UDC 629.031

V. Skalozubov, DSc, Prof.,
O. Vierinov,
A. Kanivets,
V. Kochnieva,
D. Bundiev,
H. Hayo
Odessa Polytechnic National University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: valer_nov13@ukr.net

RISK-INFORMED METHOD FOR QUALIFYING STRATEGIES FOR OPERATION CONTROL OF METAL OF SAFETY RELATED SYSTEMS OF NUCLEAR POWER PLANTS

В. Скалозубов, А. Вєрінов, А. Канівець, В. Кочнєва, Д. Бундєв, Х. Хайо. **Ризик-орієнтований метод кваліфікації стратегій експлуатаційного контролю металу систем, важливих для безпеки АЕС.** Актуальним питанням забезпечення безпеки та ефективності експлуатації АЕС із реакторами ВВЕР є оптимізація стратегій організації експлуатаційного контролю металу обладнання та трубопроводів систем, важливих для безпеки АЕС. Аналіз нормативно-експлуатаційної документації та відомих наукових розробок показав, що питання оптимізації стратегій експлуатаційного контролю металу систем, важливих для безпеки, вивчені недостатньо. Відомі стратегії організації та планування експлуатаційного контролю металу систем, важливих для безпеки, не враховують багаторічний досвід експлуатації АЕС з ВВЕР (близько 1000 реактор-років), результати щорічного моніторингу технічного стану та надійності обладнання та трубопроводів систем, важливих для безпеки (у тому числі і систем безперервного контролю металу), а також вплив окремих систем на показники безпеки ядерних енергетичних установок та інші актуальні фактори надійної та безпечної експлуатації. Розроблено ризик-орієнтований метод кваліфікації модернізацій та оптимізації стратегій організації експлуатаційного контролю металу систем, важливих для безпеки АЕС, заснований на аналізі результатів контролю стану цілісності металу обладнання та систем, а також імовірності руйнування (відмови) обладнання та/або трубопроводів систем, важливих для безпеки. На основі розробленого ризик-орієнтованого методу кваліфікації оптимізації стратегії організації контролю металу обгрунтовано можливість скорочення періодичності та обсягів контролю металу трубопроводу аварійної поживної води парогенераторів АЕС з ВВЕР-1000. Подальші напрями розвитку практичного застосування представленого в цій роботі ризик-орієнтованого методу розрахункової кваліфікації стратегій експлуатаційного контролю металу систем, важливих для безпеки АЕС, можуть бути пов'язані з проведенням експериментальної кваліфікації методу, а також удосконаленням детерміністських методів моделювання процесів деградації/руйнування металевих конструкцій у перехідних/аварійних режимах експлуатації ядерних енергетичних установок.
Ключові слова: кваліфікація, експлуатаційний контроль металу

V. Skalozubov, O. Vierinov, A. Kanivets, V. Kochnieva, D. Bundiev, H. Hayo. **Risk-informed method for qualifying strategies for operation control of metal of safety related systems of nuclear power plants.** The optimization of strategies for organizing operation control of metal of equipment and pipelines of safety related systems of nuclear power plants is a pressing issue in ensuring the operation safety and efficiency of nuclear power plants with VVERs. An analysis of regulatory and operational documentation, as well as well-known scientific developments, showed that the optimizing strategies for operation control of metal of safety related systems have not been sufficiently studied. Known strategies for organizing and planning operation control of metal of safety related systems do not take into account many years of experience in operating nuclear power plants with VVER (about 1000 reactor-years), the results of annual monitoring of the technical condition and reliability of equipment and pipelines of safety related systems (including continuous metal monitoring systems), as well as the influence of individual systems on the safety indicators of nuclear power plants and other relevant factors of reliable and safe operation. A risk-informed method has been developed for qualifying modernizations and optimizing strategies for organizing operation control of metal of safety related systems of nuclear power plants. The method is based on an analysis of the results of monitoring metal integrity of equipment and systems, as well as the probability of destruction (failure) of equipment and/or pipelines of safety related systems. Based on the developed risk-informed method for qualifying optimization of the strategy for organizing metal monitoring, the possibility to reduce the control frequency and scope for metal of the emergency feedwater pipeline of steam generators of nuclear power plants with VVER-1000 is substantiated. Further directions for the development of the practical application of the risk-informed method presented in this paper for the calculation qualification of strategies for operation control of metal of safety related systems of nuclear power plants can be related to experimental qualification of the method, as well as the improvement of deterministic methods for modelling processes of degradation/destruction of metal structures in transitional/emergency operating modes of nuclear power plants.
Keywords: qualification, operational control of metal

