UDC 691.714:620.169.1

Kuschenko I.V.*, assistant*
ORCID 0000-0002-3338-6793 kigorvlad@gmail.com
State Higher Educational Establishment
«Preazov State Technical University»

ASSURANCE OF STRUCTURAL STEEL SURVIVABILITY BASED ON RESERVATION OF PRODUCTION FACILITIES CORROSION PROOFNESS

The paper deals with the task of selecting quality and reliability indices of means and methods of corrosion protection considering structural strength requirements. Systematized description of standard (basic, characteristic) impacts and representative values of negative corrosiveness factors is provided. For corrosion protection design, classification features of steel structures and their protective coatings based on criticality rating are specified. Design indices of structural steel durability are discussed. The developed methodology involves an analytical–experimental estimate of reliability and availability factors of corrosion protection. Logistical system has been generated for reserve planning of survivability of structure on the basis of corrosion proofness signs. A method is proposed for calculating compensation for corrosion losses when comparing competitive advantages of corrosion protection systems. The index of corrosion protection level is specified for managing process safety on the basis of risk reduction.

Keywords: *reliability, structural and process safety, survivability, corrosion hazard, risk assessment.*

Кущенко І.В.*, асистент*
Державний вищий навчальний заклад
«Приазовський державний технічний університет»

ЗАБЕЗПЕЧЕННЯ ЖИВУЧОСТІ СТАЛЕВИХ КОНСТРУКЦІЙ НА ОСНОВІ РЕЗЕРВУВАННЯ КОРОЗІЙНОЇ ЗАХИЩЕНОСТІ ПРОМИСЛОВИХ ОБ'ЄКТІВ

В статті розглянуто питання обґрунтування показників якості й надійності систем протикорозійного захисту з урахуванням вимог резервування міцності конструкцій. Здійснено систематизоване описування нормативних (базових, характеристичних) впливів і репрезентативних значень корозійної агресивності. Для проектування захисту від корозії встановлені класифікаційні ознаки сталевих конструкцій та їх захисних покриттів за категорією відповідальності. Обґрунтовані проектні показники довговічності сталевих конструкцій. Розроблена методика включає розрахунково-експериментальну оцінку коефіцієнтів надійності та готовності. Сформована логістична система резервування живучості конструкцій за ознаками корозійної захищеності. Запропоновано метод розрахунку компенсаційних корозійних втрат при порівнянні конкурентних переваг систем протикорозійного захисту. Встановлено індекс рівня корозійної захищеності для управління технологічною небезпекою на основі зниження ризиків.

Ключові слова: *надійність, конструктивна і технологічна безпека, готовність, живучість, корозійної небезпеки, оцінка ризиків.*

Introduction. Nowadays metal use in construction industry, building facility architectural expressiveness means improvement and methods of corrosion protection should support the long-term service life of structures. It should be noted that in present there are no effective mechanisms that would satisfy the economic approach to increasing the corrosion protection measures efficiency when assuring reliability and process safety of metal structures [1 -- 3].

Review of the latest research sources and publications. In the field of construction, process safety is linked with the regulation of approaches to preventing emergency situations on the basis of buildings and installations reliability program-oriented management methods. The concept of preventing progressive ageing of fixed assets is based on the process-based approach to the problems of construction facilities ensuring technological safety [4]. Technological safety is an important structural component of enterprise safety, which characterizes the system of measures to maintain serviceability, improve the performance of building, installation and utility structures, which have completely or largely exhausted their service life and which are a source of potential hazard with respect to facility technological functions in the course of modernization, refurbishment, and life extension. According to this approach the concept of corrosion risk hazard includes a specified certain condition or situation (threat) where the probability of damage increases due to the fact that given corrosion state or deviation from normal operation are a potential cause (threat) of hazard [5].

