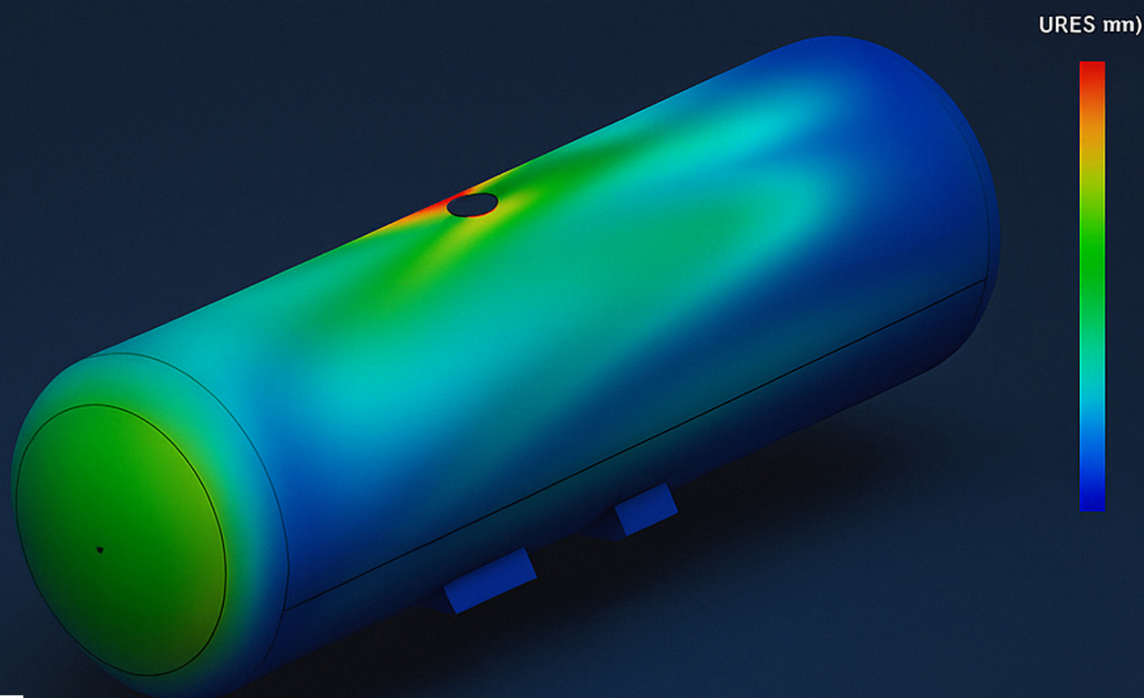


OLEKSIJ FOMIN, IURII SHCHERBYNA,
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STUDY OF THE STRESSED AND DEFORMED STATE OF A TANK WAGON BOILER FOR TRANSPORTATION OF CHEMICAL CARGO UNDER THE INFLUENCE OF CORROSION

MONOGRAPH



2025
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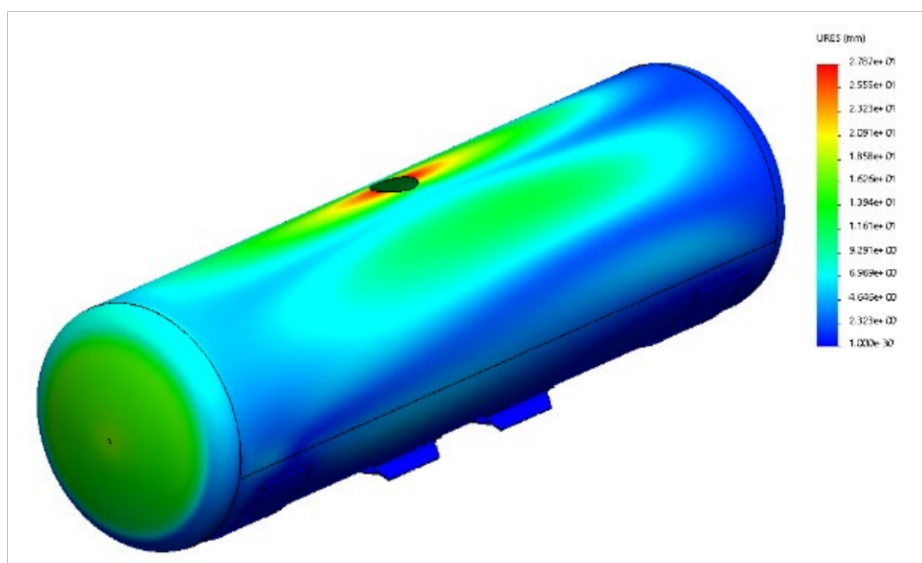
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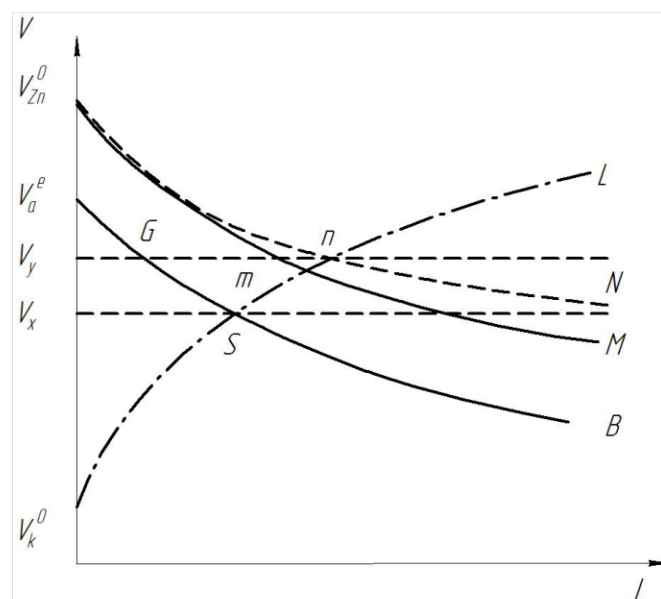
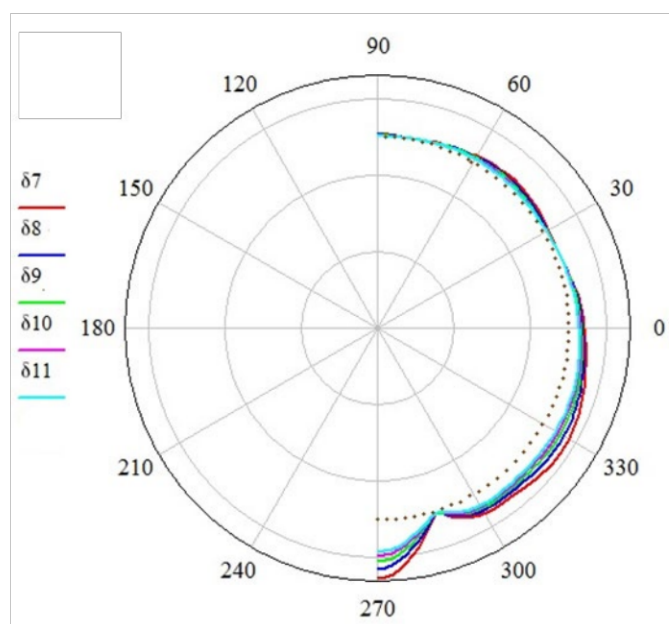
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*The Department of Cars and Carriage Facilities
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This monograph is dedicated to the pressing issue of ensuring the reliability and safety of the operation of tank wagons intended for the transportation of chemical cargo under conditions of corrosion wear. The work comprehensively investigates the influence of corrosion on the stressed and deformed state of the tank wagon boiler.

Chapter 1 assesses the effect of corrosion on the operability of boilers of tank wagons intended for the transportation of chemical loads. The mechanisms of corrosion damage to the inner surface of the boilers are analyzed, statistical information on corrosion-related malfunctions is presented, and the behavior of metals and alloys in aggressive chemical environments is considered. The application of non-destructive testing methods for determining the actual thickness of the boiler metal is substantiated.

Chapter 2 focuses on the theoretical foundations for calculating the stressed and deformed state of a tank wagon boiler using the Mathcad software environment. The basic principles of calculating discrete models of physical shells are outlined, the calculation method and necessary input data are defined. An algorithm for determining the stress-strain state of the cylindrical shell of the boiler in the Mathcad environment is presented.

Chapter 3 presents a study of the stressed and deformed state of the boiler shell of a tank wagon and an assessment of its fatigue strength in case of corrosion wear using computer simulation. The calculation method is described, and a computational model of the boiler based on the 15-1443-14 tank wagon model in the SolidWorks software complex is developed and described. The results of the conducted research are provided and analyzed.

Chapter 4 offers proposals for increasing the service life of tank wagon boilers. Methods of protection against metal corrosion are considered, a set of technical solutions for protecting the inner surface of the tank wagon boiler from corrosion is developed, and an algorithm for calculating the tread protection system is proposed.

This monograph is intended for researchers, engineers, postgraduate students, and students specializing in the fields of railway transport, materials science, metal corrosion, and structural strength.

It can also be used as a учебное пособие (teaching aid/textbook) for relevant academic disciplines.

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ABSTRACT

Object of Research: The stressed and deformed state of a tank wagon boiler intended for the transportation of chemical cargo.

Subject of Research: The influence of corrosion wear on the stressed and deformed state and fatigue strength of the tank wagon boiler.

Research Methods: The study employed a comprehensive approach, including the analysis of scientific and technical literature and regulatory documents, statistical analysis of operational data, theoretical modeling of the stressed and deformed state using the finite element method in Mathcad and SolidWorks software environments, and the development of an algorithm for calculating the tread protection system. The impact of various degrees of corrosion wear on the stress distribution and deformation behavior of the boiler structure was evaluated.

Brief Conclusions: The conducted research established the patterns of changes in the stressed and deformed state of the tank wagon boiler under the influence of corrosion. A significant impact of corrosion-induced wall thinning on the increase in stress levels and the reduction of the structure's fatigue strength was revealed. The developed computer model allows for predicting the residual life of the boiler, considering the actual corrosion wear. A set of technical solutions for protecting the inner surface of the boilers from corrosion is proposed, including the selection of optimal materials and the application of cathodic protection, which contributes to increased safety and extended service life of the tank wagons. The obtained results can be used in the development of methods for assessing the technical condition and predicting the service life of tank wagons operated under conditions of exposure to aggressive chemical environments.

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INTRODUCTION

The transportation of chemical cargo by rail plays a crucial role in the global economy, facilitating the movement of essential industrial and consumer goods. Tank wagons are indispensable assets in this process, designed to safely and efficiently convey a wide range of liquid and gaseous chemical substances. However, the aggressive nature of many transported chemicals poses a significant challenge to the structural integrity and operational reliability of these specialized railway vehicles. The primary threat in this context is corrosion, a natural electrochemical process that degrades metallic materials over time, particularly when exposed to reactive environments.

The boilers of tank wagons, which directly contain the transported chemical substances, are particularly vulnerable to corrosion. The internal surfaces of these vessels are in constant contact with potentially corrosive media, leading to a gradual thinning of the metal walls and the formation of corrosion products. This degradation can significantly compromise the structural strength of the boiler, increasing the risk of leaks, ruptures, and ultimately, catastrophic failures. Such incidents can have severe consequences, including environmental contamination, economic losses, and, most importantly, threats to human life and safety.

Understanding and mitigating the effects of corrosion on tank wagon boilers is therefore of paramount importance for ensuring the safe and sustainable transportation of chemical cargo. This necessitates a comprehensive investigation into the mechanisms of corrosion in the specific context of tank wagon operation, an assessment of its impact on the structural integrity of the boilers, and the development of effective strategies for corrosion protection and prevention.

Existing research in this area has addressed various aspects of corrosion in railway transport, including the general principles of metallic corrosion, the behavior of specific materials in different chemical environments, and the application of various corrosion protection techniques. However, a focused and integrated study specifically addressing the stressed and deformed state of tank wagon boilers under the influence of corrosion, combining theoretical analysis, experimental data, and computational modeling, remains a critical need.

This monograph aims to bridge this gap by providing a comprehensive analysis of the stressed and deformed state of tank wagon boilers subjected to corrosion wear. It will delve into the specific corrosion challenges encountered in the transportation of diverse chemical loads, examining the types and rates of corrosion that typically occur on the internal surfaces of the boilers. Furthermore, the work will explore the consequences of this material degradation on the structural integrity of the tank wagons, focusing on how corrosion-induced

thinning and surface degradation affect the stress distribution and deformation behavior of the boiler shell under operational loads.

To achieve these objectives, the monograph will employ a multi-faceted approach. It will begin with a thorough review of existing literature on corrosion in railway transport and the mechanical behavior of materials in corrosive environments. Subsequently, it will present theoretical frameworks for analyzing the stressed and deformed state of thin-walled cylindrical shells, adapted to account for the effects of corrosion-induced material loss. The application of computational tools, specifically the Mathcad and SolidWorks software environments, will be central to this analysis, enabling the simulation of stress and strain distributions in corroded boiler structures under various loading conditions.

The study will also incorporate the analysis of real-world data, including statistical information on tank wagon boiler malfunctions related to corrosion, and the application of non-destructive testing methods for assessing the extent of corrosion damage in operational vehicles. This empirical data will serve to validate the theoretical models and computational simulations, providing a more accurate understanding of the actual impact of corrosion on the structural integrity of tank wagon boilers.

Based on the findings of the theoretical analysis, computational modeling, and empirical data analysis, the monograph will propose a range of technical

solutions and recommendations for increasing the service life and operational safety of tank wagon boilers. These proposals will encompass strategies for selecting corrosion-resistant materials, implementing effective corrosion protection systems, and developing optimized maintenance and inspection protocols. Special attention will be paid to the development of an algorithm for calculating tread protection systems, a crucial aspect of mitigating external corrosion.

Ultimately, this monograph seeks to provide a comprehensive resource for researchers, engineers, and industry professionals involved in the design, operation, and maintenance of tank wagons for chemical cargo transportation. By providing a deeper understanding of the complex interplay between corrosion and the structural integrity of tank wagon boilers, this work aims to contribute to the development of safer, more reliable, and more sustainable practices in the transportation of hazardous chemical substances. The findings and recommendations presented herein are intended to inform future research, guide engineering design decisions, and ultimately enhance the safety and efficiency of the chemical transportation sector. Moreover, the integrated approach and the detailed analysis of theoretical models and practical applications make this monograph a valuable учебное пособие (teaching aid/textbook) for students and academics in relevant engineering disciplines.

1 ASSESSMENT OF THE EFFECT OF CORROSION ON THE OPERABILITY OF BOILERS OF TANK WAGONS WHICH ARE INTENDED FOR THE TRANSPORTATION OF CHEMICAL LOADS

1.1 Corrosion of the inner surface of tank wagon boilers

One of the essential factors affecting the integrity of the shell of a tank wagon boiler is internal corrosion. This phenomenon is a process of spontaneous destruction of metal as a result of its interaction with an aggressive environment. In most cases, corrosion proceeds according to the electrochemical principle when the metal is in contact with an aqueous environment.

Corrosion of the internal surface of the boiler is one of the main reasons for the impossibility of performing operational functions and is associated with the influence of many factors - high water content of transported products, increased acidity, the content of impurities that increase the rate of corrosion processes, modes of transportation, temperature, surface condition metal boiler, etc. These factors can affect the rate of corrosion: in some cases they can reduce it, and in others - increase it. Regardless of this, the fundamental danger of corrosion is determined by the presence of a water phase in the transported media.

The process of corrosion is the cause of a decrease in the technical resource of the wagon, a partial or complete violation of the functioning of the system, the inability to participate in the transportation process.

Boilers of tank wagons are vulnerable to corrosion caused by physical processes of contacting different environments and chemical reactions occurring in them as a result of interaction. Over time, corrosion reduces the integrity of the boiler and eventually penetrates its structure, causing a change in thickness and leading to perforation of the shell, which can lead to the leakage of chemical wagons into the environment and the occurrence of a further man-made disaster.

Since most corrosion occurs inside the boiler, the extent of the danger is usually unknown and hidden until external signs appear, which are often too late to remedy. Timely detection of such "dangerous" zones is a priority task when conducting technical diagnostics of the boiler surface, in connection with which the development of forecasting methods to detect them at an early stage occupies a special place in the evaluation of the technical condition of the wagon structure.

The most characteristic types of corrosion observed during the operation of tank wagons include:

- general corrosion - occurs on the entire surface of the boiler;
- local corrosion - appears in certain places where the liquid phase of a chemical substance accumulates or is located;

- pitting corrosion - occurs on horizontal surfaces, on the bottom of the boiler and in places where the liquid phase accumulates (bottom sheets).

- weld metal corrosion - occurs when the welding metal interacts with the boiler metal, causing an electrolytic reaction.

In order to detect corrosion, the boiler must first be emptied of the contents of the chemical cargo, and then a complete internal cleaning using pressure jet cleaning must be performed. Next, non-destructive testing is carried out to check the thickness of the metal at various points of the boiler, depending on the chosen place of measurement. Appropriate measurements are made for the lower, middle and upper part of the boiler shell. When corrosion is detected, measures are taken to eliminate it, in accordance with the restoration technology approved by the repair company.

1.2 Statistical analysis of tank wagon 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 wagons with boilers of increased strength and corrosion resistance, which should ensure the maintenance-free operation of the wagon 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 wagons for the transportation of acids shows that corrosion damage is the cause of 60-65% of cases of wagon failures.

The assessment of the technical condition of the boilers of tank wagons is carried out in order to establish the possibility of safe operation in case of detection of defects, or after the estimated service life has been exhausted.

Technical diagnostics can be carried out by studying the chemical composition, mechanical properties and structure of the metal. To determine the final service life based on corrosion wear, it is necessary to measure the actual thickness of the boiler shell elements.

Corrosion damage is a metal surface defect that causes a local reduction in wall thickness with the formation of corrosion products on the surface. Stress concentration occurs in places where some defects are formed. Timely detection of such places is an important task of diagnosis.

In the course of conducting static studies of various types of corrosion of tank wagon boilers, approximate static relationships between them were obtained, which are presented in fig. 1.1.

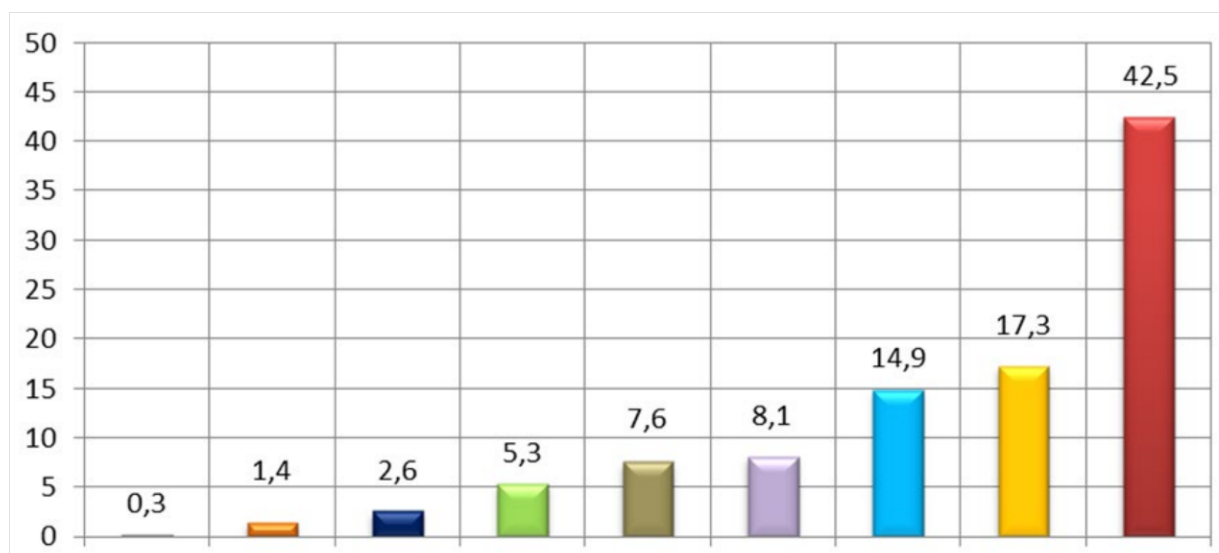


Figure 1.1 – Ratio of types of corrosion (in percent)

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

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 wagon 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.

