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To cite this article: A Nikiforov *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1032** 012034

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Methodology for assessing the residual resource during the operation of high-temperature units

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Abstract. The article analyses the main methods for determining the residual resource of these aggregates. Considering the imperfection of the above methods for estimating the residual resource, a method was developed for determining the residual resource of the linings of high-temperature units. The main parameters, which influence the residual resource of the lining, were determined during the operation of the units. In order to take into consideration the influence of temperature stresses on the residual resource of the sintering furnace, we examined a schedule for heating the furnace after an overhaul and calculated the temperature stresses that occur during heating and compared them with the acceptable values. Considering the temperature of the working medium, which exceeded the calculated one – was made according to the records of the operation logs. In general, the obtained result reflects a picture of the actual operation of the sintering furnace between its repairs. For its implementation into real operation, it is necessary to combine a number of measuring processes into a single information complex: a continuous measurement of the lining temperatures during heating; a burner performance (from the position of the torch profile and fuel oil spills); the quality of the resulting technological cakes, etc.

1. Introduction

According to the definition, the residual resource of a high-temperature unit is the total operating time of the unit (in the number of hours, smelts, etc.) from the moment of the last control of its condition (or repair) until the moment of reaching the limit state, which is characterized by the equipment shutdown to prevent an emergency or its inexpedient operation.

Thus, the assessment of the residual resource is primarily necessary during the operation and in the supervision of the operation. In the supervision of the operation, the assessment of the residual resource acquires utmost importance, since the trouble-free operation of high-temperature units is directly proportional to the traumatism rate, that is, a threat to the life and health of the enterprise employees.

Moreover, the residual resource assessment is carried out to determine the real residual value of the equipment [1]. The analysis of the specifics of the operation of high-temperature units shows that using the standard values of the equipment depreciation from reference books, it is possible to obtain data on its condition and residual resource that do not reflect the real situation at all.

The important aspect of determining the residual life of the equipment is its operation with parameters exceeding those allowed by the manufacturer. At the same time, even a small period of time when working in off-design modes can significantly affect the duration of the unit's working



campaign. The literature provides data on the study of factors affecting the wear of the lining and the development of operating recommendations to increase the working campaign of the units [2].

The distinctive feature of the lining operation is that for the most part of it, the main reason for taking it out for repair is the unsatisfactory condition of the lining. Lining destruction is mainly caused by thermal activity, and the frequency of the various stages of the wear mechanism depends on the thermal field in the lining [3]. In this case, the residual thickness of the lining reaches a critical value, exceeding of which can lead to the destruction of the enclosing structures of the equipment of the high-temperature unit. As a result, in this article we will consider the operation of those high-temperature units, the preventive maintenance schedule of which is determined by the state of the lining.

2. Formulation of the problem

The problem of determining the residual resource of high-temperature equipment is divided into two components. First, it is necessary to decide on a method for determining the residual resource that is most suitable for a given unit, or to develop our own method. Secondly, it is planned to determine the parameters of the factors affecting the wear of the lining, which must be considered when determining the residual resource by any method.

3. Theory

A wide range of industrial high-temperature units supposes a significant number of methods for determining the residual resource of these units, taking into account the specifics of the operation of a particular unit. In this connection, we carried out the following gradation of the above mentioned methods.

First, it is the determination of the residual resource by the method of expert assessments. The method involves the participation of highly qualified specialists (experts) in the field of operation of high-temperature units to assess the current state of the unit according to the developed scale. The scale does not have a digital expression and, as a rule, contains no more than five forms of the equipment state, such as HAZOP [4]. The experts make their judgments on the basis of either their personal inspection of the equipment or an inspection report. The method is also widely used to analyze the hazard of an accident in the design of industrial facilities.

The use of the expert assessment method has a number of advantages:

- there is no need to use complex mathematical tools;
- the installation of additional measuring equipment is not required on the analyzed high-temperature units;
- the simplicity of the method, which allows the expert to carry out work to determine the residual resource without long preliminary preparation.

