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PREDICTION OF OPERATION LIFE EXTENSION OF HEAT POWER EQUIPMENT

В.І. Скалозубов, Д.С. Пірковський, М. Алалі, Р. Альгербі. **Прогнозування строків продовження експлуатації теплоенергетичного обладнання.** На основі аналізу відомих досліджень установлено, що визначальними факторами прогнозування строків продовження експлуатації теплоенергетичного обладнання (теплообмінники, насоси, арматура) є кількість і швидкість накопичення циклічних термічних та динамічних навантажень у перехідних режимах нормальних умов експлуатації, при порушенні нормальних умов експлуатації та в аварійних режимах (за винятком корпуса ядерного реактора). Представлено метод визначення прогнозних оцінок строків продовження експлуатації теплоенергетичного обладнання залежно від амплітуд напруги в перехідних та аварійних режимах, кількості і швидкості накопичення циклічних навантажень, міцнісних параметрів метала корпусів теплоенергетичного обладнання (за винятком корпуса реактора). Метод реалізовано на прикладі парогенераторів реакторних установок із ВВЕР з використанням експлуатаційних даних 1-го блока Південно-Української АЕС (на 2010 р.). У результаті встановлена припустима швидкість накопичення циклічних навантажень при продовженні строків експлуатації на 30, 40 и 50 років. Отримані результати визначають недостатню обґрунтованість роботи атомних станцій у «маневрених» режимах із змінною потужністю реактора. У цьому випадку кількість циклічних навантажень на обладнання різко зростає, та обмежуються строки безпеки експлуатації. Розроблений метод і отримані результати розрахункового прогнозування строків продовження експлуатації теплоенергетичного обладнання можуть бути використані для галузевих програм по продовженню експлуатації українських атомних електростанцій, а також для вдосконалення нормативних документів, які регламентують умови та вимоги до допустимого безпечного продовження експлуатації теплоенергетичного обладнання підприємств атомної і теплової енергетики. Подальше вдосконалення запропонованого в роботі метода прогнозування строків продовження експлуатації теплоенергетичного обладнання може бути засновано на розвитку методів аналізу надійності теплоенергетичного обладнання та баз даних по порушенням у процесі експлуатації. Матеріали представленої роботи використовуються в навчальному процесі для підготовки, перепідготовки і підвищення кваліфікації спеціалістів енергетичної галузі.
Ключові слова: прогнозування, продовження експлуатації, теплоенергетичне обладнання

V. Skalozubov, D. Pirkovsky, M. Alali, R. Algerby. **Prediction of operation life extension of heat power equipment.** Based on the analysis of known researches, it is revealed that the quantity and accumulation rate of cyclic thermal and dynamic loads in the transient modes of normal operation conditions, when violating normal operation conditions and in accident conditions (except for the nuclear reactor vessel) are the key factors of prediction of operation life extension for a heat power equipment (heat exchangers, pumps, armature). The method for predictive estimation of terms of operation life extension of a heat power equipment depending on stress amplitudes in transient and accident conditions, quantity and accumulation rate of cyclic loads, strength metal parameters of a heat power equipment vessels (except for a reactor vessel) is provided. The method is implemented on the example of steam generators of WWERs and using operational data of South-Ukraine-1 (by 2010). Admissible accumulation rate of cyclic loads during operation life extension by 30, 40 and 50 years is a result. The results define insufficient substantiation of nuclear power plant operation in the “maneuverable” modes with a variable reactor power. In this case, the quantity of cyclic equipment loads increases dramatically, and terms of safe operation are limited. The developed method and the obtained results of prediction of operation life extension of heat power equipment can be used for industry programs to extend the operation of Ukrainian nuclear power plants, as well as to improve the regulatory documents governing the conditions and requirements for acceptable safe extension of the operation life of heat power equipment of nuclear and thermal power enterprises. Further improvement of the method proposed in the work for predicting operation life extension of heat power equipment can be based on the development of methods for analyzing the reliability of heat power equipment and databases on operation disturbances.The materials of the presented work are used in the educational process for the training, retraining and advanced training of specialists in the energy industry.
Keywords: prediction, operation life extension, heat power equipment

