Journal of Chemistry and Technologies

pISSN 2663-2934 (Print), ISSN 2663-2942 (Online).

journal homepage: http://chemistry.dnu.dp.ua
editorial e-mail: chem.dnu@gmail.com

UDC 620.193

ASSESSMENT OF THE CORROSION IMPACT ON THE SERVICEABILITY OF TANK WAGON BOILERS DESIGNED FOR CHEMICAL CARGO TRANSPORTATION

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Received 2025; accepted 2025; available online 15 July 2025

Abstract

The paper investigates the influence of corrosion processes on the operational reliability of tank car boilers intended to transport chemical cargoes. The main corrosion mechanisms, material characteristics, operating conditions, and the impact of various aggressive environments were analyzed. The study uses a combination of field inspection data from inspection of tank cars, statistical analysis, and thermodynamic modeling based on standard electrode potentials and corrosion rates. The results demonstrate a clear dependence of the intensity of material degradation on the type of chemical cargo. Statistical analysis has shown that after 4 years of operation, 25 % of tanks have through damage, and after 6 years, 68 % have already been damaged. This indicates the need for timely diagnostics and modernization of corrosion protection. The article also discusses promising protection technologies such as nanomaterial-based coatings, pulsed cathodic protection, and integrated monitoring systems. Practical recommendations for preventing corrosion, optimizing maintenance, and extending the service life of railcars are proposed. The results can be used to enhance the safety and efficiency of transporting hazardous goods.

Keywords: Tank cars; Maritime Transport; Chemical transportation; Metal degradation; Corrosion resistance; Cargo safety; Corrosion prevention; Transport engineering; Structural integrity; Corrosive environments.

ДОСЛІДЖЕННЯ ВПЛИВУ КОРОЗІЇ НА ЕКСПЛУАТАЦІЙНУ НАДІЙНІСТЬ КОТЛІВ ВАГОНІВ-ЦИСТЕРН, ПРИЗНАЧЕНИХ ДЛЯ ПЕРЕВЕЗЕННЯ ХІМІЧНИХ ВАНТАЖІВ

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Анотація

У статті досліджений вплив корозійних процесів на експлуатаційну надійність котлів вагонів-цистерн, призначених для перевезення хімічних вантажів. Проаналізовано основні механізми корозії, характеристики матеріалів, умови експлуатації та вплив різних агресивних середовищ. У дослідженні використано поєднання даних польових обстежень вагонів-цистерн, статистичного аналізу та термодинамічного моделювання на основі стандартних електродних потенціалів і швидкостей корозії. Результати демонструють чітку залежність інтенсивності деградації матеріалу від типу хімічного вантажу. Статистичний аналіз показав, що через 4 роки експлуатації 25 % резервуарів мають наскрізні пошкодження, а через 6 років – вже 68 %. Такі данні свідчать про необхідність своєчасної діагностики або модернізації антикорозійного захисту. Також обговорюються перспективні технології захисту які включають покриття на основі наноматеріалів, імпульсний катодний захист та інтегровані системи моніторингу. Запропоновано практичні рекомендації щодо запобігання корозії, оптимізації технічного обслуговування та подовження терміну служби вагонів.

Ключові слова: Цистерни; Морський транспорт; Хімічні вантажі; Деградація металу; Корозійна стійкість; Безпека перевезеня вантажів; Запобігання корозії; Транспортне машинобудування; Структурна цілісність; Корозійні середовища.

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doi: 10.15421/jchemtech.v33i2.321726

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Introduction

The transportation of chemicals in tank cars requires increased attention to the technical condition of their structural elements, including the internal surfaces of boilers. Corrosion processes significantly reduce operational reliability, leading to leakage of hazardous substances and increasing the risk of transportation accidents. This paper considers the urgent need to develop effective methods of early diagnosis and preventive measures to prevent corrosion damage and extend the service life of tank cars.

Corrosion of metal materials in chemical transportation systems remains an urgent problem. Aggressive environments, such as sodium hypochlorite solutions and mineral acids, significantly accelerate the destruction of carbon and stainless steels used in boiler production [1–3]. Insufficient maintenance and improper material choice are the main causes of premature failures.

