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Ensuring the reliability of corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes

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The article addresses the issue of ensuring the reliability and durability of steel structures used in oil and gas complexes. Attention is drawn to the need for research and improvement of scientific, technical, and technological developments in the field of corrosion-mechanical resistance of metal structures. The article describes the results of experimental research aimed at analyzing the causes and mechanisms of metal strength loss during operation, and proposes a method for predicting the residual working life of structures. The obtained results make a significant contribution to the development of technical and design measures to enhance the efficiency and reliability of oil and gas complexes

Keywords: destruction, corrosion, steel structures, mechanical stability, degradation

Забезпечення надійної корозійно-механічної стійкості трубопроводів та сталевих конструкцій нафтогазових комплексів

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Стаття присвячена аналізу факторів для забезпечення надійності сталевих конструкцій та трубопроводів, які використовуються у нафтогазових комплексах. Проаналізовано протиріччя та невизначеності у сучасних науково-технічних й технологічних розробках щодо забезпечення надійної корозійно-механічної стійкості й тривалості сталевих конструкцій нафтогазових комплексів та інших оболонкових металоконструкцій відповідального призначення. Звертається увага на необхідність дослідження та вдосконалення науково-технічних та технологічних розробок у галузі корозійно-механічної стійкості металевих конструкцій. В статті описані результати експериментальних досліджень, що спрямовані на аналіз причин та механізмів втрати міцності металу у процесі експлуатації. Отримали подальший розвиток розробки та застосування ефективних методів моніторингу та діагностики, зокрема використання ефекту коронного розряду для виявлення дефектів діелектричних покриттів. Виявлені недоліки методів оцінки працездатності конструкцій та їх залишкового ресурсу вказують на те, що у сучасний період особливо важливими є розрахункові методи, які базуються на критеріях тріщиностійкості, що чутливі до змін структури металу під час тривалої експлуатації, особливо в умовах корозійно-активних технологічних середовищ при змінних динамічних навантаженнях. Пропонується метод прогнозування залишкового робочого ресурсу конструкцій, що дозволяє систематично впливати на умови їх експлуатації для оптимізації роботи. Проведений аналіз може стати важливим внеском у розробку технічних та конструкторських заходів для підвищення ефективності та надійності нафтогазових комплексів.

Ключові слова: руйнування, корозія, сталеві конструкції, механічна стійкість, деградація

Introduction

Modern scientific and technical and technological developments in relation to providing of reliable corrosivemechanical firmness and duration of steel constructions of oil and gas complexes and other thecal metallic constructions of the responsible setting, that is subject to Government service of mountain supervision and industrial safety of Ukraine, contradiction and vagueness educed. Absent reasonable recommendations are for practical application with the aim of providing of corrosive-mechanical firmness of constructions that function in technologically aggressive environments at variable temperature-barometric terms and loading.

There was a necessity of system study of reasons, terms and mechanisms of corrosivemechanical damages of equipment with the protracted term of exploitation that will allow substantially to promote operating reliability of industrial equipment. Experimental researches find out reasons and grounded the mechanisms of loss of durability of metal with the increase of term of that causes his degradation, especially during the protracted exploitation in corrosive environments. Methods of foresight of remaining working (accident free) resource of metallic constructions that allow purposefully to regulate them the operating state was analyzed. It gives possibility in good time to apply technical and designengineering measures for the increase of terms of exploitation of such constructions. The got results of experimental tests of metallic standards of the different setting create a base for the comparative analysis of steels on the different parameters of firmness to the cracks. The article is devoted to the analysis of modern anti-corrosion materials that are used to protect the structures of oil and gas-bearing complexes. Various compositions and properties of these materials are considered, as well as their effectiveness in preventing corrosion damage to metal elements. The main advantages and areas of application of modern anti-corrosion materials in the oil and gas industry, in particular in the production, transportation and storage of petroleum products, are outlined. The possibilities of their improvement and the prospects of their use in the future for the most effective protection of the infrastructure of oil and gas complexes from corrosion were also studied. The results of the analysis will allow to deepen the understanding of modern opportunities and trends in the field of anti-corrosion materials to ensure the long-term and reliable functioning of the oil and gas infrastructure.