Introduction

Many years of nuclear power experience have defined technical and economic suitability of extension of operation life of nuclear power units after design operation life. The developed nuclear powers have carried out work on technical and economic suitability and substantiation of possibility to extend operation life of nuclear power units since the late 1970s. A lot of researches and many years of

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experience have defined technical feasibility in principle and economic suitability to extend the specified lifetime by 40…50 years or more. So, for an example, the analysis showed that the economic loss because of decommissioning of the USA NPPs in 1990s was about 119 billion US dollars, and costs of technical and economic maintenance of life operation extension would be no more than 60 million US dollars. For 2000…2014 USA renewed operation licenses for 49 nuclear power units (installed capacity of 34 GW). It has made a profit of 350 billion dollars, reduced emissions of carbon dioxide by 150 million tons and sulphur oxides by 2.5 million tons. And 20 power units were built by 2020.

For the period till 2034, the costs of extension of operation life of the operating NPPs of Ukraine are estimated from 9.326 to 11.650 billion UAH. For all scenarios of development of a nuclear power complex, suitability of operation extension of operating power units of Ukraine is confirmed for following criteria: safety level, additional electricity production, payback on operation life extension, Social Security Fund income, etc.

However operation life extension after the design life of heat power equipment (heat exchangers, pumps, and armature) requires sufficient scientific and technical substantiation. From nuclear power experience, the programs for extension of operation life of heat power equipment (HPE) have to contain the following main stages:

– analysis of normative, design and operational documentation;
– analysis of operating experience, tests, control, repair and maintenance;
– analysis of the actual reliability for the all operation life;
– analysis of the causes of ageing/degradation of the equipment;
– assessment of the current technical condition;
– generalization of results and substantiation of extension time of operation life.

Usually subjective technical decisions set the term to extend HPE operation without sufficient substantiations.

Such approach defines relevance of the offered work.

Analysis of recent publications and problem statement

The HPE vessel is the critical element for operation life extension. The predicted time of operation life extension depends on the current key parameters of technical condition of the HPE vessel and their rate during operation. Integrity and thickness of metal are the key parameters of technical condition of the HPE vessel.

The review analysis of mechanisms of degradation/destruction of the HPE vessels in work [1] showed that cyclic thermal and dynamic loads (CL) caused by transients under normal operation conditions (NOC), the violation of normal operation conditions (VNOC) or the design accidents (DA) are dominant factors.

The statistical analysis of representative data on results of operational control of technical condition in work [2] also confirmed dominance of metal fatigue failure of the HPE vessel because of CL (except for the nuclear reactor vessel).

The work [3] has shown that destruction of the HPE vessels because of CL happens much earlier than inadmissible “thinning” of the HPE vessels because of corrosion-erosion wear (the “leak before break” concept). Application of different methods for non-destructive test of metal of the armature vessel also confirms this concept [4].

The work [5] has analysed operational data on defects of heat-exchanging pipes of steam generators (SG) of nuclear power plants. The result is that CL is basic cause of leaks in SG pipes. Use of different technologies of metal control for other power facilities has confirmed these results [6, 7].

It should be noted that codes of strength analysis of the equipment and pipelines [8] are also oriented to admissible quantity of CL, and the ratio of quantity of the actual CL to admissible one defines strength conditions. Admissible CL for each specific HPE are determined in Technical Regulations for Safe Operation.

Thus, the analysis of known researches of the causes and mechanisms of degradation showed that the quantity of CL in NOC, VNOC and emergency operation, and their accumulation rate is a dominant factor to predict time of HPE life extension. These conclusions define the purposes and problems of the represented work.

Purpose and objectives of the study to develop a method to predict time of HPE life extension using quantity of CL in NOC, VNOC and accident modes.