Modern anti-corrosion technologies, including nanomaterial-based coatings, cathodic protection, and real-time monitoring systems, show significant potential for extending the service life of transportation tanks [4–10; 16; 24]. Unlike marine or pipeline systems, tank cars face unique challenges related to dynamic loads and chemical exposure during rail transportation. In particular, anti-corrosion coatings based on nanomaterials and innovative polymers efficiently protect metal structures [5–7].

Numerous papers discuss the safety of transporting dangerous goods. Studies emphasize the need to improve the design and materials used in transport systems such as tanks, containers, and pipelines. Extending the service life of structures is possible through the use of high-strength materials and corrosion prediction techniques [8–15; 19; 25].

Modern techniques such as pulsed cathodic protection and real-time monitoring prevent corrosion failure in trunk pipelines and transport vessels used in corrosive environments [24; 26–30]. While most previous studies have focused on the corrosion of ships and pipelines [31–40], insufficient attention has been paid to the peculiarities of tank cars. Therefore, this paper aims to fill this gap by providing a comprehensive analysis that combines field inspection data, statistical analysis, and thermodynamic evaluation specifically for the rail transportation of chemicals.

Studies of dynamic loads and corrosion of wagon structures show that optimization of design solutions can significantly extend their service life. For example, loads on containers placed on platforms under conditions of shunt impacts and transport on ferries have been studied. The problems of improving the environmental friendliness of marine vessels by using alternative fuels and protecting the hull of ships from corrosion are also considered [41–44].

Cathodic protection technologies and intelligent corrosion monitoring systems play important roles in preventing material degradation in transport systems. In particular, corrosion monitoring systems for the seagoing ships allow for the prevention of accidents in time [45–48]. Using prediction models and high-precision protection technologies can significantly improve the performance of structures [49–51].

Special attention is paid to preventing the thermochemical degradation of materials, especially concrete and metals, when exposed to high temperatures and aggressive media. Research also aims to develop anti-corrosion coatings for marine transportation and pipelines that transport liquids in aggressive environments, including supercritical CO_2 [52–58].

Despite significant progress in material science, existing anti-corrosion technologies do not always provide adequate protection in the long term, especially when exposed to complex external factors such as chemical, mechanical, and thermal stresses. The task is compounded by the need to adapt transportation systems to transport modern substances, including hazardous chemical compounds and new energy carriers such as liquefied gases and supercritical CO_2.

The study aims to analyze the main types of corrosion damage to boilers' internal surfaces, statistically assess the frequency of defects depending on their service life, thermodynamically model the corrosion behavior of materials, and develop practical recommendations for improving corrosion resistance and operational safety.

Methods and materials

Materials and Operational Conditions

Due to their mechanical strength and economic feasibility, tank wagons for chemical cargo transportation are primarily constructed from carbon steels (such as 09G2S) and low-alloy steels. However, these materials are highly susceptible to various types of corrosion when exposed to aggressive chemical media such as sulfuric acid, sodium hypochlorite, and organic acids.

Corrosive processes are predominantly promoted by an aqueous phase within the transported cargo, elevated acidity, chemical impurities, and operational parameters such as temperature and transportation modes. These conditions lead to material degradation through general, localized, and pitting corrosion, particularly in areas of liquid accumulation.

Statistical analysis of tank car boiler malfunctions

The experience of operating rolling stock for the transportation of acids shows that a significant share of failures is associated with intensive corrosion processes caused by the chemical activity of the cargo being transported. The influence of an aggressive environment leads to loss of cargo, shortening of the service life and increase in the labor cost of repairing wagons. This largely applies to tanks for the transportation of chemical cargoes. As practice shows, after four years of operation, 25 % of tanks have through corrosion damage in the boiler, up to five years – 52 %, and up to six years – 68 %.

Currently, the main task in the development of railway rolling stock is the creation of tank cars with boilers of increased strength and corrosion resistance, which should ensure the maintenance-free operation of the car in the period between major repairs.