Introduction

The results of the safety analysis of Ukrainian nuclear power plants (NPPs) with VVER-type nuclear reactors found that leaks of pipelines of safety related systems (SRS) are the dominant group of

DOI: 10.15276/opu.2.68.2023.05

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

accidents for ensuring safety. Therefore, regulatory and operational documentation determines the necessary requirements for methods and strategies for organizing operational control of metal (OCM) of SRS.

However, the organization of SRS OCM in full during the process of scheduled preventive repair (SPR) of power units can significantly increase the SPR duration, and accordingly reduce the operating efficiency of the NPP. Therefore, a pressing issue in the NPP operation is the scientifically grounded (qualified) optimization of strategies for SRS OCM, which consists of the maximum permissible reduction in OCM scopes while ensuring the necessary conditions for safe operation. To solve these problems, it is necessary to develop methods for qualifying modernization of strategies for SRS OCM that determines the relevance and purpose of the presented work.

Literature review and problem statement

The work [1] defines the general requirements for the SRS maintenance and inspection. The optimization of OCM strategies was not considered in this work.

The work [2] considers the issues of optimizing NPP SPRs. However, the issues of optimizing the OCM during the SPR process were also not considered.

The work [3] defines the general requirements for the organization of technical maintenance, repair and inspection of SRS at NPPs with VVER. However, issues of optimizing strategies for SRS OCM were also not considered.

The standard program for periodic monitoring of the condition of the base metal, welded joints and surfacing of equipment and pipelines of NPPs with VVER [4] defines methods and ways for realizing SRS OCM during SPR. Issues of optimizing the organization of SRS OCM were also not considered in this work.

The work [5] considers the issues of predicting the conditions of fatigue failure of metals and alloys. The optimization of metal control strategies has not been sufficiently studied in this work.

The work [6] analyses known probabilistic methods for substantiating the possibility of modernizing strategies for maintenance, scheduled repairs, monitoring and testing of SRS.

As a result of the analysis, it was recognized that methods based on assessments of the impact of modernization on the probability of nuclear accidents are not acceptable for optimizing strategies for SRS OCM.

Thus, an urgent issue is the development of a method for qualifying strategies for SRS OCM at NPPs.

The purpose of the study is to develop a method for qualifying strategies for SRS OCM at NPPs based on a risk-informed approach.

The purpose of the work determines the solution of the following **tasks**:

1. Basic provisions of the qualification method;
2. Analysis of qualification results.

Basic provisions of the qualification method

The distribution of defects in the metal of pipelines and welded joints is random. However, thanks to periodic inspections and existing patterns of crack growth, it is possible to predict the distribution of the number of defects by size depending on time. The number of defects in the pipeline metal per unit of weld length or weight is estimated according to statistics.

The distribution of the number of defects by their size a is described by the Weibull dependence, with the distribution density:

$$l(a) = \frac{m}{\theta} a^{m-1} \exp\left(-\frac{a^m}{\theta}\right),$$

where θ is the distribution scale parameter, m is a shape parameter characterizing the spread in values of a.

The dependence graph is shown in Fig. 1.

Depending on the control method and ways, a different probability of detecting defects can be provided. For any method, there is a limitation on the size of the detected defect – the size of the defect that cannot be detected by this method. The probability of detecting a defect depending on its size is described by the relationship:

$$w(a) = 1 - \exp\lambda(a - a_0),$$

where a_0 is the limiting smallest size of the detected defect, depending on the sensitivity of the control method, λ is constant. Additional probability $1 - w(a)$ is the probability that a defect of a given size will not be detected during inspection.