The purpose of work defines the solution of the following tasks:

– development of basic provisions of a method;

– application of a method for a specific example of NPP SG;

– analysis of results of calculation modelling.

Method for predicting operation life extension of heat power equipment

According to [8], nominal allowable stress for the HPE vessel loaded with internal pressure has accepted as minimum of the following values:

$$[\sigma] = \min\left\{\frac{R_m^T}{n_m};\ \frac{R_{p0.2}^T}{n_{0.2}};\frac{R_{mt}^T}{n_{mt}}\right\}, \tag{1}$$

where $n_m = 2.6$, $n_{0.2} = 1.5$, $n_{mt} = 1.5$.

Admissible design values of loading cycles $[N_0]$ for each group j of the operational modes are determined by the maximum design value of the mode from group j or by total admissible quantity of loading cycles for group j. Everyone group j of the operational modes is characterized by the maximum admissible value of design quantity of loading cycles $\max[N_0]_j$. Thus, the condition is obvious:

$$\sum_{i=1}^{n_j} N_i(\alpha \cdot \sigma_i) \le \max[N_0]_j, \tag{2}$$

where, according to [8]: $\alpha_1 = 1$ (NOC), $\alpha_2 = 1.2$ (VNOC), $\alpha_3 = 1.4$ (DA).

According to [8], the maximum permissible number of loading cycles for the mode group j is determined by formulas:

$$\left.\begin{aligned}
[\sigma_{aF}] &= \frac{E^T e_c^T}{n_\sigma (4[N_0])^m} + \frac{R_c^T}{n_\sigma \left[(4[N_0])^{m_e} + \dfrac{1+r}{1-r}\right]} \\
[\sigma_{aF}] &= \frac{E^T e_c^T}{(4 n_N [N_0])^m} + \frac{R_c^T}{(4 n_N [N_0])^{m_e} + \dfrac{1+r}{1-r}}
\end{aligned}\right\}, \tag{3}$$

$$\left.\begin{aligned}
[\sigma_{aF}] &= \frac{E^T e_c^T}{n_\sigma (4[N_0])^m} + \frac{R_{-1}^T}{n_\sigma \left(1 + \dfrac{R_{-1}^T}{R_m^T}\dfrac{1+r}{1-r}\right)} \\
[\sigma_{aF}] &= \frac{E^T e_c^T}{(4 n_N [N_0])^m} + \frac{R_{-1}^T}{1 + \dfrac{R_{-1}^T}{R_m^T}\dfrac{1+r}{1-r}}
\end{aligned}\right\}, \tag{4}$$

where, according to [8]: n_σ, n_N is stress safety factor and load safety factor, respectively, m, m_e are material characteristics, r is stress ratio, R_c^T is strength characteristic:

$$R_c^T = R_m^T (1 + 1.4 \cdot 10^{-2} Z^T). \tag{5}$$

Characteristics E, Z^T, R_m^T are accepted as equal to the minimum values in the operation temperature range taking into account ageing. Stress safety factor $n_\sigma = 2$ and load safety factor $n_N = 10$.

Exponents m, m_e and endurance limit R_{-1}^T are accepted according to [8].

For:

$$(\sigma_F)_{\max} < R_{p0.2}^{(T_{\min})} \text{ и } 2(\sigma_{aF}) < [R_{p0.2}^{(T_{\min})} + R_{p0.2}^{(T_{\max})}], \tag{6}$$

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stress ratio is calculated by a formula:

$$r = \frac{(\sigma_F)_{\max} - 2(\sigma_{aF})}{(\sigma_F)_{\max}}. \tag{7}$$

If stress ratio $r < -1$ or $r > 1$, calculation accepts $r = -1$.