The most dangerous types of corrosion include pitting corrosion and ulceration, because due to the small size of the ulcers and their filling with corrosion products, such destruction is quite difficult to detect and eliminate in a timely manner. After 3...5 years of operation, ulcers up to 4...5 mm deep appear on the lower belt.

With long-term use of chemicals, the rate of corrosion increases, as a rule, from the lower belt to the upper. In addition to chemical reactions between the cargo and the protective coating of the metal surface of the boiler, contact occurs between the upper parts of the cylindrical shell of the boiler and the gas space saturated with oxygen. The analysis of corrosion products indicates a significant content of iron hydroxide, which is confirmed during technical diagnostics of tank boilers.

Chemical cargoes are corrosive-active substances. Sulfuric and oxygen-containing compounds are the greatest danger. Their concentration depends on the type of chemical cargo, processing methods and origin. Sulfur and sulfur compounds have a corrosive effect on the metal of the boiler as a result of direct interaction, or as a result of the action of oxidation products of these compounds on the contact surface.

Sulfuric compounds are corrosive even at low temperatures. According to their corrosiveness, they are classified into active (elemental sulfur, hydrogen sulfide, ethyl mercaptan) and inactive (sulfides, disulfides and polysulfides, thiophanes). Oxygen-containing compounds are represented by naphthenic acids.

It should be noted that sulfur compounds are more aggressive for metals and alloys than self-oxidation products of naphthenic acids. An assessment of the potential corrosion aggressiveness of a specific type of chemical cargo can be provided only on the basis of a chemical analysis of its composition and concentration of acids and sulfur compounds.

1.3 Thermodynamics of the process of chemical corrosion of metal with oxidants

The interaction of metals with elementary oxidants can be used to determine their chemical activity, evaluating it by the change in Gibbs free energy (ΔG) under appropriate conditions. The reaction of metal oxidation proceeds spontaneously if, as a result, the Gibbs free energy of the system decreases ($\Delta G < 0$).

As a rule, metals are oxidized by elements whose electronegativity is higher than that of the metal. However, the chemical activity of the metal is affected by the chemical activity of the elementary oxidant, as well as the dissociation energy of the molecules of the elementary oxidant.

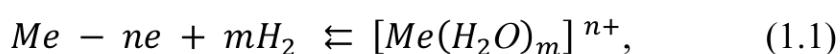
The energy of dissociation of elementary oxidant molecules is significant, so it is used to increase anti-corrosion properties of metal and improve a number of mechanical properties of products by saturating the surface layer, for example, with nitrogen (nitriding method).

The interaction of metals with complex oxidants depends on the stability of these compounds, which is determined by the temperature and nature of the environment. The study of reactions of the interaction of metals in aqueous solutions is complicated by the hydrolysis of salts, and sometimes by precipitation

of hydroxides or basic salts. In aqueous solutions, the process of converting metals into ions consists of several stages: breaking of chemical bonds between atoms, ionization of free metal atoms, and hydration of the formed ions. As a result of the analyzed transformation, the energy released during the hydration of metal ions is spent on the breaking of chemical bonds and metal ionization. Of the three components of the overall energy balance, only one - ionization energy - is directly determined by the position of the metal in the periodic table. Therefore, the ionization energy cannot unambiguously characterize the activity of metals in the reactions of aqueous solutions.

Ionization energy acts as only one of the factors along with others that determine the energetic effect of the reaction. A more objective measure of the reductive activity of metals in aqueous solutions of a chemical cargo is the electrode potential that occurs at the interface between the metal and the solution.

The electrode potential between the metal and the solution arises when the metal (Me) is immersed in an aqueous salt solution containing hydrated $[Me(H_2O)_m]^{n+}$ ions. The cause of the electrode potential is the transition of a certain amount of metal into the solution in the form of positively charged ions as a result of the interaction of the metal with the dipoles of the aqueous solution:



The metal acquires a negative charge, and the near-surface layer of the solution, enriched with metal ions, is positive. This leads to the formation of an electric double layer at the metal-solution interface and the occurrence of a certain potential difference or potential jump. The process of the transition of metal ions into the solution and vice versa is reversible, and when the rates of ionization of the metal and the discharge of its ions are equal, a dynamic equilibrium occurs between the oxidized form and the reduced form of the substance. The potential difference that occurs at the phase interface in reversible systems when equilibrium is reached between the oxidized and reduced forms of the substance is the equilibrium electrode potential. The equilibrium potential of the metal is established at the electrode, when only the ions of the given metal participate in the exchange process. The magnitude of the electrode potential of a metal depends on the nature of the metal, the activity of the metal ions in the solution, and the temperature. The value of the equilibrium electrode potential can be determined using general thermodynamic equations. For a metal electrode, the equilibrium potential established upon reaching equilibrium can be calculated by the Nernst equation:

$$E_{Me^{n+}/Me} = E_{Me^{n+}/Me}^o + \frac{0,0059}{n} \lg [Me^{n+}], \quad (1.2)$$

where $E_{Me^{n+}/Me}^{n+}$ – equilibrium electrode potential of the metal, V;

$E_{Me^{n+}/Me}^o$ – standard metal electrode potential, V;

n – the number of electrons given by the metal;

$[Me^{n+}]$ – concentration of metal ions, mol/l.

To characterize the properties of metals by the magnitude of their electrode potentials, it is necessary that the latter be comparable values. For this purpose, standard electrode potentials of metals are used, which are measured with respect to the potential of a standard hydrogen electrode under the same completely comparable conditions. Electrode potentials of metals measured in a solution of their own ions at a temperature of 298 K and the concentration of metal ions in the solution $[Me^{n+}] = 1 \text{ моль/л}$, are called standard electrode potentials.

Placing the metals in the order of increasing algebraic value of their standard electrode potentials, a series of standard electrode potentials is obtained. The value of the standard electrode potential quantitatively characterizes the reducing power of the metal and the oxidizing power of their ions. The smaller the algebraic value of the potential, the higher the reducing power of this metal and the lower the oxidizing power of its ions. According to the Nernst equation, the oxidation-reduction capacity of a metal depends on the activity

(concentration) of the oxidized and reduced forms of the substance, and for chemical reactions involving ions H^+ and OH^- and from the pH of the solution.

Based on the values of redox potentials, it is possible to determine the possible direction of the spontaneous course of redox reactions. Knowing the value of the standard oxidation-reduction potentials makes it possible to find out the depth (degree) of the spontaneous course of oxidation-reduction reactions in a certain direction.

The electrode potential serves as a measure of the change in Gibbs free energy (ΔG) in the system and thus indicates the direction of the oxidation-reduction process. At constant pressure and temperature, the drop in the standard Gibbs energy (ΔG^0) is equal to:

$$\Delta G^0 = -\Delta E^0 nF, \quad (1.3)$$

where F – Faraday's number (96485 K1);

n – the number of electrons per one transferred ion;

ΔE^0 – difference of standard potentials of the system, V.

Since the sign "-" at ΔG^0 corresponds to the involuntary flow process, the more ΔE^0 , the more negative the value of the Gibbs energy and the more probable the electrode process.

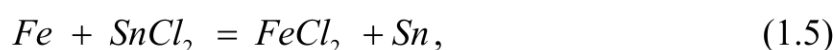
To determine the direction of the spontaneous course of oxidation-reduction processes, the EMF calculation of the system is determined by the potential difference of the oxidation-reduction electrodes involved in this process. The reaction proceeds involuntarily in the direct direction if the EMF of the system is positive, i.e. the condition is fulfilled:

$$E_{PC} = \Delta E = E_{\text{ОКИС.}} - E_{\text{ВІДНОВ.}} > 0, \quad (1.4)$$

The value of the electrode potential of a metal can be used to predict the behavior of metals in relation to water, solutions of acids, alkalis and salts.

Metals can interact with salt solutions. In reactions with aqueous solutions of salts, the separation of an electron from an active metal atom is carried out by a metal ion that is in the solution and acts as an oxidant. Metals with a more negative standard electrode potential displace other metals with a more positive standard electrode potential from salt solutions.

So, for example, in reaction (1.5), ions will act as oxidants Sn^{2+} , since the standard potential of tin is greater than that of iron:



$$E_{Fe^{2+}/Fe}^O = -0,44B, \quad (1.7)$$

$$1 Sn^{2+} + 2e = Sn, \quad (1.8)$$

$$E_{Sn^{2+}/Sn}^O = -0,136B, \quad (1.9)$$

EMF of the system $\Delta E = E_{Sn^{2+}/Sn}^O - E_{Fe^{2+}/Fe}^O = -0,136 - (-0,44) = 0,304B$, is positive, and the reaction proceeds spontaneously in the forward direction. Since metal ions in aqueous solutions are hydrated, the endothermic dehydration of the less active metal ion, which was initially in the solution, and the exothermic hydration of the formed more active metal ion are added to the specified stages. When considering specific cases of such reactions, it should be remembered that in aqueous solutions of salts, not only metal ions can act as an oxidant, but also hydrogen ions of water, which can be found in chemical cargoes in different concentrations. Therefore, mutual displacement of metals from solutions of their salts practically occurs only in the case of metals located in a series of potentials after magnesium. Alkaline and alkaline earth metals interact with water molecules and decompose them, displacing hydrogen. When moving from water to non-aqueous solvents, the relative position of metals in a range of voltages can change.

The reason for this is that the solvation energy of ions of different metals changes differently when passing from one solvent to another.

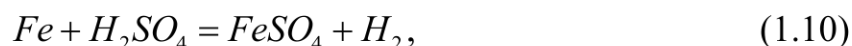
During the interaction of metals with acid solutions, oxidizing agents can be either hydrogen ions H^+ or acid anions. The interaction of metals with acids should be considered taking into account the following factors:

- 1) values of the standard electrode potential;
- 2) oxidizing capacity of the acid residue;
- 3) acid concentration.

When metals react with dilute acids (with the exception of dilute nitric acid), the oxidizing agent is a hydrogen ion H^+ . To such acids that contain an ion as an oxidizing agent H^+ , include acids that do not contain oxygen in the anion (oxygen-free acids): HF, HCl, HBr, HI, H₂S, H₂Se, H₂Te or acids with stable anions that have low oxidation-reduction potentials (H₂C, H₃BO₃, H₃PO₄, etc.) , as well as diluted sulfuric acid H₂SO₄.

Dilute acids containing only hydrogen ions as an oxidizing agent H^+ can interact with relatively strong reducing agents. Only metals whose oxidation-reduction potential is lower than the potential of the hydrogen electrode dissolve in such acids $2H^+ / H_2$, that is, with metals that are in the range of standard potentials to the left of hydrogen.

The reaction proceeds with the release of hydrogen according to the principle discussed below:



$$E_{Fe^{2+}/Fe} = -0,44B, \quad (1.11)$$

$$E_{Me^{n+}/Me} < E_{2H^+/H_2}, \quad (1.12)$$

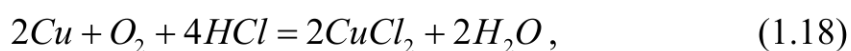
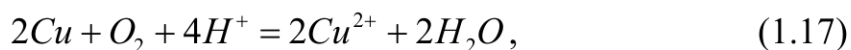
Therefore, the reaction is possible and will proceed in the direct direction.

An excess of hydrogen ions in acids prevents the formation of hydroxides, so most active metals dissolve well in acids. However, in a number of cases, when metals interact with diluted acids, compounds are formed on the surface of some metals that form compounds that are difficult to dissolve in acids, forming protective films from reaction products that inhibit the reaction. Thus, lead does not dissolve in sulfuric acid when its concentration is below 80%, since the $PbSO_4$ salt formed when lead interacts with sulfuric acid is insoluble and creates a protective film on the surface of the metal. In order to dissolve in such acids low-reactivity metals, which are in a series of standard potentials after hydrogen, the presence of any other oxidizing agent whose potential would be higher than the potential of this metal in an acidic environment is necessary. Yes, copper can dissolve in hydrochloric acid in the presence of oxygen. The potential of copper is:

$$E_{Cu^{2+}/Cu}^0 = +0,34B, \quad (1.13)$$

Oxygen potential at pH = 0:

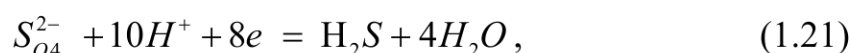
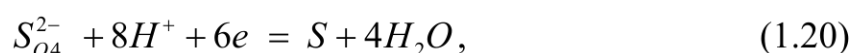
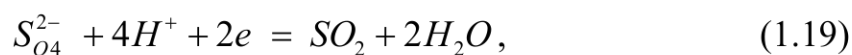
$$E_{O_2/H_2O}^0 = +1,23B, \quad (1.14)$$



Hydrochloric acid here plays the role of a medium, and does not itself participate in the oxidation process. If two oxidizers are present in the system at the same time, then always choose the oxidizer with a large potential value.

The oxidizing properties of acids due to the anion of the acid are more complicated, since in most cases the element forming the anion of the acid can be

reduced to different degrees of oxidation. In concentrated sulfuric acid, the ion – S_{O4}^{2-} , the recovery of which can proceed according to the following reactions:



The degree of reduction of sulfur from the ion S_{O4}^{2-} depends on the nature of the reducing agent. The products into which the sulfate ion in concentrated sulfuric acid passes during the reaction with metals depend on the activity of the metals: the more active the metal (more negative potential $E_{Me(n+)/Me}$), the deeper is the reduction of sulfur (+6) in the sulfate ion. Metals standing in a series of standard potentials after hydrogen interact with concentrated sulfuric acid to form sulfur oxide (IV) SO_2 . When interacting with more active metals that are in the range of standard potentials to hydrogen, the reduction products can be a mixture consisting of SO_2, S, H_2S . Since one of the ion reduction products predominates in the mixture – S_{O4}^{2-} , then based on experimental data, the following approximate

scheme of interaction of concentrated sulfuric acid with metals can be conditionally accepted.

Reaction:



Possible byproducts (depending on metal activity):

- $\uparrow H_2S$ (if the metal is *active*)
 - $\rightarrow S$ (if the metal is *moderately active*)
 - $\downarrow SO_2$ (if the metal is *inactive*)
- (1.22)

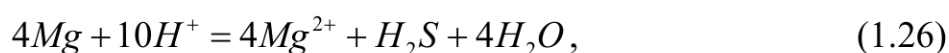
Explanation:

- Active metals (e.g., Zn, Mg) reduce concentrated H_2SO_4 to H_2S .
- Moderately active metals (e.g., Cu) produce Sulfur (S).
- Inactive metals (e.g., Hg, Au) lead to SO_2 formation.

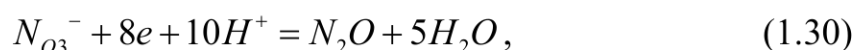
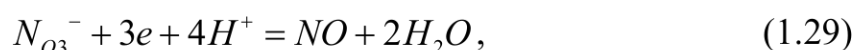
However, it is not possible to accurately establish the oxidation-reduction potential at which only sulfur oxide (IV), only sulfur or hydrogen sulfide is obtained. In many ways, the degree of reduction of the ion $S_{O_4}^{2-}$ will depend on the granulometric composition of the metal, temperature and other factors. Hydrogen is practically not released in concentrated sulfuric acid, as the oxidizing agent is the sulfate ion due to its much higher potential.

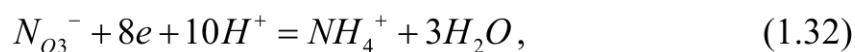
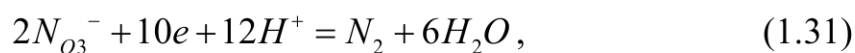
An example of a redox reaction:





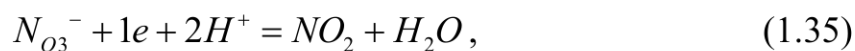
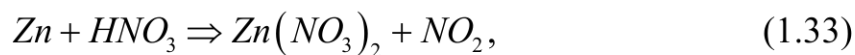
Nitric acid and even its diluted aqueous solutions oxidize metals without releasing hydrogen. Just as in concentrated sulfuric acid, in nitric acid of any concentration the oxidizing agent will be the anion - $N_{O_3}^-$ due to the much higher potential of the nitrate ion compared to the potential of the hydrogen electrode. Reduction of nitrate ion $N_{O_3}^-$ can proceed as follows:





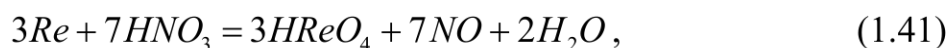
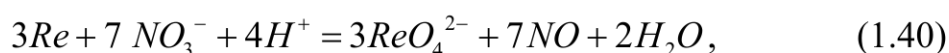
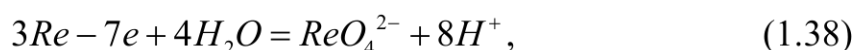
The degree of nitrate ion reduction depends on both the acid concentration and the redox potential of the metal. The higher the acid concentration, the less deeply the ion is reduced $N_{O_3}^-$. In reactions of metals with concentrated nitric acid, nitrogen dioxide is usually released NO_2 regardless of the activity of the metal.

Let us give the following example of chemical reactions:



Elements characterized by a high degree of oxidation form oxygen-containing acids as a result of interaction with concentrated nitric acid.

At the same time, nitric acid is reduced to NO .



In dilute nitric acid during the reaction with metals, the reaction products depend on the activity of the metals: the more active the metal (more negative potential $E_{Me^{n+}/Me}^{n+}$), the deeper is the reduction of nitrogen (+5) in the nitrate ion. When diluted nitric acid acts on metals, water, metal nitrate and, depending on the activity of the metal: NO , N_2O , N_2 , NH^+ .

On the basis of experimental data, the following approximate scheme of interaction of diluted nitric acid with metals can be conditionally accepted:

Reaction:



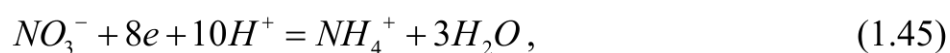
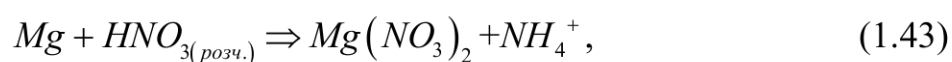
Possible reduction products (depending on metal activity):

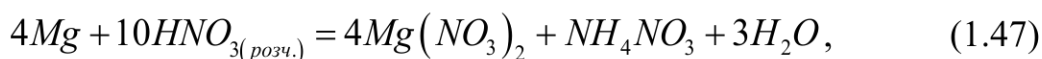
- $\uparrow \text{NH}_4^+$ (ammonium ion) – if the metal is *active* (e.g., Mg, Zn).
 - $\rightarrow \text{N}_2, \text{N}_2\text{O}$ (nitrogen gas, nitrous oxide) – if the metal is *moderately active* (e.g., Fe, Sn).
 - $\downarrow \text{NO}$ (nitric oxide) – if the metal is *inactive* (e.g., Cu, Ag).
- (1.42)

Key Notes:

- Active metals reduce dilute HNO_3 to NH_4^+ (or even NH_3 in some cases).
- Moderately active metals typically produce N_2 or N_2O .
- Inactive metals usually yield NO as the main product.

An example of the composition of a redox reaction of the interaction of a metal with dilute nitric acid:





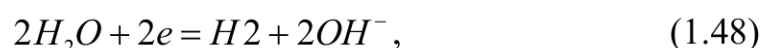
Determine exactly to what degree of oxidation the ion is reduced $N_{O_3}^-$ it is difficult for diluted nitric acid to interact with metals. Most often, a mixture of the above-mentioned substances is obtained, but the higher the activity of the metal, the finer the metal, the more diluted the acid, the deeper the reduction of the NO_3^- ion. It should be borne in mind that the nitrogen oxides indicated in the reactions are only the predominant oxides among other ion reduction products $N_{O_3}^-$. Being regenerated, nitric acid first of all forms lower oxides, which are then oxidized to higher ones.