Among the significant disadvantages, the following can be distinguished: the subjectivity of the expert in assessing the technical condition of the equipment is possible, which can arise both as a result of a mistake of the expert himself and as a result of the impossibility to assess the condition of the equipment without using additional diagnostic tools (or measurements during the operation). An additional disadvantage is the limited choice of forms of the equipment state, since the actual state of the equipment may not be fully described by the chosen form.

Secondly, this is the determination of the residual resource by the calculation method. This is a classic method according to which the residual resource is determined by the statistical data: the operating time of the equipment after the last repair, mean time to failure (MTTF) and others [5].

The method can give adequately accurate values when the unit is operating without significant changes in the operating parameters, a wide volume of constantly updated data for a given high-temperature unit when calculating MTTF, no significant changes in the material design, materials used, etc.

The lack of accurate data on MTTF, as well as the presence of non-stationary operating modes, which significantly affect the wear of the unit elements, reduces the reliability of calculating the residual resource.

Thirdly, these are instrumental methods for determining the residual resource [6]. In the literature, they have different names, but the essence of the methods is as follows. During the operation of the equipment, the necessary parameters are measured; their mathematical processing is made, taking into account the available statistics (for determining and constant correction of MTTF). Further, during the operation, the residual resource of the unit is determined.

These methods include the following [7]:

- assessment of the residual resource by the loading cycles;
- diagnostics of the residual resource of the equipment by changing the parameters of its technical condition;
- residual resource assessment by changing the technological parameters;
- diagnostics of the residual resource according to the development of corrosion damage;
- residual resource assessment based on the changes in the quality indicators and the equipment performance;
- residual resource assessment based on the equivalent operating temperature;
- residual resource assessment based on the given stresses and equivalent pressure;
- residual resource assessment by the load asymmetry coefficient.

It is worth noting the high reliability of the results obtained (when using measurements on the operating equipment). The disadvantages include the use of a significant number of sensors, as well as taking into account a limited number of parameters when assessing the residual resource by any of the methods.

Thus, based on the analysis of the existing methods for determining the residual resource, the following conclusions can be made. The most preferable is the instrumental method, which makes it possible to assess the residual resource with a sufficiently high accuracy directly during its operation. The application of this method supposes not only the presence of a significant amount of initial data measured on-line, but also the corresponding mathematical apparatus for their processing.

Taking into account the main disadvantage of the instrumental methods for assessing the residual resource - a limited number of parameters in its assessment, one more method was developed for determining the residual resource of the lining of high-temperature units, the essence of which is as follows.

Let us select the parameters that determine the residual resource of the lining:
 the magnitude of the arising temperature stresses exceeding the ultimate strength of the used refractory materials and their duration;
 the excess of the smelt temperature over the calculated value and the duration of contact of the smelt with the lining;
 acidity (or basicity) of the slag exceeding the calculated value and the duration of the influence of the slag with the acidity (or basicity) of the slag exceeding the calculated one;
 other factors.

The above parameters can be quantified to determine the residual resource of the lining, including directly during its operation.

In the developed method, the value of the wear rate of refractory materials of the lining of high-temperature units is proposed to be adjusted by coefficients that take into account the deviations of the operating parameters from the calculated ones according to the following formula:

$$K_B = \frac{B_{exc} \cdot \tau_1 + B_{calc} \cdot \tau_2}{B_{calc} \cdot \tau_{total}}, \quad (1)$$

where B_{exc} – a parameter the value of which at a given time exceeds the calculated value;

B_{calc} – a calculated value of the considered parameter;

τ_1 – time (duration) of the effect of the parameter B_{exc} , h;

τ_2 – time (duration) of the effect of the parameter B_{calc} , h;

τ_{total} – the total time (duration) of the effect of the parameter B on the lining, h.

The product of the correction factors will give a general correction factor, which will show how much the mean time to failure (MTTF) decreases.

