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EFFICIENCY OF STEAM GENERATORS AT NUCLEAR POWER PLANTS

В.І. Ковальчук, І.Л. Козлов, О.А. Дорож, А.А. Мачков. **Ефективність експлуатації парогенераторів атомних електростанцій.** Розглянуто можливість комплексної оцінки ефективності експлуатації парогенераторів ядерних енергоустановок з водо-водяними реакторами, заснованої на показнику ефективності роботи обладнання OEE (overall equipment effectiveness). Запропоновано розглядати ефективність як ймовірність функціонування з позицій доступності, продуктивності і якості продукту. Метою роботи є оцінка можливості використання показника OEE для аналізу ефективності експлуатації парогенераторів атомних електростанцій в комплексних умовах: реактор – парогенератор – турбіна. Досягнення поставленої мети дозволить отримати комплексний показник моніторингу ефективності парогенеруючих систем атомних електростанцій і мати інструмент для систематичного контролю працездатності парогенераторів. Для оцінки організаційно-екологічної ефективності організаційної структури запропоновано індивідуальні, групові та інтегральні показники, що відображають частку або зниження абсолютного показника в системі порівняно з базовим. Дослідження базується на аналізі багаторічних результатів експлуатаційних показників блоків з парогенераторами ПГ-1000, які є співставними. Показано, що основним елементом системи паротворення, який визначає її ефективність, є теплогенеруюче джерело. Оцінений внесок в ефективність усіх аспектів експлуатації. Показано, що показник ефективності експлуатації обладнання OEE дозволяє характеризувати ефективність експлуатації парогенераторів ядерних енергоустановок з водо-водяними реакторами, і може застосовуватися для моніторингу та управління процесом їх експлуатації. В результаті дослідження визначено, що ефективність функціонування парогенератору підвищується в міру досягнення максимального значення його продуктивності.
Ключові слова: парогенератори, режими роботи, ефективність, критерій ефективності, показник OEE (overall equipment effectiveness), оцінки ефективності

V. Kovalchuk, I. Kozlov, O. Dorozh, A. Machkov. **Efficiency of steam generators at nuclear power plants.** The possibility of a comprehensive assessment of steam generators efficiency at nuclear power plants with water-water reactors, based on the indicator of OEE (overall equipment effectiveness) is considered. It is proposed to consider efficiency as the probability of functioning from the standpoint of availability, performance and product quality.The aim of the work is to evaluate the possibility of using the OEE indicator to analyze the efficiency of NPP steam generators in complex conditions: reactor – steam generator – turbine. Achieving this goal will provide a comprehensive indicator of monitoring the efficiency of steam generating systems and have a tool for systematic monitoring of steam generators. To assess the organizational and environmental efficiency of the organizational structure, individual, group and integrated indicators are proposed, which reflect the share or decrease of the absolute indicator in the system compared to the baseline. The study is based on the analysis of long-term performance of units with steam generators PG-1000, which are comparable. It is shown that the main element of the steam generation system, which determines its efficiency, is the heat generating source. The contribution to the efficiency of all aspects of operation is estimated. It is shown that the efficiency index of OEE allows to characterize the efficiency of steam generators operation at nuclear power plants with water-water reactors, and can be used to monitor and control the process of their operation. In result of research, it is defined that steam generator efficiency increases in process of achievement of the maximum value of its productivity.
Keywords: steam generators, operating modes, efficiency, efficiency criterion, OEE indicator (overall equipment effectiveness), efficiency evaluations

Introduction

Nuclear power plants use a typical scheme for converting nuclear energy into electricity. Nuclear reactions heat a water coolant under high pressure, which is pumped from the reactor through a steam generator, where it gives part of the heat to the secondary circuit and returns to the reactor. The water of the secondary circuit is under less pressure, so it boils, forming steam for the turbine.

Steam generators are used for two- and three-circuit NPPs. Steam generators, along with turbine condensers and intermediate heat exchangers (with a three-circuit circuit), are the main heat exchangers of nuclear power plants, the characteristics of which significantly affect the efficiency and economic performance. The steam generator at the NPP provides heat exchange between the first and second circuits, as well as steam production for the turbine.

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Steam generator is a heat exchanger for the production of water vapor with a pressure above atmospheric due to the primary coolant coming from the nuclear reactor [1]. This is a recuperative heat exchanger, in which heat energy is transferred from the coolant of the first circuit to the working fluid of the second circuit through the heat exchange surface and thus generates steam that feeds the turbine (Fig. 1).