Definition of unsolved aspects of the problem. The developed standard is DSTU BV.2.6-193:2013 «Corrosion protection of metal structures. General specifications» is aimed to update the national legal and regulatory framework in accordance with modern objectives of building industry and harmonize this framework with European Union regulations in particular related to implementation and introduction of Directive 89/106/EU. Improvement of operational requirements considering modern scientific developments and provisions of international standards is aimed at corrosion protection of metal structures in civil and industrial engineering. The project was developed for the purpose of intelligent design of corrosion protection at all stages of metal structure life cycles.

According to the technical assignment, the objects of standardization are corrosion attacks, means and methods of metal structure corrosion protection, implementation of the process approach to reliability and quality control on the basis of ISO 9001. Draft standard specifies common design criteria and methods for assessing the indices of corrosion resistance and durability of metal structures and their protective coatings.

Improvement of corrosion protection quality involves the use of primary protection measures (requirements for corrosion resistance of materials for bearing and enclosing structures) and secondary protection (requirements for durability of protective coatings and special equipment of electrochemical protection) in accordance with operational rules [6]. Operating conditions of building units are defined as the effects of impacts or provided conditions on the specified level of facility specifications. Regulatory requirements are confirmed based on the limit state concept using computational models of corresponding range of characteristics of mechanical strength and resistance of steel structures and protective coatings in corrosive environments. Provisions of DSTU BV.2.6-193: 2013 are aimed to meet the industrial safety requirements prevent environmental and technogenic threats, reduce economic risks due to corrosion damages [7].

Problem statement. In the course of facility design reliability and structural safety are ensured via improvement of design codes, including the development of the basis, principles and methods of limit state design. Trouble–free operation of buildings and installations of structures (hereinafter referred to as structures) is linked to assuring process safety based on the methodology of total quality control.

Fixed assets depreciation high level and limited life span of structures pose a significant thread to process safety. Process safety is an important structural component of enterprise safety, which characterizes the system of measures for maintaining serviceability and improving performance of structures that have completely or largely exhausted their design life. Such facilities are viewed as a source of potential hazard in the course of their modernization (refurbishment), revamp, and service life extension.

The purpose of this paper is to substantiate the composition and structure of indicators determining corrosion state (*IDCS*), for program–oriented management of industrial facilities process safety.

The methodology of *IDCS*–based safety management comprises a process approach to choosing means and methods of corrosion protection (*MMCP*). Assurance of process safety is viewed based on considerations of «soft» conflict of the system survivability theory. The essence of «soft» approach in developing programs of reliability assurance (*PRA*) and analysis of survivability is in justification of solutions (subsystem *U*) considering information parameters of technical conditions (subsystem I) and material flows (subsystem *Q*) providing conditions for trouble–free operation (Fig. 1).

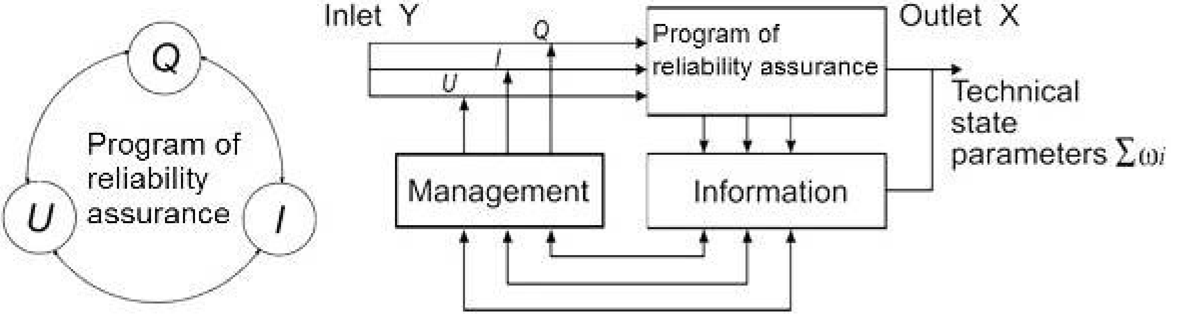

Figure 1 – Structural and organizational model of material (Q), information (I) and management (U) components for assuring process safety

Survivability is an important characteristic of structural capability to maintain a partial operable state under negative impacts in the presence of defects and damage. Thus, assurance of technological safety provides with formation of survivability assessment structural and organizational model considering *IDCS* of structures.