For a number of units, a more important indicator is the value of the wear rate of refractory lining materials per unit of time (or per one smelt), taking into account the deviation of the operating parameters from the calculated ones and is determined by the formula, v_{exc} , mm / smelt:

$$v_{exc} = v_{calc} \cdot K_{\sigma} \cdot K_t \cdot K_A, \quad (2)$$

where v_{calc} – the design rate of the wear of refractory materials of the lining of casting ladles, mm/smelt;

K_{σ} – the accounting factor for the magnitude of the arising temperature stresses;

K_t – the accounting factor for the excess of the smelt temperature over the calculated value and the duration of contact of the smelt with the temperature exceeding the calculated value;

K_A – the accounting factor for the acidity (or basicity) of the slag exceeding the calculated value and the duration of the influence of the slag with the value of the acidity (or basicity) of the slag exceeding the calculated one.

In this case, the residual resource n_{exc} (in the number of smelts), taking into account the correction factor for any moment of time, will be determined by the formula:

$$n_{np} = \frac{\delta_{ini} - \delta_{min}}{v_{exc}}, \quad (3)$$

where δ_{ini} – initial lining thickness, mm; δ_{min} – rejection thickness (the minimum lining thickness at which the lining on the casting ladle changes), mm.

Consequently, the method for determining the residual resource is as follows. Based on the statistical data, the parameters influencing the value of the lining residual resource are determined. Further, according to various methods, the calculation (or measurement) of the digital values of the selected parameters is performed. A number of parameters require initial temperature data, which must be recorded during the operation of the equipment. For this purpose, during the construction of the lining of thermal units we propose to install temperature sensors in the lining at specified distances from its inner surface. The number of sensors and the distance from the inner surface should be selected according to the operational limitations connected with the possibility of emergency situations (leakage, metal leakage, etc.) [8].

To take into account the parameter "the magnitude of the arising temperature stresses exceeding the ultimate strength of the used refractory materials and their duration", the calculation of the temperature stresses is performed based on the data obtained (temperature distribution). These values of the temperature distribution (when determining the temperature of the inner surface of the lining) can be used to determine the parameter "excess of the smelt temperature over the calculated value and the duration of contact of the smelt with the temperature exceeding the calculated value with the lining." Then, after calculating the correction factors, the residual lining resource is determined.

The implementation scheme of the developed method is shown in figure 1.

The developed method for determining the residual life of high-temperature equipment allows continuous monitoring of both the thermal state of the lining and its residual life. In this case, one of the determining factors of the destruction - temperature stresses exceeding the ultimate strength of the material – are calculated according to the developed scheme based on numerical methods.

4. Experimental results

Let us determine the residual life of the sintering furnace lining based on the developed method.

Sintering furnaces are rotary drum kilns, where gases, brickwork and processed material participate in heat exchange, but due to the rotation of the furnace and the movement of the material, the heat exchange scheme is complex. The material receives heat from both sides. The open surface of the material receives heat from the gases by radiation and convection, and from the brickwork – by radiation. The closed surface of the charge receives heat from the brickwork of the furnace by radiation through a thin gas layer that separates the material from the brickwork. The heat from the surface layers into the deeper, inner layers is transferred during mixing of the material by pouring and moving it; therefore, the issue of heat distribution into the depth of the material layer for these furnaces is solved very simply, regardless of the heat transfer process.

A special feature of the furnace is its length – 100 meters, of which 90 meters are lined with fireclay bricks. This feature imposes a limitation on the heating rate of the furnace. Due to the fact that at high heating rates the elongation of the furnace body with the coefficient of the thermal expansion of steel is $10 \cdot 10^{-3} \text{ m} / (\text{m} \cdot ^\circ\text{C})$ and the elongation of the brickwork along the working surface of a brick is $5 \cdot 10^{-3} \text{ m} / (\text{m} \cdot ^\circ\text{C})$, a situation may arise when the steel of the furnace body will not “keep pace” with the expansion of the lining fireclay. Thus, the heating rate must be selected so that the temperature on the inner surface of the lining during the entire heating process does not exceed the temperature on the outer surface of the lining by more than two times.

