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Monte-Carlo method for assessing and predicting the reliability of thermal power plant equipment

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Abstract This paper presents the results of developing a methodology for assessing and predicting the technical condition of boiler plants and steam turbines. The proposed method is based on generalized experimental data on failures to predict the damage of the principal elements and components of thermal power plants by Monte-Carlo simulation. The proposed method considers the complexity of technological processes, turnaround time, failure rate, and condition of the residual metal life. It allows developing approaches to assessing each element's safety to obtain a reliable and representative sample of failure statistics to reliability assessment of boilers and steam turbines of thermal power plants. According to the results, the probability of failure operation of steam boilers and turbines is 0.037 in the 100 MW conditions. The obtained results can be used to create predictive models that provide approaches to prolonging the operational state of elements of boiler plants and steam turbines of thermal power plants. It can be used in the implementation of projects of digital energy systems for monitoring and diagnostics of the main power equipment of thermal power plants.

Keywords: Reliability indicators; Technical condition; Monte-Carlo method; Boiler plant; Steam turbine; Park resource; Forecasting

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1 Introduction

The high energy demand requires a reliable and continuous supply of electricity to customers. A thermal power plant (TPP) is a complex and multinode system for the combined electric and thermal energy production. In reliability studies of generating systems, the source of energy for generation is generally considered recyclable. It implies that the single source of unavailability in power generation is a breakdown of the unit. Today, thermal power plants generate 36% of electric energy and 46% of heat, in the form of hot water and steam, from the total volume of products on the market [1]. At the same time, about 92% of the generating units were put into operation before 1989. By the current period, most of the main stock of heat and power equipment is both morally and physically obsolete [2,3]. As a result, this leads to an increase in the failure rate. The concept of failure has a probabilistic nature of the occurrence. Therefore, to date, there is a whole theory for assessing the risk of failure as an indefinite or unclear time of occurrence of the event.

In [4] overviewed the risk assessment methods at a TPP with special emphasis on methods for analyzing and assessing the risks of TPPs as well as approaches for human reliability evaluation and their effect on operation safety of TPP. In the theory of risk assessment of any event, there are two main methods: qualitative and quantitative. Qualitative risk assessment involves a verbal description of the risk situation, systematization of potential hazards, and heuristic decision-making aimed at reducing the negative consequences of the risk and preventing the occurrence of risk situations.

In qualitative assessment [5], descriptive and informal methods are used to give a comparative assessment of the level of risk. These methods include historical analysis (historical-associative method or analogies), expert method, SWOT (strengths – weaknesses – opportunities – threats) analysis, rating method, and graphical ranking method. This estimation method is applicable in cases of complete uncertainty of the object under consideration.

When solving the problem of assessing and predicting the reliability of power equipment, it is advisable to use a quantitative assessment of the risk of failure. This type of problem is characterized by the certainty or partial uncertainty of the occurrence of an event. The quantitative risk assessment method includes the following analysis tools:

- statistical method;
- sensitivity analysis (method of variation of parameters);

- method of checking the stability (calculation of critical points);
- scenario method (method of formalized description of uncertainties);
- simulation modeling (statistical testing method, Monte-Carlo method).

Traditionally, reliability analyses are based on deterministic methods such as Life Data Analysis. These methods are generally used for non-repairable equipment in the manufacturing and automobile industries [6]. In [7] a failure probability model for intensively used thermal power plants was developed. They used the lognormal and Weibull hazard models based on the observed data well. The accidents tended to occur many times at the same power generation unit under heavy-duty conditions. Jagtap *et al.* [8] presented reliability, availability, and maintainability analysis framework for evaluating the performance of a circulation system of water (WCS) used in a coal-fired power plant. The subsystem's optimized failure rate and repair rate parameters are used to suggest a suitable maintenance strategy for the water circulation system of the thermal power plant.

By analyzing the existing methods for assessing the risk of failure of power equipment of thermal power plants, it is advisable to focus on two: statistical and simulation modeling (Monte-Carlo method). Therefore, the purpose of this work is to develop a methodology for assessing and predicting the technical condition of boiler plants and steam turbines of thermal power plants, taking into account their reliability and efficiency indicators, based on the use of the Monte-Carlo method [9, 10].