The control effectiveness can be assessed by the probability of detecting defects of a certain size, for example, according to the probability of detecting defects with the size equal to the wall thickness of a given pipeline. Fig. 2 shows the dependences $w(a)$ and $1 - w(a)$ at different control efficiency E, which was set according to the probability of detecting a defect with the size equal to the thickness of the pipeline wall.

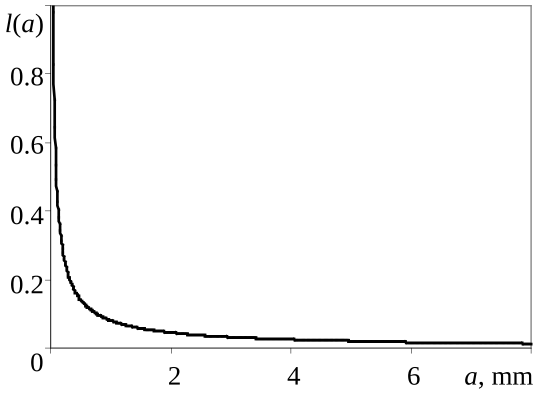

Fig. 1. Distribution of the number of defects by their size

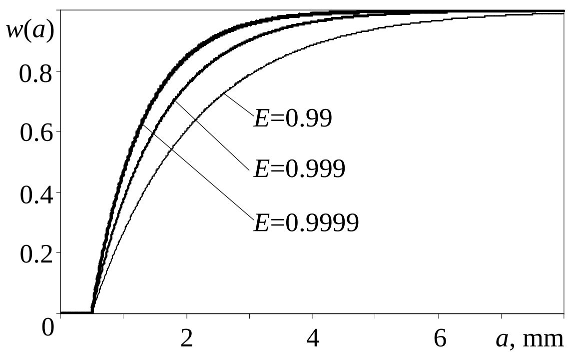

Fig. 2. Probability of detecting a defect depending on its size

Experience in control of metal [7–10] allows us to obtain the actual distribution of the number of detected defects, described by the empirical relationship:

$$N(a) = \frac{A}{a^n}\{1 - \exp[-\alpha(a - a_0)]\} \quad \text{at} \quad a \geq a_0. \tag{1}$$

The coefficients in the equation are determined with the control method and the characteristics of the controlled metal.

Normalizing the existing distribution (1), it is possible to obtain the distribution of detected defects by their sizes:

$$P(a) = \frac{N(a)}{\int_{a_0}^{a} N(a)da}.$$

Based on the distribution of detected defects and the probability of their detecting with the applied control method, the initial distribution of defects before inspection can be obtained. However, it is impossible to obtain such a distribution by simply dividing the listed distributions, since the probability of detecting a defect is limited to the range $a > a_0$.

We propose, given the form of the equation describing the initial distribution of defects, to select the coefficients included in it so that the distribution of detected defects is calculated using the equation:

$$d(a) = l(a)w(a). \tag{2}$$

Normalizing the existing distribution (2), it is possible to obtain the distribution of detected defects by their sizes:

$$D(a) = \frac{d(a)}{\int_{a_0}^{a} d(a)\mathrm{d}a},$$

which should be as close as possible to the distribution $P(a)$ obtained with statistical data on control experience. A comparison of these distributions is shown in Fig. 3.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

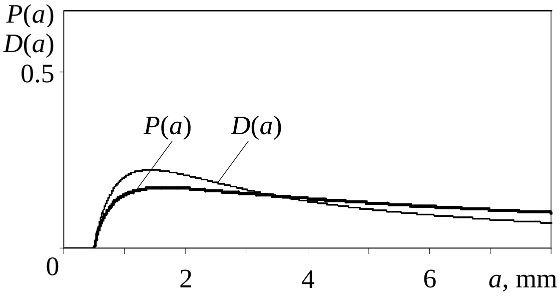

Fig. 3. Comparison of distributions of detected defects by their sizes based on calculated data $D(a)$ and control experience $P(a)$

As a result, not only the initial distribution of defects can be obtained, but also the predicted distribution of defects after inspection:

$$B(a) = L(a)(1 - w(a)),$$

where $L(a) = \dfrac{l(a)}{\int_0^{a_k} l(a)\mathrm{d}a}$.

