Problems of Industrial Safety Examination in Modern Conditions and New Resource Evaluation Methodology

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Abstract: A paper presents a fundamentally new approach to the evaluation of health and metal resource potentially dangerous equipment of thermal power stations, based on the identification of patterns of change in the structural-phase state, and the internal stress fields in the long-running metal and welded joints spectrally-acoustic method, taking into account the structural factor. Information about changing the structural state of the metal in the process of long-term operation of heat-resistant steels is given.

Introduction
The technical condition of industrial equipment at many enterprises in Russia does not meet the requirements of the current regulatory documentation. So, according to the latest data of Rustekhnadzor, about 70% of the technical devices of hazardous industrial facilities (TDHIF) have worked out the estimated period. And further operation of such equipment is unsafe. At the end of the last century, an industrial safety examination system (ISE) was created in Russia, using the regulatory framework of which the real state of the TDHIF was assessed and its performance was predicted. However, starting in 2014, a new ISE system was created, which rejected all the methodological developments created earlier (almost 20 years), recognizing them as illegitimate.

According to the requirements of the current regulatory documents of Rustekhnadzor [1, 2] for all technical devices, when performing an expert examination of industrial safety, it is necessary to calculate (estimate) the residual resource. However, nowhere is the methodological approach to this work written out. At present, Rustekhnadzor has not decided on the question of how to consider this resource (estimate). In addition, there is practically no basis for legitimate methodological documents for the technical diagnosis and examination of industrial safety of technical devices, buildings and structures. There are no standards for the dismantling of the base metal and welded joints for various equipment after a long service life. Methodical instructions (normative base) are necessary in order that after carrying out certain regulated diagnostic work, it would be possible to estimate the period of further operation of the equipment (according to the algorithm of work to be performed) and, if necessary, to check (by the customer or the controlling body) the scope of work performed by the expert, That is, at least in the first approximation, the quality of technical diagnosis. In addition, the state criminalized the
experts for the quality of the expertise, not providing it, to a sufficient extent, with legitimate regulatory documentation.

From the foregoing it is clear that the new ISE system is in a "clean" state and, in the absence of a regulatory framework, it is not possible to fulfill the RF laws and the requirements of Rustekhnadzor in the required volume. At present, there is no single terminology of definitions in Russia either, nor is there a single methodological approach to assessing the residual resource, while Rustekhnadzor documents require such work. There are also several definitions of the limiting state [3].

**Theory**

Let us draw your attention to the developments of the leading scientist in the field of strength, safety and the resource of Corresponding Member of the Russian Academy of Sciences prof., Doctor of Technical Sciences Makhutov N.A. and his school in the field of residual resource assessment [4]. Two methods for estimating the residual resource are proposed: - one by the criterion for the formation of cracks; - another according to the criteria of crack resistance.

**Method for assessing the resource by the criterion for the formation of cracks.** The determination of the residual resource is carried out using data on the technical state, obtained by experimental and calculated methods, for the following limit states:

- formation of cracks under cyclic loading;
- development of cracks under cyclic loading;
- the appearance of viscous or brittle fracture in the presence of initial technological and operational cracks.

When calculating the remaining resource, the cyclical, temporary, corrosive and other damages accumulated during the previous operation are taken into account here, as well as the main design, technological and operational factors that change the characteristics of the limiting states. The evaluation of the technical state for the subsequent determination of the residual life of the equipment elements is made by combined experimental and calculated (standard and non-standard) methods. When assessing the technical state by destructive and non-destructive methods, physicomechanical characteristics, the characteristics of the stress-strain state and the characteristics of the state of the crack defects (their depth, length, location and orientation) should be obtained.

Based on the analysis of all the above characteristics, the residual resource is evaluated for the resistance to cyclic destruction.

**Another technique for assessing the technical condition and residual life by crack resistance criteria** is used for critical equipment elements in which defects in the assessment of the technical condition are found to be unacceptable and allowed by the control standards (if any). With a single loading, the remaining life and survivability are determined:

- on critical temperatures of brittleness and minimum temperatures of metal of bearing elements during operation;
- by the critical stress intensity or strain rate coefficients by stress intensity or strain rates for the corresponding design defects and operating stresses.

