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ASSESSMENT OF RELIABILITY AND TECHNICAL RISKS IN THE OPERATION OF HEAT ENGINEERING UNITS

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A method for assessing technical risks arising during the operation of heat engineering units is presented. Risk assessment is based on the data on the residual life of the unit's lining and an evaluation of the severity of the consequences of an accident. To obtain primary data when assessing the residual life, an instrument method is used that allows continuous monitoring of the thermal state of the lining. Thermomechanical stresses exceeding the ultimate strength of the material are shown to be the determining destruction factor. These stresses are calculated according to the developed scheme based on numerical methods.

Keywords: reliability, accident risk, unit lining, residual lining life.

During the operation of heat engineering units, their reliability and safety are maintained through professional training of maintenance personnel, maintenance and (or) repair operations, as well as implementation of automation systems. All this requires signficant time and financial resources. Repair, modernization, and introduction of new structural and technological solutions contribute not only to maintaining the specified level of reliability and safety of units, but also to extending their service life.

The degree of technical risk is an important indicator of the reliability and safety of equipment. Technical risk evaluation allows repairs to be conducted with maximum efficiency, thereby preventing accidents. It is important to assess technical risks during unit operation in order to estimate its condition at a given moment in time. This approach increases the reliability of the entire risk assessment procedure.

In this paper, we propose a methodology for assessing technical risks during unit operation based on the residual life of the lining and the severity of accident consequences. The calculation of residual life is carried out taking into account the technological parameters of unit operation, such as thermomechanical stresses, lining heating temperatures, and the strength of the refractory materials used.

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FORMULATION OF THE PROBLEM

Equipment accident is an event consisting in the destruction of equipment accompanied by a possible explosion or release of hazardous substances. The creation of emergency conditions during the operation of heat engineering units is unacceptable, due to the possibility of significant financial losses and injuries to maintenance personnel.

The risk of accidents is often assessed using such a reliability indicator as the residual life of a unit. This quantity is used to estimate the time period remaining until the unit should be withdrawn for repair. Consideration of the reduction in the service life of essential equipment in optimization calculations leads to an increase in economic efficiency of up to 37%. When calculating the most probable capital expenses and fuel costs, the economic effect ranges from 5 to 15% [1].

Evaluation of the residual life of a unit requires, first of all, an analysis of statistical data on its operation. In principle, the duration of unit operation before failure can be calculated based exclusevely on statistical data. However, an analysis of statistical data provides more accurate information that can be used to adjust repair plans, thereby improving the efficiency and safety of equipment usage.

Currently, the analysis of statistical data is performed as the initial stage of different methods for estimating the residual life of equipment [2]. Literature sources [3, 4] highlight the importance of this stage as a starting point for further calculations. High-quality statistical analysis requires reliable information about the parameters of the equipment, as well as its main components. Statistical data on unit operation may lack necessary analytical information (e.g., the required parameter is not measured, no primary sensors operate, secondary devices operate in visual inspection mode without registration, etc.). Therefore, the application of statistical data without its detailed analysis produces high errors in the estimate of residual life, since such data cannot reflect actual conditions at a given time.

Among the methods available for assessing the residual life of equipment, which are based on statistical analysis, the following three main directions can be distinguised: physical simulation, mathematical simulation, and online measurement of technological parameters.

Physical models are widely used to simulate operating conditions in heat units. Such models enable estimation of the efficiency of different refractories for the lining of a particular heat unit. Dynamic studies of several types of refractory products can be carried out in a single experiment to comparatively analyze their perfomance in a specific aggressive environment [5]. The obtained information for assessing the refractory material wear is characterized by sufficiently high accuracy and can be used in a number of units, e.g., converters, steel-pouring ladles, blast furnace chutes, etc. [6].

However, the use of physical models for assessing equipment reliability and technical risks is associated with the two main disadvantages. The first consists in the difficulty of considering the constantly changing operating factors that arise during the operation period of a particular unit (e.g., variations in the melt temperature). The second consists in the difficulty of accurate representation of actual production processes in a model, which fact distorts the validity coefficients for upscaling and introduces errors in the obtained results.