When a mixture of acids acts on metals, one of which is an oxidizing agent, and the other acts as a ligand, metals dissolve with the formation of complex compounds. In oxidation-reduction reactions involving complex compounds, as a result of the binding of a complexing ion into a complex ion (complex), a significant decrease in the concentration of this ion in the solution occurs, which leads, based on the Nernst equation (1.2), to a decrease in its oxidation-reduction potential.

Let us consider separately the process of interaction of metals with the liquid phase of water. Because water always contains hydroxonium ions H_3O^+ , it should act on metals as acids. However, the concentration of these ions and their lifetime in water are very small, so the interaction of metals with the aqueous phase of a chemical substance has certain peculiarities. In addition, in relation to metals, water can be an oxidizing agent and act as a ligand in complexation processes.

Electrode process potential $2H^+ + 2e = H_2$ depends on the pH of the medium and is determined by the ratio $E_{2H^+/H_2} = E_{2H^+/H_2}^0 - 0,059 pH$.

In a neutral environment at $pH = 7$, when the oxidant is water, for reaction (1.48) the potential of the hydrogen electrode will be equal to:
 $E_{2H_2O/H_2} = -0,059 \cdot 7 = -0,41B$.



In order for the reaction with metals to proceed with the aqueous phase of the chemical cargo, it is necessary to fulfill both of the above conditions:

1. The potential of the metal in a neutral environment must be lower than the potential of the oxidizer (water):

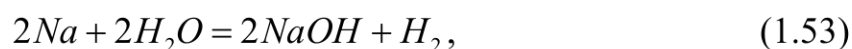
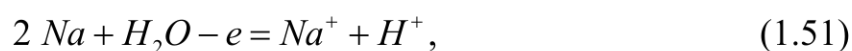
$$E_{Me^{n+}/Me}^{n+} < E_{окисл.}, \quad (1.49)$$

Theoretically, only those metals can displace hydrogen from water, the potentials of which are more negative in magnitude than -0.414V, that is, they are in the same range of voltages as cadmium.

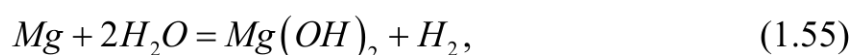
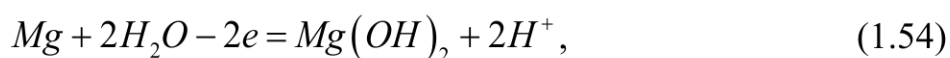
2. The reaction products of the interaction of the metal with the medium (maybe oxides, hydroxides) must be soluble in the reaction medium.

For example, the interaction of sodium with water. The calculation of the EMF value of the system taking into account the pH of the medium shows that the EMF is greater than zero and this reaction is possible:

$$\Delta E = E_{2H_2O/H_2} - E_{Na^+/Na} = -0,414 - (-0,2714) = +2,3B, \quad (1.50)$$



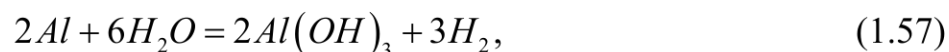
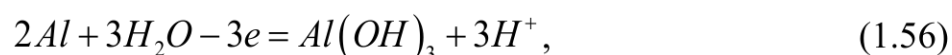
The given mechanism of interaction is characteristic mainly for alkali metals. Moreover, the better the water solubility of the formed hydroxide, the faster the reaction rate. The most active metals displace hydrogen from water and only if soluble hydroxides are formed. In the case of the formation of sparingly soluble compounds, and most metal hydroxides are just such, they passivate the surface of the metal, and the reaction, having just started, immediately stops or proceeds extremely slowly. For example, magnesium - a chemically active metal - at atmospheric temperature does not interact with water (solubility product (SOL) equals $1,1 \cdot 10^{-11}$). Magnesium displaces hydrogen only from hot water.



Metals located in the voltage range between magnesium and cadmium do not interact with water at normal temperature and do not displace hydrogen from water. When considering the interaction of metals with water, one cannot ignore the fact that most metals have a strong oxide film on the surface that has protective functions. Most often, it is the reason for the impossibility of a reaction between a sufficiently active metal and water. So aluminum, which has potential

$E_{Al(OH)_3/Al} = -1,88 B$, should react vigorously with water, but this does not happen due to the presence of a strong, water-insoluble oxide film on the surface of the metal.

Aluminum reacts vigorously with water, releasing hydrogen:



The phenomenon of inhibition of metal oxidation due to the presence of protective oxide or salt films on its surface is called passivation. In the case of atmospheric air, passivating films are formed on chromium, nickel, aluminum, cadmium, and zinc.

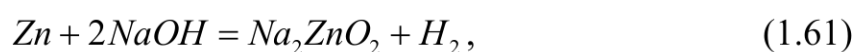
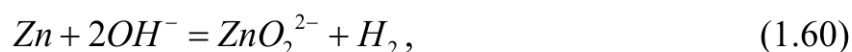
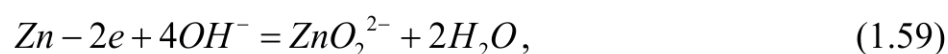
When metals interact with aqueous alkali solutions, water is the oxidizing agent.

In an alkaline medium with a concentration of hydrogen ions $[H^+] = 10^{-14} \text{ mol/L}$ the potential of the hydrogen electrode is $E_{2H_2O/H_2} = -0,059 \cdot 14 = -0,826 B$. Therefore, metals whose potentials are more negative in an alkaline environment dissolve in alkali solutions with hydrogen release $-0,826 B$. Moreover, the hydroxides of these metals must dissolve in

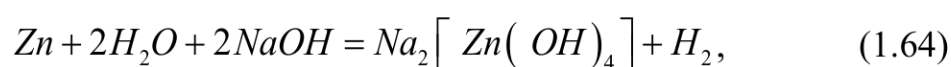
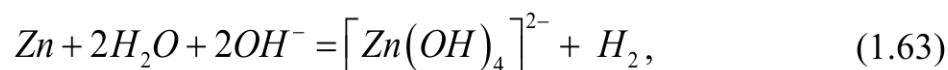
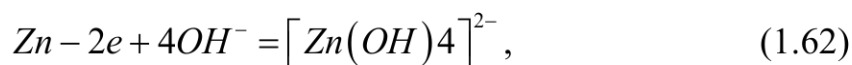
alkalis, otherwise the dissolution of the metal will practically stop due to the formation of a hydroxide film. Metals prone to the formation of hydroxocomplexes of the type will interact with alkalis $[Me(OH)_4]^{x-}$, that is, metals whose hydroxides are amphoteric $Be(OH)_2, Al(OH)_3, Zn(OH)_2, Sn(OH)_2, Pb(OH)_2, Cr(OH)_3$ etc. Simplified, instead of hydroxocomplexes, the reaction products can be written in the following form: $AlO_2^-, ZnO_2^{2-}, SnO_2^{2-}, CrO_2^-$ etc. d.

Consider, for example, the interaction of zinc with an aqueous solution of lye. The calculation of the EMF value of the system taking into account the pH of the medium shows that the EMF is greater than zero and this reaction is possible:

$$\Delta E = E_{2H_2O/H_2} - E_{Zn^{2+}/Zn} = -0,827 - (-1,220) = +0,393B, \quad (1.58)$$

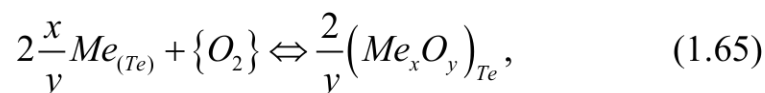


Due to the formation of complex compounds:



The interaction of metals with alkalis proceeds more easily than the more stable hydroxocomplexes formed. Anions of the type $[Me(OH)_4]^{x-}$ the most stable in Be, Zn, Sn, Al, Pb and other amphoteric metals, therefore these metals are easily dissolved in alkalis (Pb - when heated). Such metals as iron, cobalt, nickel, etc. have unstable hydroxoanions. Therefore, they interact with alkali solutions only in a finely divided state and during prolonged heating. It is impossible to unequivocally state that the possibility of reactions between metal and alkali solutions is determined only by the values of the electrode potentials of the system and the solubility product of the reaction products. When considering the interaction of metals with alkalis, it is necessary to take into account that this is a multifactorial system and an individual approach is necessary for each specific case.

We will separately consider the process of metal oxidation in an oxygen atmosphere. The process of metal oxidation can be represented by a reaction of the form:



The possibility of such a reaction is determined by the corresponding change in Gibbs energy:

$$-\Delta G_T = RT(\ln K - \Delta \ln a), \quad (1.66)$$

where K – equilibrium constant of a chemical reaction;

$\Delta \ln a$ - the algebraic sum of the logarithms of the initial activities of substances - products of a chemical reaction.

$$-\Delta G_T = RT \left(\ln \frac{a^{\frac{2}{y}}(Me_xO_2)}{a^{\frac{2x}{y}}Me \cdot P_{O_2}} - \ln \frac{a^{\frac{2}{y}}(Me_xO_2)}{a^{\frac{2x}{y}}Me \cdot p_{O_2}} \right), \quad (1.67)$$

If the metal and metal oxide are pure substances, then we get:

$$-\Delta G_T = RT \left(\ln \frac{1}{P_{o_2}} - \ln \frac{1}{p_{o_2}} \right), \quad (1.68)$$

where P_{o_2} – equilibrium pressure of oxygen in the system;

p_{o_2} - the initial pressure of oxygen in the gas phase.

Finally, we will have the expression:

$$-\Delta G_T = RT (\ln p_{o_2} - \ln P_{o_2}), \quad (1.69)$$

Thus, the process of metal oxidation is thermodynamically probable if $p_{o_2} > P_{o_2}$ ($\Delta G_T < 0$) and impossible if $p_{o_2} < P_{o_2}$;

At $p_{o_2} = P_{o_2}$ the corrosion system is in a state of thermodynamic equilibrium.

For the case of standard conditions in the corrosion system, the possibility of the corrosion process occurring at any temperature is determined from the equation:

$$-\Delta G_T^0 = RT \ln Kp, \quad (1.70)$$

It can also be estimated using tables of thermodynamic functions of substances in the standard state using the ratio:

$$-\Delta G_T^0 = \Delta H_T^0 - T\Delta S_T^0, \quad (1.71)$$

A convenient characteristic of the possibility of the course of the oxidation reaction, especially of complex corrosion systems, is the value of the oxygen potential. The thermodynamic condition of oxidation is an inequality of the form:

$$\pi_{0(z.\phi.)} > \pi_{0(Me_xO_y)}, \quad (1.72)$$

where $\pi_{0(z.\phi.)}$ – gas phase oxygen potential;

$\pi_{0(Me_xO_y)}$ - oxygen potential of the system $(Me - Me_xO_y)$.

The calculation of the oxygen potentials of the gas phase and metal oxide is carried out from the ratios:

$$\pi_{0(z.\phi.)} = RT \ln p_{O_2}, \quad (1.73)$$

$$\pi_{0(Me_xO_y)} = RT \ln P_{O_2}, \quad (1.74)$$

where p_{O_2} – oxygen pressure in the gas phase;

P_{O_2} – the equilibrium pressure of oxygen in the system $(Me - Me_xO_y)$.

1.4 Determining the thickness of the boiler metal using non-destructive testing methods

To determine the thickness of the metal shell of the boiler, acoustic control methods are used, based on the change of elastic vibrations and waves in the controlled object. Such methods are divided into two large groups:

active - using radiation and reception of acoustic vibrations;

passive - based only on receiving vibrations.

Active methods include methods based on the passage and reflection of ultrasound.

The main active method that can be used when conducting studies of metal thickness is the "Echo" method (ECHO method). Its essence consists in the production by a high-quality generator of short-term pulses (or with high-frequency filling - radio pulses, or simply short pulses). The pulse sent by the emitter, having reflected, returns back to the converter, which is currently working for reception (Fig. 1.2).

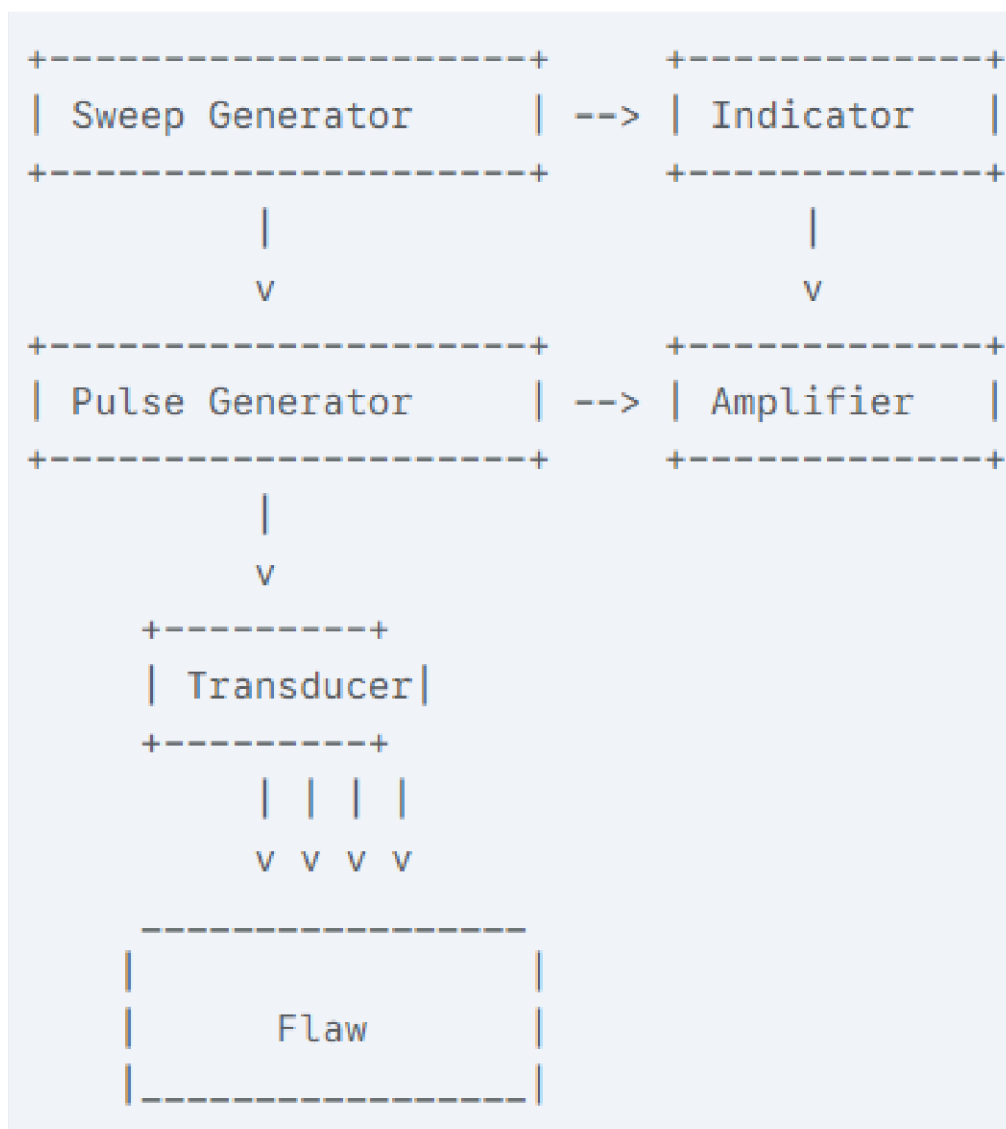


Figure 1.2 – Schematic representation of the ECHO method

From the converter, the signal is sent to the amplifier, and then to the deflection plates (Fig. 1.3). ECHO - the method allows you to control products with one-way access to them. This is especially valuable when inspecting structures that do not have two-way access. In addition, the sensitivity of the ECHO method is quite high. At the same time, the imprint of even 1% of the

energy is not only detected very well, but also measured. In addition, the ECHO method allows you to determine at what depth the surface defect is located. If the temporal distance between the probing and the one reflected from the opposite surface of the part (bottom pulse) is taken as the size of the part, then the time between the transmitted pulse and the arrival of the pulse reflected from the defect gives the depth of the defect.

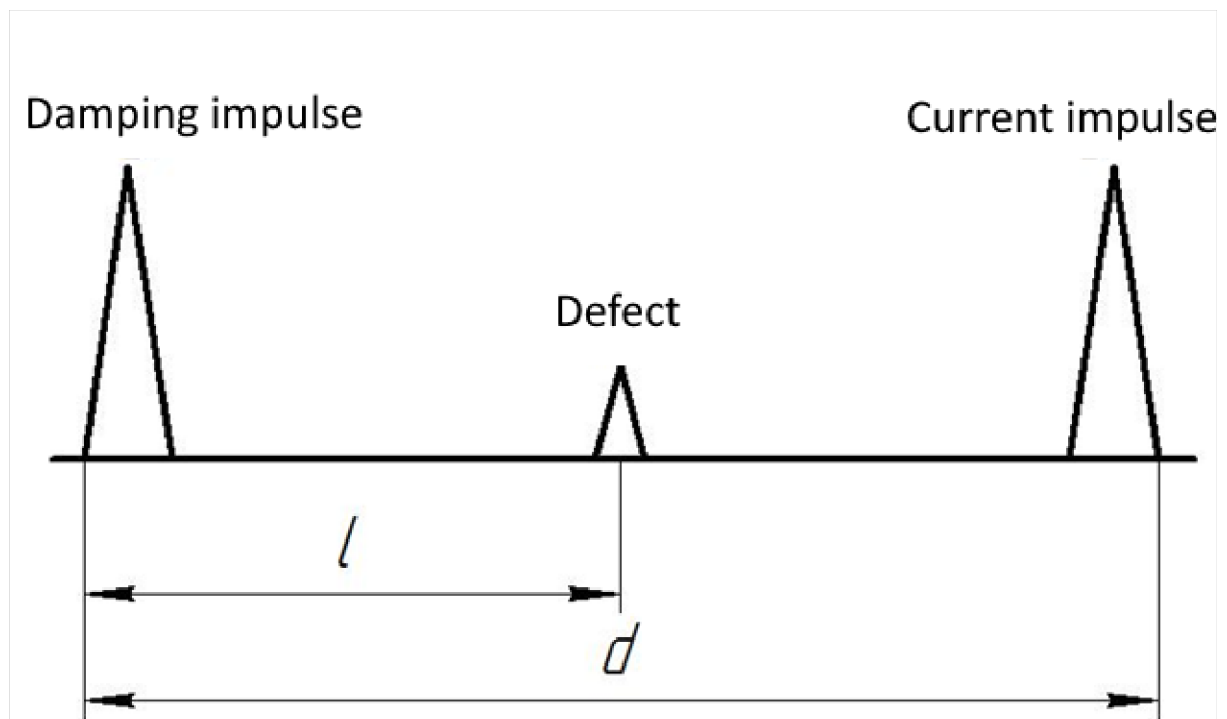


Figure 1.3 – Scheme of pulse reflection from the measured surface or defect

In addition, the size of the defect can be determined by the amplitude of the reflected signal, and by studying the spectral composition of the reflected pulse, it is possible to obtain information about the type of defect and its shape.

The main disadvantage of the ECHO method is the presence of a dead zone under the sensor, which makes it impossible to use it for thin products. The presence of a dead zone is due to the fact that with a closely located defect, at the time of arrival of the ECHO signal, it still continues to emit a probing pulse. To reduce the dead zone, the ultrasound frequency is increased, which makes it possible to reduce the duration of the probing pulse.

The duration of the pulse also determines the resolution of the method, that is, the minimum distance between defects in depth, in which their ECHO signals are perceived separately. Obviously, the decisive ability of the ECHO method in depth is equal to the duration of the probing pulse.

Increasing the frequency in order to increase the resolution is limited from above by the fact that short waves begin to reflect from the boundaries of the crystalline grains of the metal, which causes the appearance of interference. In addition, with an increase in frequency, the attenuation of USK increases.

The ECHO method is the main method of thickness measurement. Let's take a closer look at its capabilities and limitations.