For $(\sigma_F)_{\max} > R_{p0.2}^{(T_{\min})}$ and $2(\sigma_{aF}) < [R_{p0.2}^{(T_{\min})} + R_{p0.2}^{(T_{\max})}]$ stress ratio is determined by a formula:

$$r = \frac{R_{p0.2}^{T_{\min}} - 2(\sigma_{aF})}{R_{p0.2}^{T_{\min}}}. \tag{8}$$

Amplitude of the reduced local engineering elastic stress in a cycle i is found by a formula:

$$(\sigma_{aF})_i = K_{F,i}(\sigma_a)_i(\varphi_s)^{-1}, \tag{9}$$

where φ_s is a cyclic strength reduction coefficient (according to Table 5.8 [8]), $K_{F,i}$ is stress concentration coefficient in a cycle i:

$$K_F = R_{p0.2}^{T}\left(1 + 0.5\left\{\left[\frac{K_\sigma(\sigma_a)}{R_{p0.2}^{T}}\right]^2 - 1\right\}\right) / (\sigma_a), \tag{10}$$

where $R_{p0.2}^{T}$ is a material yield strength at a specified temperature, K_σ is the theoretical stress concentration coefficient determined from Appendix 3 [8].

The allowed amplitude of engineering elastic stress for temperatures specified in 5.6.4 [1] is determined by multiplying the calculated values by the ratio of the elastic modulus at the set temperature to the elastic modulus at a maximum temperature:

$$[\sigma_{aF}] = (\sigma_a)\frac{E^T}{E^{T_{\max}}}. \tag{11}$$

Stress amplitude $(\sigma_a)_i$ of half-cycle in the mode i can be determined from the equation:

$$(\sigma_a)_i = \int_0^{t_k} \frac{\mathrm{d}(\sigma_a)_i}{\mathrm{d}t} dt = \int_0^{t_k} f_1([\sigma], P)\frac{\mathrm{d}P}{\mathrm{d}t} dt + \int_0^{t_k} f_2(E^T, \alpha^T)\frac{\mathrm{d}T}{\mathrm{d}t}\mathrm{d}t, \tag{12}$$

where

$$f_1 = \frac{[\sigma]}{2P}; \quad f_2 = 0.35E^T\alpha^T. \tag{13}$$

According to [8], an assessment of strength conditions for the equipment can integrate and reduce different types of cycles to one calculation cycle. Thus the number of calculation cycles is equal to the sum of numbers of the integrated cycles, and the allowed number of cycles $[N_0]$ corresponds to the maximum amplitude $[\sigma_{aF}]$ of the integrated cycles. From conservatism, the maximum stress amplitude $[\sigma]$ can be used as the last parameter. Then, the condition for admissible loading cycles on the separate equipment/elements of the equipment is:

$$\sum_{j=1}^{3} \frac{\mu_j N_j}{[N_0](\alpha_j[\sigma_{aF}])} \le [a_N], \tag{14}$$

where α_j is coefficient depending on the mode type: $\alpha_1 = 1$ (NOC), $\alpha_2 = 1.2$ (VNOC), $\alpha_3 = 1.4$ (DA).

Follows from the equation (4) fatigue curve cyclic loads:

$$\mu_j = \begin{cases} \sqrt[m]{\dfrac{\langle\sigma_a\rangle_{\max j} - R}{[\sigma_{aF}] - R}}, & \langle\sigma_a\rangle_{\max j} > R; \\ 0, & \langle\sigma_a\rangle_{\max j} \le R; \end{cases}, \tag{15}$$

where $\langle \sigma_a \rangle_{\max j}$ is the maximum stress amplitude for group *j* of the low-frequency modes, *m* is exponent accepted according to [8]:

$$R = \frac{R_{-1}^T}{n_\sigma \left(1 + \frac{R_{-1}^T}{R_m^T} \cdot \frac{1+r}{1-r}\right)}. \tag{16}$$

For an assessment of admissible operation life or a current reserve of admissible quantity of cycles it is introduced the maximum accumulation rate of the operational modes of group *j*:

$$W_j = \frac{\Delta N_j}{\Delta t}, \tag{17}$$

It reflects the maximum increment of the operational modes ΔN_j for time Δt from operating experience.