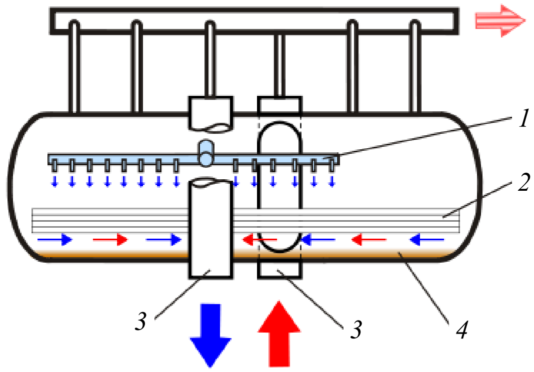

Fig. 1. Horizontal steam generator: *1* – feed water collector (input of the 2nd circuit); *2* – heat exchange tubes (inside the 1st circuit); *3* – vertical collectors (horizontal GHG), inlet and outlet coolant of the 1st circuit; *4* – the most probable places of accumulation of sludge

A typical steam generator consists of tubular packages closed on collectors, through which the primary coolant is pumped. The tubes are immersed in the coolant of the secondary circuit. During long (tens of years) service on defects there are and develop defects. This leads to the overflow of the coolant of the first circuit to the second, complicating the radiological situation. At scheduled shutdowns of the reactor, the condition of the heat exchange tubes is monitored and the defective ones are blocked. In rare cases, it is necessary to change the steam generator completely, but usually the service life of the steam generator is equal to the service life of the reactor. Therefore, given that the steam generator is an element of the nuclear-to-electrical energy conversion chain, the relevance of the possibility of assessing the effectiveness of its performance indicators in the monitoring mode is beyond doubt.

Analysis of recent research and publications

Steam generators are elements of the technological chain that converts the internal energy of nuclear fuel into electricity. Like any technological equipment, there is a system that produces the working fluid as the final product to perform mechanical work in the turbine. The following resources are used for production: nuclear fuel energy, water, electricity and others. The ratio of output and expended resources, expressed in one dimension, allows us to judge the degree of perfection of the system, i.e. its efficiency [2]. There are a number of criteria for quantifying this ratio [2, 3].

Equipment utilization factors allow us to assess how existing equipment is being used [2]. Distinguish the utilization rate of all available equipment (K_{aae}):

$$K_{aae} = Q_{ie}/Q_{ae},$$

and installed equipment utilization factor (K_{uie}):

$$K_{uie} = Q_{oe}/Q_{ie},$$

where Q_{ae}, Q_{ie}, Q_{oe} – the number of units of equipment, respectively, available, installed, operating.

These indicators do not allow judging the efficiency of operation of the equipment, as they consider only the ratio of existing equipment. And such aspects of operation as duration, reliability and others remain out of consideration.

Equipment as production facilities operate under the influence of intensive and extensive factors. The results depend on how effectively they are used.

Extensive use of available capacity in production is primarily an increase in equipment operating time over a period. It also takes into account the amount of equipment actually working out of the total amount of equipment of the enterprise. The general estimation allowing defining efficiency of use of the equipment is carried out by means of the indicator representing factor of use of production capacity (K_{use}) [3]:

$$K_{use} = Q_{app}/Q_{epc},$$

where Q_{app} – is the actual output, Q_{epc} – an indicator of the estimated production capacity.

A more complete assessment of efficiency allows the addition of this ratio indicator that take into account the extensive load of the equipment (K_{eel}):

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$$K_{eel} = B_{awt}/\Phi_c; \qquad K_{eel} = B_{awt}/\Phi_r; \qquad K_{eel} = B_{awt}/\Phi_{pu},$$

where B_{awt} is the actual time worked, and Φ_c, Φ_r and Φ_{pu} are the corresponding time funds – calendar, regime and planned useful.

However, the issues of reliability and quality of operation remain beyond consideration.

To assess the organizational – environmental efficiency of the organizational structure proposed individual, group and integrated indicators that reflect the share or decrease of the absolute indicator in the system compared to the base [4].

The closer the integrated indicator to 1, the higher the environmental performance of the organizational structure. The indicator allows comparing on the criterion of environmental friendliness not only enterprises within one industry, but also enterprises of different sectors of the economy, despite the fact that the composition of indicators within each of the groups may be different [4].