For comparison, Fig. 4 shows the initial distribution of defects *L(a)* and the distribution of defects after inspection $B(a)$ with different efficiency.

During the time before the next inspection, the pipeline metal will experience N loading cycles. Accepting the linear growth of a crack as a base model, depending on its initial size, it is possible to determine the final size of the crack for a given point in time.

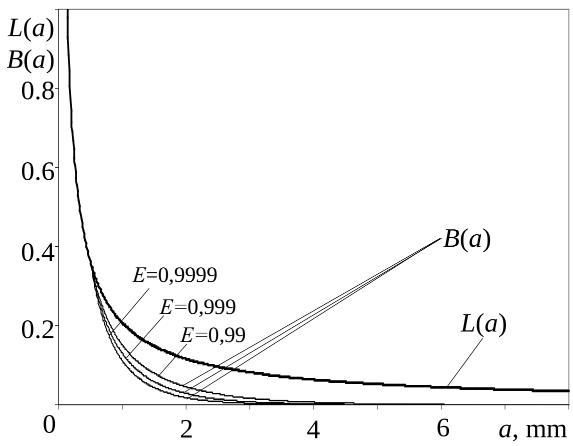

Fig. 4. Initial distribution of defects $L(a)$ and distributions of defects after inspection $B(a)$ with different efficiency

The kinetic equation for crack growth (Paris–Erdogan equation) has the form:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^n, \tag{3}$$

where C і n are constants, ΔK is the change in stress intensity factor during one loading cycle. According to [5], ΔK is defined as $\Delta K = \Delta\sigma\sqrt{\pi a}$, where $\Delta\sigma$ is the voltage range per cycle.

In accordance with equation (3), the number of cycles at which a crack reaches size a_k can be found from the dependence:

$$N = \int_{a_0}^{a_k} \frac{\mathrm{d}a}{C(\Delta\sigma\sqrt{\pi a})^n}, \tag{4}$$

where a_0 is initial crack size; $a_к$ is final crack size.

Integrating expression (4) and making the replacement $A = \dfrac{1}{C\Delta\sigma^n \pi^{n/2}}$, we obtain:

$$N = A\int_{a_0}^{a_k} \frac{\mathrm{d}a}{a^{\frac{n}{2}}} = A\left[-2\frac{a_k^{1-\frac{n}{2}}}{n-2} + 2\frac{a_0^{1-\frac{n}{2}}}{n-2}\right] = \frac{2A}{n-2}\left[a_0^{\frac{2-n}{2}} - a_k^{\frac{2-n}{2}}\right],$$

whence for $\alpha = \dfrac{2-n}{2}$ $(n \neq 2)$ we get:

$$N = -\frac{A}{\alpha}(a_0^{\alpha} - a_k^{\alpha}). \tag{5}$$

Having solved equation (5) for a_k, we obtain:

$$-\frac{N\alpha}{A} = a_0^{\alpha} - a_k^{\alpha}, \quad a_k^{\alpha} = a_0^{\alpha} + \frac{N\alpha}{A}, \quad a_k = \left(a_0^{\alpha} + \frac{N\alpha}{A}\right)^{\frac{1}{\alpha}},$$

$$a_k = \left(a_0^{\alpha} + \frac{N\alpha}{\dfrac{1}{C\sigma^n\pi^{n/2}}}\right)^{1/\alpha} \Rightarrow (a_0^{\alpha} + N\alpha C\sigma^n\pi^{n/2})^{1/\alpha},$$

$$a_k = (a_0^{\alpha} + \alpha C(\sigma\sqrt{\pi})^n N)^{1/\alpha}.$$

Depending on the number of loading cycles before the next inspection, the crack size at the time of inspection will be obtained for its any initial size. For example, for a = 3 and N = 2.5·10^5, we get a_N = 4.6.

Thus, the current sizes of the defects can be determined with the initial size of the defect and taking into account the growth of the defect after a certain number of loading cycles. The corresponding dependences for different numbers of loading cycles during the interval between controls are presented in Fig. 5.

