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ANTICORROSIVE PROTECTION OF STRUCTURES IN ROBUST DESIGN

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The study suggests a method for determining the characteristic and desired values of corrosion resistance indicators to estimate the reliability parameters of systems of anticorrosive protection of structures (SAPS). The approach is based on developing robust (resistant to external influences) systems for designing measures of primary and secondary protection of metal structures against corrosion. Technological methods of diagnostics and maintenance are substantiated to improve the ways of using the constructions at all stages of their life cycle. Stronger corrosion resistance, that is, resistance to aggressive operating environments, is provided by effective methods of primary and secondary protection of metal structures from corrosion. The design is aimed at developing the provisions of the current standards of EN 1990 on the SAPS. It is established that the proposed requirements are aimed at ensuring the quality of metal structures and are achieved through calculations by the method of limit state design (LSD) using reliability coefficients (EN 1991). Robustness and durability are ensured in accordance with the provisions of EN 1993. The characteristic values of the quality indicators of protective coatings (EN ISO 12944, EN 1461) and structural material (EN 1993-1-4) are used. However, the procedures mean that such operating conditions are limited as for estimating the durability.

The proposed technique will improve the measures for anticorrosive protection of structures based on the robust design. The implementation of the method justifies the design and technological preparation of work to extend the durability of the structures. Effective procedures of primary and secondary protection have been introduced, and the requirements of the ISO 9001 international standards have been implemented

Keywords: metal structures, durability, robust design, anticorrosive protection, corrosion resistance

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1. Introduction

Efforts to ensure durability of metal structures are associated with substantiating the requirements for corrosion resistance at the stage of design work. In the provisions of EN 1993, the design procedure for durable structures is carried out using the characteristic values of the properties of the coatings (EN ISO 12944 and EN 1461). Thus, the quality indicators of the materials of metal structures are taken in accordance with the data of EN 1993-1-4.

The procedure entails limitations in assessing the actual technical state of the structures as well as analysing the environmental parameters, characteristics and conditions of the technological process for estimating durability during wear. Therefore, it is essential to establish a methodological approach to assessing the corrosion protection of metal structures, which is stipulated by the standards of EN 1990, EN 1991, and EN 1993 in accordance with the reliability requirements. The presence of deterioration processes caused by the material aging, corrosion or endurance degradation is supposed to be taken into account through the reasonable choice of materials for metal structures and their protective anti-corrosion coatings in accordance with the provisions of EN 1993-1-4 and EN 1993-1-10. Prevention of losing the bearing strength and durability can be achieved by means of a design margin in the conditions of primary protection and providing an appropriate secondary corrosion protection system. It should be noted that the described procedure for assessing the reliability of structures (EN 1990 and EN 1991) is implemented, for example, when establishing the rules for determining the fire resistance of steel structures in EN 1993-1-2.

The development of the methodology for using these procedures makes it possible to confirm the compliance of the reliability indicators with the standards and to increase the efficiency and rationality of the systems of anticorrosive protection of structures (SAPS) at the operational stage. It becomes important to substantiate the principles of ensuring the durability of metal structures and to develop information models for managing the technological safety of buildings and structures while using them in conditions of corrosive processes.

2. Literature review and problem statement

Improving the use of metal structures in construction largely depends on the effectiveness of measures to ensure corrosion resistance, as has been noted in a number of studies.

Studies [1–3] substantiated the necessity of developing SAPS according to the data on the corrosive aggressiveness of the environment and the actual operational state of construction metal structures.

General requirements for protective coatings are stipulated by the standards of DSTU-N B C.2.6-186:2013. The provisions of DSTU B C.2.6-193:2013 rationalise the need to control the quality of the structures and protective coatings, taking into account the type and degree of atmospheric aggressiveness. To ensure corrosion resistance, the characteristics of protective coating systems and corrosion-resistant steels are used according to the list proposed in Appendices D–F of DSTU B C.2.6-193:2013. Depending on the degree of aggressiveness of operational influences, quality indicators of corrosion protection measures are developed and agreed with the customer. For operating conditions, it is proposed to take into account the processes of degradation of the structures' material and coatings with due regard to the design margin and the choice of an anticorrosive protection system. At the same time, the account of operational impacts is limited when assigning effective and high-quality measures to ensure the corrosion resistance of metal structures, which leads to a decrease in their service life.

It becomes important to determine the qualitative and quantitative values of corrosion resistance of materials and protective coatings to normalize corrosion effects and their combinations using statistical methods.