When determining the residual life, the following criteria are taken into account for the crack resistance criteria: mechanical loads (internal and external pressure, own weight of the product, weight of other elements, reaction of supports, etc.); Temperature effects; Vibration; Seismic loads; Loads of emergency modes; Residual stresses; Nominal strain stresses from mechanical loads, etc.

To assess the residual life of the equipment in accordance with the above methods, it is necessary to have a powerful testing laboratory and a staff of highly qualified specialists. This work is highly specialized and has a high cost. Hence it follows that it is **not feasible to assess the residual resource by these methods for all technical devices**, both technically and economically. These techniques are acceptable for expensive equipment such as oil and gas complexes, where the damage from accidents is maximized.
For the equipment of 2-4 hazard class categories, a large number of resource estimation techniques developed by both industry institutes and individual expert organizations were proposed. Most of them are not approved by the bodies of Rustechnadzor. One of the most important drawbacks of all these techniques is the lack of analysis of the structural-phase state of the metal being diagnosed. Nowhere, except energy, do not take into account the changes that occur in the structure of the metal in the process of long-term operation.

We propose a new methodology for estimating the resource, based on an integrated approach taking into account the structural factor.

Obviously, the total time of safe operation of any equipment consists of the time of operating the equipment up to the moment of examining $\tau_{c.s}$ (current state) of the current and the further operating time of the equipment until the limit state is reached $\tau_{res}$ (residual life).

$$\tau_{ls} = \tau_{c.s} + \tau_{res}$$

(1)

In the metal of equipment that has worked for a long time under difficult stress conditions, often in aggressive environments (before the time of inspection), complex physicochemical and structural changes occur. The structure is the most important index of metal, characterizing its performance. In the memory of the metal, at the time of the diagnosis, all types of thermal effects and loads were detected, to which the metal was exposed, beginning with its manufacture and ending with a certain period of operation (in our case $- \tau_{c.s}$). The main thing is to correctly understand and evaluate these changes. However, the structural-phase state of the metal after running-in ($\tau_{c.s}$) Is one side of the question. On the other hand, to assess the real resource, it is also necessary to take into account macro-defects (sometimes they are permissible, they are often not eliminated, but simply missed) that occurred during the manufacture, repair, operation of equipment during the flow $\tau_{c.s}$. These defects have a significant effect on the reliability of the resource estimate.

At the same time, the current state of the equipment at the time of diagnosis characterizes the coefficient of its current technical condition $K_c$, which can be represented as

$$K_c = f(K_{str.c}, K_{reg}, K_{def}) \rightarrow \tau_{c.s},$$

(2)

where, $K_{str.c}$ – the structural coefficient of the metal in the current state. $K_{reg}$ – the coefficient, which takes into account the operating modes (temperature, pressure (on-load), cyclicity, medium), $K_{def}$ – factor, taking into account the presence of defects in manufacturing, installation and Repair in the main metal and welded joints. $K_{str.c}$ is determined by the nature of the change in the structural-phase state and internal stress fields, the redistribution of the sources of the stress fields and their density. $K_{str.c}$ can be expressed as a function of the structure parameters in the form

$$K_{str.c} = f(\sigma_{in}, \tau, \rho_{\pm}, \rho_{\mu}, d_{gr}, \gamma_{c}),$$

(3)

where $\sigma_{in}$ is the amplitude of the internal stress fields, MPa; $\tau$ – tangential stresses; $\rho_{\pm}$ – the excess density of dislocations; $\rho$ – the scalar density of dislocations; $\mu$ – the density of sources of internal stress fields; $d_{gr}$ is the grain size, mkm; $\gamma_{c}$ – a coefficient that takes into account the size and nature of the distribution of carbide phases in the metal. For each class of materials, engineering methods for calculating the structural coefficient are developed. For the steels most studied by us, a structural criterion is proposed that is worked out on long-term heat-resistant steels at all stages of the life cycle (from the initial state to reaching the limiting state and destruction), which has the following form

$$K_{str} = \left(\frac{\sigma_{in} + \tau}{\mu} + \frac{\rho_{\pm}}{\mu} \gamma_{c} \cdot d_{gr}^{-1/2}\right),$$