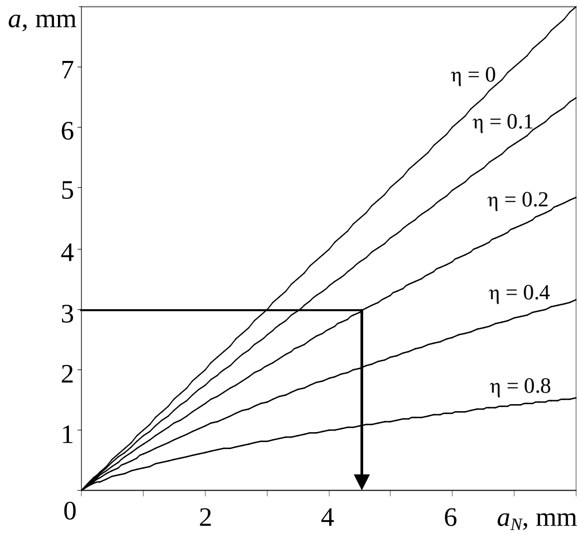

Fig. 5. Current sizes of defects depending on the initial size and number of loading cycles at $\eta = N/[N_0]$

Analysis of qualification results

An example of using a risk-informed method for optimizing metal control of an emergency steam generator feedwater pipeline is given below.

Initial data

The name of the pipeline is the emergency feedwater pipeline to the VVER-1000 steam generator.

Operating parameters are P = 8 MPa, T = 300 °C.

The working medium is 2nd circuit water.

Material is Steel 20.

Pipeline diameter is 108 mm.

Wall thickness is 8 mm.

Pipeline group according to DNAOP 0.04-1.05-90 (PNAE G-7-008-89) “Rules of arrangement and safe operation of equipment and pipelines for nuclear facilities” is B.

Category of welded joints according to PNAE G-7-010-89 “Equipment and pipelines of nuclear power units. Welding and alloying joints. Rules of control” is IIIa.

The permissible number of loading cycles [N_0] is calculated in accordance with PNAE G-7-002-86 “Rules of strength calculation for equipment and pipelines of nuclear power plants”. For this pipeline, [N_0] = 1.321·10^4 cycles were obtained.

The distribution of the number of defects by their size is shown in Fig. 6.

The probability of detecting a defect depending on its size is shown in Fig. 7 (at E = 0.999 and a_0 = 0.5).

The distribution of the number of detected defects (at A = 234 mm^n; n = 1.37; a_0 = 0.5; α = 0.08 mm^{-1}) is shown in Fig. 8.

Normalizing the found distribution, we obtain the distribution of detected defects by their sizes:

$$P(a) = \frac{N(a)}{\int_{a_0}^{a} N(a)\mathrm{d}a}.$$

For a_0 = 0.5, we obtain the distribution shown in Fig. 9.

Predicted distribution of defects after inspection:

$$B(a) = L(a)(1 - w(a)), \text{ where } L(a) = \frac{l(a)}{\int_{0}^{a_k} l(a)\mathrm{d}a}.$$

Accepting a_k = 2 mm and control efficiency E = 0.999, we obtain the distribution shown in Fig. 10.

A current defect size chart depending on the initial size and number of loading cycles is shown in Fig. 11.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