We will consider the accuracy of the measurement for the simplest case, when the measurement is performed according to the first bottom signal. If the

speed c propagation of ultrasound in the object is known, then, by measuring time t passage of ultrasound in the object in the forward and reverse directions, determine the thickness according to the formula:

$$h = 0,5ct, \quad (1.75)$$

We will evaluate the distance measurement error both in relation to thickness measurement and in relation to determining the coordinates of defects. The relative error is determined by an equation of the form:

$$\frac{\Delta h}{h} = \frac{\Delta c}{c} + \frac{\Delta t}{t}, \quad (1.76)$$

Adjustments to the speed of sound are performed on a sample or section of a control sample of known thickness in the same way as thickness is measured, so the errors of speed and time measurement are approximately the same, then we will have an equation of the form:

$$\frac{\Delta h}{h} = \frac{2\Delta t}{t}, \quad (1.77)$$

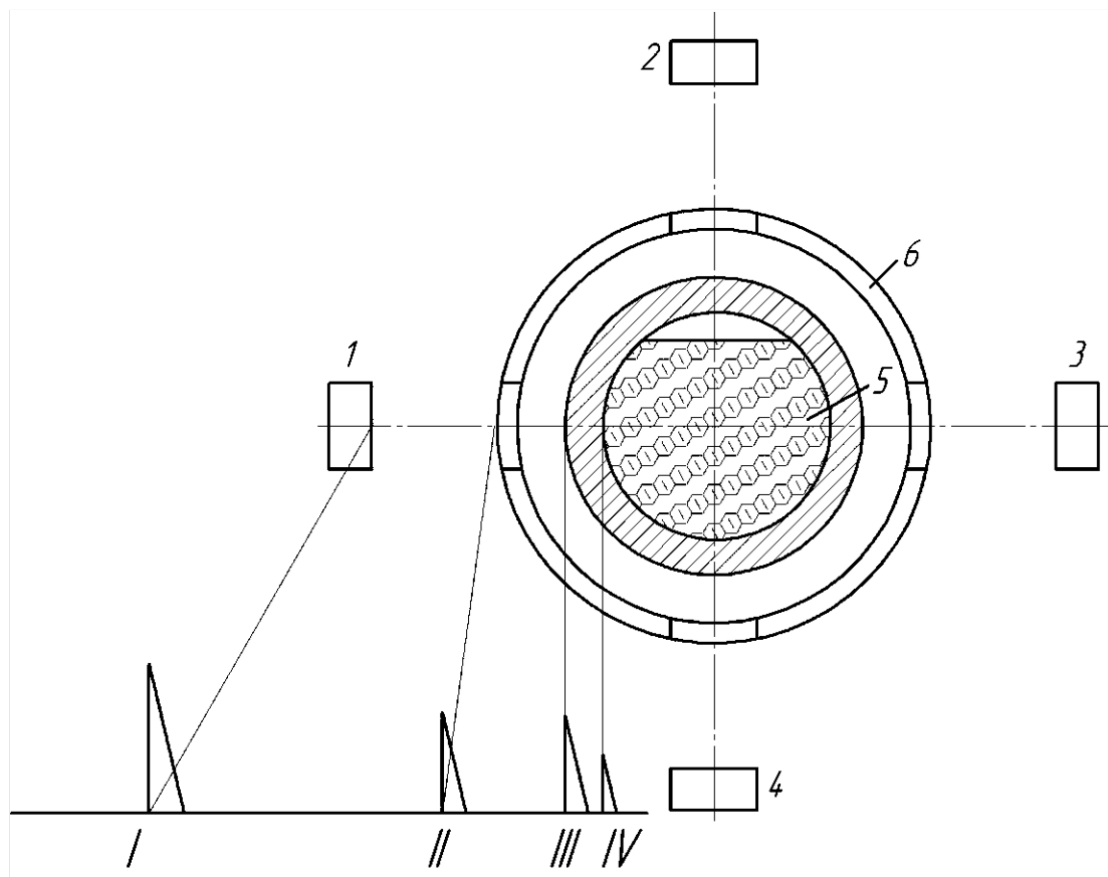
There are devices with automatic adjustment of the sound speed, in which the factors that affect the accuracy of the speed and thickness measurements are different.

Error Δt time measurement consists of errors Δt_n , due to the influence of a number of factors, therefore $\Delta t = \sum_n \Delta t_n$.

The minimum thickness of products controlled by the ECHO method is determined by the dead zone of the thickness gauge. It is analogous to the dead zone of the flaw detector. To reduce it, in devices of groups 1 and 3, they try to obtain the minimum duration of the probing pulse, and in devices of group 2, RS - converters are used. As a result, the dead zone for thickness gauges of groups 1 and 3 is 0.2...0.3 mm, and for thickness gauges of group 2 - 0.5...1.5 mm.

The use of ultrasound to measure the diameters of the boilers of tank wagons should be rationally applied in complex installations for ultrasonic control, which also include flaw detection devices.

According to the scheme shown in fig. 1.4 control can be performed by the pulse ECHO method in a local immersion bath.



established norms) and the thickness of the boiler wall

A thin screen 6 with windows must be placed between the transducers 1–4 and the controlled cylindrical shell 5. In this way, it is possible to measure the arrival time of signals from screen II to the outer III and inner IV walls of the boiler. Since the distance from the transducer to the screen is precisely known, the time interval between the probe pulse I and the ECHO signal from the screen II serves to correct the speed of sound in the immersion liquid, which can change under the influence of temperature.

In the interval II - III, you can measure the distance from the screen to the boiler shell:

$$l = c(t_{III} - t_{II}) / 2, \quad (1.78)$$

where c – speed of sound in the environment;

t_{II}, t_{III} – arrival time of pulses II and III.

The small value of this distance, the uniformity of amplitudes and forms of ECHO signals II and III increase the accuracy of the measurement. The interval between ECHO signals III and IV can be used to measure the thickness of the boiler wall. Based on measurements that can be performed using transducers 1 and 3, 2 and 4, the boiler diameters are automatically calculated in two mutually perpendicular directions.

For example, the diameter of the boiler in the horizontal direction is equal to:

$$D = D_e - l_1 - l_2, \quad (1.79)$$

where D_e – screen diameter;

l_1 – the distance from the screen to the boiler on the left;

l_2 – the distance from the screen to the boiler on the right.

Comparing the results of measurements by all four transducers makes it possible to evaluate the shape of the boiler, to identify its possible ovality. Taking into account the results of measuring the thickness of the wall of the boiler, its internal diameter and the difference of the wall across the section are measured. Thus, the given diagram allows you to evaluate all the geometric characteristics of the cross section of the product.

In addition to the ECHO method, the resonance method can be used.

The interaction of acoustic waves that pass through the medium in different directions, in particular in a solid body of limited dimensions, leads to the emergence of standing waves at frequencies where oscillations can be excited.

Therefore, in a plane-parallel layer of a homogeneous plate, a plane wave is excited in the thickness direction due to the transfer of part of the energy of the monochromatic wave falling on the layer. From the analysis, it turns out that at frequencies that satisfy the condition of multiplicity of thickness h layer of the whole number of half-waves ($h = n\lambda / 2$, where n - an integer), the reflection coefficient of the wave energy is the minimum, and the transmission coefficient is the maximum.

The calculation shows that the amplitude of the oscillations of the layer is maximal, which is explained by the mutual amplification of direct and reverse waves in the layer. This case is a structural (geometric) resonance.

If you install an oscillation receiver behind the plate and smoothly change the frequency of oscillations in the incident wave, you will be able to observe the dependence of the signal amplitude on the frequency shown in Fig. 1.5.

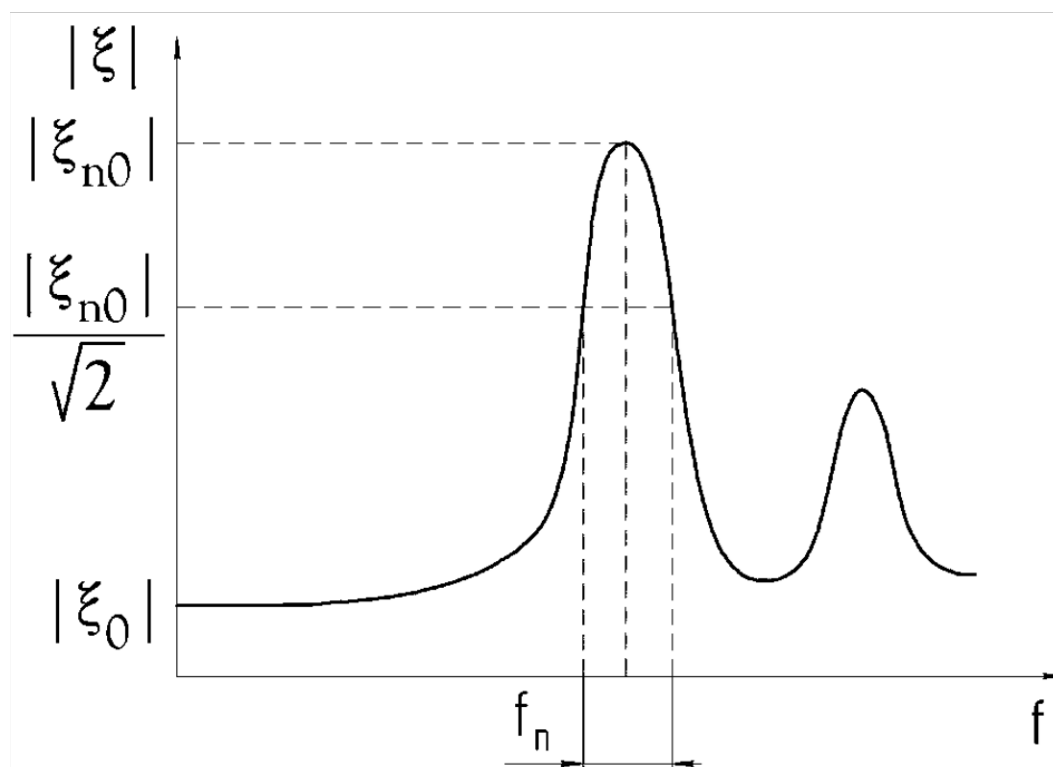


Figure 1.5 – Main characteristics of resonant oscillations when passing through a homogeneous plate.

Frequencies $f_n = nc / 2h$ are resonant, and their complete set is called a spectrum of resonant frequencies or a resonant spectrum. According to the values of resonant frequencies f_n it is possible to determine the wall thickness according to the ratio:

$$h = \frac{nc}{2fn}, \quad (1.80)$$

This can be used in resonance thickness measurement when controlling the thickness of the boiler. Number knowledge n not necessary, because it is obvious that the difference between two adjacent resonant frequencies is given by the expression:

$$\Delta f = \frac{c}{2h}, \quad (1.81)$$

Then:

$$h = \frac{c}{2\Delta f}, \quad (1.82)$$

In general, the thickness will be determined by the formula:

$$h = (m - n)c / [2(f_m - f_n)], \quad (1.83)$$

where m and n – arbitrary integers.

Suppose that the wave falling on the plate is not monochromatic, but is a short pulse. The oscillations occurring in the plate are now free oscillations, in which oscillations again emerge with frequencies at which the forward and reverse waves are mutually reinforcing. As a result, a collection of standing waves is excited, the amplitudes of which are different and decrease with increasing frequency, possibly non-monotonically. The set of frequencies of these oscillations is the frequency spectrum of natural oscillations or natural frequencies.

In the given version, the absorption of ultrasonic waves in the medium was not taken into account. This is justified, since energy losses by the body (plate) due to radiation into the environment, as a rule, exceed its losses due to internal absorption. In this case, the values of natural and resonant frequencies practically coincide. If we turn to the general case taking into account the oscillations of a body of arbitrary shape, limited in all three dimensions, we can reach similar conclusions about the existence of a spectrum of resonant and natural frequencies and the possibility of their registration in relation to the change in the amplitude of the receiver oscillations. In the general case, taking into account damping, the natural oscillations of the body can be described by the following formula:

$$\xi(x, t) = \sum_{n=0}^{\infty} \xi_n(x, t), \quad (1.84)$$

$$\xi(x, t) = A_n \varphi_n(x) e^{-\delta_n t} \sin\left(\sqrt{\omega_n^2 - \delta_n^2} \cdot t + \phi_n\right), \quad (1.85)$$

where x – coordinates of an arbitrary point of the oscillating body;

$\varphi_n(x)$ – distribution of amplitudes of oscillations by body volume (form of oscillations);

δ_n – attenuation coefficient at the n th natural frequency;

A_n – amplitude of oscillations at the n th natural frequency;

ϕ_n – phase shifts determined by the initial conditions for the occurrence of oscillations.

Amplitudes A_n depend on the amplitude and spatial distribution of the excitation force. With harmonic excitation, oscillations are described by formulas of the form:

$$f(x, y, z, t) = F(x, y, z) \exp(i \omega t), \quad (1.86)$$

where $F(x, y, z)$ – distribution in space of the amplitude of the excitation force;

ω is the circular excitation frequency.

When entering a designation $\eta = 1 / 2Q$ the general solution representing the amplitude of system oscillations at any registration point R with coordinates x_R, y_R, z_R can be represented as:

$$\xi(R) = F_0 \sum_{n=0}^{\infty} \frac{1}{M_n^* [\omega_n^2 (1 + i\eta) - \omega^2]}, \quad (1.87)$$

$$M_n^* = \frac{N_n^2}{\xi_n^2(R) \chi_n(R)}, \quad (1.88)$$

$$\chi_n(R) = \frac{1}{F_0} \int_S \frac{F(x, y, z) \xi_n(x, y, z)}{\xi_n(x_R, y_R, z_R)} dS, \quad (1.89)$$

$$F_0 = \int_S F(x, y, z) dS, \quad (1.90)$$

where S is the surface of the system on which the force acts $F(x, y, z)$;

$$N_n = \sqrt{\int_V \xi_n^2 dV}, \quad (1.91)$$

where V is the volume of the oscillating system under consideration.

Because usually $\eta \ll 1$, then at $\omega \approx \omega_n$ due to a sharp decrease in the denominator, we will have:

$$|\xi_n(x)| \approx B_n(x) / \omega_n^2 \eta, \quad (1.92)$$

Instead of the loss coefficient, the value of the object's Q factor is entered
 $Q = 1 / 2\eta$, which can be represented as:

$$Q = 2\pi W_K / W_{II}, \quad (1.93)$$

where W_K – the maximum energy of body vibrations;

W_{II} – energy dissipated during a cycle of oscillations due to mechanical losses in the body (friction, thermal conductivity) or due to radiation into the environment.

The method allows you to measure thicknesses from the minimum value:

$$h_{\min} = c / (2f_{\max}), \quad (1.94)$$

where c is the speed of sound in the material of the product;

$f_{\max}$ - the maximum frequency of the device.

Increasing this frequency to 30 MHz allows measuring the thickness of steel products starting from 0.06 mm. It is impossible to measure such thicknesses by other methods. The error is 1..2%.

The resonance method is suitable for control of measured surfaces that are relatively smooth. The change in thickness in the measurement zone should not

exceed 8%, and the average thickness is measured, not the largest decrease. However, in the contact version, a number of shortcomings of the method are also revealed: the measurement error increases to 2...5% due to the displacement of resonances under the influence of unstable acoustic contact.

Implementation of ultrasonic thickness measurement at the hardware level is carried out with the help of ECHO - pulse thickness gauge. With the development of the ECHO - pulse resonance method, it turned out to be uncompetitive with it in terms of sound range, requirements for surface roughness and geometry, and other parameters. As a result, only ECHO - pulse method is currently used. The principle of operation of the ultrasonic ECHO - pulse thickness gauge with digital display is shown in the diagram (Fig. 1.6).

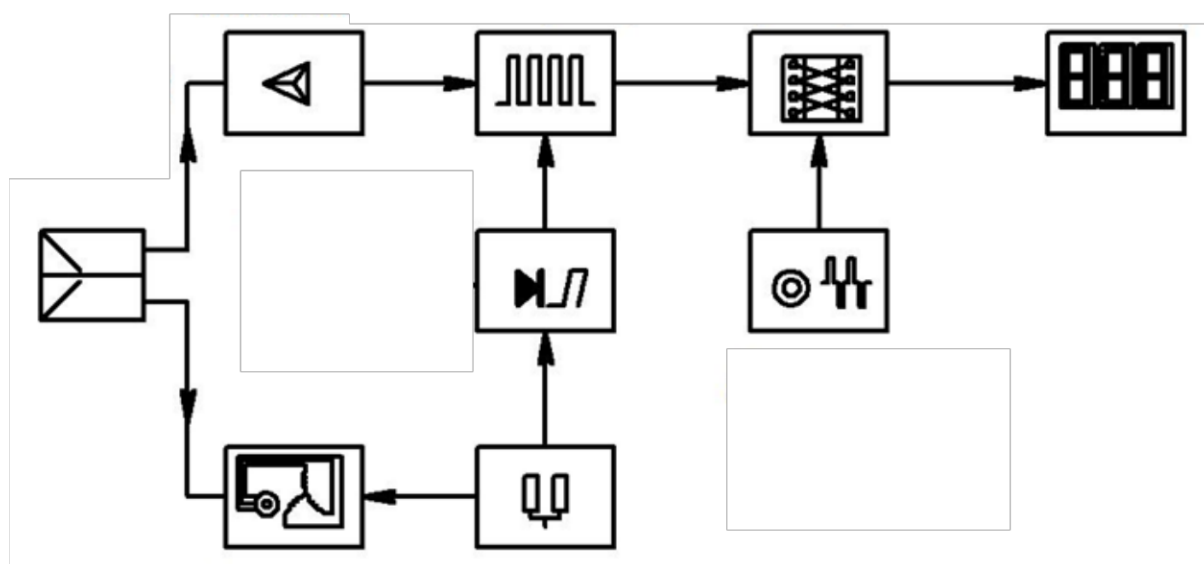


Figure 1.6 - Functional diagram of an ultrasonic
ECHO - pulse thickness gauge

The temporary diagram of the operation of this device is shown in fig. 1.7.

The synchronizer periodically produces a pulse that triggers the pulse excitation generator and the trigger pulse generator. The pulse excitation generator produces a short electric pulse 1 (Fig. 1.7 a), which excites the transmission part of the piezoelectric transducer. After reflection from the opposite wall of the measurement object, the ultrasonic pulse enters the receiving part of the piezoelectric transducer, is converted into an electrical signal and is fed to the amplifier. The principle of thickness measurement by the ultrasonic method is to measure the time between the emission of a probing pulse and the reception of the first reflected pulse. A directly emitted pulse is almost never involved in the measurement.

Due to the delay when passing through the piezoelectric transducer, due to its width, it introduces a significant error in the measurement process. Therefore, the synchronizer also starts the generator of start pulses, which with some delay, which takes into account the propagation of the ultrasonic part of the acoustic path from the radiating plate to the surface of the product, produces start pulse 2. The latter, in turn, starts the measuring generator. The rectangular pulse created by the measuring generator (Fig. 1.7, b) is stopped by the first ECHO - pulse 3 (Fig. 1.7, a), which passed through the amplifier from the product.