Among the tasks of the current stage, the most important is the systematic introduction of new technical solutions and advanced technologies aimed at increasing the durability of components and parts of rolling stock, increasing the operational reliability of the existing fleet of wagons used for the transportation of corrosive-active cargo.

The operating conditions of wagons used for the transportation of acids are characterized by the constant interaction of structural elements with a corrosive-active environment. The experience of operating tank cars for the transportation of acids shows that corrosion damage is the cause of 60–65 % of cases of car failures.

Prior to inspection, the boilers were drained entirely and internally cleaned using high-pressure jet systems to remove residual chemical substances and corrosion products. Non-destructive testing (NDT) techniques employed included:

1. *Ultrasonic thickness gauging* to detect metal thinning;
2. *Visual and endoscopic inspection* to identify localized corrosion, pitting, and weld deterioration;
3. *Electrochemical potential measurements* in critical zones to assess active corrosion processes.

Measurements were systematically conducted across three vertical zones of the boiler shell (upper, middle, and lower) to capture the corrosion profile distribution. Conducting static studies of various types of corrosion of tank car boilers, we obtained approximate static relationships between them, which are presented in Figure 1. (The data shown in Figure 1 were obtained based on field inspections of 120 tank wagons during scheduled maintenance.)

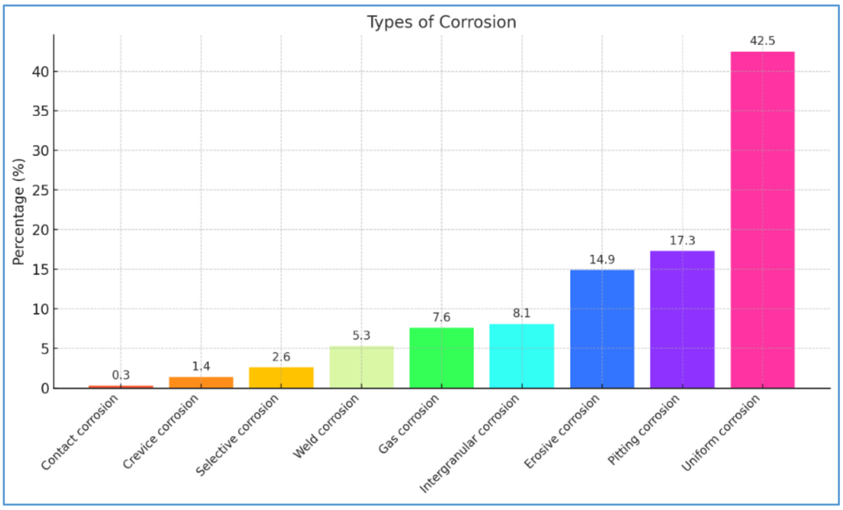

Fig. 1. Ratio of types of corrosion (in percent)

It should also be noted that certain types of corrosion occur in different combinations in tank cars operating under different conditions.

According to the nature of corrosion damage to the inner surface and the degree of action of the corrosive-active components of chemical cargoes, the tank car boiler can be conditionally divided into the following zones: the upper zone (upper sheets of the cylindrical shell), the middle zone (the middle sheets of the cylindrical shell), the lower zone (the lower sheets of the cylindrical shell parts), bottoms. Depending on the type of chemical cargo, the rate of corrosion of the lower belt is on average 0.35–0.5 mm/year.

Thermodynamic evaluation of corrosion resistance of tank car boiler materials

The corrosion of the internal surfaces of tank car boilers during chemical transportation is determined by the electrochemical properties of metals and environmental conditions. Standard electrode potentials, Nernst's equation, and analysis of the passivation capacity of materials are used to assess the probability and intensity of corrosion.

The change in the Gibbs free energy determines the thermodynamic tendency of metals to oxidize:

$$\Delta G = -nFE \, , \qquad (1)$$

where ΔG – change in the Gibbs free energy, J/mol, n – number of electrons participating in the reaction, F – Faraday number (96485 K/mol), E – electrode potential of the process, V.

Metals with negative standard electrode potentials are thermodynamically less resistant to corrosion.