For a maximum accumulation rate of the operational modes $W_j = \Delta N_j/\Delta t$, predictive value of admissible operation life or extension of the specified operation life is determined by a formula (14) with ($N_j = N_j + W_j\, t_{\text{al}}$):

$$t_{\text{al}} = \frac{[a_N] - \sum_{j=1}^{3} \frac{\mu_j N_j}{[N_0]_j (\alpha_j [\sigma_{aF}])}}{\sum_{j=1}^{3} \frac{\mu_j W_j}{[N_0]\ (\alpha_j [\sigma_{aF}])}}, \quad N_j = \sum_{i=1}^{n} N_i\,. \tag{18}$$

Analysis and discussion of results of calculated modelling

The method is implemented on the example of SGs of nuclear power plants with WWER. SG is intended for heat removal from the primary coolant and generation of dry saturated steam. The SG type is horizontal single-vessel, with a submerged heat exchange surface of horizontally located pipes. SG consists of the following main elements: vessel, distribution device of the main feedwater, distribution device of emergency feedwater, heat-transfer surface and primary collectors, separation device, balancing device of steam loading, supporting structures, levelling vessels, and hydraulic shocks.

Basic data for calculation.

The calculated zone is an insert assembly of the primary coolant collector. This zone is the most loaded because of welded seams that are stress concentrators. Vessel material is steel 10GN2MFA (10ГН2МФА).

Calculated operation modes:

– a circulating pump starts earlier than idle loop (NOC);

– no supply of feedwater to SG (VNOC);

– unfitting of the SG safety valve (DA).

The actual quantity of loading cycles for all operation life of South-Ukraine-1: N_{NOC} = 6867, N_{VNOC} = 146, N_{DA} = 1.

Strength characteristics of SG vessel material:

– ultimate strength R_m^T = 491 MPa;

– yield strength $R_{p0.2}^T$ = 304 MPa;

– restriction Z^T = 51 %;

– elastic modulus E^T= 197 GPA;

– calculated temperature t_{int} = 278 °C;

– ambient temperature t_{out} = 20 °C (we accept conservatively, without heat conductivity of vessel material, for the maximum temperature differences in wall thickness);

– calculated pressure P = 6.4 MPa;

– atmospheric pressure R_{atm} = 0.098 MPa;

– linear expansion coefficient $\alpha = 12.8 \cdot 10^{-6}$ 1/°C.

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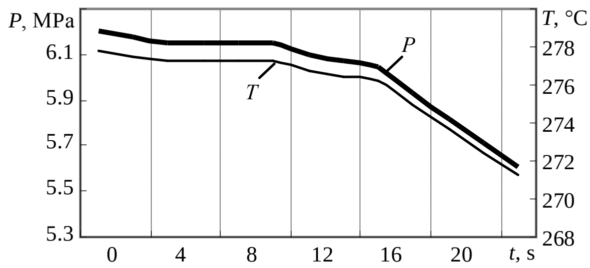
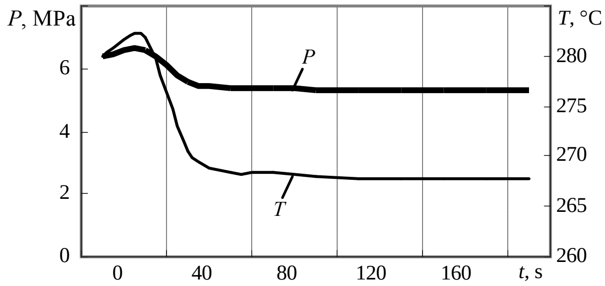
Curves of change of calculated parameters are presented in Fig. 1.



a



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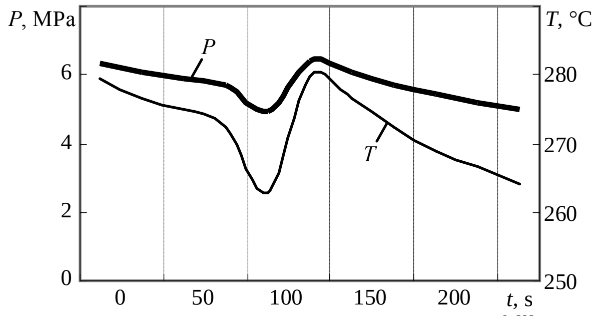

c

Fig. 1. Curves of change of calculated parameters for SG vessel in different modes: NOC (a), VNOC (b) and DA (c)

Results of calculations.