(4)

The structural criteria must be determined on equipment that is operated under difficult stress conditions at high voltages and temperatures, under cyclic and shock loads, in corrosive environments during periods of routine maintenance (the date of the diagnostic is specified, and a certain period is worked out).
For the operating organizations, this will be an additional cost, "but the game is worth the candle," because according to this (studied) current state of the equipment, it is possible to estimate the resource and the deadline for reaching the limit state with sufficient reliability.

To assess the real state of equipment, in addition to the structural coefficient, it is necessary to take into account both operating modes, and mounting, repair and metallurgical defects, and accumulated operational defects, and on their basis to choose coefficients. Therefore, to determine $K_C$, it is necessary to determine the values of $K_{reg}$ and with $K_{def}$.

From the operating conditions of the equipment, it can be represented as a coefficient depending on the number of work cycles ($N$), pressure, or load ($P$), temperature ($T$), aggressiveness of the medium ($L$).

Hence, $K_{reg} = K_NK_PK_TK_L$, the numerical values of the coefficients are developed for a specific type of equipment.

$K_{def} = K_{met}K_{rep}K_{ins}$, numerical values of coefficients are developed for the equipment being diagnosed.

As previously stated – $K_C$, the coefficient characterizing the technical state of the object of control at the time of control. Given the preservation of at least the relative constancy of $K_{reg}$ and $K_{def}$ throughout the life of the equipment, in the first approximation can be written

$$\frac{\tau_{res}}{\tau_{c,s}} = \frac{K_{l,s} - K_C}{K_C},$$

Where $K_{l,s}$ – a coefficient characterizing the technical condition of the equipment at the moment of reaching the limit state.

Here the approach is necessary purely individual, but taking into account the level of exploitation and accumulation of defects in similar equipment with close terms of operation. The determination of this coefficient was carried out on the basis of an analysis of operating conditions (the coefficients $K_{reg}$ and $K_{def}$ were determined). The structural coefficient of the limiting state is estimated from the results of a study of the base metal and welded joints of equipment that has exhausted its life. From (5), after carrying out small transformations and substituting the results of calculations and studies into the formula, we obtain the desired result – the residual operation time of the equipment.

$$\tau_{res} = \frac{\tau_{c,s}(K_{l,s} - K_C)}{K_C}. \quad (6)$$

At present, a database of equipment for the fuel and energy complex of Kuzbass is being created, and a large amount of research is needed to study the mining equipment. The proposed methodology has a significant drawback, consisting in the difficulty of defining structural criteria. It is necessary to perform non-expensive electron microscopic studies.

Results and its discussion

There are several ways to free yourself from this shortcoming. The most promising is the development of non-destructive physical methods for assessing structural changes. For a number of steels (such as Cr-Mo-Va), we have developed acoustic and magnetic structural criteria for the evaluation of damage. So, for example, for a base metal and welded joints of steam pipelines, a complex acoustic criterion of the limiting state has been developed, which allows to determine the resource of a technical device with respect to the delay time of surface acoustic waves (SAW). The criterion is based on the regularities of the change in acoustic characteristics as a function of the structural-phase state of the metal and the amplitudes of the internal stress fields. On the example of two destroyed bends (bent sections of a steam pipe) made of 12H1MF steel (Fig. 1), curves for the distribution of the SAW delay time and the amplitudes of the internal stress fields were experimentally studied. As a non-destructive testing equipment (NDT), a multifunctional highly sensitive information and computing complex ASTRON was used. The study of the nature of the microstructure, measurement of internal stress fields
was carried out in the same areas where the SAW delay measurement was performed by the spectral-acoustic method.