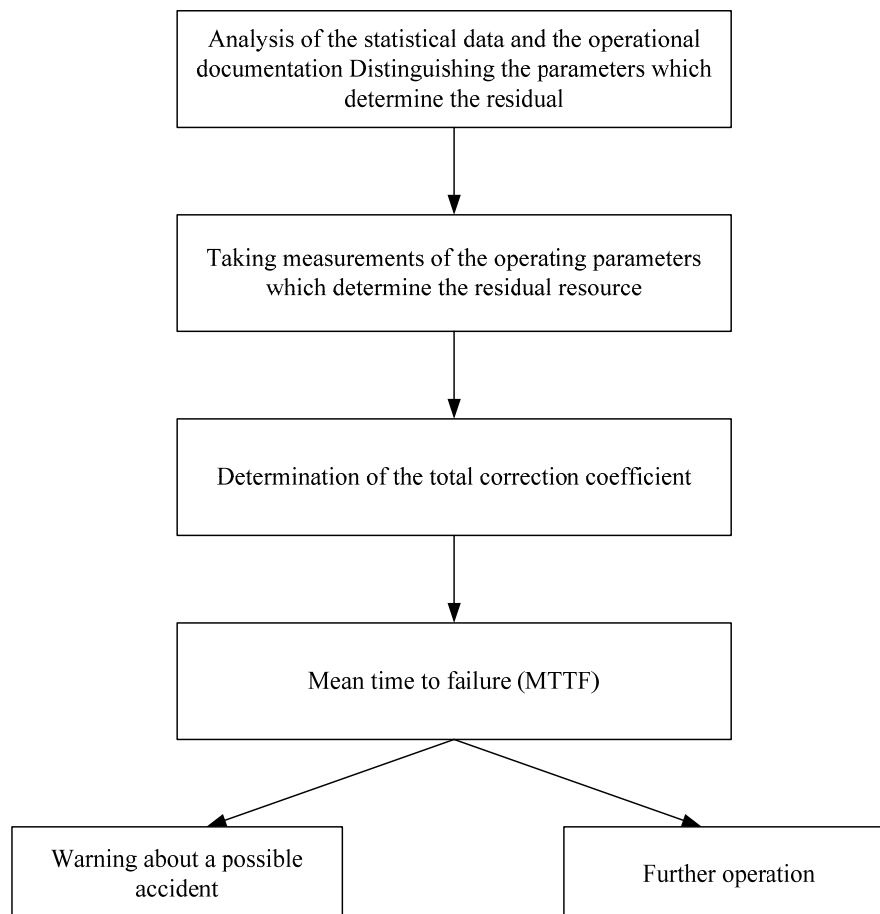


Figure 1. Diagram of the methodology for determining the residual service life of high-temperature equipment.

The initial data for the calculation will be as follows. The duration of the working campaign of the furnace before the overhaul is 48 months. After that, the furnace is shut down for the overhaul within 45 days. Periodically, during the operation of the furnace between major overhauls, it becomes necessary to carry out routine repairs (30 days), which consist in replacing part of the lining. The frequency of current repairs depends on the operating conditions and can be equal from once every three years to once a year.

Analyzing the parameters, the deviations of which during the operation of the sintering furnace can lead to an increase in the wear rate of refractory lining materials, the following can be distinguished:

- temperature stresses from high rates of temperature rise during heating (after the overhaul) and cooling (during current repairs);
- working medium temperatures exceeding the calculated ones. In this case, this factor can be justified, firstly, by the spillage of the fuel oil on the lining during the heating process; secondly, a high sintering product temperature. The effect of the high temperature of the

sintering product can be ignored due to the formation of a skull on the inner surface of the lining;

- a collapse of the skull and exposure of part of the lining to the flame of the torch. The influence of this factor is possible if the torch profile is incorrect (for example, the high temperature at the torch root can lead to the collapse of the front rings of the skull), which can be taken into account in calculations based on the sintering product quality. The analysis of the sintering product quality during the furnace operation after the overhaul shows that this factor can be neglected;
- chemical effect of aggressive working environment on the lining. We do not take into account this point, similar to the previous point.

