which determined in the previous interval.

The model for calculation of the initial conditions for SRS NO channels can be found similarly with only difference − the interval **A** the channel is in run state and is described by second graph of the complex of state graphs for modelling of SRS channel (see Fig. 3.1).

3.2.4. Results of calculations

The optimum periodicity of tests of SS channels for power operation of NPP obtained from the point of view of a maximum of availability factor is from 1040 hours till 1640 hours (Fig. 3.3):

- Containment Spray System (TQ11-31) - 1040 hours,
- Low Pressure Injection System (TQ12-32) - 1640 hours,
- High Pressure Injection (TQ13-33) - 1460 hours,
- Full Pressure Injection System (TQ14-34) - 1640 hours,
- Emergency Feedwater System (TX10-30) - 1380 hours,
- Channels of Essential Service Water System (ESWS) (QF/VF) - from 1020 till 1100 hours,
- Channels of emergency diesel generators subsystem (DGS) - from 2300 till 2940 hours.

Comment: ESWS and DGS consist of three trains which are completely independent from each other, and each of which provides for supply to this train consumers. Each of the three system channels has the own optimum periodicity.

The periodicity of complex tests (identify consideration to the importance of systems) for the group of the above systems is 1540 hours. The functional dependences $K_{\Gamma i} = f(T_i)$ has uncertainty, therefore the optimum periodicity has interval from the minimal optimum value $T_1{*} = 1440$ hours up to maximal $T_2{*} = 1660$ hours.

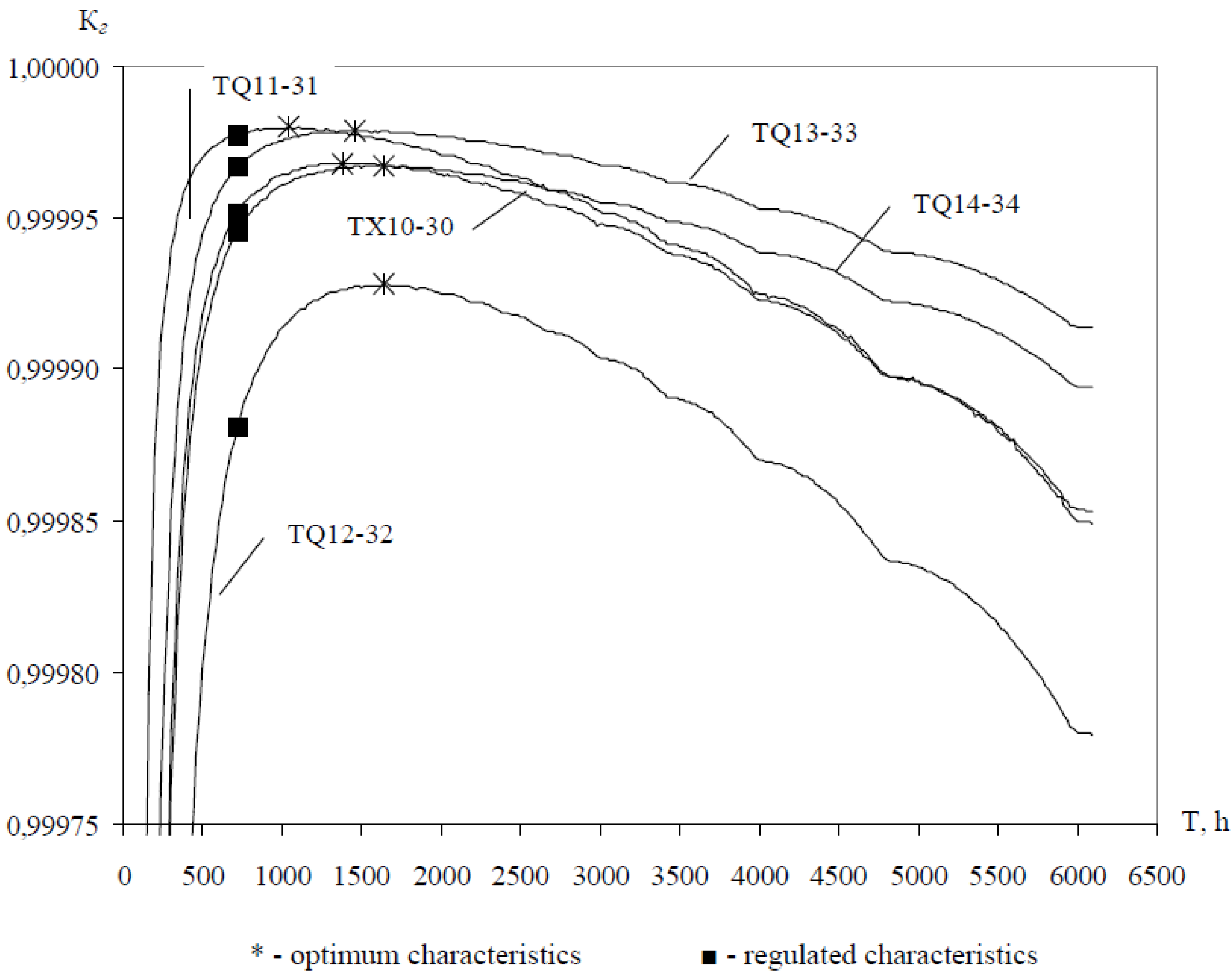


Fig. 3.3: Dependence of stationary availability factor on periodicity of tests of channels of safety systems

3.3. Substantiation of reduction of containment leakage tests

3.3.1. General provisions of a technique

Taking into account long experience of VVER-1000 operation, containment leakage test by overpressure 0.07 MPa are inefficient for the following reasons:

- the basic defects influencing containment reliability are identify at vacuumization and local containment leakage tests,

- the frequent tests by overpressure 0.07 MPa result in decrease of reliability and tightness of containment,

- containment leakage tests by overpressure 0.07 MPa always are on a critical way of scheduled repairs of power units, and depending on the weather factors around NPP they are from 1.5 till 2.5 days (at that leakage test by vacuumization is about 3 hours).

The substantiation of reduction of containment leakage tests is based on the statistical analysis of results of tests: leakage value Lк, presence of defects at tests, eliminability of defects.

A criterion of substantiation is the operational criterion of tightness (OC) $L_{кр}$ that is individual for each containment of power unit.

The elimination of one (and more) containment test is proved if the conservative estimation of leakage value for two (and more) years forward, obtained by extrapolation method, will not exceed leakage value, which is 15 % higher than OC. It is the basic quantitative condition of reduction of tests [26].