Results of strength calculation of the SG vessel at static and dynamic approximation of loadings are reduced in Tables 1 and 2.

Table 1

The strength calculation results for the SG vessel under static loading

Characteristic	Designation	Unit	Mode		
			NOC	VNOC	DA
Nominal allowable stress	[σ]	MPa	188.846		
Pressure range	ΔP	MPa	0.7	1.29	1.5
Temperature difference	ΔT	°C	6.5	14.1	17.2
Reduced stress	(σ_a)	MPa	16.064	31.476	37.31
Concentration factor	K_F	–	9.614	5.127	4.427
Amplitude of the reduced local engineering elastic stress	(σ_{aF})	MPa	154.129	161.377	165.171
The same, taking into account temperature	$[\sigma_{aF}]$	MPa	159.807	167.322	171.256
Stress ratio	r	–	0.074	0.031	0.008
Maximum permissible number of loading cycles	$[N_0]$	–	3.836·104	1.671·104	1.07·104
Actual number of loading cycles	N	–	6867	146	1
Accumulation rate of operation modes	W	mode/year	312	6	0.045
Coefficient taking into account impact of operation modes	μ	–	0.846	0.886	0.907
Cumulative fatigue damage	a	–	0.159		
Allowed operation life	t_{al}	year	33.25		

Table 2

The strength calculation results for the SG vessel under dynamic loading

Characteristic	Designation	Unit	Mode		
			NOC	VNOC	DA
Nominal allowable stress	[σ]	MPa	188.846		
Pressure range	ΔP	MPa	0.7	1.29	1.5
Temperature difference	ΔT	°C	6.5	14.1	17.2
Reduced stress	(σ_a)	MPa	14.996	35.393	117.875
Concentration factor	K_F	–	10.278	4.63	2.406
Amplitude of the reduced local engineering elastic stress	(σ_{aF})	MPa	154.439	163.87	283.607
The same, taking into account temperature	$[\sigma_{aF}]$	MPa	160.129	169.907	294.056
Stress ratio	r	–	0.072	0.016	–0.703
Maximum permissible number of loading cycles	$[N_0]$	–	3.364·104	1.609·104	2.552·103
Actual number of loading cycles	N	–	6867	146	1
Accumulation rate of operation modes	W	mode/year	312	6	0.045
Coefficient taking into account impact of operation modes	μ	–	0.848	0.9	1.557
Cumulative fatigue damage	a	–	0.182		
Allowed operation life	t_{al}	year	26.38		

Curves of variation of rate of calculated parameters with time are presented in Fig. 2.