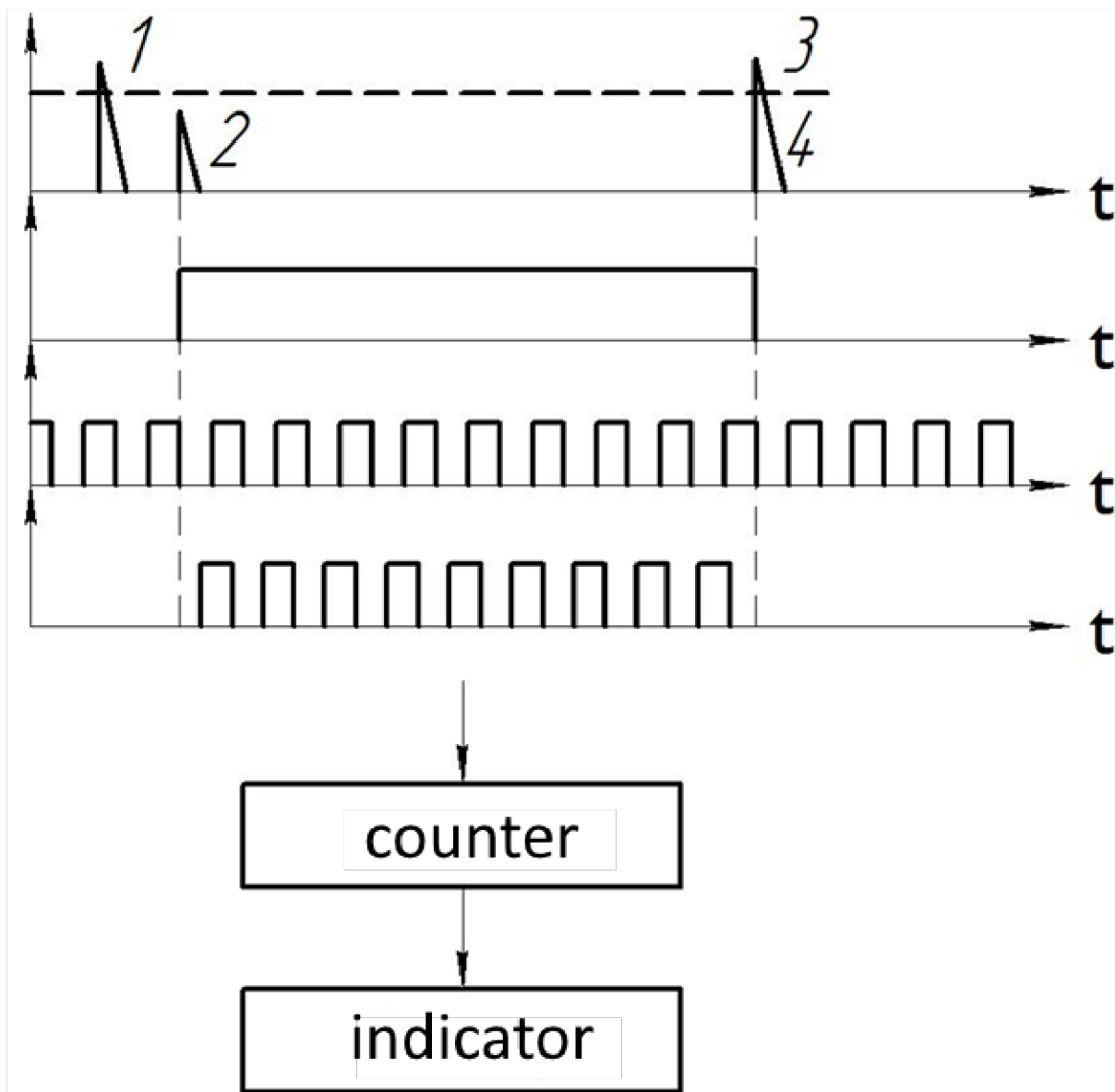


Figure 1.7 – Time diagram of work

ECHO - pulse thickness gauge with digital display:

1 - probing pulse, 2 - start pulse,

3 – ECHO – pulse from the wall of the measured object,

4 – threshold for triggering the signal to stop the measuring pulse

In order to make the measurement of the propagation time of ultrasonic vibrations independent of the amplitude of the ECHO signal, an automatic gain adjustment scheme is used, which, despite the fluctuation of the acoustic contact or the effect of surface roughness, brings the ECHO signal received from the rear wall to a constant value of 4 (Fig. 1.7 a) . Thus, the activation threshold is constantly located at the same place of the front of the ECHO signal. The front of the measuring pulse starts the counting device, which receives counting pulses (Fig. 1.7, c) from the counting pulse generator stabilized by a quartz element.

The duration of the generation period of the counter pulse generator is used as the main unit of measurement time. The choice of the frequency of the generator of counting pulses depends on the speed of propagation of ultrasonic vibrations and on the required accuracy of measurement of the time of propagation of ultrasonic vibrations, and therefore on the thickness of the wall.

Therefore, to achieve the accuracy of thickness measurement $\pm 0,1$ mm for steel with a speed of sound of 5920 m/s, a counter pulse generator frequency of 29.65 MHz is used. The duration of the period is exactly equal to the propagation time of the ultrasonic pulse through a steel plate with a thickness of 0.1 mm (the path of the pulse back and forth). The frequency of the generator for other materials is proportional to the propagation speed of ultrasonic vibrations in the medium.

In thickness gauges of certain systems, adjustment to the required sound speed is carried out by switching the frequency of the counter pulse generator. In microprocessor-based thickness gauges, at a fixed frequency of the generator of counting pulses, the adjustment to the required speed is carried out by software.

The counter started by the edge of the measuring pulse is stopped by the fall of the same pulse. The content of the counter (Fig. 1.7, d) then indicates how many counting units have been accumulated during the duration of the measuring pulse. This information is fed to a digital indicator that shows the thickness of the product being measured.

The main reason that determines the error of ECHO - pulse thickness gauges is the difference in the speed of propagation of ultrasound in different materials, as well as a change in the speed of sound propagation due to external factors, for example, a change in ambient temperature.

To compensate for the effect of changes in the speed of ultrasound in the material of the product, thickness gauges have been developed that carry out independent calibration. In such devices, two piezo plates or two piezoelectric transducers installed at a given distance are used. An approximate scheme of such a thickness gauge has the following form:

The piezo transducer of the thickness gauge with automatic calibration is shown in fig. 1.9.

Piezo element 2 emits and receives an ultrasonic pulse that has passed normally to the metal surface. Piezo element 9, installed at a distance a_1 receives an ultrasonic pulse emitted by a piezo transducer. For geometric reasons, it is easy to express the thickness h metal through distance a_1 between piezo plates and time t_1 and t_2 propagation of ultrasonic pulses in two ways.

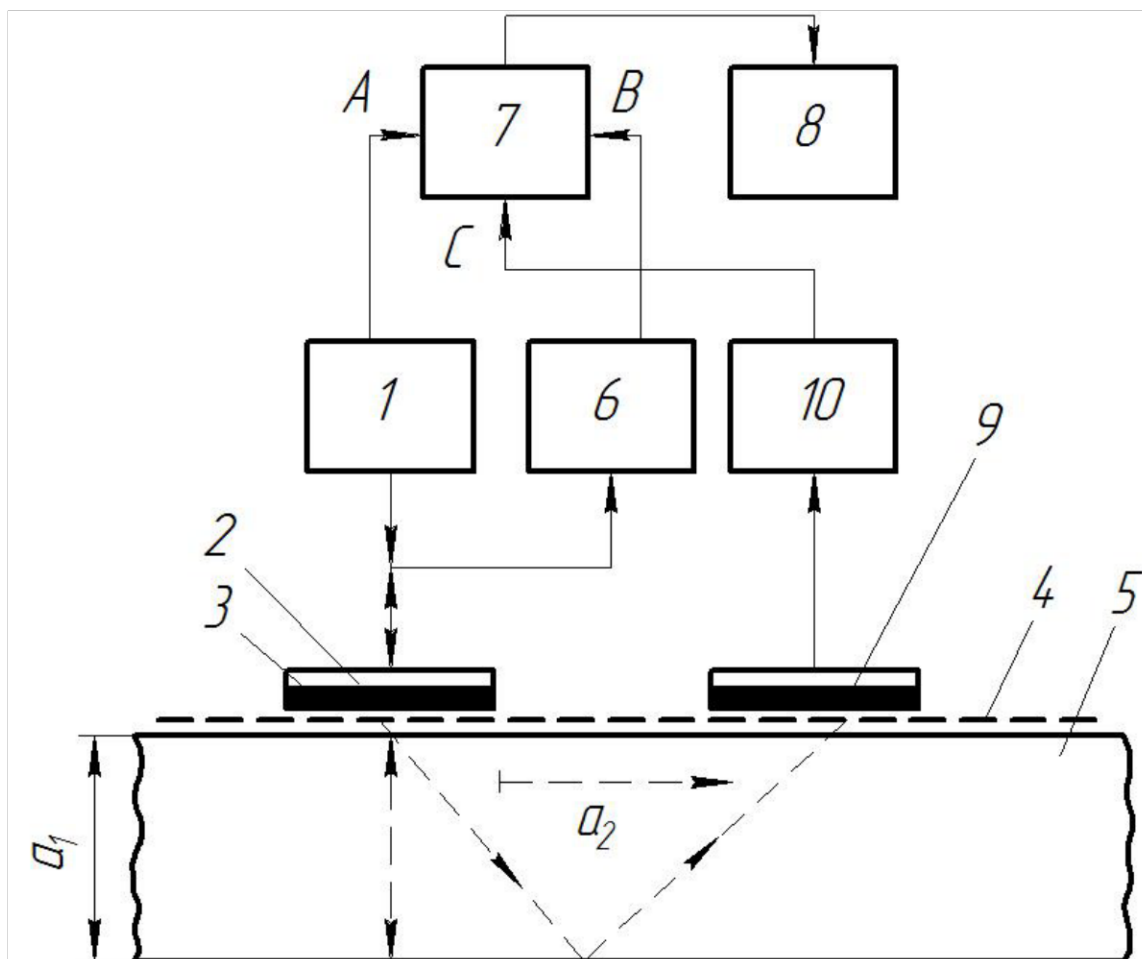


Figure 1.8 – Functional scheme of the ultrasonic ECHO - pulse self-calibrating
thickness gauge:

1 – generator, 2 and 9 – receiving and transmitting piezo elements,

3 – protective protector, 4 – contact liquid, 5 – controlled product, 6 and 10 –
amplifiers, 7 – time interval meter, 8 – indicator.

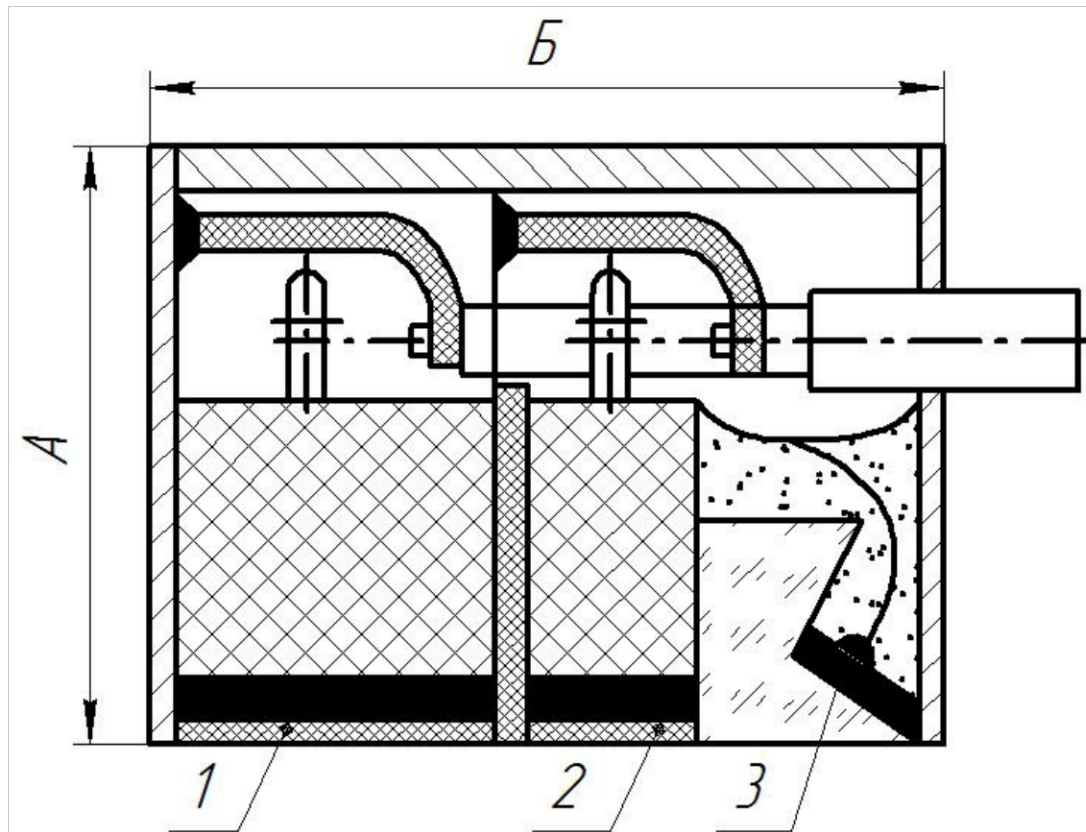


Figure 1.9 – Design of a piezo transducer for an auto-calibrating thickness
gauge.

1 – receiving – emitting piezo element,
2 – receiving piezo element; 3 – piezo element for reception of main waves

$$h = \frac{a_1 t_1}{2\sqrt{t_2^2 - t_1^2}}, \quad (1.95)$$

Thus, using one longitudinal type of ultrasonic oscillations, we exclude from the measurement results the speed of elastic oscillations, and accordingly, the error introduced by it.

Conclusions according to section 1

Corrosion of the internal surface of the tank wagon boiler is the dominant factor affecting the standard service life of the tank wagon. The rate of corrosion damage to the boiler depends on the physical and chemical properties of the metal and cargo, the shape and plane of the surfaces in contact with the aggressive environment, external factors (temperature, humidity of the surrounding environment, load or pressure at the point of contact, etc.), as well as protection conditions.

For the purpose of timely detection and elimination of various types of defects caused by corrosion, the question arises of carrying out technical diagnostics according to previously established terms on the basis of statistical data on the current technical condition of the tank wagon using refined methods of forecasting the resource of wagons.

2 THEORETICAL FUNDAMENTALS OF THE CALCULATION OF THE STRESSED AND DEFORMED STATE OF A TANK WAGON BOILER USING THE MATHCAD SOFTWARE ENVIRONMENT

When carrying out engineering and technical calculations of the stress-strain state of cylindrical shells of tank wagons, momentless shells are used as calculation models. In accordance with such calculations, the load in the form of internal pressure, which acts on the shell, is considered constant in magnitude, and the stress values are determined without taking into account bending, torques and transverse forces. At the same time, calculation errors are partially taken into account using various coefficients.

The calculated model of the cylindrical shell of the tank wagon boiler must take into account the uneven load along the meridional coordinate, since the boiler perceives different inertial forces during the braking period at the initial and final moment of changing the mode of movement of the wagon. In addition, the shell of the boiler is loaded with variable pressure from the liquid mass of the cargo with a significant density along the circumferential coordinate. It is also necessary to take into account the fastening of the shell of the tank to the frame: in most designs, in the pivot section, a semi-rigid fastening of a part of the circumference is used, with a free support on the bearing supports, which perceive vertical and

horizontal loads, and in the places where the shaped legs are located, a rigid one is used, which prevents the boiler from moving in the longitudinal direction during traction and braking forces.

The determination of the stress-strain state requires the use of approximate calculation methods, among which the most effective is the numerical calculation method using a differential series of equations for physically orthotropic shells based on the basic provisions of the semi-momentless theory of shells in compliance with the basic Kirchhoff-Leav hypotheses.

2.1 Basics of calculation of discrete models of physical shells

The cylindrical part of the tank wagon boiler can be represented as an orthotropic shell (Fig. 2.1), which has different elastic properties in three mutually perpendicular directions.

In accordance with the accepted notations on the diagram, we have:
 R , h , $\alpha_1 R$ – radius, thickness, length of the cylindrical shell of the boiler, respectively. The position of any point on the surface of the shell is determined by dimensionless coordinates α and β , moreover α characterizes the position of the point along the forming, β – along the arc of the cross section, so that the

product αR is the distance to any point along the creative shell, βR - arc distance relative to a certain fixed section.

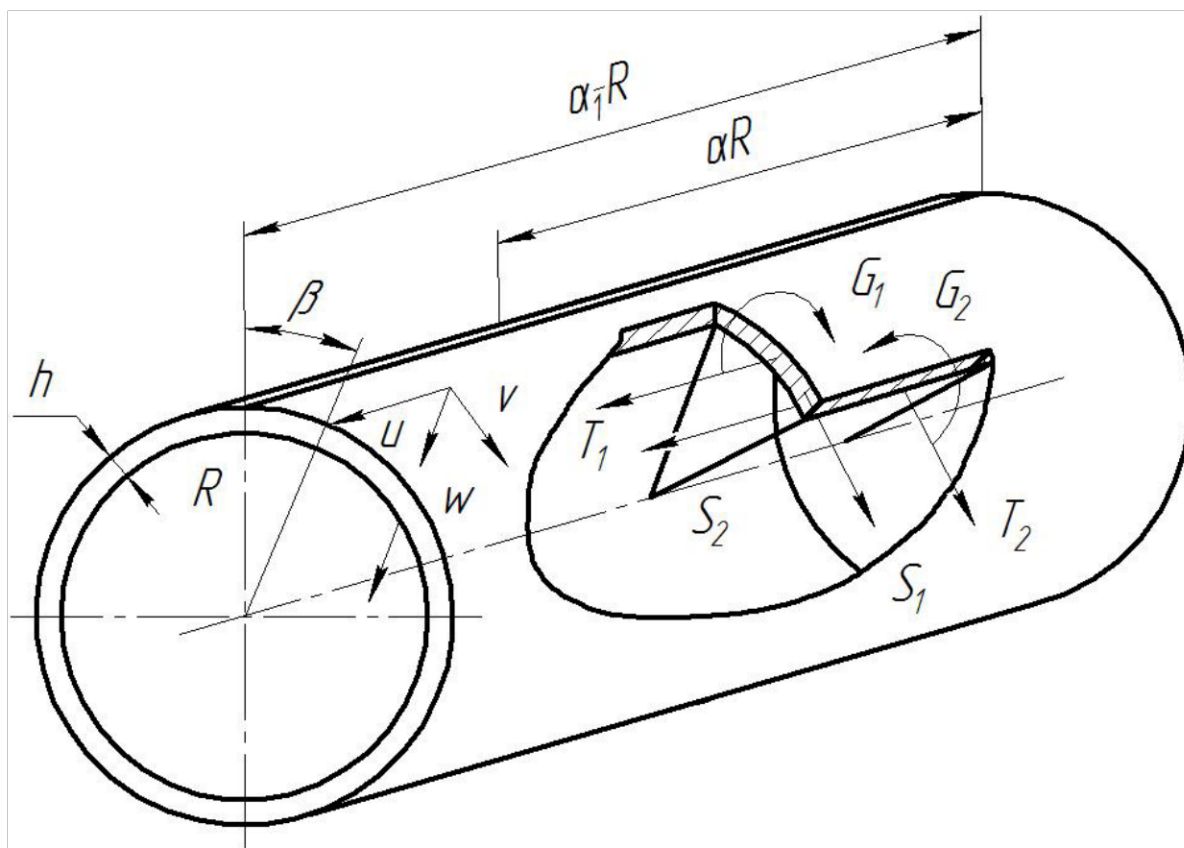


Figure 2.1 – Scheme of the cylindrical part of the boiler as an orthotropic shell

A coordinate system is located on the middle surface of the undeformed shell xyz , which has an axis x coincides with the original axis y - with a tangent to the guide, axis z - perpendicular to the surface, and it is directed to the center of curvature of the shell. Components of the external surface load $p_1(\alpha, \beta)$, $p_2(\alpha, \beta)$, $p_3(\alpha, \beta)$ and displacement $u(\alpha, \beta)$, $v(\alpha, \beta)$, $w(\alpha, \beta)$ directed along the axes x, y, z in accordance.

The positive directions of the main internal force factors and moments that occur during shell deformation are shown in Fig. 2.1.

When building a general theory of shells, the main tasks are taken into account:

1) differential equations of equilibrium of an infinitesimally small element of the median surface:

2)

$$\begin{aligned}\frac{\partial T_1}{\partial \alpha} + \frac{\partial S_2}{\partial \beta} + p_1 R &= 0 \\ \frac{\partial T_2}{\partial \beta} + \frac{\partial S_1}{\partial \alpha} - Q_2 + p_2 R &= 0, \\ T_2 + \frac{\partial Q_1}{\partial \alpha} + \frac{\partial Q_2}{\partial \beta} + p_3 R &= 0\end{aligned}\tag{2.1}$$

$$\begin{aligned}\frac{\partial G_{12}}{\partial \alpha} - \frac{\partial G_2}{\partial \beta} + R Q_2 &= 0 \\ \frac{\partial G_{21}}{\partial \beta} - \frac{\partial G_1}{\partial \alpha} + R Q_1 &= 0\end{aligned},\tag{2.2}$$

where T_1, T_2, S_1, S_2 – normal forces and shear forces;

G_1, G_2, G_{12}, G_{21} – bending and torque moments;

Q_1, Q_2 – transverse forces.