Additional (by a qualitative level analysis) conditions of reduction of tests are:

a) the absence of defects of containment elements,

b) during scheduled preventive maintenance of a power unit performance of all regulated works on preservation of availability of containment elements (maintenance service, local tests, inspections, etc.),

c) opportunity of realization of local leakage tests of replaced and/or reparable containment elements.

The numerical criterion of planning of the reduced containment leakage test is the check of performance of an inequality:

$$L_{экстр}(N+2) \leq 1{,}15 L_{кр}, \qquad (3.9)$$

where: $L_{экстр}(N+2)$ top boundary of leakage value (with the top tolerance limit), obtained by the conservative approach with extrapolation for 2 years forward taking into account results of N last containment tests.

3.3.2. Mathematical tool of a technique

The initial data are:

- leakage value before defects removal in test i - $L1_i$, % /day,

- leakage value after critical defects removal in test *i* (final leakage value) - $L2_i$, % /day.

Value $L1_i = L2_i = L_{\kappa i}$, if: the defects are absent; the defects have been, and they have been removal after tests by overpressure (after measuring $L_{\kappa i}$); the defects have been, but they have been not eliminated.

If the defects have been detected during overpressure tests, and they have been removal before measuring $L_{\kappa i}$, then $L2_i = L_{\kappa i}$, $L1_i = L^{\kappa}_{\partial e\phi}$,

$$L^{\kappa}_{\partial e\phi} = \begin{cases} L_p, & for\ 1.3225 \cdot L_{\kappa p} < L_p < 0.3 \\ 1.3225 \cdot L_{\kappa p}, & for\ L_p < 1.3225 \cdot L_{\kappa p} \\ 0.3, & for\ L_p > 0.3\ or\ L_p - unspecified \end{cases} \tag{3.10}$$

The conservative extrapolation estimation of leakage value for 2 years forward is:

$$L_{\text{экстр}}(N+2) = 2 \cdot L_{cp}(\Delta_i) + 2 \cdot L_{cp}(\Delta L2_i) + L2_{max}, \tag{3.11}$$

were: $L_{cp}(\Delta_i)$ - average value, $i = 1, ..., N$, which takes into account impact of critical defects,

$L_{cp}(\Delta L2_i)$ - average value, $i = 1, ..., N$, which takes into account the trend of final leakage value $L2$,

$L2_{max}$ - maximal leakage value $\Delta L2_i$, $i = 1, ..., N$ in N tests after determination of OC.

Weight function taking into account that result of each next test has greater contribution to prediction, than result of the previous test, is ($\sum_{i=1}^{N} m1_i = 1$)

$$m1_i = \frac{1/2^{N-i}}{\sum_{i=1}^{N} \frac{1}{2^{N-i}}}, \text{ i=1,…,N}, \tag{3.12}$$

The design equation for $L_{cp}(\Delta_i)$:

$$L_{cp}(\Delta_i) = \sum_{i=1}^{N} m1_i (L1_i - L2_i)\,. \tag{3.13}$$

Weight function taking into account that result of each next test has greater contribution to prediction, than result of the previous test, is determined using (3.12) and $\sum_{i=1}^{N} m2_i = 1$

The design equation for $L_{cp}(\Delta L2_i)$ is:

$$L_{cp}(\Delta L2_i) = \sum_{i=2}^{N} m2_i \cdot \Delta L2_i\,, \tag{3.14}$$

$$\Delta L2_i = \begin{cases} \dfrac{L2_i - L2_{i-1}}{\Delta t_i}, & npu\ L2_i > L2_{i-1}, \\ 0, & oherwise \end{cases} \qquad i=2,\ldots,N;$$

Δt_i – time between containment leakage tests i and i-1, year.

The design equation for estimating the statistically maximal final leakage value after determination of OC is:

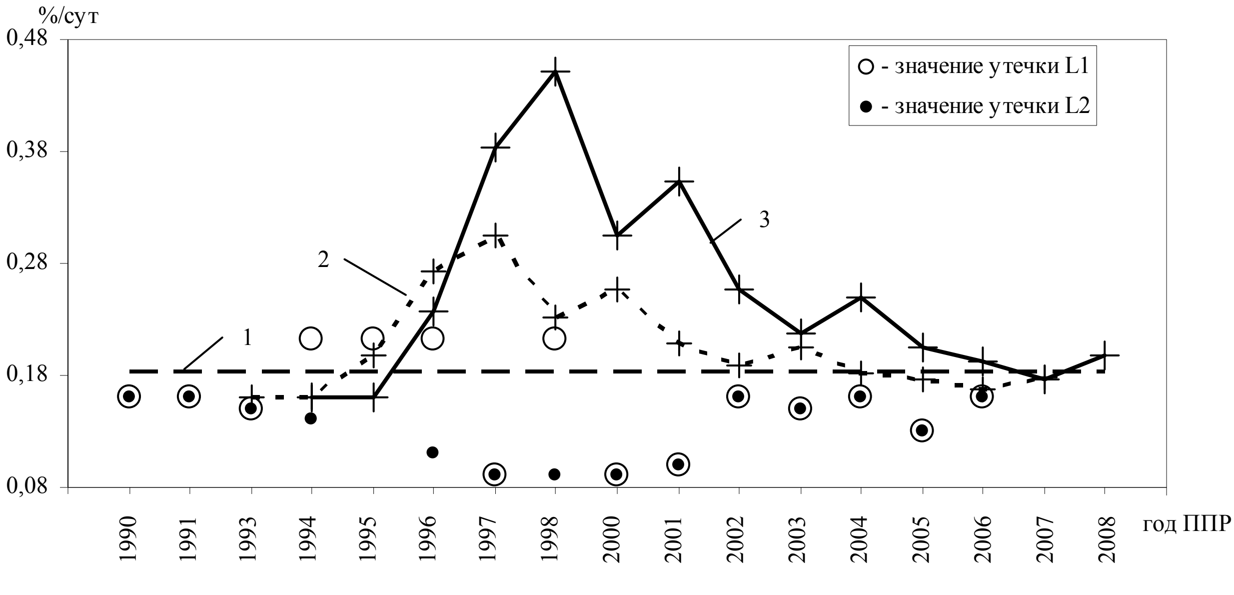
$$L2_{max} = \max_{i=1\ldots N}(L2_i)\,. \tag{3.15}$$

3.3.3. Results of calculations

The analysis for power units with VVER-1000 has allowed to draw a conclusion about an opportunity to exclude containment leakage tests by overpressure (carry out of containment test only by vacuumization) in preventative maintenance 2008 year, for example (Fig. 3.4, 3.5):