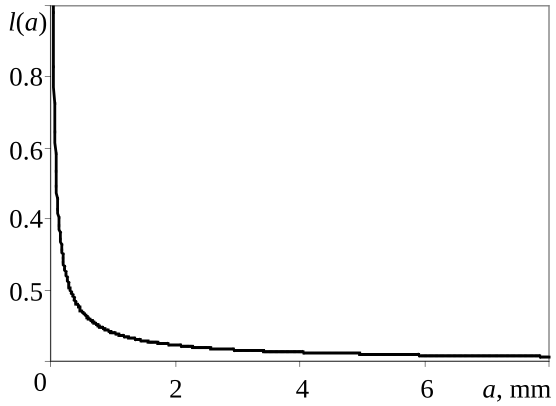

Fig. 6. Distribution of the number of defects by their size

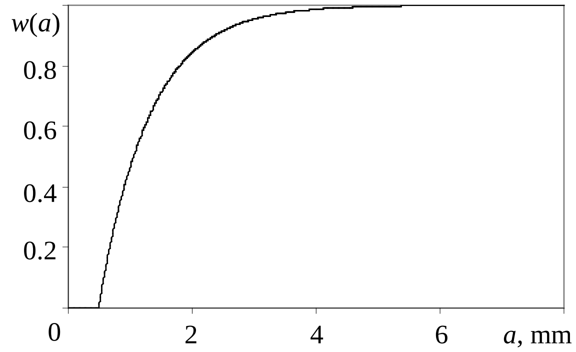

Fig. 7. Probability of detecting a defect depending on its size

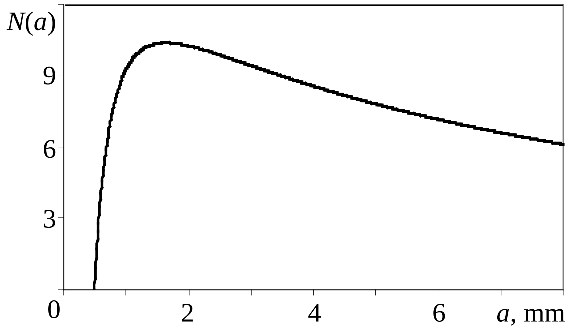

Fig. 8. Distribution of the number of detected defects for the emergency feedwater pipeline to the VVER-1000 steam generator

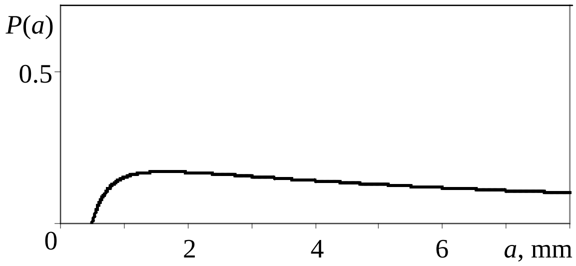

Fig. 9. Distribution of the number of detected defects after normalization

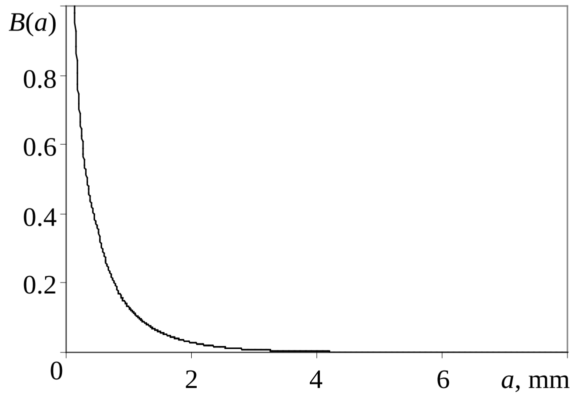

Fig. 10. Predicted distribution of defects after inspection

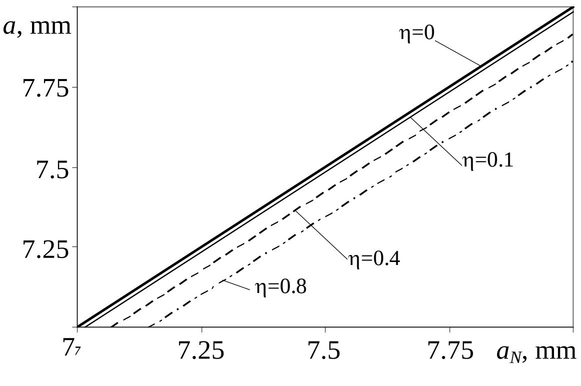

Fig. 11. Current sizes of defects depending on the initial size and number of loading cycles at $\eta = N/[N_0]$

The proportion of defects with sizes ranging from marginal to critical at the time after the last inspection is calculated using the equation:

$$P(N) = \frac{\int_{a_N^{\text{пр}}}^{a_N^{\text{кр}}} B(a_N)\mathrm{d}a_N}{\int_0^{a_N} B(a_N)\mathrm{d}a_N}.$$

Accepting $a_N^{\text{кр}} = 8$ mm, we obtain the distribution *P(N)* shown in Fig. 12.