Review of the research sources and publications

Many domestic and foreign researchers have studied the problems of crack resistance and brittleness of metals used in aggressive environments with hydrogen sulfide impurities in oil and gas fields. The analysis of scientific sources shows that existing methods of calculating the durability of pipelines and tanks used both in Ukraine and abroad usually provide for independent consideration of corrosion fatigue and creep processes, although in reality these phenomena often occur simultaneously in various combinations. This issue has been studied, in particular, by such scholars as: S. Maksymov, S. Polyakov, S. Nesterenko, V. Panchenko, and O. Stepova.

Definition of unsolved aspects of the problem

The methodology for analyzing and assessing the reliable corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes is actively developing, so the development of new and improvement of existing approaches, models and methods for ensuring reliable corrosion and mechanical resistance of pipelines and steel structures and their computer implementation remain an urgent task for our country.

Problem statement

Description of analytical methods for ensuring reliable corrosion and mechanical resistance of pipelines and steel structures of oil and gas complexes.

Basic material and results

Today, the main task is to maintain and increase hydrocarbon production. This goal can be achieved in two ways: by developing new fields and increasing hydrocarbon production from existing wells. It is important to note that maintaining and increasing hydrocarbon production is associated with technological operations in the well, which often include the use of killing fluids. The main purpose of these fluids is to avoid fluid leakage and preserve the primary filtration and capacitive characteristics of the productive reservoir. There are different types of damping fluids depending on their composition, but the most common are fluids based on polymeric structuring agents and inorganic salts [1].

The use of polymeric chemicals makes it possible to obtain structured process fluids with high rheological characteristics. However, most polymers have low thermal stability and low resistance to microbial degradation. This leads to a loss of structural and rheological properties of such process fluids under the influence of thermobaric conditions in the wellbore. In addition, the destruction of polymeric components can cause contamination of productive formations and a decrease in well production rate. Alternative options for such fluids are process fluids based on inorganic salts. These fluids are either naturally occurring (formation water with known mineralization) or artificially produced (inorganic salt brines of appropriate composition and concentration). Such fluids have advantages, including the ability to widely adjust their density, minimal impact on rock volume, and preservation of the original properties of productive formations. They are also characterized by low freezing point and high thermal stability. The disadvantages include high fluid consumption for killing due to the lack of an impermeable screen (filter casing) on the well walls and absorption of the solution by the pores of productive formations [2].

In addition, the use of produced water as a killing fluid can cause microbiological corrosion due to the presence of sulfur-reducing, thione and other types of bacteria in produced water, depending on its composition [3]. For this reason, it is common to use killing fluids of artificial origin, which are thoroughly cleaned of excess mechanical impurities that may be a clogging agent in the productive formation before use.

The problems of crack resistance and brittleness of metals operating in aggressive environments with hydrogen sulfide impurities in oil and gas fields have been studied by many domestic and foreign researchers [5].

The analysis of scientific sources shows that existing methods for calculating the strength of pipelines and tanks used both in Ukraine and abroad usually involve independent consideration of corrosion, fatigue and creep processes, although in reality these phenomena often occur simultaneously in various combinations. In addition, the analysis of existing methods of non-destructive testing of metal damage and degradation shows their limited effectiveness in assessing the service life of industrial equipment. Thus, the identified shortcomings of methods for assessing the performance of structures and their residual life indicate that in the modern period, calculation methods based on crack resistance criteria that are sensitive to changes in the metal structure during long-term operation are especially relevant, especially in conditions of corrosive technological processes and environments with variable dynamic loads. In addition, in today's challenging conditions for the oil and gas industry, when the renewal of physically and morally obsolete fixed assets is limited by financial circumstances, it is important to maintain and extend the service life of industrial equipment, including metal structures and pipelines, by increasing the overhaul interval.

Thus, the development and use of modern crack resistance criteria in regulatory and technical documents that take into account hydrogen sulfide degradation of the metal will allow for a more accurate prediction of the residual life of steel during long-term operation. Most of the corrosion inhibitor is located in the water plug of the gas-liquid flow. Thus, a condensed liquid with organic acids and water containing a minimal amount of inhibitor can accumulate in the upper part of the pipeline. This can cause a corrosion process [4]. Corrosion inhibitors dissolved in liquid water can accumulate for a month before passing through the pipeline. Whereas condensate, moving at the speed of the gas phase, can form only during its passage through the pipeline at any point where the temperature and pressure conditions favor condensation.