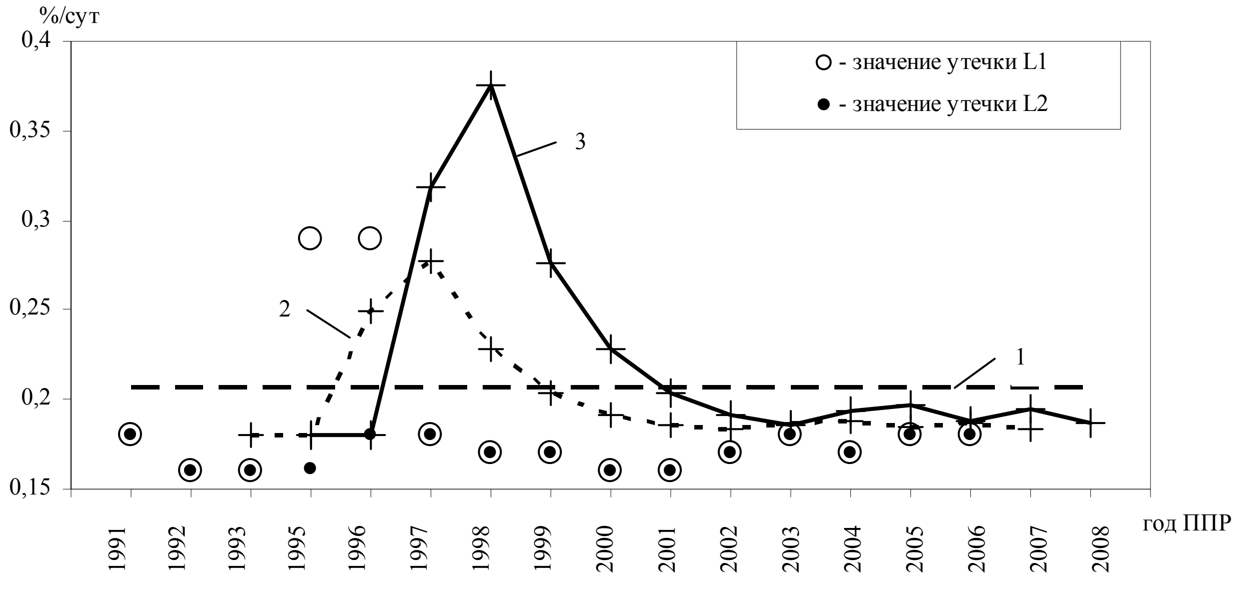
- for power unit 1 of Zaporozhye NPP is necessary the complete test (vacuumization and overpressure) to confirm the design characteristics of containment;

- for power unit 2 of Zaporozhye NPP - to exclude a test by overpressure.



1 - assessment criterion 1,15 (0,14+0,02), 2 - conservative prediction for 1 year, 3 - conservative prediction for 2 years

Fig. 3.4: Change of containment leakage value for ZapNPP-1



1 - assessment criterion 1,15 (0,17+0,01), 2 - conservative prediction for 1 year, 3 - conservative prediction for 2 years

Fig. 3.5: Change of containment leakage value for ZapNPP -2

3.4. Change of strategy of tests and repairs of the equipment under conditions of increase of a fuel cycle

3.4.1. General provisions of a technique

One of ways to increase the installed nuclear capacity factor (INCF) is to introduce a fuel cycle of 18 months. This will allow to reduce a number of repairs in one complete cycle from four to three (at the same duration of a full fuel cycle). At that, time between preventive maintenances (PM) of power unit is increased. Therefore, to introduce a fuel cycle of 18 months (18 months between the starts of PMs), in particular, it is necessary to prove an opportunity of change of strategy of tests / inspections of the NPP equipment.

This task is solved using probabilistic methods of a modelling / assessment of reliability of components. The methods of the probability theory, mathematical statistics, the reliability theory and the probabilistic safety analysis of NPP are used [26].

The extension of time between PMs results in increase of failure probability of the equipment. Compensating measures are:

- to realize additional tests of the equipment during operating repair of power unit,

- to change periodicity of revision (major repairs) of the equipment.

The change of the schedule / nomenclature of tests / revision of the equipment is acceptable, if the inequality is true:

$$P_{\text{изм}} \le P_{\text{б}}, \qquad \text{P}_{\text{б}} = \begin{cases} P_{норм}, & for\ P \le P_{норм}; \\ P, & for\ P > P_{норм}, \end{cases} \tag{3.16}$$

where: $P_{изм}$ - failure probability of the equipment assessed for the changed schedule / nomenclature of tests / revision of the equipment,

$P_{б}$ - base value of failure probability of the equipment,

P - failure probability of the equipment assessed for current schedule / nomenclature of tests / revision of the equipment using available operational statistics,

$P_{норм}$ - normative failure probability of the equipment.

All failure probabilities are estimated for the top confidential bound with confidential probability q = 0.95.

The basis of the mathematical tool is model of time variation (for some years) of failure probability of the equipment, taking into account available or probable additional tests / revision.

It is supposed, that test of the equipment incompletely restores its operability, i.e. test cannot detect some failures. These defects can result in failure of the equipment and shutdown of power unit in future. The degree of restoration of the equipment after tests (efficiency of tests) is assessed as a failure quota detected during tests of the equipment of total of failures using operational statistics.

It is supposed, that major repairs (revision) of the equipment completely restores its operability (eliminates all negative consequences of the previous operation).

3.4.2. Mathematical tool of a technique

The top bounder of failure probability on one demand is determined using the bottom bounder of probability of non-failure operation and taking into account [27] is:

$$P_{mp}(d) = \begin{cases} 1-\exp\left(-\dfrac{\chi_q^2(2d+2)}{2K_2(N,d+1)}\right), \; for \; d \le \dfrac{N}{2}, \\ \exp\left(-\dfrac{\chi_q^2(2(N-d))}{2K_2(N,N-d)}\right), \; for \; d > \dfrac{N}{2}. \end{cases} \quad (3.17)$$

where: $K_2(N, m) = m \,/\, \sum_{i=0}^{m-1}(N-i)^{-1}$

d - number of failures of the given type (for example, number of fails to open),

N - number of demands,

$\chi_q^{2}(l)$ - quantile of a chi-square distribution with number of freedom degrees l, appropriate to confidential probability $q = 0.95$.

The top bounder of failure rate of a standby mode is determined using [27]:

$$\lambda = \frac{\chi_q^2(2d+2)}{2T_\Sigma} \qquad (3.18)$$

where: T_Σ - total interval of observation, where the failures of the equipment are detected, it correspond to product $MT_{набл}$, M - number of the same type elements, $T_{набл}$ - observation period.