From equations (2.2) transverse forces Q_1 and Q_2 are equal to:

$$\begin{aligned} Q_1 &= -\frac{1}{R} \left(\frac{\partial G_{21}}{\partial \beta} - \frac{\partial G_1}{\partial \alpha} \right) \\ Q_2 &= -\frac{1}{R} \left(\frac{\partial G_{12}}{\partial \alpha} - \frac{\partial G_2}{\partial \beta} \right), \end{aligned} \quad (2.3)$$

3) dependencies for the main deformation components and displacement components:

$$\varepsilon_1 = \frac{1}{R} \frac{\partial u}{\partial \alpha}, \quad (2.4)$$

$$\varepsilon_2 = \frac{1}{R} \left(\frac{\partial v}{\partial \beta} - w \right), \quad (2.5)$$

$$\omega = \frac{1}{R} \left(\frac{\partial u}{\partial \beta} - \frac{\partial v}{\partial \alpha} \right), \quad (2.6)$$

$$\chi_1 = \frac{1}{R^2} \frac{\partial^2 w}{\partial \alpha^2}, \quad (2.7)$$

$$\chi_2 = \frac{1}{R^2} \left(\frac{\partial^2 w}{\partial \beta^2} + w \right), \quad (2.8)$$

$$\tau = -\frac{1}{2R^2} \left(\frac{\partial u}{\partial \beta} - \frac{\partial v}{\partial \alpha} - 2 \frac{\partial^2 w}{\partial \alpha \partial \beta} \right), \quad (2.9)$$

where $\varepsilon_1, \varepsilon_2, \omega$ - deformations of elongations and displacement of the middle surface of the shell,

χ_1, χ_2, τ - deformations of bending and torsion resulting from the transition of the middle surface of the shell into a deformed state.

4) the relationship between forces, bending moments and deformations:

5)

$$T_1 = \frac{E_1 h}{1 - \nu_1 \nu_2} \left(\varepsilon_1 + \nu_2 \varepsilon_2 + \frac{h^2}{12 R^2} \chi_1 \right), \quad (2.10)$$

$$T_1 = \frac{E_2 h}{1 - \nu_1 \nu_2} \left(\varepsilon_2 + \nu_1 \varepsilon_1 + \frac{h^2}{12 R^2} \chi_2 \right), \quad (2.11)$$

$$S_1 = Gh \left(\omega + \frac{h^2}{12 R^2} \tau \right), \quad (2.12)$$

$$S_2 = Gh \left(\omega - \frac{h^2}{12 R^2} \tau \right), \quad (2.13)$$

$$G_1 = -\frac{E_1 h^3}{12(1 - \nu_1 \nu_2)} \left[\chi_1 + \nu_2 \chi_2 + \frac{1}{R} (\varepsilon_1 + \nu_2 \varepsilon_2) \right], \quad (2.14)$$

$$G_2 = -\frac{E_1 h^3}{12(1 - \nu_1 \nu_2)} (\chi_2 + \nu_1 \chi_1), \quad (2.15)$$

$$G_{12} = -\frac{Gh^3}{12} \left(2\tau + \frac{\omega}{R} \right), \quad (2.16)$$

$$G_{21} = \frac{Gh^3}{6}\tau, \quad (2.17)$$

where E_1, E_2 – modulus of elasticity of the material of the cylindrical shell of the boiler in the directions α, β ;

ν_1 is the coefficient of transverse compression in the direction β when stretched in the direction α ;

ν_2 - coefficient of transverse compression in the direction α when stretched in the direction β ;

G – shear modulus.

Substituting (2.4 – 2.9) into formulas (2.10 – 2.17), we will have expressions for forces and bending moments due to displacement $u(\alpha, \beta), v(\alpha, \beta), w(\alpha, \beta)$:

$$T_1 = \frac{E_1 h}{(1 - \nu_1 \nu_2) R} \left[\frac{\partial u}{\partial \alpha} + \nu_2 \left(\frac{\partial v}{\partial \beta} - w \right) + c^2 \frac{\partial^2 w}{\partial \alpha^2} \right] - T_{1t}, \quad (2.18)$$

$$T_2 = \frac{E_2 h}{(1 - \nu_1 \nu_2) R} \left[\frac{\partial v}{\partial \beta} - w + \nu_1 \frac{\partial u}{\partial \alpha} - c^2 \left(\frac{\partial^2 w}{\partial \beta^2} + w \right) \right] - T_{2t}, \quad (2.19)$$

$$S_1 = \frac{Gh}{R} \left[\frac{\partial u}{\partial \beta} + \frac{\partial v}{\partial \alpha} + c^2 \frac{\partial^2 w}{\partial \alpha \partial \beta} \right], \quad (2.20)$$

$$S_2 = \frac{Gh}{R} \left[\frac{\partial u}{\partial \beta} + \frac{\partial v}{\partial \alpha} - c^2 \frac{\partial^2 w}{\partial \alpha \partial \beta} \right], \quad (2.21)$$

$$G_1 = \frac{D_1}{R^2} \left[\left(\frac{\partial^2}{\partial \alpha^2} + \nu_2 \frac{\partial^2}{\partial \beta^2} \right) w + \frac{\partial u}{\partial \alpha} + \nu_2 \frac{\partial v}{\partial \beta} \right] - G_{1t}, \quad (2.22)$$

$$G_2 = -\frac{D_2}{R^2} \left[\left(\frac{\partial^2}{\partial \beta^2} + \nu_1 \frac{\partial^2}{\partial \alpha^2} \right) w + w \right] - G_{2t}, \quad (2.23)$$

$$G_{12} = \frac{Gh^3}{6R^2} \left(\frac{\partial v}{\partial \alpha} + \frac{\partial^2 w}{\partial \alpha \partial \beta} \right), \quad (2.24)$$

$$G_{21} = \frac{Gh^3}{6R^2} \left(\frac{\partial u}{\partial \beta} - \frac{\partial v}{\partial \alpha} - 2 \frac{\partial^2 w}{\partial \alpha \partial \beta} \right), \quad (2.25)$$

Value $D_1, D_2, c^2, T_{1t}, T_{2t}, G_{1t}$ and G_{2t} are found by the expressions:

$$D_1 = \frac{E_1 h^3}{12(1 - \nu_1 \nu_2)}, \quad (2.26)$$

$$D_2 = \frac{E_2 h^3}{12(1 - \nu_1 \nu_2)}, \quad (2.27)$$

$$c^2 = \frac{h^2}{12R^2}, \quad (2.28)$$

$$T_{1t}(\alpha, \beta) = \frac{E_1 h}{1 - \nu_1 \nu_2} (\alpha_{1t} + \nu_2 \alpha_{2t}), \quad (2.29)$$

$$T_{2t}(\alpha, \beta) = \frac{E_2 h}{1 - \nu_1 \nu_2} (\alpha_{2t} + \nu_1 \alpha_{1t}), \quad (2.30)$$

$$G_{1t}(\alpha, \beta) = \frac{(\alpha_{1t} + \nu_2 \alpha_{2t}) E_1 h^2}{1 - \nu_1 \nu_2} \frac{1}{6}, \quad (2.31)$$

$$G_{2t}(\alpha, \beta) = \frac{(\alpha_{2t} + \nu_1 \alpha_{1t}) E_2 h^2}{1 - \nu_1 \nu_2} \frac{1}{6}, \quad (2.32)$$

We reduce the original equations to a system of three differential equations in displacements under arbitrarily distributed force loads. At the same time, substituting moments into formula (2.3). G_1, G_2, G_{12}, G_{21} we will get:

$$Q_1 = -\frac{D_1}{R^3} \left(\frac{\partial}{\partial \alpha} \nabla^2 w + \frac{\partial^2 u}{\partial \alpha^2} - \frac{1 - \nu_2}{2} \frac{\partial^2 u}{\partial \beta^2} + \frac{1 + \nu_2}{2} \frac{\partial^2 v}{\partial \alpha \partial \beta} \right), \quad (2.33)$$

$$Q_2 = -\frac{D_1}{R^3} \left(\frac{\partial}{\partial \beta} \nabla^2 w + \frac{\partial w}{\partial \beta} - (1 - \nu_1) \frac{\partial^2 v}{\partial \alpha^2} \right), \quad (2.34)$$

Excluding all internal shell forces in equation (2.1) using (2.18 – 2.34), we obtain a system of three differential equations with respect to three basic functions: $u(\alpha, \beta)$, $v(\alpha, \beta)$, $w(\alpha, \beta)$. This system has the following form:

$$\left\{ \begin{aligned} & \frac{\partial^2}{\partial \alpha^2} + \mu_1 \frac{\partial^2}{\partial \beta^2} + (\nu_2 + \mu_1) \frac{\partial^2}{\partial \alpha \partial \beta} - \nu_2 \frac{\partial}{\partial \alpha} + c^2 \left(\frac{\partial^3}{\partial \alpha^3} - \mu_1 \frac{\partial^3}{\partial \alpha \partial \beta^2} \right) = \\ & = -\frac{(1 - \nu_1 \nu_2) R^2}{E_1 h} p_1(\alpha, \beta) \\ & (\nu_2 + \mu_1) \frac{\partial^2}{\partial \alpha \partial \beta} + \lambda \frac{\partial^2}{\partial \beta^2} + \mu_1 \frac{\partial^2}{\partial \alpha^2} - \lambda \frac{\partial}{\partial \beta} + c^2 (\nu_2 + 3\mu_1) \frac{\partial^3}{\partial \alpha^2 \partial \beta} = \\ & = -\frac{(1 - \nu_1 \nu_2) R^2}{E_1 h} p_2(\alpha, \beta) \\ & -\nu_2 \frac{\partial}{\partial \alpha} + c^2 \left(\frac{\partial^3}{\partial \alpha^3} - \mu_1 \frac{\partial^3}{\partial \alpha \partial \beta^2} \right) - \lambda \frac{\partial}{\partial \beta} + c^2 (\nu_2 + 3\mu_1) \frac{\partial^3}{\partial \alpha^2 \partial \beta} + \\ & + \lambda + c^2 \left[\frac{\partial^4}{\partial \alpha^4} + 2(\nu_2 + 2\mu_1) \frac{\partial^4}{\partial \alpha^2 \partial \beta^2} + \left(\frac{\partial^2}{\partial \beta^2} + 1 \right) \lambda \right] = \\ & = \frac{(1 - \nu_1 \nu_2) R^2}{E_1 h} p_3(\alpha, \beta) \end{aligned} \right., \quad (2.35)$$

When solving tasks related to the distribution of force interaction on the elements of the boiler shell, it is convenient to reduce the system of three differential equations to one equation of the eighth order relative to the decisive

function. Through the decision function, all force and deformation factors of the shell are expressed with the help of differential operators.

When only longitudinal surface load is applied to the shell $p_1(\alpha, \beta) \neq 0$, $p_2(\alpha, \beta) = 0$, $p_3(\alpha, \beta) = 0$ let's introduce the decision function $\Phi(\alpha, \beta)$, associated with movements, the following differential dependencies:

$$u = \frac{1}{\mu_1} A_{11} \Phi_1, \quad (2.36)$$

$$v = \frac{1}{\mu_1} A_{12} \Phi_1, \quad (2.37)$$

$$w = \frac{1}{\mu_1} A_{13} \Phi_1, \quad (2.38)$$

where A_{11}, A_{12}, A_{13} – algebraic additions to the system of equations (2.35).

Then, as a result of substituting (2.36 – 2.38) into the system of equations (2.35), the second and third equations will turn into identities, and the first will become the decisive equation in the action $p_1(\alpha, \beta) \neq 0$.

$$L\Phi(\alpha, \beta) = \frac{R^4}{D_1} p_1(\alpha, \beta), \quad (2.39)$$

In the given formula (2.39):

$$L = \left[\begin{aligned} & \frac{\partial^8}{\partial \alpha^8} + a_{6,2} \frac{\partial^8}{\partial \alpha^6 \partial \beta^2} + 2v_2 \frac{\partial^6}{\partial \alpha^6} + a_{4,4} \frac{\partial^8}{\partial \alpha^4 \partial \beta^4} + a_{4,2} \frac{\partial^6}{\partial \alpha^4 \partial \beta^2} + \lambda \frac{\partial^4}{\partial \alpha^4} + \\ & + a_{2,6} \frac{\partial^8}{\partial \alpha^2 \partial \beta^6} + a_{2,4} \frac{\partial^6}{\partial \alpha^2 \partial \beta^4} + a_{2,2} \frac{\partial^4}{\partial \alpha^2 \partial \beta^2} + \lambda^2 \frac{\partial^4}{\partial \beta^4} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 + \\ & + \frac{1 - v_1 v_2}{c^2} \lambda \frac{\partial^4}{\partial \alpha^4} \end{aligned} \right], \quad (2.40)$$

$$a_{6,2} = \frac{\lambda - v_2^2}{\mu_1} + 4\mu_1, \quad (2.41)$$

$$a_{4,4} = 2\lambda \left[3 + \frac{v_1}{\mu_2} (1 - v_1 v_2) - 4v_1 (v_2 + \mu_1) \right], \quad (2.42)$$

$$a_{4,2} = a_{4,4}, \quad (2.43)$$

$$a_{2,6} = \lambda a_{6,2}, \quad (2.44)$$

$$a_{2,4} = 2\lambda (a_{6,2} - v_2), \quad (2.45)$$

$$a_{2,2} = \lambda \left(\frac{\lambda - v_2^2}{\mu_1} - 2v_2 \right), \quad (2.46)$$

$$\lambda = \frac{E_2}{E_1} = \frac{v_2}{v_1}, \quad (2.47)$$

$$\mu_i = \frac{G}{E_i} (1 - v_1 v_2) \text{ при } (i = 1; 2), \quad (2.48)$$

Displacements u , v , w , forces, bending moments and other factors based on (2.36 – 2.38) are related to the decision function $\Phi(\alpha, \beta)$ by the following differential relations:

$$u(\alpha, \beta) = \lambda \frac{\partial^2 \Phi}{\partial \alpha^2} + \frac{c^2}{\mu_1} \left[\mu_1 \frac{\partial^6}{\partial \alpha^6} + (\lambda + 2v_2 \mu_1 + 4\mu_1^2) \frac{\partial^6}{\partial \alpha^4 \partial \beta^2} + \right. \\ \left. + \lambda(5\mu_1 + 2v_2) \frac{\partial^6}{\partial \alpha^2 \partial \beta^4} + 2\lambda(4\mu_1 + v_2) \frac{\partial^4}{\partial \alpha^2 \partial \beta^2} + \lambda^2 \frac{\partial^2}{\partial \beta^2} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 \right] \Phi, \quad (2.49)$$

$$v(\alpha, \beta) = -\lambda \frac{\partial^2 \Phi}{\partial \alpha \partial \beta} - \frac{c^2}{\mu_1} \left[(\mu_1 + v_2) \frac{\partial^6}{\partial \alpha^5 \partial \beta} + (\mu_1 + v_2)(2v_2 + 4\mu_1) \frac{\partial^6}{\partial \alpha^3 \partial \beta^3} + \right. \\ \left. + (\lambda + v_2^2 + 3\mu_1 v_2) \frac{\partial^4}{\partial \alpha^3 \partial \beta} + \lambda(\mu_1 + v_2) \frac{\partial}{\partial \alpha} \left(\frac{\partial^5}{\partial \beta^5} + \frac{\partial^3}{\partial \beta^3} \right) + \lambda v_2 \frac{\partial^4}{\partial \alpha \partial \beta^3} \right] \Phi \\ , \quad (2.50)$$

$$w(\alpha, \beta) = -v_2 \frac{\partial^3 \Phi}{\partial \alpha^3} - \lambda \frac{\partial^3 \Phi}{\partial \alpha \partial \beta^2} - \frac{c^2}{\mu_1} \left[\mu_1 \frac{\partial^5}{\partial \alpha^5} + \left[\lambda - (v_2 + 2\mu_1)^2 \right] \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} - \right. \\ \left. - \lambda \mu_1 \frac{\partial^5}{\partial \alpha \partial \beta^4} \right] \Phi, (2.51)$$

$$T_1(\alpha, \beta) = \frac{E_1 h}{R} \left[\lambda \frac{\partial^3 \Phi}{\partial \alpha^3} + \frac{c^2}{1 - v_1 v_2} \left(\frac{\partial^7}{\partial \alpha^7} + \left(\frac{\lambda - v_2^2}{\mu_1} + v_2 + 4\mu_1 \right) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \right. \\ \left. \left. + \left(5\lambda - 6v_2^2 - 4\mu_1 v_2 + 2v_2 \frac{\lambda - v_2^2}{\mu_1} \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} + \lambda \left(\frac{\lambda - v_2^2}{\mu_1} - v_2 \right) \frac{\partial^7}{\partial \alpha \partial \beta^6} + \right. \right. \\ \left. \left. + \left(7(\lambda - v_2^2) + 2 \frac{v_2}{\mu_1} (\lambda - v_2^2) - 4\mu_1 v_2 \right) \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} + 2v_2 \frac{\partial^5}{\partial \alpha^5} + \right. \right. \\ \left. \left. + 2\lambda \left(\frac{\lambda - v_2^2}{\mu_1} - v_2 \right) \frac{\partial^5}{\partial \alpha \partial \beta^4} + \frac{\lambda^2}{\mu_1} \frac{\partial^3}{\partial \alpha \partial \beta^2} \right) \Phi \right] (2.52)$$

$$T_2(\alpha, \beta) = \frac{D_2}{R^3} \left[v_1 \frac{\partial^7}{\partial \alpha^7} - (1 - 2v_1 v_2 - 4v_1 \mu_1) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} - \right. \\ \left. - (4(\mu_1 - v_2) + 5v_2) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} - \lambda \frac{\partial^7}{\partial \alpha \partial \beta^6} + \frac{\partial^5}{\partial \alpha^5} - 4\mu_1 \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} - \right. \\ \left. - \lambda \frac{\partial^5}{\partial \alpha \partial \beta^4} + \frac{\lambda v_2}{\mu_1} \frac{\partial^3}{\partial \alpha \partial \beta^2} \right] \Phi, (2.53)$$

$$\begin{aligned}
 S_1(\alpha, \beta) = & \frac{c^2 Gh}{R} \left[-\frac{v_2}{\mu_1} \frac{\partial^7}{\partial \alpha^6 \partial \beta} + \left(\frac{\lambda - 2v_2^2}{\mu_1} - 4v_2 \right) \frac{\partial^7}{\partial \alpha^4 \partial \beta^3} - \right. \\
 & - \left(\frac{\lambda + v_2^2}{\mu_1} + 2v_2 \right) \frac{\partial^5}{\partial \alpha^4 \partial \beta} + \lambda \left(\frac{v_2}{\mu_1} + 4 \right) \frac{\partial^7}{\partial \alpha^2 \partial \beta^5} + \\
 & \left. + \frac{\lambda^2}{\mu_1} \frac{\partial^3}{\partial \beta^3} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 + 6\lambda \frac{\partial^5}{\partial \alpha^2 \partial \beta^3} \right] \Phi
 \end{aligned} \quad , \quad (2.54)$$

$$\begin{aligned}
 S_2(\alpha, \beta) = & \frac{c^2 Gh}{R} \left[-\frac{v_2}{\mu_1} \frac{\partial^7}{\partial \alpha^6 \partial \beta} + \left(\frac{\lambda - 2v_2^2}{\mu_1} - 4v_2 \right) \frac{\partial^7}{\partial \alpha^4 \partial \beta^3} + \right. \\
 & + \lambda \left(\frac{v_2}{\mu_1} + 4 \right) \frac{\partial^7}{\partial \alpha^2 \partial \beta^5} + \frac{\lambda^2}{\mu_1} \frac{\partial^3}{\partial \beta^3} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 - \\
 & \left. - \left(\frac{\lambda + v_2^2}{\mu_1} + 4v_2 \right) \frac{\partial^5}{\partial \alpha^4 \partial \beta} + 8\lambda \frac{\partial^5}{\partial \alpha^2 \partial \beta^3} \right] \Phi
 \end{aligned} \quad , \quad (2.55)$$

$$\begin{aligned}
 G_1(\alpha, \beta) = & -\frac{D_1}{R^2} \left[v_2 \frac{\partial^5}{\partial \alpha^5} - (\lambda - v_2^2) \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} + \lambda \frac{\partial^3}{\partial \alpha^3} - \right. \\
 & - \lambda v_2 \frac{\partial}{\partial \alpha} \left(\frac{\partial^4}{\partial \beta^4} + \frac{\partial^2}{\partial \beta^2} \right) + c^2 \left(4(v_2 + 2\mu_1) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \\
 & \left. + \left(2(3\lambda - v_2^2) + \frac{v_2}{\mu_1} (\lambda - v_2^2) \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} + \frac{\lambda(\lambda - v_2^2)}{\mu_1} \frac{\partial^7}{\partial \alpha \partial \beta^6} \right) \Phi \left. \right]
 \end{aligned} \quad , \quad (2.56)$$

$$\begin{aligned}
 G_2(\alpha, \beta) = & -\frac{D_2}{R^2} \left[v_1 v_2 \frac{\partial^5}{\partial \alpha^5} + v_2 \frac{\partial^3}{\partial \alpha^3} - \lambda \frac{\partial}{\partial \alpha} \left(\frac{\partial^4}{\partial \beta^4} + \frac{\partial^2}{\partial \beta^2} \right) - \right. \\
 & -c^2 \left(v_1 \frac{\partial^7}{\partial \alpha^7} + \left(1 + \frac{v_2}{\mu_1} - \frac{v_1(v_2 + 2\mu_1)^2}{\mu_1} \right) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \\
 & + \left(\lambda(1 - v_1 \mu_1) - (v_2 + 2\mu_1)^2 \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} + \\
 & \left. \left. + \frac{1}{\mu_1} \left(\lambda - (v_2 + 2\mu_1)^2 \right) \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} - \lambda \frac{\partial^7}{\partial \alpha \partial \beta^6} \right) \right] \Phi
 \end{aligned} \tag{2.57}$$

The decisive function under the action of only the radial surface load on the shell is written as follows:

$$L\Phi(\alpha, \beta) = \frac{R^4}{D_1} p_3(\alpha, \beta), \tag{2.58}$$

The equations of the general theory of shells have a general character. Based on them, it is possible to determine the stress-strain state of the shells under the action of an arbitrary surface load. To solve the problems of strength and stability of shells, the equation of the moment technical theory (equation of isotropic flat shells) has become widely used. Such equations can be written by imposing certain restrictions on the change in the stress-strain state of the shell. At the same time, equations for determining the stress state with a high degree of

variability in the direction of the structural and contour of the shell are obtained from the general equations of the shell theory.