In [4], one of the methods for solving problems arising at this stage was presented. Such research findings have been extensively applied in mechanical engineering and logistics studies of industrial enterprises [5]; however, the purpose of these indicators is not reflected in the aforementioned national standards. The possibilities of a detailed analysis of operational and emergency impacts and environmental conditions for a calculated assessment of durability, taking into account wear processes, are limited.

In studies devoted to ensuring the quality of industrial products by methods of robust design [4, 5], the principle of the signal-to-noise ratio approach is used by minimising variations in the indicators of durability and reliability by the objective criterion of robustness. This approach was also used for assessing the performance of construction metal structures based on modern diagnostic methods, which made it possible to form models and algorithms for risk analysis using expert qualimetry methods [6].

The requirements for regulating the technological safety of construction metal structures formulate the criteria for assessing the indicators of maintainability and survivability of the structures and are stated in [7]. Based on the provisions of the norms (clause 4.3 of DSTU B C.2.6-193:2013), it becomes necessary to conduct a study to identify the operational characteristics of the operability of metal structures and create an effective monitoring system for maintenance and repair.

Moreover, additional capabilities of information technologies provide conditions for registration and accumulation of data for monitoring the parameters of technical conditions and performing diagnostics in order to prevent emergency situations with construction facilities [8–10]. Studies [11, 12] were devoted to the implementation of qualimetric diagnostic methods. The measures considered in the works were aimed at quality function deployment, QFD. When structuring the quality functions, the target technological function of the research object (the 'construction-structure-environment' system) was analysed. Survivability at each stage of the structure's life cycle was ensured based on the conditions of technological safety through the deployment of the specified functions and operations. The conditions for ensuring durability and serviceability were met, which excluded the object from reaching the first or second marginal states [13, 14].

It can be concluded that ensuring technological safety during the operation of an object consists in describing design situations in conditions of corrosive effects of the environment and the state of the structures. The implementation is associated with the use of statistical methods for determining the qualitative and quantitative values of the corrosion resistance of the materials and protective coatings, with normalising corrosion effects and their combinations and assessing the reliability parameters of the SAPS.

Thus, the problem is to identify significant factors in corrosive environments and their influence on the durability of the SAPS. The system for structuring data on the state of primary and secondary corrosion protection should be determined during the technical diagnostics of structures. Analysis of the factors of aggressiveness of the environment and the parameters of the technical state based on monitoring the structures will determine the area of technological rationality and constructive adaptability of the SAPS. This technique will make it possible to select and economically substantiate the specifications of the ways and methods of primary and secondary protection of metal structures against corrosion in conditions of their exposure to aggressive environments.

3. The aim and objectives of the study

The aim of the study is to develop a methodology for assessing the performance and technological rationality of the means and methods of anti-corrosion protection during monitoring and technical diagnostics of metal structures based on the actual state, taking into account the factors of the operating mode. This will ensure the reliability and quality of anti-corrosion protection by taking into account the operational characteristics of the environment and a reasonable choice of the SAPS at the stage of designing. In practice, requirements are established for the indicators of the durability of primary and secondary protection, depending on the specified service life of the metal structures and the degree of aggressiveness of the environment.

Achievement of the research aim is associated with the phased implementation of the following tasks:

– to structure the data of the operational state of the SAPS in the conditions of corrosive environments;

– to determine the technological rationality and constructive adaptability of the SAPS;

– to substantiate the economic value of the specifications of the ways and methods of primary and secondary protection of metal structures against corrosion.

4. Research materials and methods

4. 1. Analytical description of the operational state of metal structures in conditions of corrosive wear

Changes in the qualitative characteristics of metal structures under conditions of irreversible degradation processes of a random nature occur at the stage of construction and during the operation of buildings and structures. Wear is associated with the occurrence and accumulation of corrosive damage to the elements of the metal structures, with the destruction of their protective anticorrosive coatings. The consequence is a change in the geometric characteristics of sections and mechanical properties of the material as well as a decrease and loss of performance properties [15].

When structuring the operational state data and identifying the level of corrosion hazard, the technical state parameters of structures are described by the methods of quality function deployment (QFD). The principle of structural description in the form of separate matrices is based on the provisions outlined in [11, 12]. The description is carried out by a structural organization model based on the structure of the House of Quality (HoQ) (Fig. 1) in the form of a target technological function of the object.