If the analyzed equipment is divided into some elements, then the failure probability of group of elements is determined taking into account their logic structure according to criterion of failure.

The failure probability for design number of cycles is the sum of independent probabilities for each cycle.

The quantitative estimation of efficiency of n tests generally is:

$$\alpha_{исп} = \frac{\sum_{i=1}^{n} d_i}{d_\Sigma}, \qquad (3.19)$$

where: d_i - number of failures detected during a kind i of tests of the equipment,

n - number of kinds of tests for the equipment,

d_Σ - total number of failures of the equipment, including failures detected during tests / inspections and between tests using, for example, external survey, monitoring, etc.

The general formula describing change of failure probability of a component of the equipment taking into account tests / revision / repairs is:

$$P_к = \begin{cases} 1-\exp(-\lambda t), \ при\ t < T, \\ \langle 1-\exp\{-\lambda(t-Ti)\}\rangle(1-A_i)+A_i, \ otherwise \end{cases} \qquad i = \left[\frac{t}{T}\right], \qquad (3.20)$$

where: λ - failure rate (a kind of failure) of component,

T - periodicity of operating repair of power unit,

$[x]$ - integer part of x,

t - current time varied from zero to *трев* - periodicity of revision,

A_i - factor taking into account jumping change of failure probability after test during operating repair of power unit or PM of power unit.

The recurrence relations for factors A_i are:

$$A_1 = (1 - \exp(-\lambda T))\,(1 - \alpha_T) \tag{3.21}$$

$$A_i = \begin{cases} \left\langle \{1 - \exp(-\lambda T)\}(1 - A_{i-1}) + A_{i-1} \right\rangle (1 - \alpha_{ППР}), \ for \ \dfrac{i}{N_{исп} + 1} - \left[\dfrac{\mathrm{i}}{\mathrm{N}_{\text{исп}} + 1} \right] = 0, \\ \left\langle \{1 - \exp(-\lambda T)\}(1 - A_{i-1}) + A_{i-1} \right\rangle (1 - \alpha_T), otherwise \end{cases}$$

$$i = 2,3,\ldots, \left[\frac{t}{T} \right] + 1,$$

where: *tППР* - time between PMs, years,

k - number of PMs up to the moment t, $k = [t/t_{ППР}]$,

$\alpha_{ППР}$ - degree of restoration of a component after tests during PM of power unit,

α_m - degree of restoration of a component after tests during operating repair of power unit,

$N_{исп}$ - number of operating repairs between PMs of a power unit.

3.4.3. Results of calculations

Using the actual operational data total failure probability P and degree of restoration during tests $\alpha_{\text{исп}}$ are obtained for the following equipment:

1) Fast acting motor operating valves of emergency core flooding system (ECFS)

2) Check valves of ECFS

3) Relief valves of hydroaccumulator of ECFS

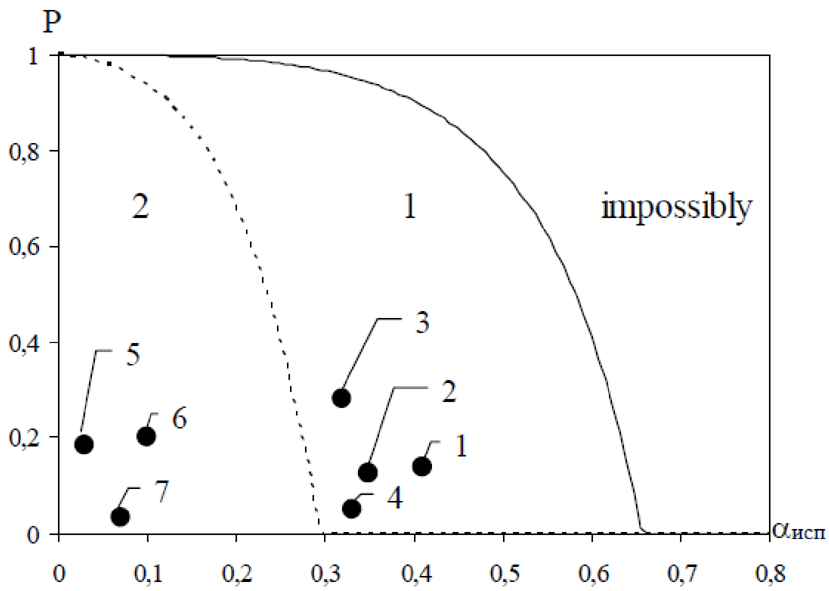
4) Motor operation valves with passage diameter > 15 of Emergency primary gas evacuation system

5) Steam dump valve to atmosphere (BRU-A)

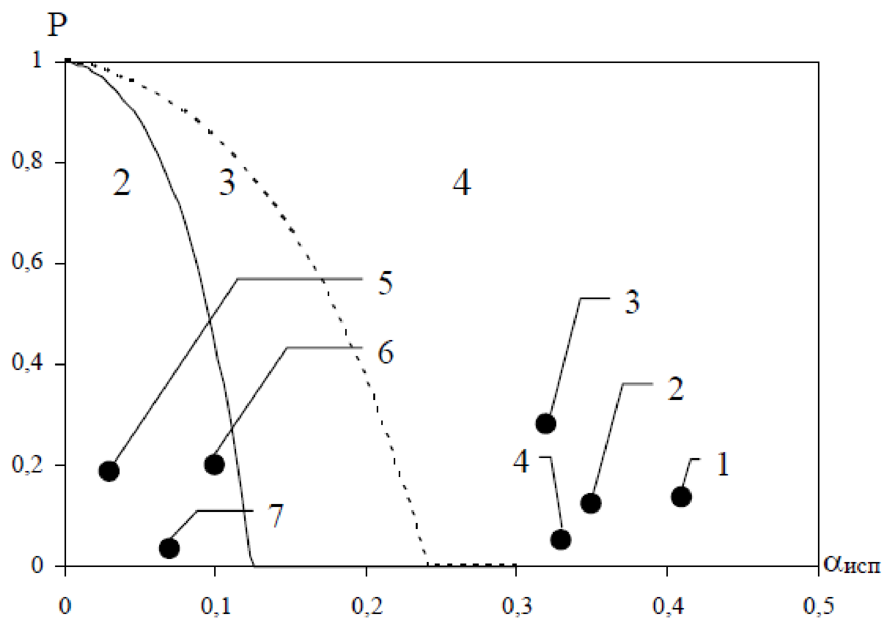
6) Main steam isolation valve of Fast-acting steam isolating valve (FASIV)