2 Method

2.1 Theory of risk assessment and analysis of failures of thermal power plant equipment

Ensuring the reliability of operating equipment and finding ways to reduce the cost of repairing equipment makes it necessary to apply and develop diagnostic methods. There are many factors (vibration, electrical, thermal) that can be used to assess the condition of the equipment. However to evaluate the general condition of the operating equipment is quite a difficult task. A comprehensive assessment requires a whole range of technical means and various diagnostic methods that systematize the generalized indicators of the power plant.

Currently, the determination of the assessment of reliability and cost-effectiveness indicators of operating equipment, taking into account the actual technical condition of boiler plants of thermal power plants, is quite an urgent task. As shown in Fig. 1 the main causes of technological failures of steam boiler installations are violations in the operation of economizers, intermediate superheaters, including superheaters with a radiation shield, evaporation surfaces and other elements, including failures of traction units [11–13]. Currently, there is no effective mechanism and a unified system for predicting the failure of elements of the boiler unit of power plants in case of accidental occurrence of defects, which leads to a decrease in the safe and reliable operation of the equipment as a whole. Determination of the actual technical condition of the main and auxiliary specific equipment or the entire power plant is determined by the technical condition of the equipment elements.

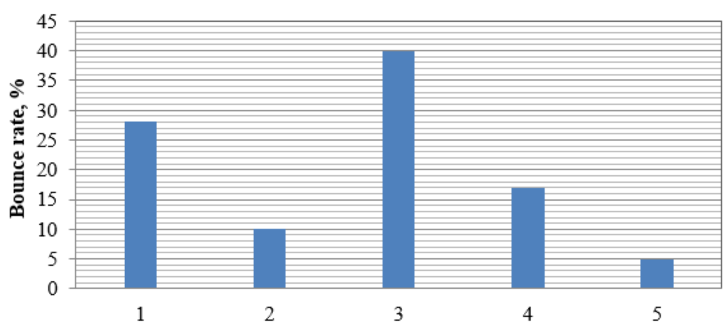

Figure 1: Failure diagram of steam boilers: 1 – economizers; 2 – intermediate superheaters; 3 – superheaters, including radiation screen superheaters; 4 – evaporative surfaces; 5 – other elements, including failures of traction units.

According to statistics [14], 40% of the total number of failures of the main equipment relate to steam boilers, and 16% to turbines.

In thermal power plants, all scheduled repairs are carried out based on the repair cycle, which is primarily determined by the assigned inter-repair resource of the entire power unit. When planning repairs of existing equipment without considering the actual technical condition, there is an increase in failures of equipment elements and, consequently, repair costs increase. Data analysis shows the need for a preventive maintenance system of boiler heating surfaces during the inter-repair period, which will allow the process to increase its reliability in the shortest period with minimal metal costs, funds, and labor intensity [14–16].

Also, the main reasons for the failure of steam boilers and their auxiliary equipment at thermal power plants are: high heat capacity of the combustion chambers; equipment design flaws caused by the lack of accounting data, working conditions, the choice of calculation methods; leaks of the steam-water path; long-term operation of metal heat transfer surfaces at high pressures and temperatures; violation of the operating modes of power equipment; significant loads on thermal cyclers; additional damaging factors are the processes of metal corrosion, both from the furnace side and inside the volumes of water and steam.

As shown in Fig. 2 the main causes of malfunctions in the operation of steam turbines are technological failures that occur in the flow part, bearings, oil system, control system, steam distribution, pipelines and fittings, other elements and malfunctions without actual damage [17, 18].