Mathematically, it looks like this:

$$\left| \frac{\partial^2 f}{\partial \alpha^2} \right| \approx \left| \frac{\partial^2 f}{\partial \beta^2} \right| \square |f|, \quad (2.59)$$

where f – factors acting on the shell (effort, pressure, etc.)

The variability of a function on a given interval in any direction can be characterized by a value equal to the ratio of some average for the analyzed interval of the absolute value of its derivative to the average absolute value of the function itself.

Let's simplify the decisive equation of the general theory based on formula (2.59). The decisive differential equation of this theory for the case of longitudinal loading $p_1(\alpha, \beta)$:

$$L\Phi(\alpha, \beta) = \frac{R^4}{D_1} p_1(\alpha, \beta), \quad (2.60)$$

$$L = \frac{\partial^8}{\partial \alpha^8} + a_{6,2} \frac{\partial^8}{\partial \alpha^6 \partial \beta^2} + a_{4,4} \frac{\partial^8}{\partial \alpha^4 \partial \beta^4} + a_{2,6} \frac{\partial^8}{\partial \alpha^2 \partial \beta^6} + \lambda^2 \frac{\partial^8}{\partial \beta^8} + \\ + \lambda \frac{1 - \nu_1 \nu_2}{c^2} \frac{\partial^4}{\partial \alpha^4}, \quad (2.61)$$

At the same time, the ratios (2.39 – 2.57) connecting the sought-after factors: displacements, forces, bending moments with the decisive function are also significantly simplified:

$$u(\alpha, \beta) = \lambda \frac{\partial^2 \Phi}{\partial \alpha^2} + \frac{c^2}{\mu_1} \left[\mu_1 \frac{\partial^6}{\partial \alpha^6} + (\lambda + 2\nu_2 \mu_1 + 4\mu_1^2) \frac{\partial^6}{\partial \alpha^4 \partial \beta^2} + \right. \\ \left. + \lambda(5\mu_1 + 2\nu_2) \frac{\partial^6}{\partial \alpha^2 \partial \beta^4} + \lambda^2 \frac{\partial^6}{\partial \beta^6} \right] \Phi, \quad (2.62)$$

$$v(\alpha, \beta) = -\lambda \frac{\partial^2 \Phi}{\partial \alpha \partial \beta} - \frac{c^2}{\mu_1} \left[(\mu_1 + \nu_2) \frac{\partial^6}{\partial \alpha^5 \partial \beta} + (\mu_1 + \nu_2)(2\nu_2 + 4\mu_1) \frac{\partial^6}{\partial \alpha^3 \partial \beta^3} + \right. \\ \left. + \lambda(\mu_1 + \nu_2) \frac{\partial^6}{\partial \alpha \partial \beta^5} \right] \Phi, \quad (2.63)$$

$$w(\alpha, \beta) = \nu_2 \frac{\partial^3 \Phi}{\partial \alpha^3} - \lambda \frac{\partial^3 \Phi}{\partial \alpha \partial \beta^2} - \frac{c^2}{\mu_1} \left[\mu_1 \frac{\partial^5}{\partial \alpha^5} + [\lambda - (\nu_2 + 2\mu_1)^2] \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} - \right. \\ \left. - \lambda \mu_1 \frac{\partial^5}{\partial \alpha \partial \beta^4} \right] \Phi, \quad (2.64)$$

$$T_1(\alpha, \beta) = \frac{E_1 h}{R} \left[\lambda \frac{\partial^3 \Phi}{\partial \alpha^3} + \frac{c^2}{1 - \nu_1 \nu_2} \left(\frac{\partial^7}{\partial \alpha^7} + \left(\frac{\lambda - \nu_2^2}{\mu_1} + \nu_2 + 4\mu_1 \right) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \right. \\ \left. \left. + \left(5\lambda - 6\nu_2^2 - 4\mu_1 \nu_2 + 2\nu_2 \frac{\lambda - \nu_2^2}{\mu_1} \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} + \lambda \left(\frac{\lambda - \nu_2^2}{\mu_1} - \nu_2 \right) \frac{\partial^7}{\partial \alpha \partial \beta^6} \right) \Phi \right], \quad (2.65)$$

$$T_2(\alpha, \beta) = \frac{D_2}{R^3} \left[\nu_1 \frac{\partial^7}{\partial \alpha^7} - (1 - 2\nu_1 \nu_2 - 4\nu_1 \mu_1) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} - \right. \\ \left. - (4(\mu_1 - \nu_2) + 5\nu_2) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} - \lambda \frac{\partial^7}{\partial \alpha \partial \beta^6} \right] \Phi, \quad (2.66)$$

$$S(\alpha, \beta) = S_1(\alpha, \beta) = S_2(\alpha, \beta) = \frac{c^2 G h}{R} \left[-\frac{\nu_2}{\mu_1} \frac{\partial^7}{\partial \alpha^6 \partial \beta} + \right. \\ \left. + \left(\frac{\lambda - 2\nu_2^2}{\mu_1} - 4\nu_2 \right) \frac{\partial^7}{\partial \alpha^4 \partial \beta^3} + \lambda \left(\frac{\nu_2}{\mu_1} + 4 \right) \frac{\partial^7}{\partial \alpha^2 \partial \beta^5} + \frac{\lambda^2}{\mu_1} \frac{\partial^7}{\partial \beta^7} \right] \Phi, \quad (2.67)$$

$$G_1(\alpha, \beta) = -\frac{D_1}{R^2} \left[\nu_2 \frac{\partial^5}{\partial \alpha^5} - (\lambda - \nu_2^2) \frac{\partial^5}{\partial \alpha^3 \partial \beta^2} - \right. \\ \left. - \lambda \nu_2 \frac{\partial^5}{\partial \alpha \partial \beta^4} + c^2 \left(4(\nu_2 + 2\mu_1) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \right. \\ \left. \left. + \left(2(3\lambda - \nu_2^2) + \frac{\nu_2}{\mu_1} (\lambda - \nu_2^2) \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} + \frac{\lambda(\lambda - \nu_2^2)}{\mu_1} \frac{\partial^7}{\partial \alpha \partial \beta^6} \right) \Phi \right] \quad (2.68)$$

$$G_2(\alpha, \beta) = -\frac{D_2}{R^2} \left[v_1 v_2 \frac{\partial^5}{\partial \alpha^5} - \lambda \frac{\partial^5}{\partial \alpha \partial \beta^4} - \right. \\ \left. - c^2 \left(v_1 \frac{\partial^7}{\partial \alpha^7} + \left(1 + \frac{v_2}{\mu_1} - \frac{v_1 (v_2 + 2\mu_1)^2}{\mu_1} \right) \frac{\partial^7}{\partial \alpha^5 \partial \beta^2} + \right. \right. \\ \left. \left. + \left(\lambda (1 - v_1 \mu_1) - (v_2 + 2\mu_1)^2 \right) \frac{\partial^7}{\partial \alpha^3 \partial \beta^4} - \lambda \frac{\partial^7}{\partial \alpha \partial \beta^6} \right) \right] \Phi, \quad (2.69)$$

In a separate case for an isotropic material ($\lambda = 1$) the differential equation (2.60) and the relation (2.69) turn into the corresponding dependences of the theory of hollow shells, or the Vlasov-Donnell equations.

At large values of the variable stress state, equation (2.60) turns into a polyharmonic equation due to the possibility of neglecting its last term:

$$\left[\frac{\partial^4}{\partial \alpha^4} + 2(v_2 + 2\mu_1) \frac{\partial^4}{\partial \alpha^2 \partial \beta^2} + \lambda \frac{\partial^4}{\partial \beta^4} \right] \times \\ \times \left[\frac{\partial^4}{\partial \alpha^4} + \left(\frac{\lambda - v_2^2}{\mu_1} - 2v_2 \right) \frac{\partial^4}{\partial \alpha^2 \partial \beta^2} + \lambda \frac{\partial^4}{\partial \beta^4} \right] \Phi(\alpha, \beta) = \frac{R^4}{D_1} p_1(\alpha, \beta) \quad , (2.70)$$

The simplest version of the theory of shells, which occupies an intermediate position between the general theory and the momentless theory, is the semi-momentless theory of shells developed to solve problems of axisymmetric deformation of shells under the action of loads.

The equations of the semi-momentless theory of shells were first obtained based on the adoption of static and geometric hypotheses, which allowed replacing the shell with a certain discrete-continuous model. The discrete-continuous model of the orthotropic shell consists in the fact that cylindrical shells of arbitrary shape, supported by longitudinal and transverse ribs (stringers and frames) can be considered as a thin-walled orthotropic spatial system, in the cross sections of which only tangential (normal and shear) forces can occur. Longitudinal bending and torque moments, due to their insignificant influence on the stress state of the shell, are assumed to be zero. In longitudinal sections, in addition to normal and shear forces, transverse forces and circumferential bending moments may also occur. In accordance with the static hypotheses, a thin-walled system is taken as the calculation model, which consists along the length (along the generating line) of a set of transverse elementary bending strips. Each of these strips is presented in the form of a flat curved rod, which works in a certain section not only for tension - compression, but also for transverse bending and shear. The interaction between two adjacent transverse strips in the shell is represented by the transfer of only normal and shear forces from one strip to other strips.

At the same time, a differential equation of the fourth order in the longitudinal coordinate is formed, which, when decomposing the load and all factors into series along the circumferential coordinate, is reduced to an ordinary differential equation for the n th term of the series:

$$N_n^4(\alpha) - 2r_n^2 N_n^2(\alpha) + s_n^4 N_n(\alpha) = 0, \quad (2.71)$$

where $N_n(\alpha)$ is the amplitude value of the longitudinal force, arranged in a row along the circumferential coordinate.

$$N(\alpha) = \sum_{n=1}^{\infty} N_n(\alpha) \cos n\beta, \quad (2.72)$$

where r_n^2, s_n^4 – coefficients that depend on the harmonic number of the n th term of the trigonometric series and on the elastic characteristics of the reinforcing elements of the orthotropic shell.

According to the geometric hypotheses, deformation of shell elongation along lines that are parallel to the guide of its middle surface, and shear deformation in the middle surface, as values that have little effect on the state of internal forces of the shell, are taken to be zero ($\omega = 0, \varepsilon_2 = 0$).

In this case, the deformation of the shell occurs as follows:

- the lines of this surface perpendicular to the generating line at each point remain unstretched;
- angles between lines of main curvatures (coordinate lines), straight before deformation, remain straight after deformation.

The most rational approach to simplifying the equations is that in the equations of the general theory of shells, a strong inequality of the form is assumed:

$$\left| \frac{\partial^2 f}{\partial \beta^2} \right| \ll \left| \frac{\partial^2 f}{\partial \alpha^2} \right|, \quad (2.73)$$

This means that the nature of changes in displacements and stresses in the direction of the generator is much smoother than in the direction of the contour.

If we accept the strong inequality (2.73) as a working hypothesis, then we arrive at one of the variants of the semi-momentless theory, for which the main decisive equation in the case of longitudinal loading takes the form:

$$\frac{\partial^2 \Phi}{\partial \alpha^4} + \frac{c^2 \lambda}{1 - \nu_1 \nu_2} \frac{\partial^4}{\partial \beta^4} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 \Phi = - \frac{R^2}{E_2 h} p(\alpha, \beta), \quad (2.74)$$

At the same time, the relations that connect all the sought factors with the function are significantly simplified $\Phi(\alpha, \beta)$:

$$u(\alpha, \beta) = \lambda \frac{\partial^2 \Phi}{\partial \alpha^2}, \quad (2.75)$$

$$v(\alpha, \beta) = -\lambda \frac{\partial^2 \Phi}{\partial \alpha \partial \beta}, \quad (2.76)$$

$$w(\alpha, \beta) = -\lambda \frac{\partial^3 \Phi}{\partial \alpha \partial \beta^2}, \quad (2.77)$$

$$T_1(\alpha, \beta) = \lambda \frac{E_1 h}{R} \frac{\partial^3 \Phi}{\partial \alpha^3}, \quad (2.78)$$

$$T_2(\alpha, \beta) = -\lambda \frac{D_2}{R^3} \frac{\partial}{\partial \alpha} \left(\frac{\partial^6}{\partial \beta^6} + \frac{\partial^4}{\partial \beta^4} - \frac{\nu_2}{\mu_1} \frac{\partial^2}{\partial \beta^2} \right) \Phi, \quad (2.79)$$

$$S(\alpha, \beta) = S_1(\alpha, \beta) = S_2(\alpha, \beta) = \frac{c^2 G h}{R} \frac{\lambda^2}{\mu_1} \frac{\partial^3}{\partial \beta^3} \left(\frac{\partial^2}{\partial \beta^2} + 1 \right)^2 \Phi, \quad (2.80)$$

$$G_1(\alpha, \beta) = \lambda \nu_2 \frac{D_1}{R^2} \frac{\partial}{\partial \alpha} \left(\frac{\partial^4}{\partial \beta^4} + \frac{\partial^2}{\partial \beta^2} \right) \Phi, \quad (2.81)$$

$$G_2(\alpha, \beta) = \lambda \frac{D_2}{R^2} \frac{\partial}{\partial \alpha} \left(\frac{\partial^4}{\partial \beta^4} + \frac{\partial^2}{\partial \beta^2} \right) \Phi, \quad (2.82)$$

At $\lambda = 1$ equation (2.74) and relations (2.75 – 2.82) become known equations and relations of the semi-momentless theory, or the basic stress state.

In isotropic versions ($\lambda = 1$) these theories with their corresponding equations (2.74 – 2.82) were used in solving structural strength problems, as independent, as determination of elementary stress states: basic and with great variability.

The following assumption leads to the simplest version of the semi-momentless shell theory:

$$\left| \frac{\partial^2 f}{\partial \beta^2} \right| \ll |f|, \quad (2.83)$$

The equations of the stress state of the edge effect type are derived from the equations of the moment technical theory, if we accept the assumption directly opposite to that adopted during the derivation of the equations of the semi-momentless theory, namely:

$$\left| \frac{\partial^2 f}{\partial \alpha^2} \right| \ll \left| \frac{\partial^2 f}{\partial \beta^2} \right|, \quad (2.84)$$

Then the equation under the action of radial load:

$$\frac{\partial^4 w}{\partial \alpha^4} + \frac{1 - \nu^2}{c^2} w = \frac{R^4}{D} p_3(\alpha, \beta), \quad (2.85)$$

The power factors of the marginal effect have the form:

$$T_2 = -\frac{E_2 h}{R} w, \quad (2.86)$$

$$G_1 = -\frac{\nu_2 D_1}{R^2} \frac{\partial^2 w}{\partial \alpha^2}, \quad (2.87)$$

$$G_2 = -\frac{D_2}{R^2} \frac{\partial^2 w}{\partial \alpha^2}, \quad (2.88)$$

Equations in the form (2.86 – 2/88) have become widely used when considering the problems of axisymmetric deformation of shells under the action of radial loading. Their difference from the case of axisymmetric deformation consists in replacing the ordinary derivative with a partial one.

The asymptotic analysis of the exact equations of the theory of isotropic shells shows that, depending on the variability of external factors and the stress state, they allow certain simplifications. The degree of simplification depends on

the index of variability of the surface or edge load and, therefore, on the index of variability of the stress state.

Let's denote the variability indicator by ρ and note that it is related to the relative thickness of the shell h / R and harmonic number n when expanding the external load and the stress state in a row along the circumferential coordinate:

$$m = h^{-\rho}, \quad (2.89)$$

According to ρ one can obtain approximate equations of shell theory that describe various elementary stress states. These are equations of the boundary effect, semi-momentless theory, moment engineering theory, as well as equations of the plane problem type and plate bending. Their asymptotic errors are given by:

- semi-momentless theory and edge effect theory
-

$$\varepsilon \approx \frac{n^2}{2\sqrt{3}\lambda} \frac{h}{R} \left(\frac{\lambda - \nu_2^2}{\mu_1} + 4\mu_1 \right), \quad (2.90)$$

- momentary technical theory

$$\varepsilon \approx \frac{2 \left(\frac{\lambda - v_2^2}{\mu_1} + 4\mu_1 - v_2 \right)}{n^2 \left(\frac{\lambda - v_2^2}{\mu_1} + 4\mu_1 \right)}, \quad (2.91)$$

- tangential state equations

-

$$\varepsilon \approx \frac{2 \left(\frac{\lambda - v_2^2}{\mu_1} + 4\mu_1 - v_2 \right)}{c^2 n^2 \left(\frac{\lambda - v_2^2}{\mu_1} + 4\mu_1 \right)}, \quad (2.92)$$

The smallest asymptotic error at $\rho \rightarrow 0$ give the equations of the semi-momentless theory describing the ground state.

When increasing ρ the error of these equations grows, and at $\rho = 0,5$ is equal to one. For stress state equations with large variability, the largest asymptotic error occurs at $\rho \rightarrow 0$. When growing ρ the error drops sharply and monotonically tends to zero, practically disappearing at $\rho = 0,5$. The asymptotic error of the equations of bending and tangential states at $\rho \leq 0,5$ is significant, at $\rho \geq 0,5$ approaches zero.

The stress-strain state of the shell can be asymptotically divided into elementary stress states, each of which is described by known approximate equations of the theory of shells and flat bodies.