The concept of corrosion hazard includes *IDCS* or situation (threat) where the probability of damage increases. Thus, conditions are being created for logistical management and analysis of *PRA* structural solutions risks extending industrial facility life.

Works provisions development [5-9] has allowed proposing classification of technical and process risks signs under restoration of structure corrosion protection while maintaining and repairing facilities in their actual state (Table 1).

Upon characteristics of secondary protection (durability of protective coatings), structure service life is set on the basis of SCPSS quality indices analysis. Structural steel calculations for corrosion resistance, durability and repairability are carried out based on the limit states of the first and second groups considering *IDCS* (Table 2).

Corrosion protection reliability factors ($\gamma_{zк}$, γ_{zn}) specify permissible deviations of strength, deformation and performance properties of structural members determined for a fixed design case and specified service life ($T_{n\gamma}$, year).

Block diagrams of reliability indices are represented as flow graphs describing changes in the corrosion state of structural steel considering structural and process alternatives of corrosion protection during facility's specified service life.

Table 1 – Signs classification of technical and process risks under restoration of corrosive structure serviceability

Conditions of *SCPSC*	Class of risk	Description of risk	Characteristic of losses	Risk (R_i, point)	Extent of potential damages, *MWA**
Corrosion hazard	1	Catastrophe	Partial or complete failure of structures and installations	9–10	> 72500
	2	Critical	Losses exceed the estimated amount of gross income in the case of facility restoration	7–8	25000–72500
Degree of corrosion protection	3	Allowable	Losses do not exceed the estimate value of returns in the case of service life extension and engineering modernization of facilities	5–6	2500 – 25000
	4	Acceptable	Losses do not exceed the quality-related expenses during facility service life.	1–4	< 2500

**MWA - minimum wage amount*

Steel structure availability factor (K_g) is an important logistic characteristic of structural safety:

$$K_g = \frac{T_{zk} + T_{z\gamma}}{T_{zk} + nT_{z\gamma}}, \qquad (1)$$

where n – number of repair cycles for renewal of corrosion protection at facility specified service life.

Table 2 – Parameters of corrosive structures serviceability based on risk classes of SCPSS

Designation of criticality category	Redundancy conditions / Condition for compliance with criticality category	Risk class	Interval estimate of failure based on technical criterion:		Reliability factor	
			A_z	h_k, mkm	γ_{zn}	γ_{zk}
C1	*SR* / Allows degradation of decorative features of secondary protection	3	0,85	-	0,99	0,95
		4	0,90		1,00	0,99
C2	*SR* / Does not allow degradation of protective features of secondary protection	3	0,55	-	0,95	0,9
		4	0,60		0,99	0,95
C3	*PR* / Allows degradation of protective features of secondary protection	3	0,40	50	0,90	0,85
		4	0,45	30	0,95	0,9
C4	*PR* / Allows degradation of features of primary protection	3	0,30	100	0,85	0,8
		4	0,35	70	0,90	0,85

Categories of criticality of steel structures based on the level of corrosion protection are specified depending on partial (within acceptable limits) degradation of primary protection efficiency (reliability factor γ_{zk}) parameters and secondary protection (reliability factor γ_{zn}, composite index of protective properties A_z, thickness of corrosion products under the paint coat h_k, corresponding to failure criterion of protective properties).

Functional reliability reserve under the terms of primary (*PR*) and secondary (*SR*) protection is achieved via setting a required level of corrosion protection (ZI – ZIV) or corrosion hazard (KI – KV) considering data presented in Table 3.