Evaluations of the efficiency of individual aspects of operation of steam generators with WWER-1000 and WWER-440 are considered in [5, 6]. There are no comprehensive assessments of the efficiency of steam generator operation.

The above allows us to state that the existing approaches do not allow a comprehensive assessment of the efficiency of the technological element – the NPP steam generator.

The performed analysis convinces of the relevance of such an assessment to improve the circuit design and technological characteristics of such systems.

The most complex indicator of the functioning of systems, including steam-generating NPPs, is efficiency. It is a defining property of any purposeful activity, which is expressed by the degree of achievement of the goal, taking into account the cost of resources and equipment time. Seyit Nakajima proposed a general complex OEE efficiency (overall equipment effectiveness), as a central component of the methodology for determining the possibilities of improving the efficiency of process productivity and ways to achieve this improvement [7, 8]. By the end of the last century, the concept of OEE began to be widely used in the practice of improving the management of equipment and technological systems in the Western world [9, 10].

Purpose of the work

The purpose of the work is to evaluate the possibility of using the OEE indicator as an indicator of the efficiency of NPP steam generators in complex conditions: reactor - steam generator - turbine.

To achieve this goal it is necessary to solve the following tasks:

– choose an integrated criterion for evaluating the effectiveness of the system and propose a method for determining it;

– determine the range of efficiency criteria for existing NPP steam generation systems.

Materials and methods of research

The system of steam generation of WWER units consists of four main elements:

$$\underbrace{\text{heat source} \Rightarrow \text{steam generator} \Rightarrow \text{turbine}}_{\text{control}},$$

each of which is a complex or element of equipment, real estate and personnel that convert fuel energy into final product (mechanical work).

The most important asset in these complexes is equipment. Production assets, and above all equipment, must work for the maximum time with the maximum allowable load. Effective asset management involves regular preventive maintenance and systematic elimination of losses associated with readjustment, maintenance and other processes. The concept of General Equipment Care (TPM) based on an integrated OEE equipment performance indicator designed to monitor measure and process specific performance indicators, and helps to achieve these goals [10].

The OEE indicator is built as product of three criteria:

– Availability (A);
– Performance (P);
– Quality (Q).

Availability criterion *A* analyzes the loss of time, excluding the planned shutdown time, for unscheduled stops *DTL* (down time loss): equipment failures and failures, stops due to shortage of raw materials, lack of storage space, etc. It calculated as the ratio of *OT* (operating time), when the equipment was working and producing products, to the planned time of production, or planned production time *PPT* (planned production time):

$$A = \frac{OT}{PPT}.$$

Operating time is defined as the difference between the scheduled production time *PPT* and the time of unscheduled stops *DTL*:

$$OT = PPT - DTL.$$

The criterion of productivity *P* takes into account the losses associated with the loss of speed of production units (for example, in our case, units of heat) due to equipment operation, quality of raw materials, and the impact of the human factor. It is determined by the ratio of the actual number of units of *TP* (total pieces) released during the operating time *OT* and the maximum possible number of products per unit time *IRR* (ideal run rate):

$$P = \frac{TP}{OT \cdot IRR}.$$

Quality criterion *Q* takes into account the losses associated with low quality products (quality loss) and is determined by the ratio of the number of suitable products *GP* (good pieces) to the total number of products *TP* (total pieces) released during the operating time *OT:*

$$Q = \frac{GP}{TP}.$$

All considered criteria are relations of one-dimensional sizes. In mass tests, the ratio of positive results to the total number of tests is likely. Therefore, the criteria can be considered opportunities for availability, performance and quality, and the efficiency indicator, respectively, the probability of occurrence of the event - the efficiency of the system element [11].

The results of evaluating the efficiency of steam generators. The object of observation is the results of operation of typical steam generators GHG-1000 units WWER-1000, available in open sources.

The mode of operation of the steam generator is continuous between scheduled maintenance, which is assigned at the time of scheduled preventive repairs.

To assess the readiness of the device for operation, it is necessary to allocate from the total period of operation of the unit intervals due to the inoperability of the steam generator itself, which may be due to emergency failures and routine maintenance.

According to the operation of power units 3 and 4 type WWER-440 NPPP for the period from 1971 to 2017 there were equipment failures and, in particular, due to failures of steam generator pipes (Table 1).