Mathematical modeling is the most widely used method at all stages of reliability and technical risk assessment, including statistical analysis, evaluation of operational technological parameters, and risk assessment. Among the positive aspects of mathematical modeling are the high accuracy of the results obtained and the availability of software applications for different purposes [7]. According to [8], the use of nonlinear models with multiple uncertainties can serve as a reference for monitoring the wear of cylinder liners and predicting their service life. The reported model exhibited good performance characteristics with an error ranging within 5%.

The advantages of mathematical modeling also include the possibility to correct the results by obtaining data online. The software applications developed thus far enable online monitoring of the conditions and emergence of structural damages, at the same time as avoiding their false identification [9].

The publication [10] reported the calculaton of the local stress-strain state of unit elements to assess their thermomechanical life cycle. It was shown that the characteristics determined for the model object should be compared with the corresponding durability specification developed on the basis of the results of thermomechanical fatigue tests. It is important to note that mathematical modeling is not intended for a complete and comprehensive determination of residual life, but rather a tool to adress a number of issues in this process.

Modern technologies provide the possibility of online monitoring of the technical condition of equipment. The most important technological parameter for assessing the residual life of a heat unit is the thickness of the lining. This parameter can be measured online, either directly or indirectly. The direct measurement method involves direct control of the lining thickness by means of regular inspections using special equipment. Such methods include acousto ultrasonic-echo technique (AU-E), electromotive force (EMF), chemical analysis, scanning electron microscopy, energy-dispersive spectroscopy (SEM-EDS), and x-ray diffraction (XRD) [11 – 13].

The acousto ultrasonic-echo (AU-E) method [14] measures the thickness of refractory layers and deposited material due to the propagation of tension waves. This method is used to determine the refractory thickness and to detect anomalies (cracks, gaps, metal penetration into the lining). By combining the data from AU-E and temperature measurements performed using thermocouples, it is possible to estimate the warning temperature at which the lining reaches its minimum permissible thickness. Industrial research has shown that the AU-E method is capable of estimating the thickness of refractories, as well as the growth and localization of cracks or anomalies, with an accuracy of 4 – 7%.

At the same time, the direct measurement method evaluates accurately only the actual condition of the lining, rather than its residual life. The main disadvantages of the direct measurement method consist in the high cost and complexity of operations; thus, simpler and cheaper measurements that can indirectly assess the thickness of the lining appear to be more preferrable. Such methods determine the parameters of both lining [15] and the entire technological process [16] by means of temperature measurements performed at different points of the unit. Indirect estimation of the lining residual life can be carried out according to different parameters. For example, the study [17] assessed the impact of reduction in steel temperature on the ladle life in a single duty cycle. The error of the method was estimated at 11%.

Therefore, from all of the above, it can be concluded that both direct and indirect methods can be used to accurately assess the wear of refractory material online. However, the information obtained by these methods is only an intermediate step when assessing equipment reliability and technical risks. The next step involves assessment of the risk of unit failure.

The HAZOP (hazard and operability study) method is widely used to analyze the hazard level and operability of units, which consists in specification and identification of problems with the hazard and operability of the system [18, 19]. These methods are used to perform risk assessment taking into account the technological parameters of equipment with high presision in a short period of time. The key factor is the proper compilation of evaluation criteria for this equipment, allowing the exceedance of critical values of these parameters to be avoided [20, 21].

Hence, the methodology for assessing the reliability and technical risks during the operation of heat engineering units should include the following stages:

– assessment of the impact of equipment technological parameters on the wear rate of that part that determines the reliability of equipment operation. The lining was selected as such a part, as determining the duration of the operation period, as well as the frequency and duration of repairs. Assessment of the impact of technological parameters should be carried out for each unit type separately, taking the specifics of its operation into account;

– calculation of the actual wear rate of the lining, taking into account the technological parameters of unit operation on the basis of mathematical simulation. The lining wear rate should be adjusted in accordance with statistical data on the operation of a given unit;

– assessment of technical risk, considering the severity of accident consequences. A slight destruction of the lining on a boiler unit operating under vacuum results only in a decrease in the efficiency of its operation. However, a similar destruction of the lining of a steel-melting furnace can lead to immediate shutdown of the unit, significant material costs for repair (given that repair of nearby equipment is also possible), as well as possible injuries to personnel.