The pipeline in question is modelled during a probabilistic safety analysis, so the consequences of its failure are assessed as having high impact significance. Based on the calculated data at different control frequencies and, accordingly, different values of the parameter η, a risk matrix is formed, shown in Fig. 13. The matrix cell, which corresponds to the risk category assessment found for options calculated at all values η is highlighted in Fig. 13.

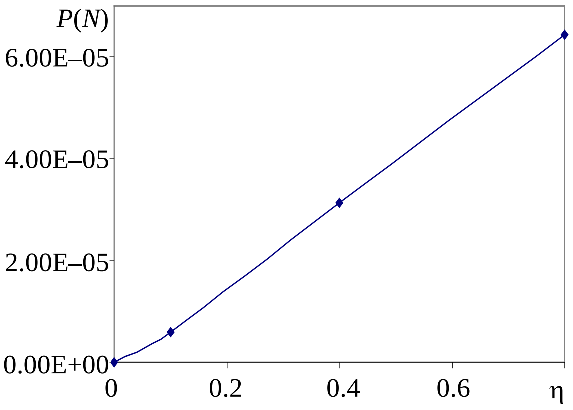

Fig. 12. Probability of pipeline failure during the period between inspections at different $\eta = N/[N_0]$

With a more realistic (less conservative) approach to assessing consequences using Fussel-Vesely PSA significance indicators regarding risk increase/decrease (see, for example, [6]), this control of this pipeline generally falls into the low risk area. In this case, a strategy of reducing frequency and scope in relation to design (regulatory) metal control programs is acceptable.

			Significance of consequences		
			low	medium	high
Probability of failure	high	$\geq 1 \cdot 10^{-3}$			
	medium	$1 \cdot 10^{-5} - 1 \cdot 10^{-4}$			
	low	$< 1 \cdot 10^{-5}$			

Fig. 13. A risk matrix

Conclusion

1. The optimization of strategies for organizing operation control of metal of equipment and pipelines of safety related systems of nuclear power plants is a pressing issue in ensuring the operation safety and efficiency of nuclear power plants with VVERs. An analysis of regulatory and operational documentation, as well as well-known scientific developments, showed that the optimizing strategies for operation control of metal of safety related systems have not been sufficiently studied.

2. A risk-informed method has been developed for qualifying modernizations and optimizing strategies for organizing operation control of metal of safety related systems of nuclear power plants. The method is based on an analysis of the results of monitoring metal integrity of equipment and systems, as well as the probability of destruction (failure) of equipment and/or pipelines of safety related systems.

3. Based on the developed risk-informed method for qualifying optimization of the strategy for organizing metal monitoring, the possibility to reduce the control frequency and scope for metal of the emergency feedwater pipeline of steam generators of nuclear power plants with VVER-1000 is substantiated.

Література

1. Підвищення безпеки ядерної енергетики з урахуванням уроків важких аварій / Кондратюк В. А., Письменний Є. М., Вєрінов О. М., Філатов В. І., Остапенко А. І. *Ядерна та радіаційна безпека*. 2022. № 3. С. 76–81. DOI: https://doi.org/10.32918/nrs.2022.3(95).08.
2. Алали М. Управление ресурсом и продление эксплуатации теплоэнергетического оборудования. LAP LAMBERT Academic Publishing, 2020. 146 с. ISBN 978-620-2-55726-9.
3. Нестерук Д. Анализ прочности при сейсмических воздействиях насосов систем, важных для безопасности ЯЭУ с ВВЭР. LAP LAMBERT Academic Publishing, 2021. 65 с. ISBN 978-620-4-71803-3.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