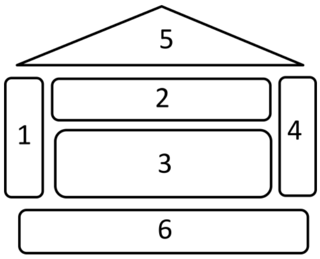


Fig. 1. The HoQ structural organization model: 1 – CTQs, WHATs, and Ys as the technological function; 2 – HOWs and Xs as technical characteristics; 3 – Relationship Matrix as the matrix of technological parameters and constraints; 4 – Customer Importance Levels per CTQ Critical to Quality, with CTQ for standardized quality criteria; 5 – Correlation Matrix (Optional) as the matrix of correlation coefficients; 6 – Calculated Importance Values of the HOWs as the target technological function of the research object

Parametric characteristics of the structural components of the model: 1 denotes the technological function: the production and technological characteristics of the construction in the conditions of the existing industrial process and the dependence of the state on the operational environment. 2 stands for technical characteristics: architectural, structural and technical characteristics of the actual operational state of the structure as a whole. 3 is the matrix of technological parameters and restrictions: an array of data corresponding to the technical characteristics of the structure. 4 denotes standardized quality criteria: standards of the indicators of reliability and durability. 5 is the matrix of correlation coefficients: functioning relations and existing correlation procedures between technical characteristics and parameters of the actual technical condition. 6 means the target technological function: the procedure for controlling the research object, which provides the interrelation between the results of monitoring and prognostic measures to ensure the characteristics of the operational state of the SAPS.

The analytical dependence of the description of the actual state of elements of metal structures under conditions of corrosive wear [$\Phi(N)$, g/m^2] was obtained by the method of active experimentation using the fractional replication $2^{15\text{-}10}$. This dependence reflects the programmed test actions with varying the parameters of the design form (j) and factors of corrosive effects (i):

$$\Phi(N) = A_i + A_j + A_{i,j} + A_{i,j-1}, \tag{1}$$

$$A_{i,j} = a_0 \sum_{i=0}^{i=N} \sum_{j=0}^{j=L} a_{i,j} \Big/ T_k, \tag{2}$$

where $A_{i(j)}$) is the system variable of corrosion losses, g/m^2/yr; $a_{i(j)}$ is the weight characteristic of the parameters of the constructive form (i, j); a_0 is the corrosion losses of S235 steel (g/m^2) as a result of accelerated corrosion tests; T_k is the time interval corresponding to steady-state corrosion losses (a year).

An expert assessment of the state of the generalized indicator of the protective properties of coatings (A_z) is presented in the form of the dependence:

$$A_z = \sum_{i=1}^{i=N} B_i X_i, \tag{3}$$

where B_i is the weighting factor of the type of destruction; X_i is the relative estimate of the i-type of destruction.

The results of evaluating the indicators by formulae (2) and (3) help to establish the standard service life of the protective coating system (PCS):

$$T_Z = \Delta P(N) / A_n, \tag{4}$$

where P(N) is the corrosion losses of unprotected steel corresponding to the number of accelerated test cycles N down to the specified failure characteristics, g/m^2.

4. 2. Determination of technological rationality and constructive adaptability of the SAPS

Requirements for the quality and reliability of the SAPS are set when assigning the category of responsibility for corrosion protection [16]. An expert assessment of the reliability coefficient is carried out using the calculation formula:

$$\gamma_{zn} = \frac{1}{1 + b_{\exp}\left(-cB_{oz}\right)}, \tag{5}$$

where γ_{zn} is the secondary protection reliability factor; b=300 and c=2.2 are dimensionless coefficients, or graphical dependence; c is the coefficient of kinetics of corrosion wear, taken with regard to the group of corrosion resistance of steel.

The technical criterion of failure, which is the exhaustion of protective properties (A_Z=0.35), is a combined indicator of the SAPS for the estimated assessment of the service life of the secondary protection. This assessment takes into account the corrosion state of the surface of steel structures (h_k=100 μm) during the destruction of the coating:

$$h_k = A_k / \rho = 100\,\mu\text{m}, \tag{6}$$

where h_k=100 μm is the thickness of corrosion products under the layer of paint, corresponding to the criterion of failure of protective properties; A_k is the corrosion loss of the reference sample with a protective coating for a time interval t_0 (a year), which determines the manifestation of failure, that is, the exhaustion of the protective properties of the coatings and the violation of the operational state of the structures as a result of corrosion destruction, g/m^2; ρ is the density of the corrosion products, g/cm^3.