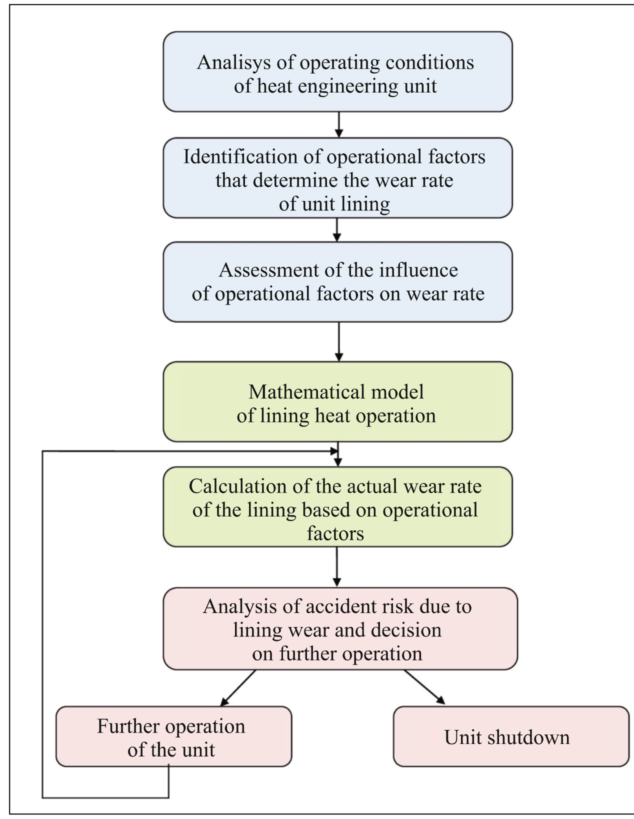

Fig. 1. Scheme of the method for assessing equipment reliability and technical risks during operation of a heat engineering unit.

METHOD FOR RELIABILITY AND TECHNICAL RISK ASSESSMENT

The analysis of the technological operation of heat engineering units allowed us to distinguish those parameters that affect the wear rate of the lining:

– thermomechanical stresses emerging in the lining during its heating and cooling;

– the maximum temperature of the lining during operation;

– thermomechanical characteristics of the refractories used;

– the level of acidity (basicity) of the slag used;

– the residence time of melt in the unit.

During the lining operation, the actual loads and thermomechanical stresses differ from the calculated ones, being crucial for the duration of the lining operation period [22, 23]. Technological parameters, measured online, are used to assess reliability indicators. Temperature measurements provide the basis for calculating thermomechanical stresses, which are used to evaluate the technological parameters of unit operation by the indirect method.

Thus, the assessment of equipment reliability and technical risks during unit operation consists in the following. At the first stage, a numerical evaluation of the parameters determining the wear rate of the lining is carried out, based on the analysis of the technological parameters of unit operation. At the second stage, the correction factor and actual wear rate of the lining are calculated based on a mathematical model of the lining heat performance, taking the technological parameters into account. At the third stage, the data obtained are used to analyze the risk of the entire unit failure due to the lining failure (taking into account the severity of accident consequences). If the risk of an accident has been rated as minor, then recalculation of the actual wear rate of the lining is performed using the refined technological parameters. The implementation of the developed method is shown in Fig. 1.

The statistical data on the duration of the lining operation period show significant deviations from the average value. This is due to a number of factors affecting the lining, as well as the specifics of technological processes. Unfortunately, it is impossible to consider all factors in the developed model. The impact of each individual factor on the process of refractory wear can be analyzed on the basis of operational data, provided that only one factor is involved.