7) Valves for control of FASIV with passage diameter > 15

Fig. 3.6 represent the generalized diagrams with acceptable strategy of tests / revision of the specified equipment in conditions of increase of time between PMs from 12 to 18 months. Design periodicity of major repairs of the equipment is one time per 4 years. Numbers on the diagrams meet to the obtained results (P, $\alpha_{исп}$) for group 1-7 of the equipment.



a) test of the equipment during operating repair of power unit are absent



b) test of the equipment during operating repair of power unit are present

Fig. 3.6: Required number of the PM of power unit periods ($t_{ППР}$ = 1.5 year) before major repairs (revision) of the equipment

3.5. Conclusions for chapter

(1) The theoretical basis of optimization of periodicity of scheduled tests of SRS for power operation of NPP is developed. At that:

- the complex of graphs used for modelling functioning of any existing elements of the SRS equipment is developed,

- analytical dependences for the description of the various schedules of SRS functioning are obtained. The analytical dependences for availability factor as function dependent on periodicity of scheduled measures are obtained,

- the risk-informed approach using models of the probabilistic safety analysis to assess the significance of systems from the point of view of decrease of risk is developed. This approach allows to determine common (collective) periodicity of tests of a number of systems involved in complex tests.

(2) Using the data on failures and defects of Zaporozhye NPP for operating period the reliability parameters of the equipment of some SRSs are calculated. The increase of periodicity of scheduled tests of SRS participating in complex tests ZapNPP-5 (TQ11-31, TQ12-32, TQ13-33, TQ14-34, TX10-30, VF/QF, DGS, TF, TY) in two times is offered.

(3) The technique of a substantiation of an opportunity of realization of the reduced containment leakage test (leakage test only by vacuumization) is developed. Time of scheduled repair of power unit will be 1 − 1.5 days shorter.

(4) The technique of a substantiation of change of strategy of tests and repairs of the equipment under conditions of increase of a fuel cycle is developed. It is established, if failure probability of the equipment and degree of restoration during tests increase, then the period between major repairs (revision) of the equipment:

- increases, if tests realize during operating repair of power unit,

- reduce, if tests of the equipment don’t realize during operating repair of power unit.

(5) Using the data on failures and defects of power units of Zaporozhye NPP,

Khmelnitskiy NPP, South-Ukrainian NPP the practical recommendations to choose optimum periodicity of repairs under conditions of increase of fuel cycle are submitted. For example, for Fast acting motor operating valves (FAMOV) of ECFS of power units the following is established:

- if the operating repair of power unit is not scheduled, then the major repairs and operational tests of FAMOV are required during each PM, but not rare one time per 25 months,
- if the operating repair of power unit is scheduled, then the major repairs of FAMOV is required one time per 4 PMs (one time per 6 years), but not rare one time per 87 months, and operational tests of FAMOV are required during PM and operating repair of power unit, but not rare one time per 11 months.

Chapter 4. OPTIMIZATION OF STRATEGIES FOR EXTENDING THE OPERATION OF SYSTEMS IMPORTANT FOR THE SAFETY OF NUCLEAR POWER PLANTS

4.1. Concept

Operation extension of the heat engineering equipment of the safety related systems of nuclear power utilities important for the safety of nuclear power utilities during the beyond design basis period is one of the most effective directions of the development of nuclear power engineering. Economic expenditures on complete replacement of systems and equipment (except for the nuclear reactor pressure vessel) cannot be compared to the expenditures on the removal from service and construction of new electrical power units [28].

According to the sectorial programmes of operation extension of ukrainian nuclear facility life extension of the 1st and 2nd electrical power units of Rovenskaya NPP; the 1st, 2nd and 3rd electrical power units of Yuzhno-Ukrainskaya NPP and the 1st, 2nd, 3rd and 4th electrical power units of Zaporozhskaya NPP has been realized for the moment. Operation extension benefits figure up to billions of American dollars.

According to IAEA recommendations and sectorial programmes of operation extension of Ukrainian nuclear facility overriding problems are [29, 30]:

- reliability analysis of operating experience, inservice inspection, maintenance and repair of safety related systems of nuclear power utility;
- surveillance and condition monitoring of systems and equipment upon the expiration of installed life;
- analysis of strength system rate, equipment and structures of safety related system of nuclear power utility (including the external severe abuse – earthquakes, tornados, floods, etc.)

Basic limitations of technical data reports (e.g. [35, 36]) on operation extension of Ukrainian nuclear facility are as follows.

1. Rates of residual life, degradation/ware rates and the duration of operation extention terms of separate systems and equipment are insufficiently substantiated.

2. Rates of optimal efficiency of strategy of operation extension in relation to providing of the necessary reliability level of safety related systems of nuclear power utility and corresponding economic expenditures are insufficiently substantiated.

These ideas define the rationale of the development and application of the companion analysis of the efficiency optimization method of strategy of operation extension of safety related system of nuclear power utility.

4.2. Principle of the efficiency optimization method of strategy of operation extension

1. The efficiency optimization of strategy of operation extension is the defining of the maximum allowed operation life extension providing the necessary level of reliability and minimizing economic expenditures.

2. The criterion of the efficiency optimization of strategy of operation extension is the ratio of the duration of the relative operation life extension during the beyond design basis period $\Delta T_п$ and the corresponding expenditures of technical and organizational measures taken to extend the operation:

$$K_{opt} = \frac{\Delta T_n}{T_0} \frac{C_0}{\Delta C_n}, \tag{4.1}$$

where T_0 is the operation life designated by the project; C_0 – equivalent cost of the system extended for operation; ΔC_0 –- total expenditures of technical and organizational measures in operation extension, including the change and repair of system components.

The efficiency optimization of strategy of operation life extension is defined by a condition

$$K_{opt} \to \max. \tag{4.2}$$

3. Parameters of efficiency optimization of operation extension:

- rates of residual life for the moment of operation extension of pacing rates of system reliability

$$\Delta P_{op} = \begin{pmatrix} P_1 - P_{1\partial} \\ P_2 - P_{2\partial} \\ \\ P_n - P_{n\partial} \end{pmatrix}, \tag{4.3}$$

where P_1, P_2, …, P_{n} – are the current values of pacing rates of reliability for the time of operation extension; $P_{1\partial}$, $P_{2\partial}$, …, $P_{\mathrm{n}\partial}$ – maximum permissible rates of pacing indicators of reliability;

- indicator of expenditures on technical and organizational measures on operation extension ($\Delta C_{\text{п}}/\mathrm{C}_0 = \Pi_{\mathrm{c}}$);

- indicator of maximum allowed operation life extension

$$\Pi_{\Delta T} = \frac{\Delta T_n}{T_0}, \tag{4.4}$$

4. The duration of the operation life extension is defined by the rates of residual life and degradation/ware rate of system components

$$\Delta P = V_n \Delta T_n \tag{4.5}$$

under condition that $V_n > 0$ from equation (4.5) it can be interfered that

$$\Delta T_n = \min\left\{\frac{\Delta P_{op}}{V_n}\right\}, \tag{4.6}$$

where V_n is the degradation/ware rate of critical as to reliability system components during the beyond design basis period of operation.