Due to the large length of the furnace, the effect of the torch radiation and the significant effect of temperature stresses do not take place on the entire length of the furnace, but only on the first zone about 5-15 meters long. This is the zone: starting from 4-5 meters to 20-30 meters from the hot edge of the furnace. More than 95 % of all the furnace emergency shutdowns and current repairs are related to the lining of this zone. All the measurements and calculations given in the work refer to the lining of the zone from 5 to 20 meters from the hot edge of the furnace.

To take into account the influence of temperature stresses on the residual life, it is necessary to consider the heating schedule of the sintering furnace after major repairs, as well as to calculate the temperature stresses arising during heating and make their comparison with allowable values.

Let us consider the heating schedule for a high-temperature unit (a sintering furnace) (figure 2).

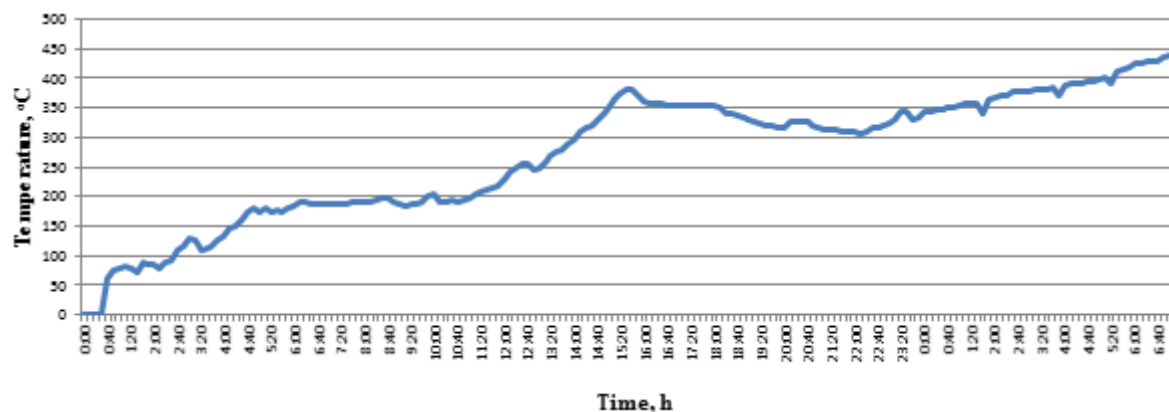


Figure 2. Heating schedule of the sintering furnace after the overhaul.

The heating graph shows that from 0 h 30 min to 1 h 10 min there is a jump in temperature, the average heating rate is 2 °C / min. After that, the heating rate is 0,44 °C / min up to 4 hours 40 minutes. Then a temperature exposure (shelf) is carried out for 6 hours 30 minutes. Then the heating temperature is raised at an average rate of 0,61 °C / min to the temperature of 381 °C, after which an exposure (shelf) is again made for relaxation of temperature stresses for 13 hours. And at the end of the heating process, the temperature is raised by 0,27 °C / min to the temperature of 438 °C.

Let us calculate the temperature fields in the lining of the sintering furnace based on the available heating schedule according to the method described in [9]. At the known temperatures along the lining cross section, we find the values of temperature stresses. When heated from the average temperature, in the high-temperature section a compression stress (σ_{compr}) arises, whereas in the low-temperature section a tensile stress (σ_{tens}) does.

Compression and tensile stress graphs are shown in figure 3. The compressive strength of the material used is 25 MPa; the tensile strength is 5 MPa. For clarity, compressive and tensile strengths are shown as horizontal lines.