In situations where the gas phase is not moving fast enough to ensure that the upper part of the pipe is wetted with water droplets containing the corrosion inhibitor from below, corrosion of the upper part of the cylindrical pipe occurs. Therefore, it is necessary to ensure either a constant injection of the inhibitor into such pipelines or to use cleaning pistons to distribute the corrosion inhibitor from the bottom of the pipe to the top. For this purpose, polymer balls, gel pistons and pistons with special corrosion inhibitor sprays are used. To predict such conditions, analytical models for predicting this type of corrosion are used [10]. Controlling erosion and corrosion requires determining and evaluating the relative impact of flow-accelerated corrosion or erosion on corrosion. Only then can measures be taken to prevent these phenomena.

According to I. Chudyk, if the main cause is accelerated corrosion caused by damage to the protective coating, there are two options: take measures to prevent damage to the coating or accept the damage to the coating and apply methods to control the corrosion process [11].

If the main cause of failure is the erosion of the metal layer (usually the lower part of the inner surface of the structure), it is necessary to find the optimal solution for the pipeline structure and system and the right choice of material [6]. Determining the type of erosion-corrosion process is often not a difficult task. Erosion-corrosion, which occurs from the single-phase flow of water or solid particles in suspension, is characterized by the presence of various features such as smoothed grooves, piercing grooves, shallow pits and depressions with a characteristic horseshoe-shaped profile, often with an orientation along the flow [15].

One of the characteristic features of an aggressive environment is the appearance of isolated spots on the metal surface, which can then develop into a normal rough surface [8]. In the presence of cavitation and an aggressive environment in the form of impacts of liquid droplets, damage begins in the form of deep pits with sharp edges that can combine into a honeycomb structure. The corrosion atlas [7] and reference books on corrosion identification and control contain images of various manifestations of corrosion-erosion with descriptions of control methods and examples of their application. Compared to oil wells, gas and gas condensate wells show a higher level of corrosion activity from the very beginning of operation.

This is because all natural gas fields produce a certain amount of water and also contain additional natural gas components that, condensing in the gas stream as the temperature and pressure drop, dissolve in water and make it corrosive. Most underground hydrocarbon deposits do not actually contain dissolved oxygen in their fluids. This is a favorable factor, since it is known that even a small amount of oxygen, even at the level of billions of volume fractions in the gas-liquid mixture of the flow, significantly enhances corrosion processes. At the same time, carbon dioxide (CO2) and hydrogen sulfide (H2S) can be present in different concentrations in the flows of raw materials from both oil and gas fields [9]. In-situ corrosion in the absence of oxygen depends on the concentration of CO2 and H2S in the downhole flows. The terms "sweet corrosion", which describes corrosion caused by CO2, and "sour corrosion", which indicates problems with H2S, are used to distinguish which of these two gases prevails in a particular area [7].

Other factors that affect the rate of corrosion processes in pipelines include temperature, pressure, fluid flow pattern on the metal surface, and impurities in the aqueous phase of the fluid [14].

In general, corrosion "attacks" have different characteristics that can cause uneven zones of metal loss along the inner surface of the pipe. The erosion-corrosion process is the result of a combination of an aggressive chemical environment and high fluid velocity along the inner surface of the pipe. This can occur due to the rapid movement of the flow near a stationary object or due to the rapid movement of the object in a stationary flow. It is generally accepted that there is a relationship between erosion-corrosion rates and flow turbulence. While flow structure can lead to serious corrosion problems due to its high velocity, erosion-corrosion per se is not observed in straight pipelines where there are no mechanical impurities.

However, when the flow pattern changes, such as in a hydraulically rough pipe or nozzle, liquid droplets or gas bubbles collide and generate shock waves that destroy the protective surface film. Particulate matter can cause accelerated attacks by removing the protective mineral or corrosion inhibitor film. However, flow regime maps do not reflect the effects of mechanical impurities such as sand, corrosion products or scale, which are known as erosion-corrosion accelerators.

In the mechanics of fracture of metal structures, the critical stress intensity parameter is widely used to assess the toughness of the metal, which characterizes the metal's resistance to crack opening and propagation. Its threshold (critical) value during tests in corrosive environments is denoted by Kssc, MPa·m1/2. Fatigue cracks in the samples were grown using a TsDMpu-10 hydraulic pulsator (Germany) at a loading frequency of 10-15 Hz and a cycle asymmetry factor of r=0.1-0.2. Tests to determine the Ki parameter were carried out at the UME-10 installation according to the standard method described in [14], both in air and in a corrosive solution with H2S (NASE method). The material for the study was pipe steel, the characteristics of which are given in Tables 1 and Table 2.