The developed method for the assessment of equipment reliability and technical risks during the operation of heat engineering unit in terms of residual life allows continuous monitoring of the thermal condition of the lining and its residual life. The determining factor of destruction is thermomechanical stresses exceeding the ultimate strength of the material, which are calculated according to the developed scheme based on numerical methods.

When a lining material is applied to the unit, temperature sensors are installed at a specfic distance from the inner surface of the lining. The number of sensors and the distance from the inner surface of the lining are selected based on the operational limitations associated with the possibility of accidents (loss of sealing, metal leak, etc.). In the process of determining the temperature fields of the lining using temperature sensors, readings are taken and subsequently temperature fields are calculated from the cross-section of the lining using whatever difference scheme, as well as thermomechanical stresses are calculated based on the developed mathematical model [24].

The calculation stage for the actual wear rate of the lining involving the parameters of unit operation implies the registration of their deviation from the acceptable values obtained in laboratory conditions and incorporated in the calculations [25 – 27]. Then, using the dependence of the residual lining life on thermomechanical stresses, the residual lining life is determined in real time.

In the proposed method, the technological parameters are taken into account by correction coefficients, which depend on the deviation of these parameters from the standard values. These standard values are directly adopted from the technological regulations for the equipment operation or technical documentation for either equipment or materials. As an example, the ultimate strength of the refractory materials used is taken according to the manufacturer specifications.

Let us consider the influence of deviations in technological parameters from the standard values on the correction coefficient values for batch-operated heat engineering units.

Thermal stresses in the lining constitute the determining condition in the evaluation of residual life. Indeed, reduction in the lining thickness due to thermomechanical stresses is the most common cause for the unit to be taken out of service for repair. The value of the correction coefficient ω is estimated by the magnitude of the deviation of thermomechanical stresses from the calculated values (taking the duration of stress action into account):

$$\omega = \frac{\sigma_{exc}}{\sigma_{str}} \times \frac{\tau_{exc}}{\tau_{total}}, \quad (1)$$

where σ_{exc} is the average value in MPa of thermomechanical stresses over the time period in which their values exceed the ultimate strength of the refractory material; σ_{str} is the design (normative) ultimate strength of the refractory material in MPa; τ_{exc} is the time period in minutes during which the values of thermal stresses exceeds the values of the ultimate strength of the refractory material; τ_{total} is the action time period in minutes of thermal stresses in the refractory layer of the lining.

The value of the actual wear rate of the refractory in mm/day is proposed to be adjusted using coefficients that are sensitive to the deviation of technological parameters from the calculated values, according to the following formula:

$$\vartheta_{est} = \vartheta_{calc} K_1 K_2 K_3, \quad (2)$$

where ϑ_{est} is the design wear rate of the working layer of the lining in mm per day; K_1 is the correction coefficient to accommodate for the arising thermomechanical stresses; K_2 is the correction coefficient to accommodate for the maximum temperature during the course of the lining operation; K_3 is the correction coefficient to accommodate for the use of a refractory material with a strength below the rated value.

The estimated wear rate is taken as the average wear rate of the working layer of the unit lining on the basis of statistical data. At the same time, the correction coefficients are determined by the deviation of a technological parameter from its standard value (Table 1).

The value of the correction coefficient to accommodate for the influence of the lining temperature and the strength of the refractories can also be derived from Table 1. For exam-

TABLE 1. Correction coefisient values

Correction coefficient	Value of correction coefficient upon the deviation of technological parameter from the standard value					
	1.5 to 2.0 times	2.0 to 2.5 times	2.5 to 3.0 times	3.0 to 3.5 times	3.5 to 4.0 times	4.0 times and above
K_1 (in case of thermomechanical stresses exceeding standard values)	1.015	1.02	1.03	1.05	1.08	1.10
	0 to 2%	2 to 4%	4 to 6%	6 to 8%	8 to 10%	10 to 12%
K_2 (in case of refractory temperature rising above the temperature limit)	1.01	1.02	1.03	1.04	1.05	1.06
K_3 (in case of refractory strength becoming lower than the standard value)	1.01	1.02	1.03	1.04	1.05	1.06