Table 1

Number of failures of NPPP units

Equipment, element (reason for failure)	№ block	Number of failures, times	Recovery time, days	Failure rate, 1/h
Unit equipment (without giving reason)	3	24	137.6	9.19×10^{-5}
	4	11	61.8	
GHG heat exchange pipes	3	8	88.8	2.89×10^{-5}
	4	3	37.1	

According to the operation of power units 1 and 3 type WWER-1000 PUAES for the period from 2010 to 2021, the dependences of the flow of corrosion products in steam generators with feed water (Fig. 2).

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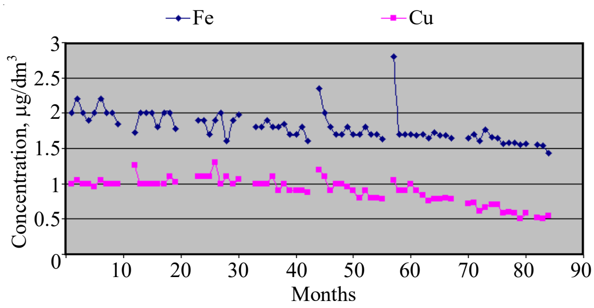
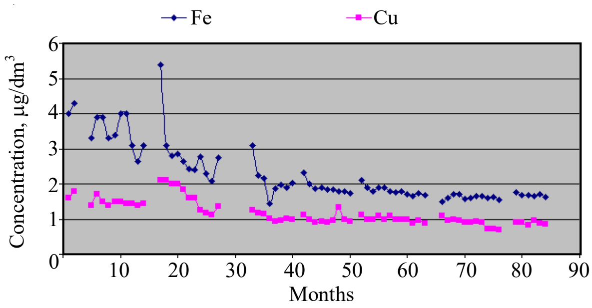
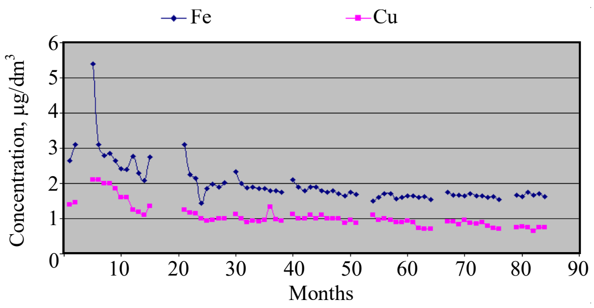


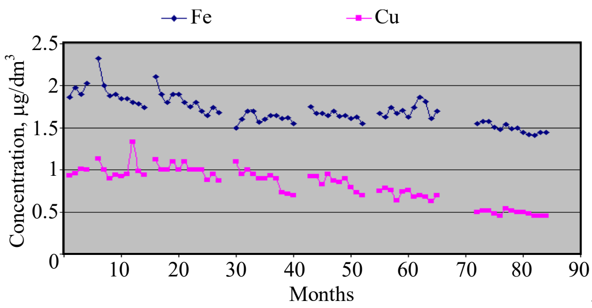
power unit No.1, 2013 – 2020 (SPM2020 y.)
a



power unit No.3, 2010 – 2018(SPM2018 e.)
b



power unit No. 3, 2011–2019 (SPM2019 y.)
c



power unit No. 3, 2014–2021 (SPM2021 y.)
d

Fig. 2. The flow of corrosion products into the volumes of steam generators:
№ 1 (*a*); № 2 (*b*); № 3 (*c*); № 4 (*d*)

The gaps in the graphs reflect the absence of the arrival of corrosion products due to the scheduled preventive maintenance and downtime of the apparatus for other reasons, which makes it possible to calculate the actually worked time required to assess the readiness criterion.

The performance of the apparatus can fluctuate from the state of shutdown to the maximum nominal value; it allows you to calculate the actual performance of the apparatus to assess the performance criterion (Fig. 3).