Table 1 – Steel brands and their purpose

Steel brands	**Purpose**	Heat treatment
10 20 20K 09g2s 17g1s VST3SP	Machine-building metal structures, oil and gas, metallurgical, chemical, agricultural, utility and other industries	Normalization

Table 2 – Chemical composition of steels

Steel brands	**Chemical composition of steels,%**							
	C	Si	Mn	P	S	Cr	Ni	Cu
10	0.12	0.30	0.55	0.035	0.035	0.15	0.10	0.10
20	0.20	0.30	0.55	0.035	0.035	0.15	0.10	0.10
20K	0.22	0.35	0.65	0.3	0.03	0.12	0.12	0.10
09g2s	1.12	0.37	1.80	0.025	0.025	0.08	0.05	-
17g1s	0.19	0.60	1.21	0.03	0.03	-	0.30	0.30
VST3SP	0.12	0.27	0.40	0.04	0.04	-	-	-

It was found that the samples of all steels withstood the full test cycle, in particular, none of the five samples of each series failed within 480 hours. At the same time, the analysis of the corrosion fatigue curves led to the following conclusions:

1) steel grades 10, 20, 20K and VX3sp have poor resistance to long-term alternating loading, in particular, after 10-15 years of operation, the ultimate long-term strength reaches stresses (150-220 MPa), the lower yield strength for these steels is 230-260 MPa, and the threshold (critical) stresses in the supports are 125-160 MPa. At the same time, 09G2S and 17G1S steels meet the requirements of the NACE standard (Standard MP-01-75-96), in particular, the σpore values are 250-262 MPa.

The results of calculating the ratio σpor/σt(σ0.2) for all grades of steel that were subjected to experimental research are shown in Table 3. The analysis of the data in Table 3 shows that the ratio σпор/σт(σ0.2) is exactly 0.86 (steel 09Г2С) and 0.89 (steel 17Г1С), i.e. these two grades of steel meet the requirements of the technical conditions of NACE, and therefore can be recommended for use in the manufacture pipes that are intended for operation in chemically aggressive environments that contain hydrogen sulfide;

2) based on the obtained experimental results, a diagram of the susceptibility to hydrogen sulfide cracking of unexploited steel grades: 10 was constructed; 20; 20K; 09G2S; 17G1C; VSt3sp. Shaded area - steels with high corrosion resistance against SCRN.

Table 3 – Threshold stresses and ratio σpor/σт(σ0.2) steels

Steel brands	**Class characteristic**	σpor MPa	σpor / σt(σ0.2)
10	ferritic	150	0,68
20	ferritic	145	0,51
20K	ferritic	160	0,66
09g2s	pearly	250	0,86
17g1s	pearly	262	0,89
VST3SP	ferritic	125	0,56

t was found that the samples of all steels withstood the full test cycle, in particular, none of the five samples of each series failed within 480 hours. At the same time, the analysis of the corrosion fatigue curves led to the following conclusions: 1) steel grades 10, 20, 20K and VX3sp have poor resistance to long-term alternating loading, in particular, after 10-15 years of operation, the ultimate long-term strength reaches stresses (150-220 MPa), the lower yield strength for these steels is 230-260 MPa, and the threshold (critical) stresses in the supports are 125-160 MPa. At the same time, 09G2S and 17G1S steels meet the requirements of the NACE standard (Standard MP-01-75-96), in particular, the σ_{pore} values are 250-262 MPa.

The results of calculating the ratio σpor/σt(σ0.2) for all steel grades that were the subject of experimental studies are shown in Table 3. Analysis of the data in Tab. 3 shows that the ratio σpor/σt(σ0.2) is exactly 0.86 (09G2S steel) and 0.89 (17G1S steel), i.e., these two steel grades meet the requirements of the Classifier of Economic Activities, and therefore can be recommended for use in the manufacture of pipes intended for use in chemically aggressive environments containing hydrogen sulfide; 2) based on the experimental results, a diagram of the susceptibility to hydrogen sulfide cracking of unexplored steel grades was constructed: 10; 20; 20K; 09G2S; 17G1S; VSt3sp. The shaded area shows steels with high corrosion resistance against SCRH.