Process safety is achieved with the time reservation of the load capacity of structural steel considering functional survivability of corrosion protection systems under an acceptable risk of industrial facilities a stress-corrosion fracture consequences . Process-approach to ensuring process safety of structures reflects *DMAIC* action strategy (define, measure, analyze, improve, control).

Table 3 – Generalized matrix of choosing SCPSS reliability index level

Degree of exposure corrosiveness K, mm per year	Range estimates of corrosion protection availability factor, K_g				
	$0<K_g\le0{,}1$	$0{,}1<K_g\le0{,}3$	$0{,}3<K_g\le0{,}5$	$0{,}5<K_g\le0{,}7$	$0{,}7<K_g\le1{,}0$
Weak-level corrosive environment, $0{,}01<K\le0{,}05$	KI	ZIV	ZIII	ZII	ZI
Low-level corrosive environment, $0{,}05<K\le0{,}15$	KII	KI	ZIV	ZIII	ZII
Average-level corrosive environment, $0{,}15<K\le0{,}30$	KIII	KII	KI	ZIV	ZIII
High-level corrosive environment, $0{,}30<K\le0{,}50$	KIV	KIII	KII	KI	ZIV
Strong-level corrosive environment, $K>0{,}50$	KV	KIV	KIII	KII	KI

Reservation as a universal method of reliability assurance is used upon established procedure of corrosion monitoring (define, measure) and *SCPSS* diagnostics (analyze, improve, control).

At the stage of corrosion monitoring, the basis for decision making is the level of process safety risk (*LPSR*) with the use of 10–point scale according to the following equation:

$$R_i = \sum_{i=1}^{i=N} Q_i P_i, \tag{2}$$

where Q_i – weight characteristic of *IDCS* significance;

P_i – detected survivability changes by the value of i-th sign.

It is proposed to manage process safety risks (R_i, point) based on the monitoring data depending on a specified class of hazard, level of threats and vulnerability of corroding structures (Table 4).

The basis for decision making upon the diagnostic data is the assessment of survivability criteria using the data of «Resource» information-analytical system (Fig.2).

Table 4 – Process safety risk (R_i, point) depending on class of hazard of SCPSS, level of threats and vulnerability of buildings and installations

Level of *SCPSS*	Level of threat (category of technical conditions)														
	Low (I)			Limited (II)			Average (III)			High (IV)			Ultimate (V)		
	Vulnerability assessment (category of responsibility)														
	V	B	A	V	B	A	V	B	A	V	B	A	V	B	A
ZI	1	1	2	2	2	3	3	3	4	4	5	5	6	6	7
ZII	1	2	2	2	3	3	3	4	4	5	5	6	6	7	7
ZIII	2	2	3	3	3	4	4	4	5	5	6	6	7	7	7
ZIV	2	2	3	3	4	4	4	5	5	6	6	7	7	7	8
KI	2	3	3	4	4	4	5	5	6	6	7	7	7	8	8
KII	3	3	4	4	4	5	5	6	6	7	7	7	8	8	9
KIII	3	4	4	4	5	5	6	6	7	7	7	8	8	9	9
KIV	4	4	4	5	5	6	6	7	7	7	8	8	9	9	10
KV	4	4	5	5	6	6	7	7	7	8	8	9	9	10	10