Conservatively (excluding the re-establishment and resource management measures) the degradation/ware rate of critical as to reliability system components can be defined according to the results of operation during the beyond design basis period:

$$V_n = V = \frac{\Delta P_p}{T_0} = \frac{P_0 - \Delta P_{op} - P_\partial}{T_0}, \tag{4.7}$$

where ΔP_p is the shorter life of the pacing indicators of reliability within the operation life T_0 defined by the project; P_0 – values of the pacing indicators of reliability in the beginning of operation overdesigned up to the rated values P_∂.

Hence, parameters of efficiency optimization of operation extension:

$$\mathit{\Pi}_{\Delta T} = \min\left\{\frac{\Delta P_{op}}{P_0 - \Delta P_{op} - P_{\partial}}\right\}, \tag{4.8}$$

$$\mathit{\Pi}_C = \frac{\Delta C_n}{C_0}, \tag{4.9}$$

5. Boundary values of the parameters of efficiency optimization of operation extension result from formulae (4.1)–(4.9)

$$0 \le \mathit{\Pi}_{\Delta T} \le 1, \tag{4.10}$$

$$0 < \mathit{\Pi}_C \le 1, \tag{4.11}$$

The condition of the optimization efficiency of strategies of operation extension

$$K_{opt} > 1 \tag{4.12}$$

Domain of optimization efficiency of strategies of operation extension is illustrated below (Fig. 4.1).

Implementation procedure of the method of the efficiency of optimization of strategies of managing the operation is illustrated below (Fig. 4.2).

4.3. Results of the design-basis justification

Implementation of the offered method of the efficiency of optimization of strategies of operation extension was realized for:

- pump cases of the safety related system of the 1st and 2nd nuclear power plant units of Zaporozhskaya NPP;

- valve cases of safety related system of the 1st and 3rd nuclear power plant units of Yuzhno-Ukrainskaya NPP;

- reinforced concrete structures cases of the spent-fuel pool of the 3rd and 4th nuclear power plant units of Zaporozhskaya NPP.

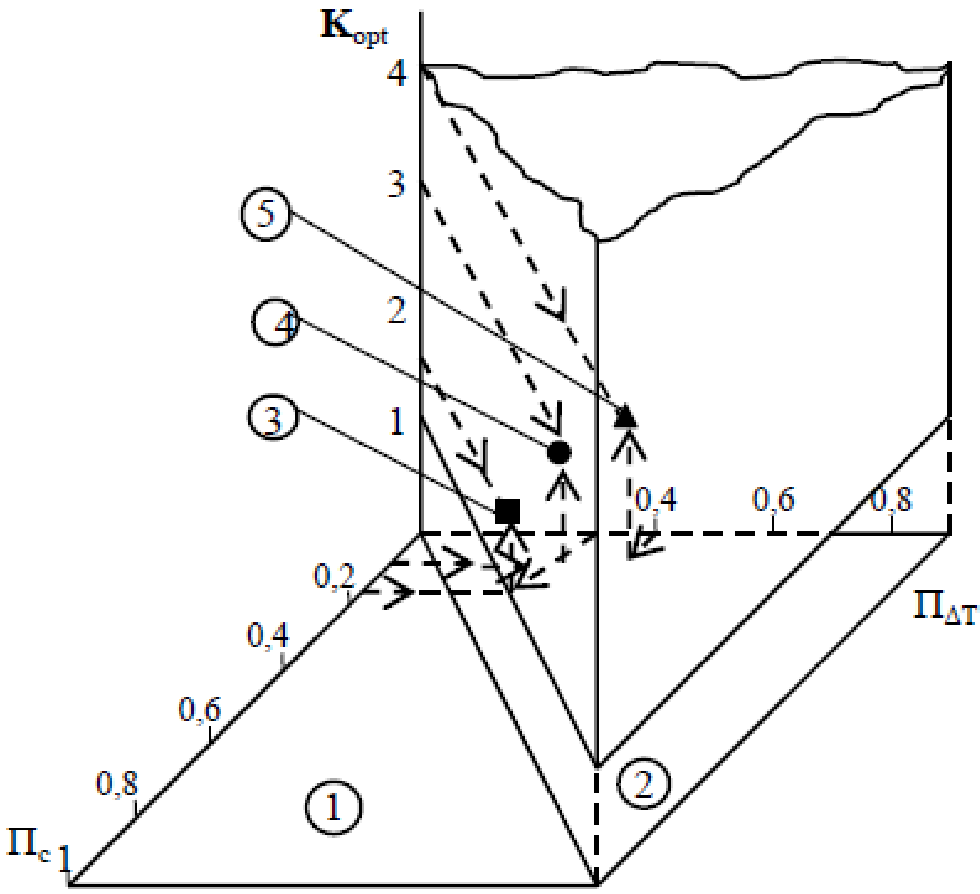
Critical parameters of reliability of the cases of the systems in question:

- wall thickness of the case δ;

- sizes of defects found r;

- dynamic stresses σ on the equipment body at the maximum design earthquake with an acceleration of the response of 0.17 g (more than 7 points on the MSK scale – 64);

- quantity of the cycles of heat loading on the body metal during the transient or accident operation *N*.