4. Skalozubov V.I., HuiYu Zhou, Komarov Yu.A. Optimization of strategies for testing and maintenance of nuclear power plant equipments. LAP LAMBERT Academic Publishing, 2018. 63 p. ISBN 978-613-9-82729-9.
5. Alhemiri S.A., Kosenko S., Orlov G. Criteria and conditions for steam-gas explosions in thermal power equipment. *III International Scientific and Practical Conference «Development of modern science, experience and trends»*. Boston, USA. 2022. pp. 416–420. DOI: 10.46299/ISG.2022.2.3.
6. Kondratyk V., Komarov Ju., Kosenko S., Fedorov D. Prevention of hydrodynamic instability conditions in safety systems with pumps of nuclear power plants. *Proceeding of Odessa Polytechnic University*. 2022. Vol. 1(65). P. 70–75. DOI: 10.15276/opu.1.65.2022.08.
7. Lobzin N. Extending the service life of nuclear reactor vessels. LAP LAMBERT Academic Publishing, 2021. 113 p. ISBN 978-620-3-86061-0.
8. Zhou HuiYu, Komarov Yu.A. Optimization of strategies for testing and maintenance of nuclear power plant equipments. LAP LAMBERT Academic Publishing, 2018. 63 p. ISBN 978-613-9-82729-9.
9. Algerby R. Extension of operation and resource management of electrical equipment of power plants. LAP LAMBERT Academic Publishing, 2020. 159 p. ISBN 978-620-2-66746-3.
10. Maliar I. Extending the service life of the VVER-1000 armature. LAP LAMBERT Academic Publishing, 2021. 131 p. ISBN 978-620-4-20590-8.

References

1. Kondratyuk, V., Pysmennyy, Y., Verinov, O., Filatov, V., & Ostapenko, I. (2022). Improvement of nuclear safety taking into account the lessons learned from severe accidents. *Nuclear and Radiation Safety*, *3*, 76–81. DOI: https://doi.org/10.32918/nrs.2022.3(95).08.
2. Alali, M. (2020). *Resource management and operation extension of thermal power equipment*. LAP LAMBERT Academic Publishing. ISBN 978-620-2-55726-9.
3. Nesteruk, D. (2021). *Analysis of the strength under seismic impacts of pumps of safety related systems of nuclear power plants with VVER*. LAP LAMBERT Academic Publishing. ISBN 978-620-4-71803-3.
4. Skalozubov, V.I., HuiYu, Zhou, & Komarov, Yu.A. (2018). *Optimization of strategies for testing and maintenance of nuclear power plant equipments*. LAP LAMBERT Academic Publishing. ISBN 978-613-9-82729-9.
5. Alhemiri, S.A., Kosenko, S., & Orlov, G. (2022). Criteria and conditions for steam-gas explosions in thermal power equipment. *III International Scientific and Practical Conference «Development of modern science, experience and trends»*, Boston, USA, 416–420. DOI 10.46299/ISG.2022.2.3.
6. Kondratyk, V., Komarov, Ju., Kosenko, S., & Fedorov, D. (2022). Prevention of hydrodynamic instability conditions in safety systems with pumps of nuclear power plants. *Proceeding of Odessa Polytechnic University*, 1(65), 70–75. DOI: 10.15276/opu.1.65.2022.08.
7. Lobzin, N. (2021). *Extending the service life of nuclear reactor vessels*. LAP LAMBERT Academic Publishing. ISBN 978-620-3-86061-0.
8. Zhou, HuiYu, Komarov, Yu.A. (2018). *Optimization of strategies for testing and maintenance of nuclear power plant equipments*. LAP LAMBERT Academic Publishing. ISBN 978-613-9-82729-9.
9. Algerby, R. (2020). *Extension of operation and resource management of electrical equipment of power plants*. LAP LAMBERT Academic Publishing. ISBN 978-620-2-66746-3.
10. Maliar, I. (2021). *Extending the service life of the VVER-1000 armature*. LAP LAMBERT Academic Publishing. ISBN 978-620-4-20590-8.

Скалозубов Володимир Іванович; Volodymyr Skalozubov,ORCID: 0000-0003-2361-223X
Вєрінов Олексій Миколайович; Oleksii Vierinov, ORCID: 0000-0002-0718-1532
Канівець Андрій Валерійович; Andrey Kanivets, ORCID: 0009-0005-6135-7470
Кочнєва Валерія Юріївна; Valeriia Kochnieva, ORCID: 0000-0001-7397-3573
Бундєв Денис Степанович; Denys Bundiev, ORCID: 0000-0002-0010-4702
Хайо Хані; Hayo Hani, ORCID: 0000-0002-5471-5496

Received September 12, 2023

Accepted October 30, 2023