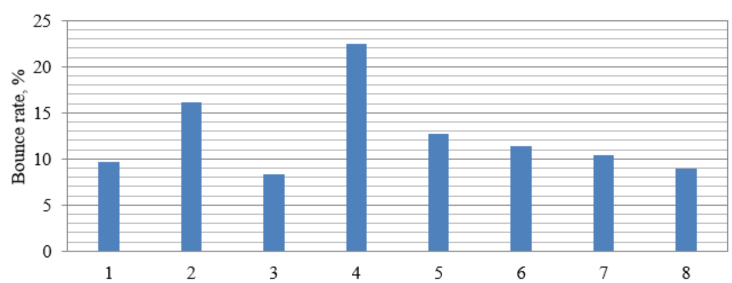

Figure 2: Failure diagram of steam turbines parts: 1 – flow part; 2 – bearings; 3 – oil system; 4 – regulation; 5 – steam distribution; 6 – pipelines and fittings; 7 – other elements; 8 – failures without damage.

In accordance with the regulatory methodology for assessing the technical condition of power equipment before and after repairs and in the period between repairs, it is advisable to use the following criteria for acceptable risk in the operation of boiler equipment of thermal power plants: the frequency of failure of the main equipment elements; the average cost per year for preventing the consequences of an accident of one of the equipment elements, which can be expressed as a mathematical expectation of damage from failure.

2.2 Reliability assessment methodology and reliability forecasting of thermal power plant equipment based on the Monte-Carlo method

The Monte-Carlo simulations are a powerful method for modeling systems for reliability analysis. It is a simulation model based on the methods used in

Monte-Carlo and has its applications in mathematical and physical models. Depending on the initial data, it is possible to use statistical methods to determine the remaining resource. Damage statistics play an important role in managing the reliability of boiler equipment, aimed at improving the reliability of the most damaged elements, in this case, heating surfaces. In this case, statistics play a decisive role in replacing pipes of heating surfaces that have not exhausted their resource, allowing to identify critical zones and minimize costs.

The statistical method makes it possible to determine the relationship between damage to equipment elements and their causes. For heating surfaces, the causes of damage are multifactorial and cover a large amount of quantitative and qualitative indicators. To determine these indicators, it is necessary to collect data on damage zones for the same type of boilers, which allow to diagnose areas of places visually. Therefore, as one of the main criteria for assessing the actual technical condition, it is proposed to use the current resource value of the main equipment involved in the release of electric and thermal energy, which takes into account important operating conditions and thermal characteristics of power equipment during the operation of steam boilers and turbines of power plants. In this case, the resource coefficients of the main equipment involved in the release of electrical and thermal energy are determined by the expressions:

$$K_{\text{res}}^{ee} = \frac{\sum\limits_{i=1}^{n} \dfrac{\Delta q_{Ti}^{\text{res}} E_i}{q_{Ti}^{\text{fact}}}}{\sum\limits_{i=1}^{n} E_i} + \frac{\sum\limits_{i=1}^{n} \dfrac{\Delta \eta_{bi}^{gr(\text{res})} Q_{bi}^{gr}}{\eta_{bi}^{gr(\text{fact})}}}{\sum\limits_{i=1}^{n} Q_{bi}^{gr}}, \tag{1}$$

$$K_{\text{res}}^{te} = \frac{\sum\limits_{i=1}^{n} \dfrac{\Delta \eta_{bi}^{gr(\text{res})} Q_{bi}^{gr}}{\eta_{bi}^{gr(\text{fact})}}}{\sum\limits_{i=1}^{n} Q_{bi}^{gr}}, \tag{2}$$

where: E_i – electricity generation turbine unit, kW h; Q_{bi}^{gr} – heat generation by gross boiler, Gcal; q_{Ti}^{fact} – actual specific heat consumption by the gross turbine unit for electricity production, kcal/kW h; $\eta_{bi}^{gr(\text{fact})}$ – actual gross efficiency of the steam boiler, %; Δq_T^{res}, $\Delta \eta_b^{gr(\text{res})}$ – amendments to the aging of the equipment to q_T andη_b^{gr}, n – number of turbine units.