TABLE 2. Estimates of accident probability due to wear of the lining working layer

Residual life of the lining working layer, % of the full life cycle	Probability, %	Accident risk estimate
100 – 50	Low	1
50 – 30	Medium	2
30 – 5	High	3
≤5	Very high	4

ple, the change in the strength of refractories will be taken into account only when this parameter decreases relative to the standard value. Other parameters, such as acidity (basicity) of the slag, may affect the wear of the lining of a particular unit. In this case, Table 1 can be supplemented with technological parameters and corresponding correction coefficients.

The residual life of the lining working layer n_{lim} as a percentage of the total service life, given the total correction factor, will be determined by the formula

$$n_{\text{lim}} = \left(1 - \frac{\theta_{\text{d}} n}{\delta_{\text{in}} - \delta_{\text{min}}}\right) \times 100, \quad (3)$$

where θ_{d} is the estimated wear rate of refractory materials of the unit lining in mm per cycle; n is the number of cycles (for batch operating units) or days (for continuous operating units) of the unit operation counted from the commissioning of the unit; δ_{in} is the initial thickness of the lining working layer in mm; δ_{min} is the minimum thickness of the lining working layer in mm at which repair is carried out.

Thus, the risk matrix assessment provides quite objective (can include a large number of gradations) and accurate (depends on the correctness of the assessment of threats and damage) results. To eliminate the shortcomings inherent in this method, let us incorporate the value of the residual life of the lining working layer into the assessment of accident probability. This value will provide data online, and will not only account for the equipment wear, but also eliminate the inertia of the assessment. The specifics of unconventional equipment can be taken into account by assessing the probability and severity of an accident.

Based on the available estimate of the lining residual life, a method for analyzing the risks of accidents in heat engineering units due to lining failure was developed. The method comprises: assessment of accident probability due to wear of the lining working layer; assessment of the severity of accident consequences; risk matrix assessment. The assessment of accident probability due to wear of the lining working layer reveals the correspondence of the residual life of the lining working layer (taken from previous calculations) and the numerical assessment of accident probability (Table 2). For example, the probability estimate of 1 implies a low accident probability, which corresponds to the residual life of the lining working layer from 50 to 100%.

TABLE 3. Estimates of the severity of accident consequences

Heat engeneering units	Damage level depending on operating conditions	Estimate of the severity of the accident consequences
Boilers, heating furnaces, sintering machines	Very low	1
Rotary furnaces: calcinating, sintering, rosting	Low	2.5
Converters, electrolysis furnaces	Medium	3.5
Water-cooled furnaces: arc steel, ferroalloy	High	4.5
Mobile mixers, pouring ladles	Very high	5

Estimates of the severity of accident consequences show the correspondence between the design of heat engineering units and conditions of their operation (Table 3).

When assessing the severity of accident consequences, the rating of 1 corresponds to a very low possible damage, which is applicable to accidents on boilers, heating furnaces, and sintering machines. For these units, lining destruction due to wear is not accompanied by the release of a high-temperature working medium and leads only a decrease in the efficiency of the unit. The rating of 2.5 corresponds to units operated outside workshops. The release of the working medium during lining destruction does not threaten to have a significant impact on both the equipment in the workshop and maintenance personnel. The rating of 3.5 differs significantly from the previous assessment due to both use of metal melts in a capacity of a working medium and the operation of units directly in the workshop; the rating of 4.5 corresponds to the possible high damage due to water cooling of the refractory; the rating of 5 with a very high level of damage corresponds to units that move through the workshop with the metal melt inside.

A matrix for assessing the risk of lining destruction of heat engineering units was compiled. The risk degree of lining destruction is equal to the product of assessment of the accident probability with corresponding assessment of the severity of the consequences. For example, the risk degree for rotary kilns with a residual life of 30 – 50% is equal to 5 (Table 4).