The thermodynamic analysis of corrosion behavior requires understanding the standard electrode potentials of construction metals. Table 1 summarizes the standard electrode potentials and general corrosion susceptibility of key materials commonly used in chemical tank wagons.

Table 1

Standard electrode potentials of construction metals at 25 °C

Metal	Standard Electrode Potential (E°, V)	Corrosion Susceptibility
Iron (Fe)	-0.44	High
Carbon Steel	~ -0.50	High
Stainless Steel (AISI 316L)	+0.00 to +0.10	Moderate
Aluminum (Al)	-1.66	Very High
Magnesium (Mg)	-2.37	Extremely High

The data in Table 1 indicate that carbon and low-alloy steels, which are commonly used for manufacturing tank wagon boilers, show relatively high corrosion susceptibility, especially under acidic and oxidizing conditions. Aluminum and magnesium, although lightweight, are even more prone to rapid corrosion and therefore require significant protection measures.

The Nernst equation is used to take into account the real conditions of electrolyte and ion concentrations:

$$E = E^{\circ} - \frac{RT}{nF} \ln \frac{a_{\mathrm{Me}^{n+}}}{a_{\mathrm{Me}}} \, , \qquad (2)$$

where R - universal gas steel (8.314 J/(mol·K), T – absolute temperature, K, $a_{\mathrm{Me}^{n+}}$ – activity of metal ions.

This allows you to adjust the electrode potential depending on the actual environment.

The behavior of metals in aggressive environments depends on their electrode potential and ability to form protective passive films. The concept of Pourbaix diagrams shows that at certain pH and potential values, a metal can be:

– active (corrosion occurs);
– passive (a protective oxide film is formed);
– dissolve in an acidic or alkaline environment.

For iron, the passivation region occurs at approximately pH > 9 or pH < 3 in some environments. The corrosion rate in different media indicates that actual operating conditions cause different corrosion rates in boilers, depending on the composition of the load.

In addition to thermodynamic tendencies, the actual corrosion rate of a material in specific environments is crucial for assessing the operational reliability of tank wagons. Table 2 presents typical corrosion rates of carbon steel in different aggressive chemical environments.

Table 2

Typical corrosion rates of carbon steel in different chemical environments

Chemical Environment	Corrosion Rate (mm/year)
Sulfuric Acid (30 %)	0.50–1.20
Sodium Hypochlorite Solution (5 %)	0.80–1.50
Acetic Acid (10 %)	0.15–0.40
Hydrochloric Acid (20%)	1.00–2.50
Distilled Water	<0.01

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As shown in Table 2, carbon steel exhibits significantly higher corrosion rates when exposed to concentrated acids and oxidizing agents such as hypochlorite solutions. These results emphasize the importance of applying effective corrosion protection methods, especially for tank wagons transporting hazardous chemical cargoes.

Results and Discussion

The research presented in this paper highlights the multifaceted effects of corrosion on the performance of tank wagons used to transport chemical cargoes. The results of experimental analyses and statistical evaluations emphasize the predominant role of corrosion types, such as pitting and weld corrosion, which are often underestimated in risk assessments. Internal corrosion significantly affects the integrity and safety of tank wagon boilers, where factors such as exposure to high acidity, impurities, and inadequate protection measures increase material degradation.

Statistical analysis shows that after four years of operation, through-wall corrosion is observed in 25 percent of tank wagons and after six years in 68 percent. This correlation between service life and the extent of corrosion emphasizes the urgent need for advanced diagnostics to detect damage early.

Figure 1 illustrates how pitting corrosion significantly contributes to structural failures. Furthermore, the thermodynamic modeling of corrosion processes in this study enhances our understanding of metal-environment interactions, allowing for better predictions of corrosion rates in varying conditions.

Creative solutions, such as anti-corrosion coatings using nanomaterials and the adoption of real-time monitoring systems, are regarded as practical approaches for reducing the adverse impacts of corrosion. These technologies facilitate the early identification of concealed corrosion hotspots, lowering the risk of severe failures. Notably, pulsed cathodic protection holds promise for prolonging tank wagons' lifespan by instantaneously counteracting corrosion reactions.