Analytical expressions (1) and (2) show the direct impact of wear (aging) of equipment on its actual performance in the TPP. The following mathematical expressions are used to determine the aging corrections of steam turbines (Δq_T^{res}) and boilers ($\Delta \eta_b^{gr(\text{res})}$):

$$\Delta q_T^{\text{res}} = \sum_{i=1}^{n} q_{Ti}^{\text{fact}} l_i \tau_{\text{res}\,i}^{t} \times 10^{-5}\,, \tag{3}$$

$$\Delta \eta_b^{gr(\text{res})} = \sum_{i=1}^{n} C_i \tau_{\text{res}\,i}^{b} \times 10^{-3}\,, \tag{4}$$

where: l_i, C_i – wear coefficients of the steam turbine and boiler, respectively; $\tau_{\text{res}\,i}^{t}$, $\tau_{\text{res}\,i}^{b}$ – duration of operation in hours at the end of the considered period of the turbine unit and boiler.

When developing methods for calculating reliability indicators, the mathematical expectation can be used to assess possible damage in the event of emergency situations that led to equipment shutdown and under-discharge of heat and electricity. Thus, the mathematical expectation for a continuous random variable is expressed as an integer within infinite limits of the product of continuously varying possible values of the random variable by the distribution density:

$$M_x = \int_{-\infty}^{\infty} K_{\text{res}}^{i} f(x)\, dx\,. \tag{5}$$

The mathematical expectation of a random variable is directly related to the average value. With an unlimited increase in the number of experiments, the arithmetic mean of the value approaches $\overline{X}$ the mathematical expectation, which in the Monte-Carlo method can be considered an estimate of the average value.

In this case, the variance of a random variable is the mathematical expectation of the square of the deviation of this value from its mathematical expectation. For a continuous random variable, the variance is determined from the expression

$$D_x = \int_{-\infty}^{\infty} \left(K_{\text{res}}^{i} - M_x\right)^2 f(x)\, dx\,. \tag{6}$$

Thus, the probability of reliable fault-free operation of main equipment with respect to electric and thermal energy at thermal power plants in the range of operating process parameters and considering the type of their functional distribution is proposed to determine the expression

$$P_i = 1 - \int_{T_1}^{T_2} K_{\text{res}}^{ee} K_{\text{res}}^{te} f(x)\, dx \tag{7}$$

where: K_{res}^{ee}, K_{res}^{te} – are the resource coefficients of the main equipment involved in the release of electrical and thermal energy, respectively.

It should be noted that in the simulation runs, the variable is randomly selected according to the type of distribution $f(x)$ and within the specified range of the studied parameters from T_1 to T_2:

$$\int_{T_1}^{T_2} f(x)\, dx = \frac{1}{n}(T_2 - T_1)\sum_{i=1}^{n} f(x_i).$$

The wear coefficients are empirical, so their values for different types of main equipment are presented in Table 1 [6].

Table 1: Wear coefficients of the main equipment.

Type of equipment	The depreciation factor
Turbine with back pressure or degraded vacuum	0.0025
The rest of the turbines	0.0085
Solid fuel boilers	0.0055
High-sulfur fuel oil boilers	0.0035
Low-sulfur fuel oil and natural gas boilers	0.0015

3 Results

There are four basic steps in the Monte-Carlo simulation procedure:

i) identify a range of likely events,

ii) create random events,

iii) make deterministic judgments based on the event's system states,

iv) calculate the occurrence number of a particular system state from all observations.

Modeling and analytical approach using the Monte-Carlo method has its advantages and disadvantages. For example, the analytical approach gives an accurate solution when considering various complexities and distributions, but keep in mind that modeling is more reliable and less limited. When performing an assessment of reliability indicators during modeling, the distribution of the probability of failure or, possibly, the characteristics of the repair activity of the main resource-determining technological equipment and individual elements, functional units of technological equipment should be known.

Analysis of the generalized experimental data and the standard methodology for assessing the technical condition of power equipment before and after repairs and in the period between repairs showed that according to the failure statistics in the main elements of boiler equipment, superheaters evaporative heating surfaces are the most damaged. The reliability of which, first of all, depends on the intensity of heat exchange, the characteristics of burning processes, as well as corrosion processes that lead to wear of the walls of heat-transmitting surfaces. Statistical data on equipment failures for 2013–2020 were summarized to perform calculations based on the developed methodology for assessing and complex forecasting the reliability of boiler plants and steam turbines (the results are presented in Figs. 3– 6). On this basis, reliability indicators (probability of failure-free operation) of equipment are calculated separately for all types of steam boilers and turbines and comprehensively for the studied types of thermal power plants TPP_1 and TPP_2. Figure 3 shows the dependence of the probability of failure-free operation on the type (station number) of the steam boiler of a thermal power plant.