1 – domain of optimization efficiency of operation extension;
2 – domain of parameters of optimization inefficiency of strategies of operation extension;
3 – pump cases of the safety related system of the 1st and 2nd nuclear power plant units of Zaporozhskaya NPP;
4 – valve cases of safety related system of the 1st and 3rd nuclear power plant units of Yuzhno-Ukrainskaya NPP;
5 – cases of the spent-fuel pool of the 3rd and 4th nuclear power plant units of Zaporozhskaya NPP

Fig. 4.1. Areas for optimizing the efficiency of the extension of operation

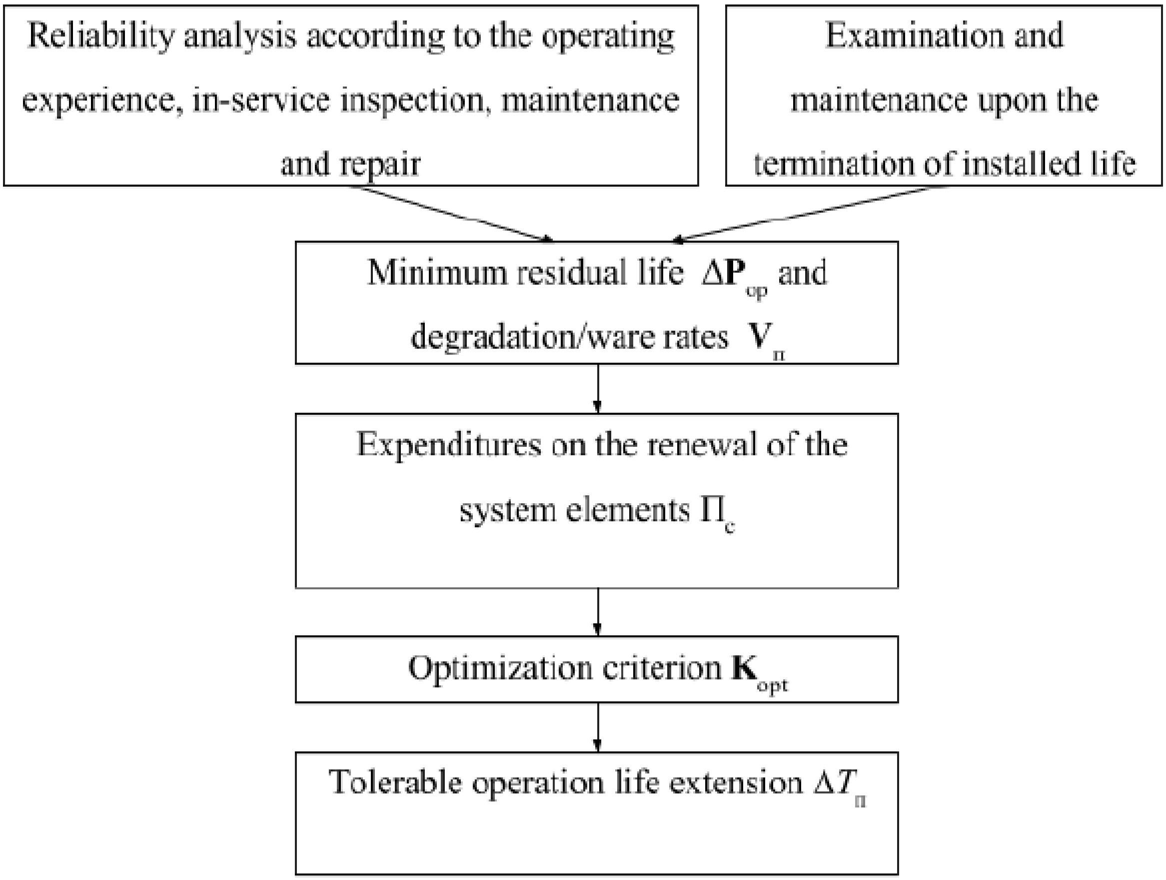


Fig. 4.2. Implementation procedure of the method of the efficiency of optimization of strategies of operation extension

Residual life is defined according to the minimum of critical reliability parameters of the systems in question:

$$\Delta P_{op} = \min\{\Delta P_{op}(\delta,\delta_\partial);\Delta P_{op}(r,r_\partial);\Delta P_{op}(\sigma,\sigma_\partial);\Delta P_{op}(N,N_\partial)\} \qquad (4.13)$$

where δ_∂, r_∂, σ_∂, N_∂ – are tolerable values of the wall thickness of the case, sizes of defects found, voltages and quantities of periods of loading accordingly.

Tolerable values of critical reliability parameters were defined according to the design and architectengineering documentation of equipment, technical specifications of normal operation, as well as according to the known calculated reliance for critical defect size and voltage on the body systems (contained, for example, in [28, 31]).

The results of the application of the offered method of optimization of strategies efficiency of operation extension are illustrated by Fig 4.1. Hence, we can give the following findings:

1. All the robust strategies correspond to the domain of maximum efficiency of operation extension of the cases of safety related systems

2. The robust operation life extension for the valve and pump cases is 10 years, for the cases of the spent-fuel pool – 13 years

3. Critical parameters of reliability, defining the residual life of the heat engineering equipment of safety related systems is the dynamic voltage on metal on the condition of beyond design basis earthquakes and the actual quantity of the cycles of loading during the transient or accident operation.

4. Optimization of test periodicity is one of the effective approaches to reduce metal degradation/wear rate of the heat engineering equipment cases [33, 34] of safety related systems during the beyond design basis operating period. In this case optimization is connected with two factors: on one hand test periodicity of safety related systems needs to be increased to be able to detect the “hidden” malfunction, on the other hand the surplus test periodicity leads to the unreasonable degradation/wear of the equipment [33, 34]. Therefore this question needs additional research during the beyond design basis period, so it will be considered by the authors in the subsequent publications.

4.4. Conclusions for chapter

(1) The original method of the optimization efficiency of the strategies of operation extension of the heat engineering equipment of the safety related systems of nuclear power utilities has been developed.

(2) The implementation of the developed method is realized for on the example of pump cases and armature of safety related systems, as well as for the cases of the spent fuel pool of Nuclear power plants with WWER. It is recognized that the reasonable time of operation extension for the pump cases and armature of the safety related systems is 10 years and for the case of the spent fuel pool is 13 years.

(3) The critical reliability parameters defining a residual life of the cases of the

heat engineering equipment are dynamic metal stresses during beyond design basis earthquakes and the actual quantity of loading cycles during transient and accident operation

(4) Optimization of test periodicity is one of effective approaches to reduce metal degradation/wear rate of the heat engineering equipment cases during the beyond design basis operating period. These questions will be considered in the next chapter.

Chapter 5. REVISION OF NUCLEAR POWER PLANTS SAFETY SYSTEMS' ROUTINE TESTING ASSIGNED PERIODICITY DURING THE DESIGN EXTENSION PERIOD

5.1. Concept

The nuclear power plants safety systems (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 [37, 38].

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 [37, 39].

Below exposed peculiarities in optimizing the SS tests periodicity during the NPPs extended lifespan are as follows [40].

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 enterprises this subject research below summarized.