The calculations show that the heating process is carried out at speeds exceeding the allowable level. Thus, the maximum value of the compression stress at the time 0 h 40 min is 1,4 times bigger than the allowable value. According to the tensile stresses, there are seven periods in which the arising

tensile stresses are higher than the allowable level, while the maximum tensile stress at the time 0 h 40 min is 3,2 times bigger than the allowable value.

Next, we will take into account the second factor - the temperature of the working environment exceeding the calculated one, according to the records of the operating logs. On this furnace, the fuel oil spillage was recorded on the inner surface of the lining during the heating process due to the unstable operation of the nozzle. Let us estimate the duration of the impact of the burning fuel oil on the lining as 20 minutes. In the process of the furnace operation until now (within 18 months), the sintering temperature has not exceeded the calculated one.

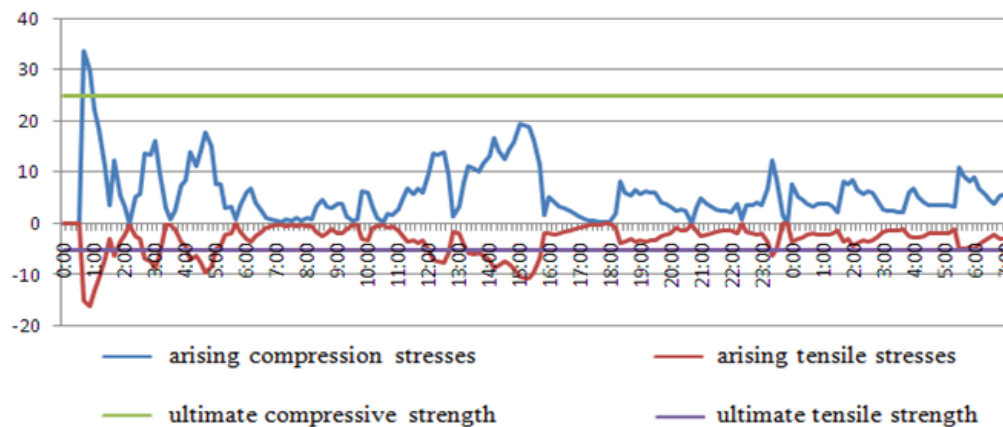


Figure 3. Arising temperature stresses.

The analysis of the sintering product quality during the furnace operation after a major overhaul shows that there were no significant deviations in the quality of the product for 18 months, in accordance with which we do not consider the effect of the flame of the torch and the aggressive working environment on the part of the lining.

We calculate the residual resource of the sintering furnace lining using two correction factors: K_σ and K_t .

The coefficient of accounting for the magnitude of the arising temperature stresses K_σ , we find by the formula:

$$K_\sigma = \frac{\sigma_{exc} \cdot \tau_1 + \sigma_{calc} \cdot \tau_2}{\sigma_{calc} \cdot \tau_{total}},$$

where σ_{exc} – the average value of stress, which for the considered period of time exceeds the allowable one according to the operating conditions of the lining, MPa;

σ_{calc} – the tension value allowed under the conditions of the lining operation, MPa;

τ_1 – the length of time during which the tension value exceeded the allowable one according to the operating conditions of the lining, h;

τ_2 – the length of time during which the tension value did not exceed the allowable one under the operating conditions of the lining, h;

τ_{total} – duration of the action of temperature stresses on the lining, h.

For calculations, the arithmetic mean value of the stresses in the considered time interval was used with a time step of 10 minutes.

Let us calculate the values of the correction coefficients separately for the compression stresses K_σ^{comp} and tensile stresses K_σ^{tens} , which are equal to 1,0029 and 1,13, respectively.

The accounting factor for the excess of the temperature of the medium over the calculated value of K_t and the duration of the contact of the medium with the temperature exceeding the calculated value is found by the formula:

$$K_t = \frac{t_{exc} \cdot \tau_1 + t_{calc} \cdot \tau_2}{t_{calc} \cdot \tau_{total}},$$

where t_{exc} – the average temperature value, which for the considered period of time exceeds the allowable one according to the operating conditions of the lining, °C;

t_{calc} – temperature value which is allowable under the operating conditions of the lining, °C;

τ_1 – the length of time during which the temperature value exceeded the one allowed by the operating conditions of the lining, h;

τ_2 – duration of time during which the tension value did not exceed the allowable one under the operating conditions of the lining, h;

τ_{total} – duration of temperature action on the lining, h.