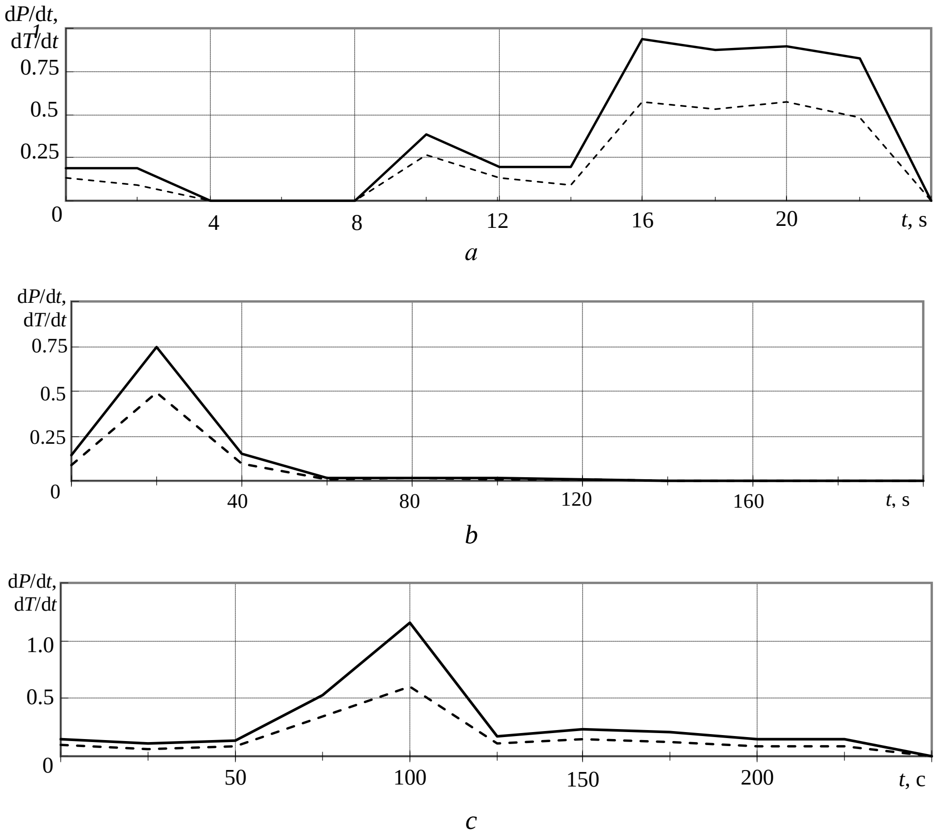

Fig. 2. Curves of variation of dependences $f_1([\sigma],P)\dfrac{\mathrm{d}P}{\mathrm{d}t}\mathrm{d}t$ *and* $f_2(E^T,\alpha^T)\dfrac{\mathrm{d}T}{\mathrm{d}t}\mathrm{d}t$ *with time t in different modes: NOC (a), VNOC (b) u DA (c)*

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Based on the carried-out calculation it is possible to evaluate a share of separate loading cycles for the NOC, VNOC and DA modes in total quantity of cycles. Fig. 3 shows the average percentage ratio of loading cycles for the NOC, VNOC and DA modes. It is also possible to evaluate a residual life of number of loading cycles for the NOC, VNOC and DA modes at the moment. The percent of a reserve of loading cycles for the separate modes is shown in Fig. 4*a*. Fig. 4*b* shows the comparative percent of a reserve of loading cycles for the separate modes with regulated admissible number of cycles.

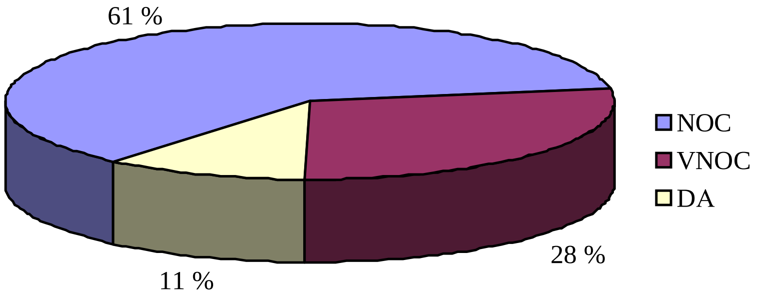

Fig. 3. Average percentage ratio of loading cycle numbers

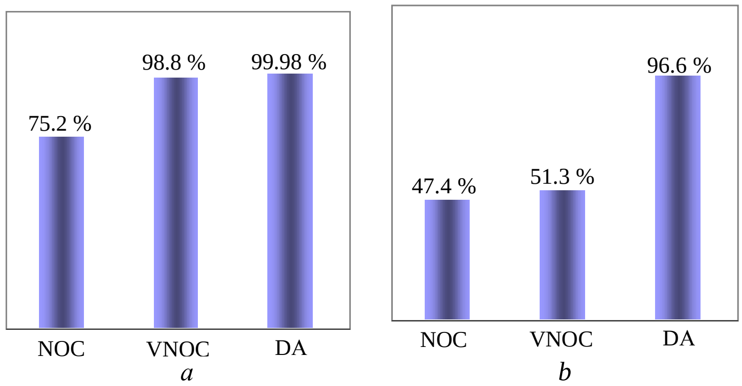

Fig. 4. The percent of a reserve of loading cycles for the separate modes (a), the percent of a reserve of loading cycles for the separate modes with regulated admissible number of cycles (b)