It can be seen that the step size for the assessment of accident severity turns out to be uneven. This is due to significant variation in operating conditions and potential risks in the course of different unit operation. The matrix for assessing the risk of lining destruction of heat engeneering units includes four levels of assessment:

TABLE 4. Matrix for assessing the risk of lining destruction of heat engineering units

Estimate of the severity of accident consequences	Estimate of accident probability			
	low (1)	medium (2)	high (3)	very high (4)
Very low (1)	1	2	3	4
Low (2.5)	2.5	5	7.5	10
Medium (3.5)	3.5	7	10.5	14
High (4.5)	4.5	9	13.5	18
Very high (5)	5	10	15	20

- 1 ≤ risk degree ≥ 7: Low. Operation of the unit can continue according to the technical regulations without restrictions;
- 7 < risk degree > 10: Medium. Operation of the unit can continue according to the technical regulations with additional control over the lining condition;
- 10 ≤ risk degree ≥ 19: High. The unit must be taken out for repair in accordance with the technical regulations;
- 20: very high. The high temperature unit must be taken out for repair immediately.

The developed risk matrix for lining destruction of heat engeneering units can be used to decide on the possibility of further operation of the equipment. The basis for such decisions is the numerical values of risk assessment. The calculation of the residual life of equipment based on obtaining data online allows the state of the equipment to be assessed at a given moment of time.

The developed model for assessing equipment reliability and technical risks during the operation of heat engeneering units can be attributed to model predictive control (MPC), which includes the solution of optimal control problem at each sampling interval in accordance with the dynamics of the system. The developed model posesses all features of MPC modelling, including analysis of the current state, selection of optimal control values, application of the first control value only for online control, and analysis reiteration at the next moment in time [28].

RESULTS

An assessment of equipment reliability and technical risks was carried out using the example of a sintering furnace. The operating conditions of the furnace were analazed based on the following initial data for calculation:

– the average duration of the sintering furnace operation before repair — 426 days;

– the thickness of the lining working layer made of compacted fireclay refractories for rotary kilns after overhaul — 200 mm; the minimum acceptable (critical) thickness — 105 mm. The principal wear of the masonry in calcination and sintering areas is chipping due to poor execution of the stopping and cooling of the furnace. Chipping occurs in areas up to several square meters to a depth of 10 – 20 mm (Fig. 2);

– the average wear rate of the furnace lining excluding operational factors — 0.223 mm/day;

– initial conditions: the temperature along the cross-section of the lining before being heated is uniform and amounts to 20°C;

– boundary conditions: on the inner surface of the lining the boundary conditions are of 1st type, on the outer surface of the lining the boundary conditions are of 3rd type.

The dependences of lining temperature variation during heating (Fig. 3*a*) and operation (Fig. 3*b*) were obtained. It can be seen that the temperature rises unevenly when the lining is heated, while the process of the lining thermal operation is accompanied by an almost stationary temperature field.

Based on the data obtained on the temperature change of the lining inner surface, thermomechanical stresses arising during heating were determined. An analysis of the obtained data and technological parameters were used to estimate the correction factors, namely:

– the deviation of operational conditions in terms of thermomechanical stresses equal to 2.4 corresponds to $K_1 = 1.02$;

Fig. 2. Chipping on the inner surface of the lining of a sintering furnace.