4. 3. Economic substantiation of specifications of the ways and methods of primary and secondary protection of metal structures against corrosion

The choice of protective coating systems includes analysing the generalized indicator of technological rationality B_{oz} according to the expert assessment of the design and technological preparation of anti-corrosion protection measures:

$$B_{oz} = \sum_{i=1}^{i=N} B_i = \sum_{i=1}^{i=N} \sum_{j=1}^{j=P} m_i b_{ij} \left(\sum_{c=1}^{c=Q} q_{ij} / 100 \cdot Q \right), \quad (7)$$

where B_i denotes complex indicators of design requirements for durability, manufacturability, preservation, and maintainability; m_i is the coefficient of significance of the complex indicator; q_{ij} is the weight characteristics of the j-th feature of the i-th complex indicator; Q is the number of experts in the group during the audit.

Based on assessing the conformity of the quality indicators of the primary and secondary protection, the main tasks were aimed at calculating and confirming the compliance of the durability indicators of the systems of anticorrosive protection of structures, SAPS, with the standards; thus, the steps involved:

– verification of the defining parameters of corrosion resistance (DPCR) of the design solutions for anti-corrosion protection, design models and signs of limit states;

– statistical analysis of the technical characteristics of the SAPS, the formation of samples of experimental data for calculating the service life of structures and their protective coatings at a given degree of aggressiveness of the impact;

– performance of definitive tests of reference samples and assessment of the physical, mechanical and protective properties of the coatings in accordance with the requirements of standards and specifications;

– analysis of the compliance of the SAPS quality and reliability indicators with the design requirements for ensuring the level of the corrosion hazard to the construction site.

The results of the quality control were used to formulate specifications for the DPCR for anti-corrosion protection and technical diagnostics of corrosion destruction (TDCD) based on signs of a corrosion hazard.

5. Research results

5. 1. The system engineering procedure

The obtained data on the working state of the SAPS in corrosive environments are the basis for the development of measures to ensure the technological safety of the constructions.

The performed systematic description of the factors of corrosiveness of technological effects of the environment determines the level of reliability, economic feasibility of structural solutions of metal structures and the system of their protective coatings.

The specified conditions for the description of environmental factors correspond to the requirements of the standards (DSTU B C.2.6-193, clauses 4.1, 4. 3, and 6.4).

The effectiveness of measures to ensure reliability is integrated into the system for monitoring the quality indicators of the SAPS during maintenance according to the actual state of the construction metal structures. The practical implementation of the technique is carried out when monitoring the state of the structures.

The defining parameters of the corrosion resistance of the metal structures were checked. The impacts and influences that the metal structures were exposed to during the expected period of operation were identified.

5. 2. Justification of the principles of the parametric design

The method for determining the technological rationality and design adaptability of the SAPS was implemented during the repair restoration of the outer surface of the metal structures of the lattice tower of the 150 metre-high exhaust pipe (exhaust tower) K502 A of the NJSC shop (non-concentrated nitric acid). The technological purpose of the structure is to remove harmful non-combustible gases that have been cleaned and have a residual degree of aggressiveness to the supporting metal structures.

The level of damage to the structures and the corrosion hazard during the period of monitoring, with the diagnostics of the corrosion state, were determined in order to preserve the architectural and constructive adaptability and to ensure technological rationality. The results of the technical diagnostics of the structure, the statistical analysis, and the characteristics of the defects and damage are shown in Fig. 2.

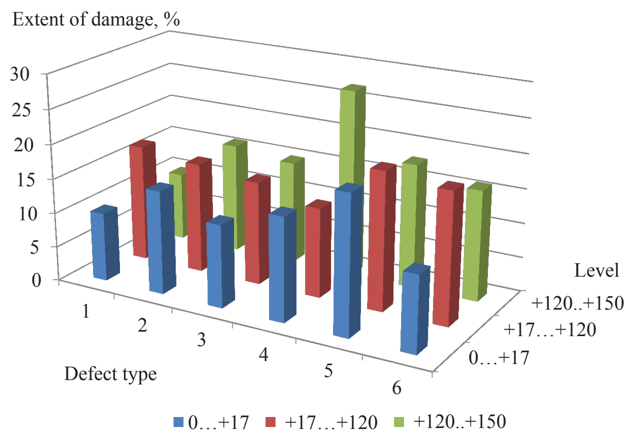


Fig. 2. Defects of the metal structures: 1 – lack of surface preparation for applying the topcoats of primer and enamel; 2 – corrosion damage to the main bearing structures; 3 – destruction of anticorrosive coating layers; 4 – defects in the metal structures during installation, welding, and assembly procedures; 5 – damage as a result of mechanical stress; 6 – other defects and types of damage

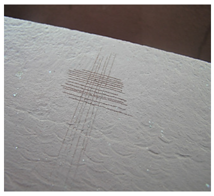
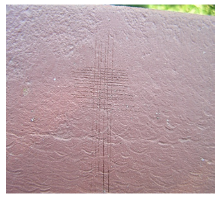
Based on the data obtained, it was concluded that the revealed intensive development of corrosion processes had been due to the force loading of the object, as well as the discrepancy between the technological parameters and the operating conditions and the established maintenance system.