The formula (18) assesses impact of admissible operation life on an accumulation rate of the operational modes. The assessment was performed for t_{al}=30, 40, 50 years. The calculation results for the SG vessel under static and dynamic loading are provided in Table 3.

Table 3

Accumulation rates W of modes for SG vessel

t_{al}, years	Loading approximation type					
	Static			Dynamic		
	W_{NOC}	W_{VNOC}	W_{DA}	W_{NOC}	W_{VNOC}	W_{DA}
30	345.78	7.418	0.05	274.41	5.89	0.04
40	259.348	5.563	0.037	205.806	4.415	0.03
50	207.482	4.451	0.03	164.64	3.53	0.024

Assessment of impact of admissible operation life on an accumulation rate of the operational modes can lead to a conclusion that accumulation of the NOC modes makes the greatest contribution. For an example, Fig. 5 shows average dependence of admissible accumulation rate of the NOC modes for different admissible operation life.

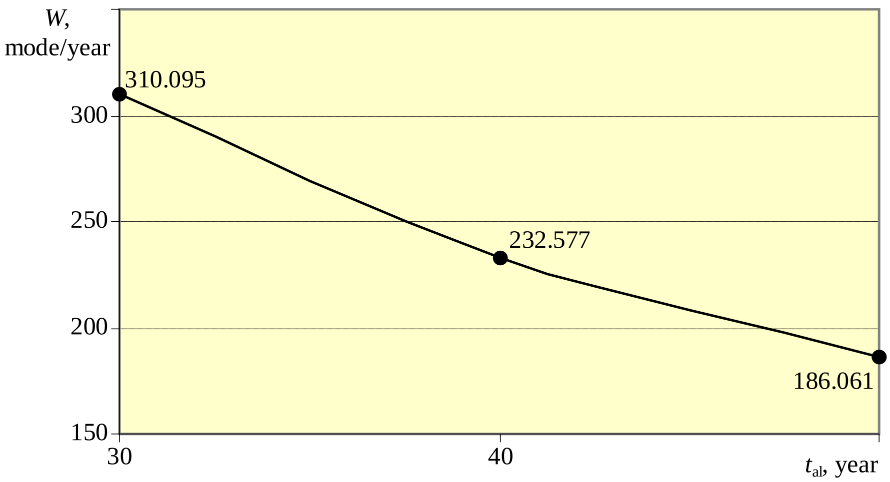

Fig. 5. Average dependence of admissible accumulation rate of modes

Conclusions

1. Based on the analysis of known researches, it is revealed that the quantity and accumulation rate of cyclic thermal and dynamic loads in the transient modes of normal operation conditions, when violating normal operation conditions and in accident conditions (except for the nuclear reactor vessel) are the key factors of prediction of operation life extension for a heat power equipment (heat exchangers, pumps, armature).

2. The method for predictive estimation of terms of operation life extension of a heat power equipment depending on stress amplitudes in transient and accident conditions, quantity and accumulation rate of cyclic loads, strength metal parameters of a heat power equipment vessels (except for a reactor vessel) is provided.

3. The method is implemented on the example of steam generators of WWERs and using operational data of South-Ukraine-1 (by 2010). Admissible accumulation rate of cyclic loads during operation life extension by 30, 40 and 50 years is a result.

4. The results define insufficient substantiation of nuclear power plant operation in the “maneuverable” modes with a variable reactor power. In this case, the quantity of cyclic equipment loads increases dramatically, and terms of safe operation are limited.

Література

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