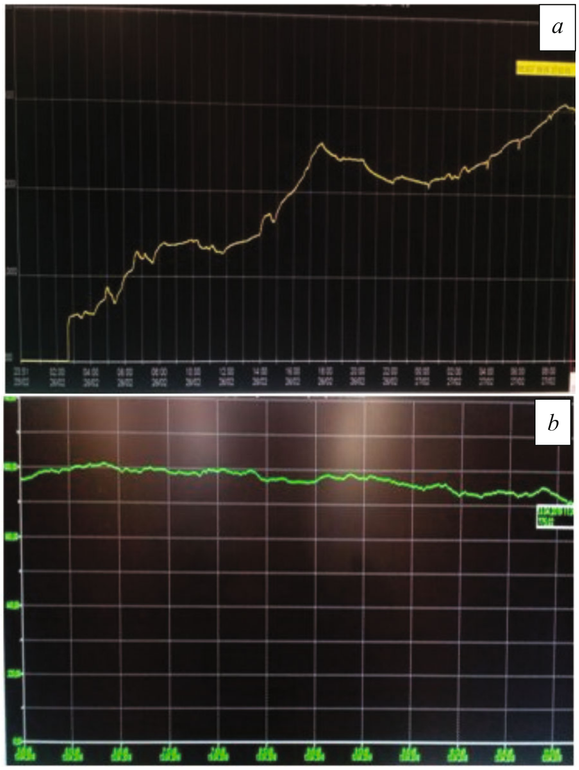

Fig. 3. Lining temperature variation in a sintering furnace.

– the increase in the lining temperature due to the surface exposure to fuel oil corresponds to $K_2 = 1.02$;

– the ultimate strength of the used refractories reduced by 2% corresponds to $K_3 = 1.01$.

The actual lining wear rate amounts to 0.234 mm/day, taking into account the operating conditions and technological parameters. The residual life of the lining working layer (in % of the total service life after 380 days of operation, given the total correction coefficient) will be 6.4%. This corresponds to the final estimate of the severity of accident consequences of 7.5. Therefore, according to the risk matrix, the operation of the unit can continue according to the technical regulations with additional control over the lining condition.

The developed method for assessing equipment reliability and technical risks can be used to determine the duration of furnace operation before the next repair taking into account the actual lining wear rate. To this end, the thickness of the worn refractory layer should be divided by the actual wear rate, taking into account the technological parameters. That said, the duration of the operating period of the furnace amounts to 406 days, which is supported by the operating data.

Let us provide an example of assessing the residual life and accident risk during the operation of another unit, i.e., a 25-t steel-pouring ladle. A preliminary analysis of the initial data on the technical condition gives the following: the maximum number of operation cycles before the overhaul — 42 casts under an average value of 40 casts; the initial thickness of the lining working layer made of periclase refractories — 135 mm; the minimum acceptable thickness of the lining working layer — 75 mm; the rate of the lining thickness reduction — 1.43 mm/cycle; the number of cast cycles at the moment of residual life assessment — 34.

In this case, the change in the rate of refractory thickness reduction is corrected by the following coefficients:

– K_1 is the correction coefficient to accomodate for the arising thermal stresses. Taking into account the emerging temperature stresses, calculated with the implication of the thermomechanical parameter changes: $K_1 = 1.05$;

– K_2 is the correction coefficient to accomodate for the maximum temperature during lining operation. No excess temperature was detected for 30 melts: $K_2 = 1$;

– K_3 is the correction coefficient to accomodate for the use of a refractory material with a strength below rated values. A decrease in the strength of periclase-carbon refractories to 2% was recorded: $K_3 = 1.01$.

The final correction coefficient is 1.0605. According to the developed method, the residual life of the lining working layer amounts to 14.06% of the total service life of the ladle; the probability of accidents is high; the estimated value of accident probability is 3; the assessment of accident severity is 5 (very high possible damage) considering the type of the unit. The risk matrix estimates the risk degree as high, which indicates the necessity to withdraw the unit for repair in accordance with the technical regulations.

The estimate of residual life gives the value of 39 casts, which is consistent with the actual number of casts that the ladle lining has produced (40 casts). This confirms the validity of the developed method. However, when subjected to additional operating factors (without taking them into account), the developed method may produce less accurate results. Nevertheless, this methodology can be recommended for assessing the residual life of equipement and technical risk during its operation using direct measurements of the operating parameters.

CONCLUSION

A method for assessing technical risks arising during the operation of heat engineering units is developed. Risk assessment is based on the data on the residual life of the unit lining and an evaluation of the severity of accident consequences. The calculation of residual life is carried out taking into account the influence of the technological parameters of unit operation, including thermomechanical stresses, ladle heating temperatures, and the strength of refractory materials. The calculation of thermomechanical stresses is performed using data on the lining temperature obtained online.

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