The calculation results presented in Fig. 3 show that all the considered steam boilers, according to statistical data, have a failure-free operation level of more than 0.984. In contrast, boiler installations Nos. 5–9 correspond to a failure-free operation level of more than 0.995. In turn, it should be noted that the use of simulation modeling methods makes it possible to determine and predict the reliability indicators of technological equipment more accurately.

Figure 4 shows the dependence of the probability of failure-free operation on the type (serial number and electrical power) of the steam turbine of a thermal power plant.

In the calculations according to the developed methods of assessment and forecasting of indicators of reliability of the main equipment of thermal power plants shows that the methods of numerical studies based on

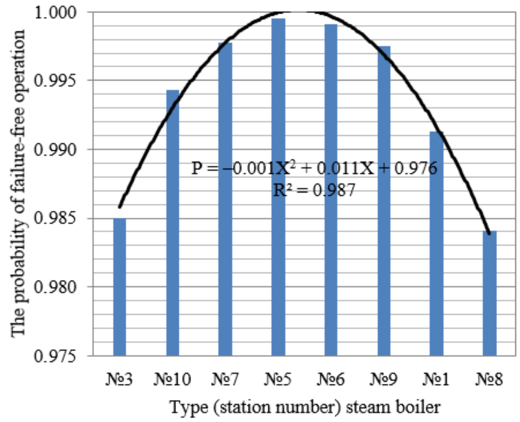

Figure 3: Dependence of the probability of failure-free operation on the type (station number) of the steam boiler of the thermal power station TPP_1.

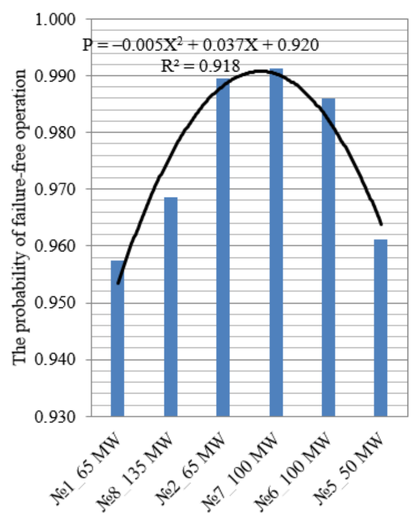

Figure 4: Dependence of the probability of failure-free operation on the type (station number and electric power) of the steam turbine of the thermal power station TPP_1.

simulation through the use of Monte-Carlo allow obtaining an adequate probabilistic characteristic of failures of the main power equipment of the TPP. According to the calculated estimates, the probability of failure-free operation of steam boilers and turbines TPP_2 was 0.963, the probability of failure is 0.037. The probability of failure-free operation of steam boilers and turbines TPP_1 made 0.819, the probability of failure is equal to 0.181. In particular, the probability of failure of steam boilers specified thermal power plants amounted to 0.950, and the probability of failure-free operation of steam turbines is equal to 0.862. For the main equipment of TPP_2, the following results were obtained: the probability of failure-free operation of steam turbines is 0.965, and for steam boilers – 0.996. Thus, the probability of failure of the main equipment TPP_2 in the studied range of technical characteristics is from 0.32% to 3.22%. It should be noted that the steam boilers considered in work have a capacity of 420 t/h. It should be noted that the paper considers statistical data on technological failures of steam turbines, which are widely used in the energy sector. The specified technical steam power equipment has an electric capacity of 50, 65, 100, and 135 MW. The efficiency of the turbogenerator for the above installations, depending on the type of cooling system, is in the range of 97.8% to 98.5%.

Figures 5 and 6 show the dependences of the probability of failure-free operation and failures of the type of steam turbines and boilers of thermal power plants, obtained based on statistical data and an experiment using a simulation model.