When calculating the accounting factor for the excess of the temperature of the medium over the calculated value of K_t and the duration of the contact of the medium with the temperature exceeding the calculated value, we obtain its value equal to 1,016.

By multiplying the obtained correction factors, we obtain the value of the total correction factor of 1,15. This value shows a 15 % reduction in mean time to failure (MTTF).

5. Discussion of the results

In general, the obtained result reflects a picture of the actual operation of the sintering furnace between its repairs. Exceeding the ultimate strength of the lining material is a determining factor in the operation of rotary kilns. To a lesser extent, the lining resistance is affected by the temperature rise of the lining. This corresponds to the calculations performed: the value of the correction factor for stresses (compression and extension) is 1.133, while the value of the correction factor for temperature is 1.016

For the implementation of the method into real operation, it is necessary to combine a number of measuring processes into a single information complex: a continuous measurement of the lining temperatures during heating; a burner performance (from the position of the torch profile and fuel oil spills); the quality of the resulting sintering products, etc.

In this case, the main problem is to obtain quality data on the operation of the furnace. These data can be obtained by any available and technologically safe method and used to calculate the residual resource criteria. The method can be translated into a computer programming language and, when temperature sensors are connected to a computer, can be used at the workplaces of operators of high-temperature units.

6. Conclusions

A method for determining the residual life of high-temperature equipment has been developed, which makes it possible to calculate the duration of the unit's trouble-free operation during the operation of the equipment. The method is distinguished by simplicity and reliability in calculating temperature stresses and determining the criterion of the residual resource. The use of this method makes it possible to move from a deterministic forecast of the residual resource to its probabilistic assessment, which is the background information for making motivated decisions to improve the reliability and safety of the equipment operation.

Further use of the developed technique will consist in creating a computational complex for assessing the wear rate and residual resource of a number of high-temperature units: arc and rotary furnaces, casting ladles, etc

References

- [1] Lucko G 2003 *A statistical analysis and model of the residual value of different types of heavy construction equipment* PhD thesis (Civil Engineering) Virginia State University and Polytechnic
- [2] Silva S N, Vernilli F, Justus S M, Marques O R, Mazine A, Baldo J B, Longo E, Varela J A 2005 *Ironmaking & Steelmaking* **32**:6, pp 459-467
- [3] Parra R, Verdeja L F, Barbes M F, Goni C 2006 *Furnace Lining Analysis and Design by Mathematical and Physicochemical Modeling Conference: Sohn International Symposium / (Advanced Processing of Metals and Materials: Principles, Technologies and Industrial Practice)* At: San Diego, California, (EEUU), pp 561-576

- [4] Frank C B 2015 *HAZOP: Guide to Best Practice* (Elsevier), p 168
- [5] Sijacki Z V 2015 RCM in power plant practice illustrated on observation of material aging and defining of component life exhaustion *International Conference Power-GEN Middle East /* (Belgrade: University of Belgrade), pp 11-12
- [6] Vengrinovich V L, Vintov D A and Dmitrovich D V 2014 *AIP Conference Proceedings*, 1581 1222
- [7] Kazakov V S and Alekseev A S 2015 *Bulletin of the Bryansk State Technical University* **2** (46) p 32
- [8] Nikiforov A S and Prikhod'ko E V 2005 *Refract And Ceram* **46**, pp 360-363
- [9] Nikiforov A S, Prikhod'ko E V, Kinzhibekova A K, Kucher E O and Niconov G N 2015 *Method for determining thermal liner state of high-temperature unit* KZ 30372-A4 G01K-013/00

Acknowledgments

This research has been funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP08855901).