5.2. 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:

$$P_1 < P_0. \tag{5.1}$$

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 (5.1).

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 [41]:

$$P_0 = \frac{N_0}{N_p}. \tag{5.2}$$

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:

$$N_0 = f_0 T_0. \tag{5.3}$$

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

$$P_1 = \int_0^{T_1} \lambda dt + P_c f_1 T_1 \,. \tag{5.4}$$

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 (5.2)–(5.4), the optimization condition (5.1) gets the following form:

$$\frac{f_1}{f_0} < \frac{1}{P_c N_p} \frac{T_0}{T_1} - \frac{1}{P_c f_1 T_1} \int_0^{T_1} \lambda dt \,. \tag{5.5}$$

The optimization parameter defining region:

$$0 \le \frac{f_1}{f_0} \le 1 \,. \tag{5.6}$$

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, [38]).

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, [42]).

5.3. 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 Fig. 5.1.

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 [37–40].

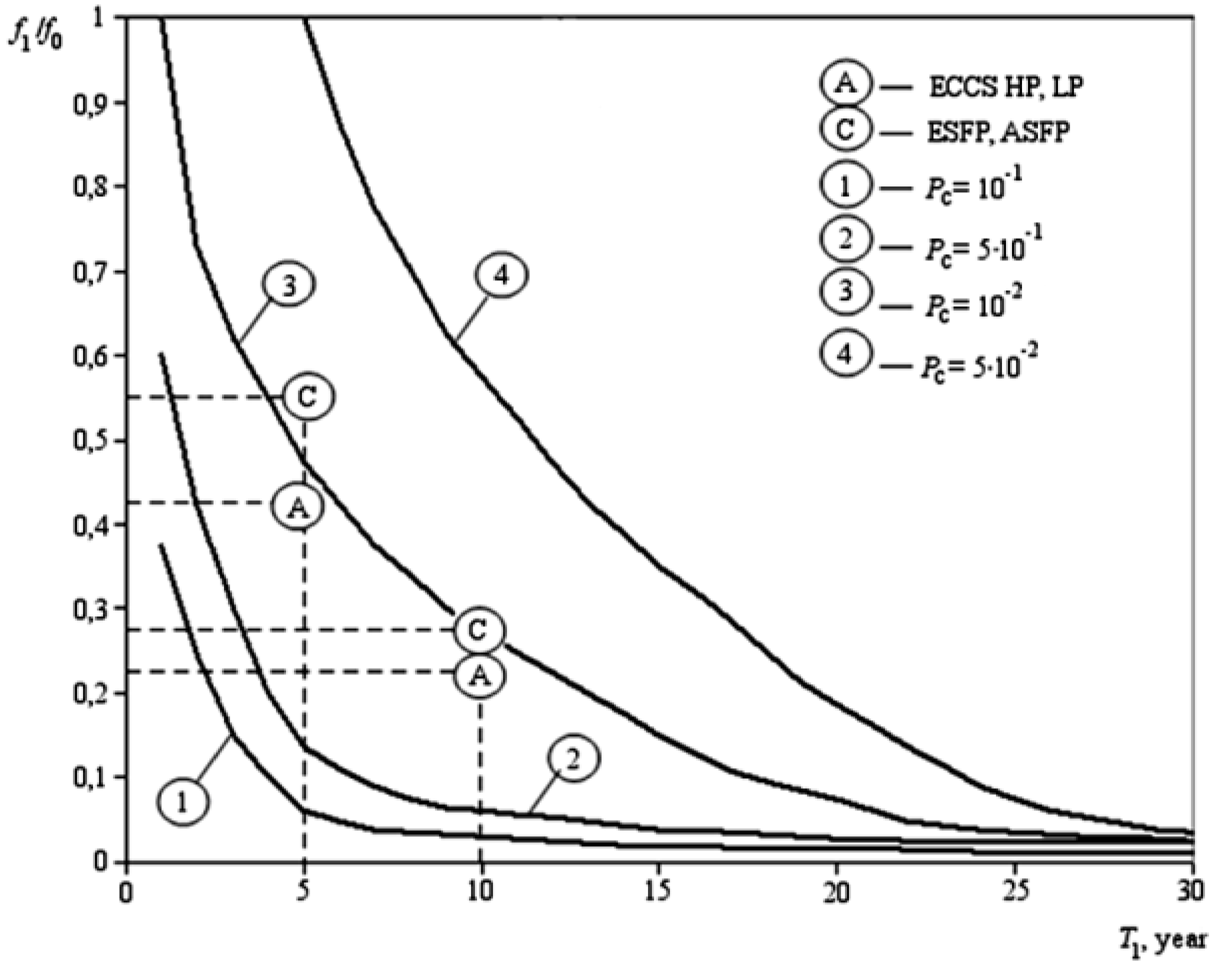


Fig. 5.1. Calculated safety systems tests periodicity optimal values regions when extended operation periods

From the results shown in Fig. 5.1, 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 (EFWP, AFWP).

The WWER-1000/V-320 project provides a three channel redundancy for each ECCS HP, ECCS LP, EFWP and AFWP 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.

Conventionally 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, EFWP and AFWP of Zaporizhzhya NPP 1st and 2nd power units are shown in Fig. 5.1. 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).

5.4. Conclusions for chapter

(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.

CONCLUSIONS

(1) It has been determined from the performed analysis of the known ROAs and experience of using them that the extent to which the ROA has presently been developed is insufficient for the ROA to be applied to matters concerned with enhancement of NPP safety, improvement of the “effectiveness–safety–reliability” models, and optimization of NPP operation practices.

(2) The elaborated scientific technical methods for further development of the ROA made it possible to substantiate and implement important measures aimed at achieving optimization of strategies for testing and maintenance of nuclear power plant equipment which have constituted the basis of regulatory documents and standards of the enterprises managed by the Energoatom Ukrainian national nuclear power generating company.

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CONTENT

AUTHORS

Vladimir Skalozubov, **Doctor of Engineering, Professor.**

Domain of scientific interests: increase of safe operation and efficiency of NPP.

E- mail: vi.skalozubov@gmail.com

HuiYu Zhou **Candidate of Technical Sciences, Senior Researcher.**

Domain of scientific interests: increase of safe operation and efficiency of NPP.

E- mail: 170021121@qq.com

Yurii Komarov, **Doctor of Engineering Science.**

Domain of scientific interests: risk-informed approaches in NPP operational activities; justification of the NPP unit's lifetime extension; optimization of periodicity and scope of testing; control and maintenance of NPP safety-related system equipment.

E- mail: odessakomarov@ukr.net