For the entire composition of the studied generating equipment of thermal power plants TPP_1, TPP_2, steam turbines are considered depending on the type, station number, electric power, and the presented steam boilers numbered No. 3, No. 2, and No. 1 have the same design and steam capacity equal to 420 t/h.

In the course of computational research and modeling, it was found that the values of the probabilities of trouble-free operation, determined on the basis of processing statistical data on failures of technological equipment (steam boilers and turbines), range from 0.968 to 0.998 for steam turbines and more than 0.998 for all considered steam boilers (No. 3, No. 2, and No. 1). Thus, compared with the failure probabilities of steam turbines determined by statistical data, the failure probabilities calculated using a simulation model for the presented set of technological objects are 0.963 and 0.967, respectively. The obtained results on the assessment of the probability of failure of steam turbines based on the simulation model give estimates closer to the actual operational parameters, which confirms its adequacy.

The polynomial dependences obtained from the results of processing the experimental data shown in Fig. 5 allow us to predict the probability of

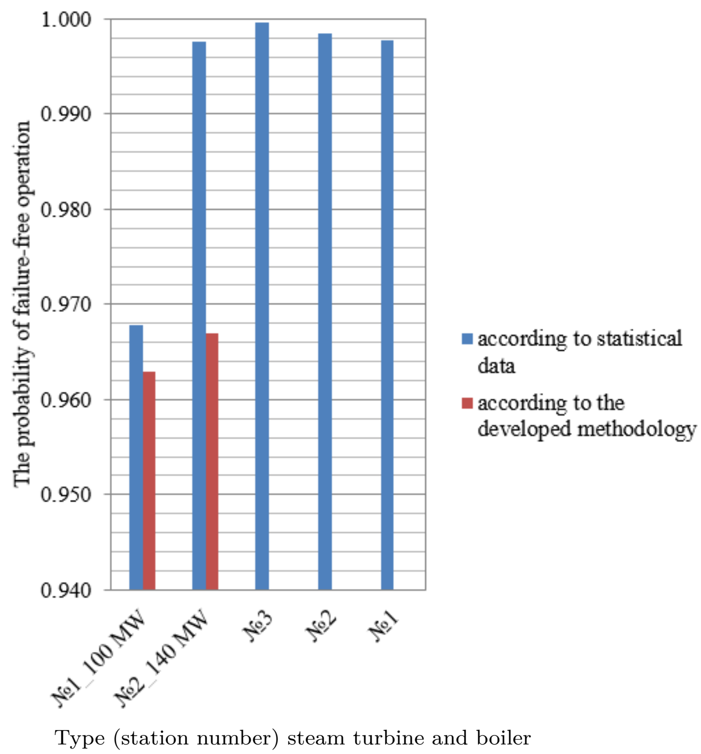

Figure 5: Dependence of the probability of failure-free operation on the type (station number and electric power) of the turbine and steam boilers (No. 3, No. 2, No. 1) of the thermal power plant TPP_2.

trouble-free operation of steam turbines by the equation $P = 0.029X+0.938$ for the coefficient of determination $R^2 = 1$ and boiler equipment by the dependence $P = 0.0009X^2 - 0.002X + 1.001$ at $R^2 = 1$ of the thermal power plant TPP_2.

Note that the predictive polynomial dependencies (Figs. 3 and 4) of the change in the probability of failure of the main equipment from the experiment number (model tests) for the entire set of generating equipment of the thermal power plant TPP_1 are characterized by determination coefficients at the level of 0.987 and 0.918, respectively, which is confirmed by the high representation of the initial statistical data on failures of nodes and systems of the studied power equipment.