In the bend "A" at a distance of 28–33 mm from the main crack from the outer surface revealed a secondary crack parallel to the main. The study was carried out in the zone of the end of the secondary crack. The average amplitude of curvature-torsion and the density of the extinction contours decrease with increasing distance from the shores of the main cracks, and in the "A" bug again increase at the secondary crack. Local internal stress fields (bending-torsion) are large, approaching the limit of strength and exceeding it; They can (with prolonged use) lead to the initiation of microcracks on the surface of the metal, their fusion, and the formation of main cracks. In the zone of the end of the secondary crack (bend "A"), an increased level of internal stresses and delay time of the surfactant (curve 1, 3, fig. 2) is recorded. In the "B" bend, these characteristics change monotonically from the rupture zone (curve 2, 4, fig. 2). It can be seen from the graphs (Fig. 2) that with increasing local internal stress fields (average curvature-torsion of the crystal lattice), the delay time of the surfactant increases, which is explained by the weakening of ultrasonic oscillations at the sources (concentrators) of internal stress fields [13, 14]. Sources, a decrease in the curvature-torsion of the crystal lattice, and the magnitude of local internal stress fields, the degree of attenuation of ultrasonic oscillations decreases and the delay time of the SAW drops [5–7]. The uniformity of the curves for changing the delay time of surfactants and changes in the amplitudes of internal stresses indicates the existence of a connection between these characteristics and the high sensitivity of the method of acoustic structuroscopy.

![Fig. 1. General type of destruction:](image)

Fig. 1. General type of destruction:

a – the character of crack opening – bend A (gap length – 2.1 m);

b – end of a crack in the section of the tube – bend B

It is established (Fig. 3) that, as the long-term strength of heat-resistant steels decreases, the delay time of the surfactant increases due to an increase in the density of sources of internal stress fields and their amplitudes. The maximum tensile strength of the surfactant corresponds to the minimum strength characteristics and the minimum long-term strength.
Fig. 2. Change of SAW delay time (ΔW – curve 1, 2) and bending-torsional stresses (τ – curve 3, 4), depending on the distance to the shores of main cracks in two destroyed bends:
Curve 1, 3 – bend "A"; Curve 2, 4 – bend "B"

Fig. 3. Influence of long-term strength of heat-resistant steels
For the delay time of SAW

The results of the studies [8–12] confirm the high sensitivity of the spectral-acoustic method to the determination of changes in the parameters of the microstructure (dislocation density, mean curvature-torsion amplitude, and density of extinction loops).
Thus, application of the spectral-acoustic method allowed to develop complex criterion limiting condition long working metal.

\[ K_f = \frac{W_f - W_0}{W_f - W_{\tau}} \cdot \gamma \]  

(7)

Which is determined by the delay time of the surfactant in the metal with the initial state of the structure \((W_0)\), in the metal that has exhausted its service life \((W_f)\) And in the controlled metal \((W_{\tau})\), where \(\gamma\) – the coefficient that takes into account the material of the element being monitored [12]. The complex criterion of the limiting state (CCLS) has been tested on a number of destroyed elements of power equipment. It has been experimentally proved that at \(K_f \geq 0.7\) the metal reaches the limiting state.

The received criterion was tested in the study of long-working 238 bends and straight sections of steam and steam pass pipes and four destroyed bends of power plants in Siberia. The data of the measurements of the acoustic characteristics give good agreement with the results of metallographic studies carried out on the cuts from the metal scraps. In addition, the criterion was tested in the diagnosis of technical devices and their elements made of steel 20, 15H1M1F, 12X2MFSR, 17GS, 09G2S, where results were also obtained, allowing to assess the structural state and life of the metal.

An acoustic criterion for evaluating the working capacity of high-pressure boiler drums has been developed. To assess the resource of the boilers of boilers made from boiler steels, a set of studies (steel 20M, 22K, 16GNM). The delay time for surfactants in the main metal of six drums of high-pressure boilers (66 or more bridges between the holes of the water pipes on each) and in the weld metal after repairs of the molybdenum-steel boiler boilers was measured by the acoustic-acoustic method.