Conclusions. The study and analysis of the problem of ensuring reliable corrosion and mechanical resistance of steel structures of oil and gas facilities is extremely important in the context of preserving and extending the service life of industrial equipment and pipelines. This study identified the main factors affecting corrosion and mechanical resistance, including the chemical composition and service life of the material, device features, and parameters of process media.

An important step in solving this problem is to improve the methods of monitoring the condition of structures and introduce advanced technologies into oil and gas production practice. One of the most promising areas is the development and application of effective monitoring and diagnostic methods, in particular, the use of the corona discharge effect to detect defects in dielectric coatings.

Given the growing activity of corrosion processes in the hydrocarbon industry, it is important to strengthen corrosion prevention and protection measures to ensure the reliability and durability of equipment and facilities of oil and gas complexes.

References

1. Максимов С.Ю. (2019). Дослідження корозійно-механічної стійкості трубних сталей тривалої експлуатації в середовищах нафтових родовищ. *Збірник наукових праць за матеріалами XII Міжнародної науково-практичної конференції «Академічна й університетська наука: результати та перспективи», присвячена 90-річчю Національного університету «Полтавська політехніка імені Юрія Кондратюка»* (6.12.2019), 211-220

2. *Механіка руйнування та міцність матеріалів: Довідниковий посібник* / Під заг. ред. В.В. Панасюка. Том 11: Міцність і довговічність нафтогазових трубопроводів і резервуарів. Г.М. Никифорчин, С.Г. Поляков, В.А. Черватюк та інші. Львів: СПОЛОМ. 2009. 504 с.

3. Нестеренко С., Донський Д., Nemah A. (2019). Моделювання антикорозійного захисту матеріалу обсадної колони в лабораторних умовах. *Вісник Національного технічного університету «ХПІ». Інноваційні дослідження у наукових роботах студентів*, 21, 69-74 https://doi.org/10.20998/2220-4784.2019.21.11

4. Панченко В.О., Папченко А.А. (2018). *Гідравлічні машини і обладнання нафтових та газових комплексів : навчальний посібник.* Суми: Сумський державний університет.

1. Maksimov S.Yu. (2019). Investigation of corrosion-mechanical resistance of pipe steels during long-term operation in oil field environments. *Collection of scientific works based on the materials of the XII International Scientific and Practical Conference «Academic and university science: results and prospects» dedicated to the 90th anniversary of the Yuriy Kondratyuk Poltava Polytechnic National University* (6.12.2019), 211-220

2. *Fracture mechanics and strength of materials: Reference guide* / Under general ed. V.V. Panasyuka Volume 11: Strength and Durability of Oil and Gas Pipelines and Tanks. AHEM. Nikyforchyn, S.G. Polyakov, V.A. Chervatyuk and others. Lviv: SPOLOM. 2009. 504 p.

3. Nesterenko, S., Donsky, D., Nemah, A. (2019). Modeling of anti-corrosion protection of casing column material in laboratory conditions. *Bulletin of the National Technical University "KhPI". Innovative research in the scientific works of students*, 21, 69-74 https://doi.org/10.20998/2220-4784.2019.21.11

4. Panchenko V.O., Papchenko A.A. (2018). *Hydraulic machines and equipment of oil and gas complexes: study guide.* Sumy: Sumy State University.

5. Райтер П. М. (2011) Моніторинг корозійно-ерозійних пошкоджень нафтогазопроводів на основі визначення структури та фазового складу багатофазного потоку свердловин. *Розвідка та розробка нафтових і газових родовищ. № 4(41).* 12-18.

6. Степова О.В., Галькевич В.І. (2012). Моніторинг корозійної безпеки газопроводів Полтавської області. *Збірник наукових праць за матеріалами V Всеукраїнського науково-практичного форуму установ НАН України «Проблеми й перспективи розвитку академічної та університетської науки».* (Полтава, 12-14.12.2012 р.). Полтава: ПолтНТУ. 15-16.
https://doi.org/10.15587/1729-4061.2017.96425

7. Степова О.В., Листопад М.А. (2011). Вплив навколишнього середовища на стан конструкцій будівельних споруд. *Матеріали ІІІ Міжнародної наукової конференції студентів та молодих вчених «Екологія. Довкілля. Молодь».* (Полтава, 11-12.05.2011 р.). Полтава: ПолтНТУ. 43-45
https://doi.org/10.15587/1729-4061.2020.194315

8. Василюк В.М., Черватюк В.А., Васьківський В.П., Федоренко Ю.Г., Ткач С.В. (2008). *Сучасні протикорозійні матеріали для захисту об'єктів нафтогазового комплексу України: Довідник-каталог.* Львів: СПОЛОМ.