The state of secondary protection was assessed to prescribe design solutions to ensure the durability of structures through the use of effective materials, means and methods of anti-corrosion protection, and maintenance and repair technologies. The indicators of maintainability, corrosion resistance and durability in aggressive environments were determined according to comparative tests of the samples and local sections of structural elements with protective coatings (Table 1). In accordance with the stated approach, requirements are formulated for determining the actual values of the corrosiveness of the effects based on the control data of the control standard Cr for operation.

Fig. 3 shows the main technical methods of conducting control definitive tests of sections of metal structures with an applied anti-corrosion coating for the indicator "Strength of adhesion at separation" (in accordance with the requirements of ISO 4624).

Table 1

Results of testing local sections of the metal structures of characteristic operation areas according to the procedure of DSTU ISO 2409:2015 (ISO 2409:2013) by method 2

Indicator	Test requirements (according to DSTU *)	Protective coating test results:	
		samples A/1 and A/2	samples A/3 and A/4
Adhesion, degree	1		

a

b

Fig. 3. Definitive tests of sections of metal structures with the applied anti-erosion coating: *a* is the positioning and installation of the ONIKS-AP hydraulic press in the working position; *b* is the recording of the representative values of adhesion strength in MPa (kgf/cm^2) at the moment of separation

5. 3. Justification of the choice of specifications, ways and methods of primary and secondary protection of metal structures against corrosion

The analysis of the results of diagnosing the metal structures of the lattice tower of the exhaust pipe K502 A of the NJSC shop under aggressive influences has determined the qualitative and quantitative characteristics of the imperfections of the primary and secondary protection. This made it possible to formulate the design repair specifications of the SAPS during the procedure for restoring the corrosion protection of the construction metal structures (Table 2).

Ultimately, the task was implemented to ensure economic substantiation of design solutions for repair restoration, rationality of the choice of the means and methods of anti-corrosion protection during the operation period, and assessment of the functional adaptability to the production conditions and operational environment. The calculated indicators of the durability of the lattice structures (*Tz*) provide an increase in the service life of the anti-corrosive coatings from 3...4 years (according to the executive documentation of the initial operation period) to 7...8 years (when using repair specifications) with the established indicators of the aggressiveness of the environment.

6. Discussion of the results of research on ensuring corrosion protection of metal structures using the robust design technology

The proposed structural presentation of the results of technical diagnostics – formulae (1) and (2) – identifies and differentiates the factors of aggressiveness of the operational environment and the parameters of the construction form. Based on this, the planning of measures for the primary and secondary protection of metal structures against corrosion under the condition control was carried out. Specification has been established defining the SAPS during the period of repair restoration of the metal structures, which corresponds to the conditions of localization with details for each specific malfunction (Fig. 1, Table 2).

The standardization of corrosion effects and their combinations and the assessment of the reliability parameters of the SAPS were performed using partial coefficients. The results obtained give grounds to assert that the systematic and timely implementation of the procedure for determining the SAPS indicators based on robust design using the QFD provisions makes it possible to predict the operation of the multifunctional system “structure-load-environment”.

The procedure for performing computational and measuring control and statistical substantiation of technical solutions will provide an increase in the corrosion resistance while confirming the compliance with the adopted specifications for the secondary protection of the metal structures.

Table 2

Repair specification of the SAPS

Name and material of the structural elements	Protective coating composition:				Total coating thickness, μm
	base layer		top layer		
	material grade	indicator, consumption	material grade	indicator, consumption	
Bearing tower, flue gas support, carbon steel and alloy steel	Base XC-068	2 layers; 60–95 g/m^2	Enamel XB-785 red and white; varnish XB-784	3 layers 2 layers	170 150
Bearing tower: – stairs, railings and platform decking; – elements of light protection	Varnish XC-724	2 layers; varnish layer thickness 20–25 μm; 155–195 g/m^2	Enamel XB-785 red and white; varnish XB-784	2 layers	120

The proposed methodology differs from the provisions of the norms in which the design of the SAPS is to be implemented by choosing materials from a limited list of reference applications. The assessment of the characteristic calculated value of individual properties of a material or mode (environment) of operation was carried out by statistical methods, taking into account the sample size and the identifying signs of the corrosion state. This will ensure the designation of the SAPS based on the indicators of the aggressiveness of the operational environments, as well as the design and technological characteristics based on the diagnosis of the actual state.