Electron-microscopic studies showed that the most serious structural changes occurred in the HAZ and in the vicinity of the crack fringe, where microcracks were detected and the amplitude of local internal stress fields increased (Fig. 4). The maximum SAW delay time (Fig. 4) was observed at a distance of 1 mm from the fracture zone (crack), the maximum amplitude of local internal stress fields (1000 MPa) was recorded here. The increase in the volume fraction of the material structure dangerous to fracture (segments of the defective \(\alpha\) phase) led to an increase in the average local internal stress fields on the one hand, and on the other hand, the growth of internal stresses (300–900 MPa in the main metal, 900–1100 MPa near the rupture zone) leads to an increase in the SAW delay time (30–45 ns in the main metal, 120–150 ns near the crack fringes.) Such regularities are explained by the weakening of ultrasonic oscillations at the sources of internal stress fields and the presence of inhomogeneities in the structure of the metal.

![Fig. 4. Change in the mean value of local internal stresses (\(\tau\)) (curve 1) and the delay time of the surfactant (\(\Delta R\)) (curve 2) and the intensity of the MN (\(\Delta IMN\)) (curve 3) when moving over the sample from the fracture zone to the base metal (sample long working metal)](image)

The established dependencies show the principal possibility of identifying zones with high values of local internal stress fields in the long working and welded metal of welded drums of high-pressure boilers made from special molybdenum steels (type 20M) by the spectral-acoustic method.
The criteria has the following form

\[ K_S = \frac{\Delta R_1}{\Delta R_2}, \]  

(8)

where \( \Delta R_1 \) and \( \Delta R_2 \) – the anisotropy of the acoustic properties in the metal after repair and in the long-running metal before repair, respectively. These values are calculated as the difference in propagation times of Rayleigh waves in the metal perpendicular and parallel to the weld:

\[ \Delta R_1 = |\Delta R_{1 \text{perp}} - \Delta R_{1 \text{par}}|, \]

\[ \Delta R_2 = |\Delta R_{2 \text{perp}} - \Delta R_{2 \text{par}}|, \]

(9)

The developed criterion is tested on the long-working and melted metal of a number of high-pressure boiler drums. Calculations of \( K_S \) showed that at \( K_S > 0.22 \), the metal of the drum of the boiler under study is in the stage of pre-destruction and repair and recovery measures are necessary [12] (Fig. 5) [12].

But in any case (to avoid large measurement errors), there is a need to perform reference electron microscope studies for each grade of steel.

And finally, for engineers-practitioners, atlas of histograms is developed, with the help of equipment (after carrying out the analysis of repair and operational documentation), which, with the knowledge of the structural criteria, the operating conditions of the specialist will find by the histogram the service life of the given technical device.

This methodology does not exclude the implementation of standard NDT and TD methods, they complement the results of our tests, at their expense refinement corrections to the corresponding coefficients are introduced.

Fig. 5. Relationship between the criterion for estimating the resource of welded drums of \( K_S \) boilers with a change in the magnitude of local internal stress fields \(<\tau>\)

Conclusions

1. At the present stage, the solution of the above-mentioned problems of industrial safety expertise (the lack of legitimate methods of technical diagnosis and resource evaluation, the absence of standards for the categorization of NDT defects, the development and introduction of new methods and equipment for technical diagnostics, etc.) is possible with the use of self-regulation mechanism. Only the community of specialists can solve the problems of ensuring the safety of potentially dangerous equipment, its diagnosis and evaluation of the resource. Neither the officials nor the bodies of Rustekhnadzor will solve these problems, either because of their workload, or the lack of relevant specialists.
2. It is shown that most of the existing various methods for estimating the resource do not take into account the nature of the change in the structural-phase state of the metal during long-term operation, which leads to a decrease in the reliability of the results obtained.

3. A new methodology for estimating the resource is proposed, based on the character of the structural parameters change during the long-term operation under difficult stress conditions and on the interrelation of these parameters with the acoustic characteristics. For various FEC equipment, work packages are carried out, including electron microscopic and non-destructive studies.

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