The graph in Fig. 2 shows the percentage of tank wagons damaged by corrosion of different degrees (light, medium, heavy) depending on the operation time. Statistical data in Figure 2 are based on operational records of chemical cargo tank wagons over 8 years.

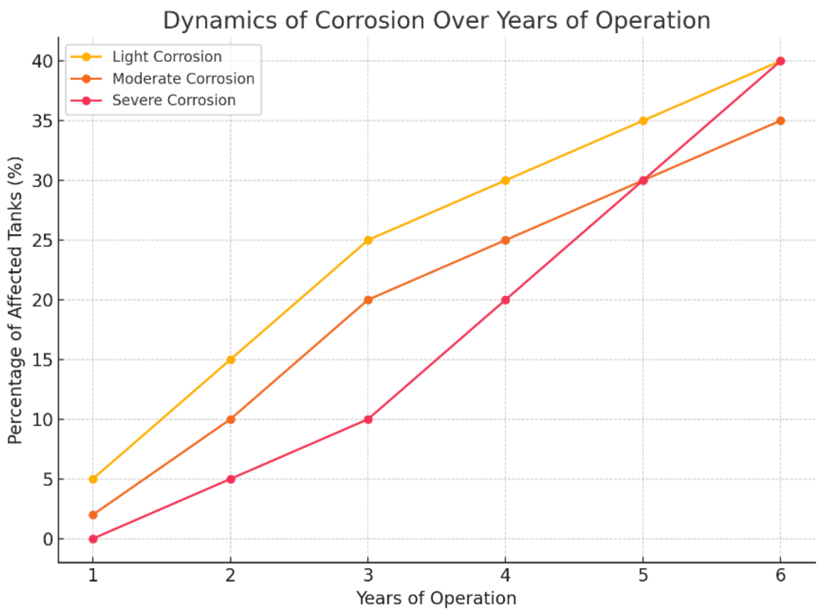

Fig. 2. Dynamics of corrosion over years of operation

With increasing service life, the percentage of wagons with heavy corrosion increases sharply, reaching 40 % by the sixth year. This emphasizes the need to implement preventive measures at the early stages of operation.

The discussion also points to gaps in existing corrosion prevention strategies, noting that long-term protection under complex environmental and mechanical stresses remains challenging. The findings favor an integrated, multi-layered approach to corrosion prevention that combines advanced coatings, predictive modeling, and robust monitoring systems. Future research should focus on adapting these solutions to new transport needs, including handling new chemical compounds and sustainable energy carriers such as supercritical CO_2.

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Moreover, the aggressiveness of the chemical environment was found to influence the rate and type of corrosion damage significantly. Strong oxidizing agents, such as sodium hypochlorite, promote intensive localized corrosion (pitting), while mineral acids like sulfuric acid predominantly lead to uniform thinning of the boiler walls. Organic acids such as acetic acid demonstrated comparatively lower corrosion rates, indicating that the chemical composition of the transported cargo must be critically considered when predicting the service life of tank wagons.

Conclusion

The study confirmed the significant impact of corrosion processes on the durability and safety of tank cars in transporting chemicals. Statistical analysis of operational data showed a sharp increase in damage frequency after four years of service, emphasizing the need for early preventive measures. Thermodynamic modeling has demonstrated that tank car boilers' susceptibility to corrosion depends mainly on the chemical nature of the cargo. Strong oxidants, such as sodium hypochlorite, significantly accelerate the development of localized corrosion, while mineral acids, such as sulfuric acid, mostly lead to uniform thinning of the boiler walls. Organic acids demonstrate a relatively lower corrosive impact. Cutting-edge solutions, including nanomaterial-based coatings, cathodic protection methods, and integrated monitoring systems, have proven extremely effective in minimizing corrosion damage and improving the safety of transporting hazardous materials. The expectancy for vehicular tank wagons can be increased through an all-inclusive approach towards using the sustainable and long-life materials with the provision also for predictive maintenance technologies, plus maintenance schedules.

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