9. Учанін В. (2020). *Високовольтний електроіскровий контроль діелектричних антикорозійних покривів металевих конструкцій.* Взято з https://www.ipm.lviv.ua/corrosion2020/Chapter_04/I_263_UCHANIN.pdf

10. Стоєв П.І., Литовченко С.В., Гірк, І.О., Грицина В.Т. (2019). *Хімічна корозія та захист металів : навчальний посібник.* Х. : ХНУ імені В.Н. Каразіна.

11. Чудик І. (2020). *Вплив пластових вод на корозію та довговічність бурильних труб.* Взято з https://www.ipm.lviv.ua/corrosion2020/ua/materials.html

12. ASTM D 5162:2015. (2015). *Standard practice for discontinuity (holiday) testing of nonconductive protective coating on metallic substrate.*

13. NACE International SP0188. *Standard Practice-Discontinuity (holiday) testing of new protective coatings on conductive substrates.*

14. Mario D. (2020). *Reliability analysis of steel buildings considering the flexibility of the connections of the GFs.* Elseveir. № 10. 2170-2181
https://doi.org/10.1016/j.istruc.2020.08.014

15. Eduardo Calixto. (2021). *Gas and Oil Reliability Engineering: Modeling and Analysis.* Gulf Professional Publishing is an imprint of Elsevier.

5. Ryter P.M. (2011) Monitoring of corrosion-erosion damage of oil and gas pipelines based on the determination of the structure and phase composition of the multiphase flow of wells. *Exploration and development of oil and gas fields. No. 4(41).* 12-18.

6. Stepova O.V., Halkevich V.I. (2012). Monitoring of corrosion safety of gas pipelines of the Poltava region. *A collection of scientific works based on the materials of the V All-Ukrainian scientific and practical forum of institutions of the National Academy of Sciences of Ukraine "Problems and prospects of the development of academic and university science".* (Poltava, December 12-14, 2012). Poltava: PoltNTU. 15-16
https://doi.org/10.15587/1729-4061.2017.96425

7. Stepova O.V., Lystopad M.A. (2011). The influence of the environment on the condition of construction structures. *Materials of the 3rd International Scientific Conference of Students and Young Scientists "Ecology. Environment Young".* (Poltava, May 11-12, 2011). Poltava: PoltNTU. 43-45
https://doi.org/10.15587/1729-4061.2020.194315

8. Vasylyuk V.M., Chervatyuk V.A., Vaskivskyi V.P., Fedorenko Yu.G., Tkach S.V. (2008). *Modern anti-corrosion materials for the protection of objects of the oil and gas complex of Ukraine: Handbook-catalogue.* Lviv: SPOLOM.

9. Uchanin V. (2020). *High-voltage electric spark control of dielectric anti-corrosion coatings of metal structures.* Retrieved from https://www.ipm.lviv.ua/corrosion2020/Chapter_04/I_263_UCHANIN.pdf

10. Stoev P.I., Lytovchenko S.V., Girka I.O., Hrytsyna V.T. (2019). *Chemical corrosion and protection of metals: study guide*. Kh.: V.N. Karazin KhNU.

11. Chudyk I. (2020). *Influence of formation waters on corrosion and durability of drill pipes.* Retrieved from https://www.ipm.lviv.ua/corrosion2020/ua/materials.html

12. ASTM D 5162:2015. (2015). *Standard practice for discontinuity (holiday) testing of nonconductive protective coating on metallic substrate.*

13. NACE International SP0188. *Standard Practice - Discontinuity (holiday) testing of new protective coatings on conductive substrates.*

14. Mario D. (2020). *Reliability analysis of steel buildings considering the flexibility of the connections of the GFs.* Elsevier. No. 10. 2170-2181
https://doi.org/10.1016/j.istruc.2020.08.014

15. Eduardo Calixto. (2021). *Gas and Oil Reliability Engineering: Modeling and Analysis.* Gulf Professional Publishing is an imprint of Elsevier.