Figure 6 shows the dependence of the change in the probability of failure of the main equipment on the number of the experiment (simula-

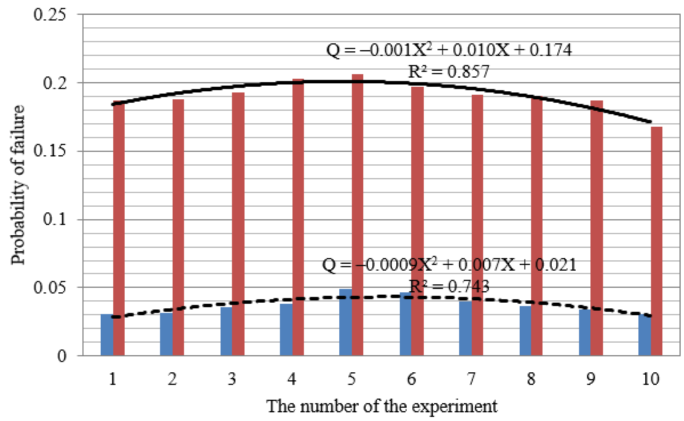

Figure 6: Dependence of the change in the probability of failure of the main equipment on the number of the experiment (simulation model) for the entire population of the studied thermal power plants TPP_1, TPP_2.

tion model) for the entire population of the studied thermal power plants TPP_1, TPP_2.

The analysis of the obtained results showed that the developed method of evaluating reliability indicators allows us to implement a stochastic (random) process, which is formed so that the probabilistic characteristics of the failure of the main power equipment coincide with similar values of the problem being solved. At the same time, the results of constructing distributions largely depend on the formed scenarios of initial parameters and their changes under various conditions of simulation tests implementation, which allows us to apply the obtained simulation results when making decisions on investment repair programs, their ranking, as well as justifying rational sizes and shapes (specific equipment composition) of thermal power plant capacity reservation, taking into account the actual technical condition of generating equipment.

The calculated determination and forecasting of reliability indicators of steam power and generating technological equipment (steam boilers and turbines) mainly allow planning the repair activities of an energy enterprise at a qualitative level, making adjustments, and implementing repair programs for resource-determining power equipment and individual functional units and elements. The polynomial dependences obtained from the results of processing the experimental data shown in Fig. 6 allow us to predict the probability of failure of the main equipment from the experiment number (simulation model) for the entire set of objects of the studied thermal power plants TPP_1 and TPP_2 according to the equation $Q = -0,001X^2 + 0.01X + 0.174$ for the technological equipment TPP_1 and according to the dependence $Q = -0,0009X^2 + 0.007X + 0.021$ for the thermal power plant TPP_2.

Thus, it should be noted that the dependence of the change in the probability of failure of the main equipment on the number of the experiment (test) for the entire population of the studied thermal power plants TPP_1, TPP_2 is characterized by determination coefficients at the level of 0.857 and 0.743, respectively. The results obtained are explained by a more representative sample of statistical data on failures of elements and components of the main equipment, as shown in Fig. 6.

4 Conclusions

Every thermal power plant in this era of modern power aims to attain reliability at a high level against sudden failures. Thermal power plant has reliable equipment and units to achieve this subject. The current research proposed a structure for the reliability evaluation of thermal power plants and their predation. The main outcomes are as follows:

1. Formed the base of multivariate statistics that take into account park resources, inter-repair period, failure rate, condition of the metal of steam boilers and turbines. It can be used for further development of predictive models that provide approaches to extend the safety state of the elements of boilers and steam turbines, as well as for the development of digital energy monitoring and diagnostics of the main equipment of thermal power plants, including more effective planning of the repair program.

2. A methodology for assessing and predicting the technical condition of TPP boiler plants based on reliability indicators based on the Monte-Carlo simulation method were developed. At the same time, the developed method specified the failures of specific elements of boiler equipment, primarily those characterized by low reliability, such as radiation superheaters and evaporative heating surfaces, economizer sections, and for steam turbines, such nodes were elements of the flow part, bearings, oil system, steam distribution system, pipelines and fittings, failures without damage and other elements, which allows for

timely diagnosis of failures and their elimination. It can also determined the reliability indicators of boiler plants and steam turbines of thermal power plants according to the actual technical condition.

3. On the basis of generalization of experimental data on failures of elements and units of the main generating equipment of TPP, mathematical correlation polynomial dependencies were developed to predict the probability of power equipment failure depending on the specific type of steam boilers and turbines.

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