The simulation by the structural-organizational HQ model (Fig. 1) has established a sequence of stages to ensure the quality and reliability of anti-corrosion protection of metal structures used in construction. This research technique reflects the strategy of the DMAIC procedure (define, measure, analyse, improve, and control).

Owing to the possibility of standardising the reliability indicators of the SAPS, the defining parameters of corrosion resistance were systematized for monitoring, diagnosing and analysing the risk of anti-corrosion protection of buildings and structures. The main advantages of using the QFD-based approach include:

– effective identification of quality indicators;

– provision of conditions for guaranteeing the properties of the means and methods of anti-corrosion protection;

– the established relationships of the structural and organizational HQ model of the design as well as operational and technological indicators of the actual technical condition eliminate any possible uncertainty of the indicators of a corrosion hazard;

– the results of monitoring based on the methods of qualimetric control and diagnostics of the structures make it possible to form an analytical and informational database for the creation of a predictive model of maintenance of metal structures, taking into account their technological rationality and economic efficiency (Table 3).

The proposed design specifications for the means and methods of anti-corrosion protection are the predominant indicators of the choice of the SAPS in comparison with the standards of DSTU B C.2.6-193:2013. This ensures technological rationality and design adaptability of the quality indicators by increasing the service life of the anticorrosive protection system.

The application of the approach ensures the extension of the service life of metal structures in the conditions of monitoring the technical state and renewing the secondary anticorrosive protection system.

The practical result of solving the problems is the implementation of statistical methods for determining the qualitative and quantitative values of the corrosion resistance of materials and protective coatings.

This approach is applied when implementing measures for corrosion protection of metal structures of fixed assets of a chemical industry enterprise under the influence of technological emissions.

It should be noted that the possible further development of such studies is aimed at solving particular problems of determining the state of specific structures when differentiating the components of corrosive operational environments.

7. Conclusion

1. A procedure has been developed for designing the SAPS in corrosive environments. The parameters of the environment were determined on the basis of the obtained operational state data during the technical diagnostics of metal structures. The qualitative and quantitative values of the corrosion resistance of the metal structures and the durability of their protective coatings have been determined.

A qualitative assessment of the reliability parameters of the SAPS was carried out for predicting or prescribing the service life of the structures taking into account the aggressiveness of the operational environment.

2. The qualitative indicators of technological rationality and constructive adaptability have been determined to comply with the purposes of the SAPS. The indicators were specified by the numerical value of the integral characteristics of the design and technological preparation. The effectiveness of the technological process for providing primary and secondary protection against corrosion was determined on the basis of the robust design methodology (with the implementation of the requirements of the international standards of ISO 9001).

3. The study has substantiated the economic value of specifying the ways and methods of primary and secondary protection of metal structures against corrosion; it was done by designing and implementing the SAPS to ensure the restoration of the secondary corrosion protection system of the lattice metal tower of an exhaust pipe. The tolerances of the SAPS were established according to the criterion of technological rationality, its constructive capability.

Acknowledgment

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Table 3

Design indicators of technological rationality of the SAPS

Type of work	Technical procedure. Material of the SAPS	Constructive (height level)	Scope of work (surface area)
Mechanical treatment, surface cleaning of K502A	Sandblasting of the metal structures, surface cleaning	Lev.+120.0125.0+125.0140.0	$S1$=400 m^2
		Lev.+0.0-17.0	$S2$=700 m^2
Surface priming of the metal structures K502A (first layer)	Application of the primer layer of the surface (the first layer is the base). Primer XC-068	Lev.+120.0125.0+1.025.0+140.0	$S3$=300 m^2
		Lev. +0.0-17.0	$S2$=700 m^2
Surface priming of the metal structures K502A	Surface priming (the first layer is the base). Primer XC-010	Lev. +0.017.0	$S2$=700 m^2
	Surface priming (second layer). Primer XC-068	Lev.+120.0125.0; +125.0140.0	$S1$=400 m^2
Surface painting of the metal structures K502A (top coat)	Surface painting (first coat+top coat). Enamel XB-785	Lev. +130.0140.0	$S4$=200 m^2

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