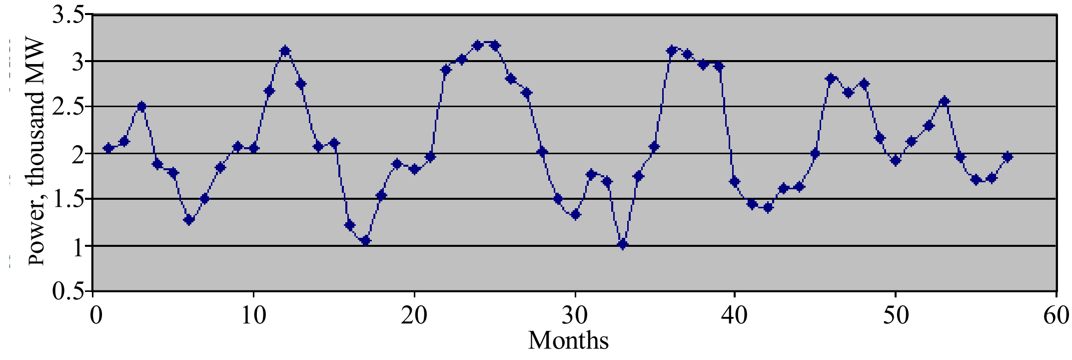


Fig. 3. Electric capacity of NPPs 2017 – 2021 y.y.

Determining the quality requires a quantitative evaluation criterion. The quality of steam can be assessed by its moisture content, which carries corrosion products that cause increased erosion wear of the turbine blades.

The OEE idea includes an algorithm for monitoring and continuous improvement. In the most general form, the calculation of OEE indicators requires a definition criteria (Table 2).

Table 2

Criteria for calculating OEE indicators

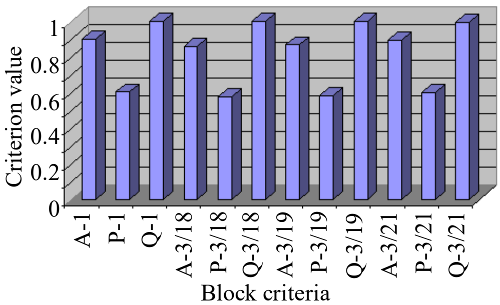
Criteria	Availability	Productivity	Quality
Relationship	actual time Quantity of products	produced Quantity of quality	products planned production
	time Planned number of products	produced Number of products	produced

Actually worked time differs from the planned duration of unplanned downtime. Adding to the planned time of production planned downtime and planned non-working hours, determines the calendar time of operation.

The product of the planned working time and nominal productivity determines the planned number of products. The actual output is equal to the product of the actual time worked and the actual productivity, proportional to the power of the units.

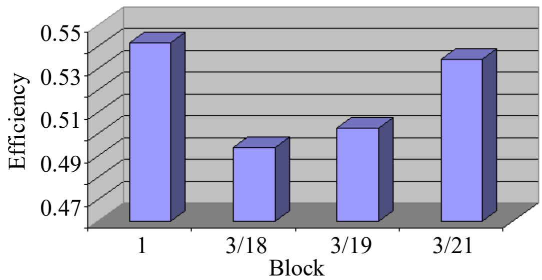
The quantity of quality products and the quantity of produced products differ in the ratio of moisture produced by steam and its normalized value.

The estimates obtained are shown in the diagrams (Fig. 4).



A-1, P-1, Q-1 power unit 1 (2013 – 2020 y.y.); A-3/18, P-3/18, Q-3/18 power unit 3 (2018 y.); A-3/19, P-3/19, Q-3/19 power unit 3 (2019 y.); A-3/21, P-3/21, Q-3/21 power unit 3 (2021 y.)

a



1– power unit 1 (2013 – 2020 y.y.); 3/18 – power unit 3 (2018 y.); 3/19 – power unit 3(2019 y.); 3/21 – power unit 3 (2021 y .)

b

Fig. 4. Values of criteria (*a*) and performance indicator (*b*)

Discussion of research results

A comparison of evaluations of performance criteria and integrated OEE performance indicator (Fig. 4) shows that the main impact is load. Largely, this is manifested at low power, compared with the nominal performance of the heat generator. In the process of operation of complex systems there is a complex intertwining of heterogeneous physical processes that form internal feedback, causing destabilizing effects.

The obtained results allow controlling the efficiency of steam generators as a complex of steam generators.

Conclusions

Based on the analysis of the integrated efficiency indicator OEE, it is proposed to consider the efficiency of the devices as the probability of a full-fledged manifestation of the functioning of all their aspects. In this case:

– to assess the effectiveness of the proposed indicator of the efficiency of OEE equipment (overall equipment effectiveness);

– the results of numerical simulations showed that the interval of the integrated efficiency index of steam generators is 0.5...0.6, with the determining criterion being productivity;

– during operation, it is recommended to provide the possibility of systematic monitoring of the parameters that determine the values of the criteria in order to increase efficiency.

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