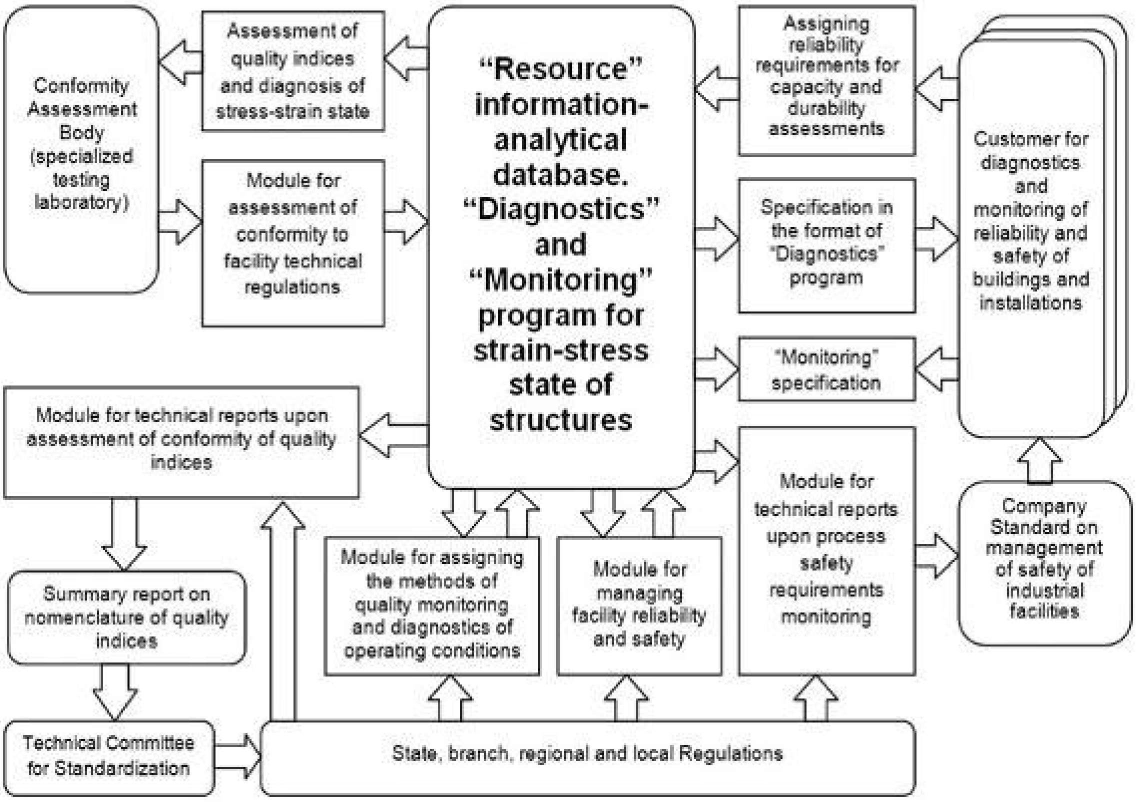

Figure 2 – Diagram of «Resource» information–analytical database for setting survivability indices of metal structures based on corrosion hazard level

The data of monitoring corrosion state of facilities (parameters of system «output») are used for reliability analysis («input» parameters) and justification of the requirements for maintainability, survivability and post-repair load capacity.

Process approach to assuring process safety of structures reflects *DMAIC* action strategy (define, measure, analyze, improve, control).

The data of facility corrosion state monitoring (parameters of system «output») allows carrying out reliability analysis (parameters of system «input») for setting process safety requirements considering indices of repairability, survivability and post–repair load capacity.

The limit state criteria in assessing *IDCS* in their actual state are set with the use of a feedback factor of structure operating conditions (ψ), using equation:

$$N = \frac{\Phi_{cr}}{\Gamma - \psi} , \tag{3}$$

where N – the largest rated force in the structural member, *kN*;

Φ_{cr} – limit force, *kN*, which can be withstood by the element of damageability Θ_f;

Γ – reliability margin ratio.

By feedback it is meant results of *IDCS* monitoring for assessing, controlling and correcting *PRA*. With accumulation of damages Θ_f the feedback factor (ψ) defines the degradation of structural performance under the specified design value of reliability margin ratio (Γ). Proposed feedback factor (ψ) provides for realization of the analytical approach to managing process safety. Process safety depends on the integral index of survivability (η), which determines reduction of service life regulation capacity at structural in–service degradation:

$$\eta = \Gamma - \frac{1}{\Gamma - \psi} . \tag{4}$$

Perturbing actions of negative internal impacts result in corrosive damages and occurrence of structural limit states signs. Capacity of service life regulation defines the permissible deviations of the reliability margin ratio design value (Γ) for assuring serviceability.

Conclusions. Logistical management in the course of structural survivability upon corrosion hazards planning allows eliminating uncertainty and subjectivity choosing design solutions of *SCPSS*. For real business, assessment of industrial facilities process safety means reducing the risks due to corrosion hazard. Thus, the theory of potential effectiveness is realized to assess risks, considering structure reliability, durability and safety.

References

1. *Gorochov E. V. Durability of Steel Structures Under Reconstruction / E. V. Gorochov, V. P. Korolev. – Rotterdam : Brookfield, 1999. – 305 p.*
   ISBN 905-4107-31-6.
2. *Ferreira M. G. S. Electrochemical and Optical Techniques for the Study and Monitoring of Metallic Corrosion / M. G. S. Ferreira and C. A. Melendres (red.) // Materialy konferencji NATO (Portugal 1989- Dordrecht–Boston–London, 1991). – NATO ASI. – Vol. 203.*
   https://books.google.com.ua
3. *Frangopol D. M.Reliability* of *Reinforced Concrete Girders under Corrosion Attack / D. M. Frangopol, K.-Y. Lin, A. C. Estes // Journal of structural Engineering. – 1996. – № 123 (3). – P. 286 – 297.*
4. *Техническая диагностика и предупреждение аварийных ситуаций конструкций зданий и сооружений / А. В. Шимановский [и др.] ; под общ. ред. А. В. Шимановский. – К. : Сталь, 2008. – 462 с.*

Tehnicheskaya diagnostika i preduprezhdenie avariynyih situatsiy konstruktsiy zdaniy i sooruzheniy / A. V. Shimanovskiy [i dr.] ; pod obsch. red. A. V. Shimanovskiy. – K. : Stal, 2008. – 462 s.

ISBN 966-7589-72-2

5. *Korolov V. Management of the Quality of Corrosion Protection of Structural Steel Based on Corrosion Risk Level / V. Korolov, Yu. Filatov, N. Magunova, P. Korolov // Journal of Materials Science and Engineering. – A&B, 2013. – № 11, Volume 3. – P. 740 – 747.*

   http://www.davidpublishing.org/journals_info.asp?jId=1876
6. *Королёв В. П. Нормативное регулирование надежности и безопасности систем противокоррозионной защиты металлоконструкций / В. П. Королёв, И. В. Кущенко // Промышленное и гражданское строительство. – 2016. – № 1. – С. 37 – 42.*

   Koroliv V. P. Normativnoe regulirovanie nadezhnosti i bezopasnosti sistem protivokorrozionnoy zaschityi metallokonstruktsiy / V. P. KorolYov, I. V. Kuschenko // Promyishlennoe i grazhdanskoe stroitelstvo. – 2016. – №1. – S. 37 – 42.

   https://elibrary.ru/item.asp?id=25280650
7. *Intelligent design and assurance of steel structure corrosion protection quality / V. Korolov, Yu. Vysotskyy, S. Grebenyuk, I. Kuschenko // EUROCORR-2011. The European Corrosion Congress: Developing Solutions for the Global Challenge (4-8 September 2011, Stockholm). – Stockholm, Book of Abstracts. – P. 647.*

   ISBN: 9781618394125
8. *Korolov V. Monitoring of steel structure corrosion state / V. Korolov, Y. Vysotskyy, A. Ryzhenkov // EUROCORR-2007: The European. Corrosion congress book of abstracts – Freiburg im Breisgau, Germany,. 2007. – P. 276.*
9. *Estimation of steel structure corrosion risk level in calculation according to limiting states / V. Korolov, Y. Vysotskyy, O. Gibalenko, P. Korolov // EUROCORR-2010. The European Corrosion Congress: From the Earth's Depths to Space Heights (13–17 September 2010, Moscow). – Moscow, 2010. – P. 534.*

Received 24.07.2017