2.2 Calculation method and input data

In this paper, to determine the stress-strain state of the cylindrical part of the tank wagon boiler under the condition of reducing the thickness of the shell to obtain the values of its maximum allowable values, it is proposed to use the classical semi-momentless theory of shells, based on the Kirchhoff-Leav hypotheses. At the same time, it should be noted that the presented calculation assumes the action of static and dynamic loads on the boiler shell. According to the calculation scheme (Fig. 2.2), the cylindrical shell freely rests on absolutely rigid supports. Such support assumes that individual segments on the surface of the shell (Fig. 2.3) can move along the diaphragm in the direction of the cylindrical part, while free rotation is allowed in the final cross-sections of the shell, but their movements are absent.

In accordance with the accepted calculation scheme, the action of the distributed load from the weight of the cargo is transferred to the boiler of the tank wagon q with height h_0 , which is perceived by supine supports q_1 , as well as the transfer of longitudinal forces is taken into account on shaped legs that prevent the boiler from shifting during transient modes of movement. Geometric dimensions $b - a$ and $d - c$ determine the length of the support parts of the supine

supports and shaped legs, respectively. The angles of the girth of the support parts for the pivot part are determined by the difference $\beta_2 - \beta_1$.

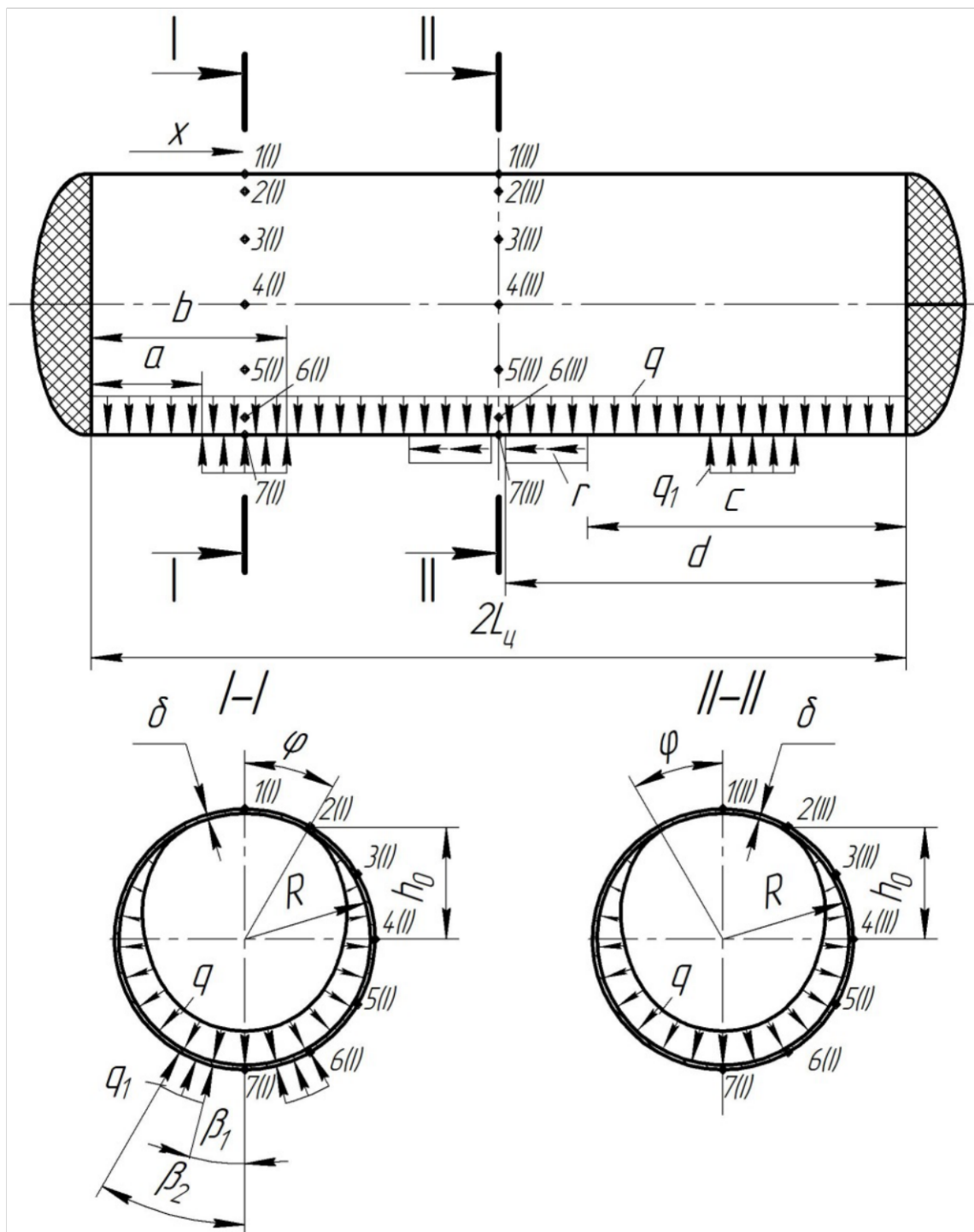


Figure 2.2 – Calculation scheme of the cylindrical shell of the boiler

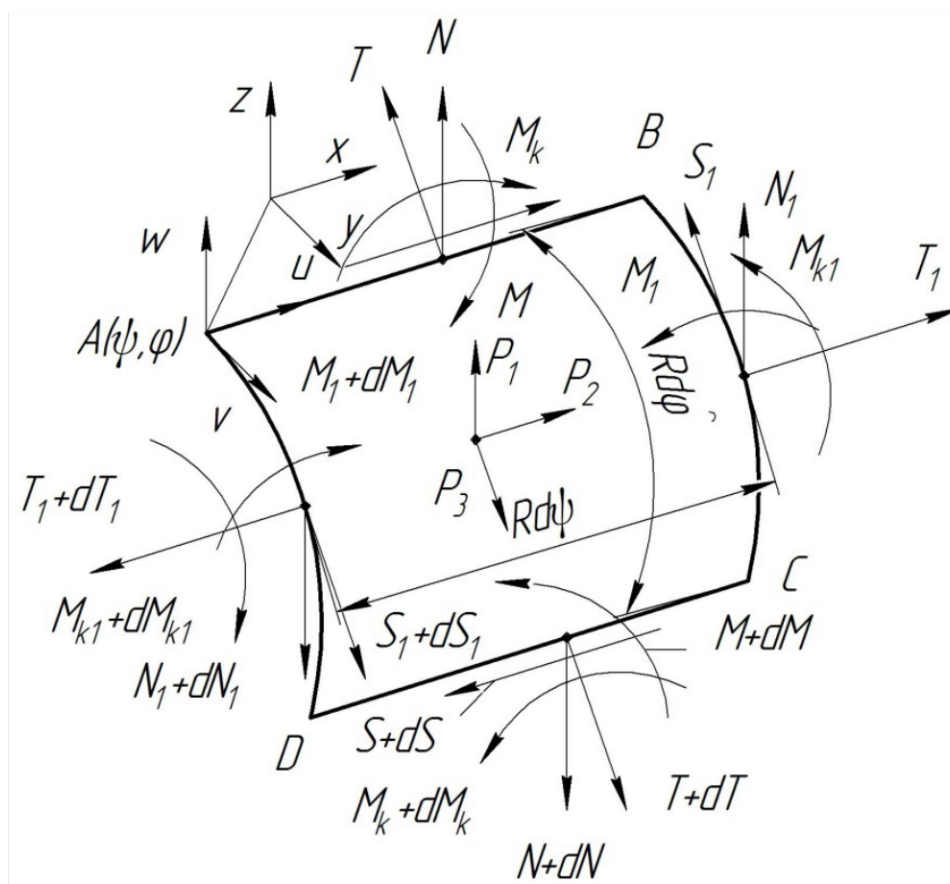


Figure 2.3 – Effect of force factors on the segment of the boiler shell

In the general case, five internal forces act on the shell segment: normal forces T , shear forces S , transverse forces N , bending moments M , torques M_k . In accordance with the semi-momentless theory of shells, it is taken into account that bending moments and forces acting in the transverse direction, as well as torques in the transverse and longitudinal directions, are equal to zero.

The algorithm for calculating the stress state of the cylindrical part of the shell of the tank wagon boiler involves the following sequence of actions:

- 1) determination of the local reference coordinate system in accordance with the adopted calculation scheme;
- 2) setting input parameters taking into account the geometry of the structure, operating loads, and elastic properties of the shell material;
- 3) determination of the bearing load in the considered design sections;
- 4) finding the longitudinal load distributed over the contact surface of the boiler shell at the location of the shaped legs;
- 5) determination of vertical and longitudinal load coefficients using Fourier series;
- 6) formation of a system of algebraic equations in matrix form for finding components of tangential displacement, shear forces and normal forces;
- 7) determination of the coefficients of the series of tangential displacement, shear forces and normal forces at the point of the shell by the angular coordinate in the studied section;
- 8) construction of the plot of bending moments and determination of their values in the considered intersection;
- 9) determination of equivalent stresses under the influence of force factors and comparison with permissible values;
- 10) variation of the input parameter of the shell thickness change and repeated calculation cycle.

The method of calculated cross-sections (cross-sections II and II-II, Fig. 2.2) involves dividing the cylindrical part of the shell into a certain number of sections and determining the required values (displacements, stresses) in the studied locations using the polar coordinate system. This makes it possible to determine the initial parameters at each separately considered point, which is located on the surface of the cylindrical shell according to the angular coordinate according to the given limit interval of its length.

The system of differential equations of equilibrium of the shell segment has the following form:

$$\left. \begin{aligned} \frac{\partial T_1}{\partial \psi} + \frac{\partial S}{\partial \varphi} &= 0 \\ \frac{\partial S}{\partial \psi} + \frac{\partial T}{\partial \varphi} - N &= 0 \\ \frac{\partial^2 M_1}{\partial \psi^2} + \frac{\partial^2 M}{\partial \varphi^2} - 2 \frac{\partial^2 M_\kappa}{\partial \psi \partial \varphi} + RT &= 0 \end{aligned} \right\} \quad (2.93)$$

where T, T_1 – normal forces;

N, N_1 – transverse forces;

S, S_1 – shear forces;

M, M_1 – bending moments;

M_κ – torque;

ψ, φ – coordinates of the cylindrical system;

R is the radius of the cylindrical shell of the boiler.

In general, linear deformations ε_x and ε_y , angular γ_{xy} , the deformation of the curvature change χ_x and χ_y and twisting γ_{xy} expressed through displacement w, v, u . Let's write those that will be needed when deriving the main ones, which represent the complete system of equations of the semi-momentless theory:

$$\left. \begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x} \\ \varepsilon_y &= \frac{\partial v}{R \partial \varphi} + \frac{w}{R} \\ \gamma_{xy} &= \frac{\partial v}{\partial x} + \frac{\partial u}{R \partial \varphi} \\ \chi_y &= \frac{1}{R} \left(\frac{\partial v}{\partial \varphi} + \frac{\partial^2 w}{\partial \varphi^2} \right) \end{aligned} \right\} \quad (2.94)$$

According to the theory, it is assumed that Poisson's ratio $\mu = 0$ and linear and angular strain $\varepsilon_y = \gamma_{xy} = 0$, that is, the elasticity ratio for forces T_y and S_y cannot be expressed through deformations. According to the considered option, such relations can be represented for force T_x and the moment M_y :

$$\left. \begin{aligned} T_x &= E\delta\varepsilon_x \\ M_y &= \frac{E\delta^3}{12}\chi_y \end{aligned} \right\} \quad (2.95)$$

where E – modulus of elasticity of the shell material;

δ is the shell thickness.

Taking into account the effect of loads P_1, P_2 and P_3 , distributed over the surface of the plane of the shell segment, we get the sum of the projections of the net forces on the normal, axis x and tangential y to the circumference of the cross-section, as well as the moment relative to the axis x . After the transformation, the differential equations of equilibrium of the shell segment will have the form (2.96).

The solution to the problem of determining additional internal forces in the cylindrical part of the boiler, caused by deformations of the contour of its cross sections, can be obtained on the basis of geometric equations (2.94), ratios (2.95) and equations (2.96). Let's convert these equations to a convenient solution, abandoning the traditional approach according to which the load P_1, P_2 and P_3 differentiable by any variable. Let's exclude the forces from the balance equations N_y , given that it is a moment ratio ∂M_y , which is applied at a distance $R\partial\varphi$ of the considered segment.

$$\left. \begin{aligned} \frac{\partial N_y}{\partial \varphi} + T_y - P_1 R &= 0 \\ \frac{\partial T_x}{\partial x} R + \frac{\partial S_y}{\partial \varphi} + P_2 R &= 0 \\ \frac{\partial T_y}{\partial \varphi} + \frac{\partial S_y}{\partial x} R - N_y + P_3 R &= 0 \\ \frac{\partial M_y}{\partial \varphi} - N_y R &= 0 \end{aligned} \right\} \quad (2.96)$$

After the transformations, we will have an equation of the form:

$$\left. \begin{aligned} \frac{\partial^2 M_y}{R \partial \varphi} + T_y - P_1 R &= 0 \\ \frac{\partial T_x}{\partial x} R + \frac{\partial S_y}{\partial \varphi} + P_2 R &= 0 \\ \frac{\partial T_y}{\partial \varphi} + \frac{\partial S_y}{\partial x} R - \frac{\partial M_y}{R \partial \varphi} + P_3 R &= 0 \end{aligned} \right\} \quad (2.97)$$

Since for forces T_y and S_y there are no elasticity ratios, they can be found from equation (2.97). By turning off the power T_x and moment M_y let's transform these equations using the relation (2.95) under the condition that the linear and angular deformations are equal to zero. Based on this, we will have:

$$\left. \begin{aligned} w &= -\frac{\partial v}{\partial \varphi} \\ \frac{\partial u}{\partial \varphi} &= -\frac{R \partial v}{\partial x} \end{aligned} \right\} \quad (2.98)$$

In accordance with the first and fourth relations (2.94), expressions (2.95) and (2.98) obtain:

$$\left. \begin{aligned} T_x &= -E\delta \int_{\varphi} \frac{\partial^2 v}{\partial x^2} R d\varphi \\ M_y &= -\frac{E\delta^3}{12} \left(\frac{\partial^3 v}{\partial \varphi^3} + \frac{\partial v}{\partial \varphi} \right) \end{aligned} \right\} \quad (2.99)$$

By substituting the expression (2.99) into the system of equations (2.97), we will have a system of integral differential equations of the form:

$$\left. \begin{aligned} -\frac{E\delta^3}{12R^3} \left(\frac{\partial^5 v}{\partial \varphi^5} + \frac{\partial^3 v}{\partial \varphi^3} \right) + T_y - P_1 R &= 0 \\ E\delta \int_{\varphi} \frac{\partial^3 v}{\partial x^3} R^2 d\varphi - \frac{\partial S_y}{\partial \varphi} - P_2 R &= 0 \\ \frac{\partial T_y}{\partial \varphi} + \frac{\partial S_y}{\partial x} R + \frac{E\delta^3}{12R^3} \left(\frac{\partial^4 v}{\partial \varphi^4} + \frac{\partial^2 v}{\partial \varphi^2} \right) + P_3 R &= 0 \end{aligned} \right\} \quad (2.100)$$

Such a system reflects the equilibrium conditions of an extremely small segment of the shell of the cylindrical part of the boiler, obtained taking into account geometric and physical relationships, i.e. it is equivalent to three groups of equations of the shell theory taking into account the hypotheses of the semi-momentless theory. The system of equations is complete and contains three equations with three unknowns.

The laws of load distribution acting on the boiler shell are represented by double trigonometric series with coefficients P_{1mn} , P_{2mn} and P_{3mn} , determined by the Fourier formulas (2.101). The combination of trigonometric functions reflects the nature of the distribution of movements according to the corresponding load.

For the adopted settlement scheme at x , which is within the length of the cylindrical part of the shell, there should be no movement w and v , due to the fact that the contour of the cylindrical part of the boiler is not deformed at the end diaphragms. Sliding along the diaphragm can occur along the cylindrical part of the shell, i.e. $u \neq 0$.

$$\left. \begin{aligned} P_1 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{1mn} \cos n\varphi \sin \lambda x \\ P_2 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{2mn} \cos n\varphi \cos \lambda x \\ P_3 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{3mn} \sin n\varphi \sin \lambda x \end{aligned} \right\} \quad (2.101)$$

where m and n – numbers of row members;

λ is the ratio of the first number of the term of the series to the length of the cylindrical part of the shell.

The nature of the distribution of additional forces is reflected in contour deformations. When the load is symmetrical with respect to the longitudinal vertical plane of symmetry of the cylindrical part of the movement w and u symmetrical, and displacements v directed obliquely. Therefore, they can be presented in the following records:

$$v = \sum \sum v_{mn} \sin n\varphi \sin \lambda x, \quad (2.102)$$

$$\left. \begin{aligned} S_y &= \sum \sum S_{ymn} \sin n\varphi \cos \lambda x \\ T_y &= \sum \sum T_{ymn} \cos n\varphi \sin \lambda x \end{aligned} \right\} \quad (2.103)$$

In formulas (2.102) and (2.103) coefficients v_{mn} , S_{ymn} , T_{ymn} unknown In the case of finding the values of the load coefficients P_{1mn} , P_{2mn} and P_{3mn} possible movements will look like:

$$\left. \begin{aligned} w &= 1 \cdot \cos n\varphi \sin \lambda x \\ v &= 1 \cdot \sin n\varphi \sin \lambda x \\ u &= 1 \cdot \cos n\varphi \cos \lambda x \end{aligned} \right\} \quad (2.104)$$

The equations of the system (2.104) are continuous within the surface of the shell and correspond to the boundary conditions at the end intersections of the cylindrical part of the shell and periodicity along the arc of the cross section.

Substituting the series from formulas (2.102), (2.103) and (2.104) into equation (2.100), the first of which is equivalent to the projection of internal and external forces on the direction of movement w , the second is equal to the projection on displacement u , and the third defines the projection on displacement v .

The work of force projections on the corresponding possible displacements is calculated by integration over the surface of the cylindrical part within the limits of $x = 0$ to $x = 2L_y$, at the angular coordinate from $\varphi = 0$ to $\varphi = 2\pi$, that is:

$$\left. \begin{aligned} & \int_0^{2L_y} \int_0^{2\pi} \left(\cos n\varphi \sin \frac{m\pi x}{2L_y} \right) \left(\cos k\varphi \sin \frac{i\pi x}{2L_y} \right) dx d\varphi \\ & \int_0^{2L_y} \int_0^{2\pi} \left(\sin n\varphi \sin \frac{m\pi x}{2L_y} \right) \left(\sin k\varphi \sin \frac{i\pi x}{2L_y} \right) dx d\varphi \\ & \int_0^{2L_y} \int_0^{2\pi} \left(\cos n\varphi \cos \frac{m\pi x}{2L_y} \right) \left(\cos k\varphi \cos \frac{i\pi x}{2L_y} \right) dx d\varphi \end{aligned} \right\} \quad (2.105)$$

Given the orthogonality of trigonometric functions, if $n = k$ and $m = i$ these integrals will be equal $L_y \pi$, and in case $n \neq k$ and $m \neq i$ they will be zero.

The system of integral differential equations (2.100) in the process of determining the work will be reduced to the systems of algebraic equations (2.106) with respect to the coefficients of the series v_{mn} , S_{ymn} , T_{ymn} . According to these equations, the coefficients of the series are found, and according to formulas (2.103) there are balanced forces, which are associated with deformations of the contour of the sections of the cylindrical shell. The forces at the studied points are the addition of series at the given coordinates x and φ .

Coefficients of normal force and moment with known coefficients v_{mn} can be determined by the expression (2.99), then the system of equations will have the form (2.107).

$$\begin{vmatrix} -\frac{E\delta^3}{12R^3}n^3(n^2+1) & 0 & 1 \\ \frac{E\delta R^2\lambda^3}{n} & -n & 0 \\ \frac{E\delta^3}{12R^3}n^2(n^2-1) & \lambda R & n \end{vmatrix} \times \begin{vmatrix} v_{mn} \\ S_{ymn} \\ T_{ymn} \end{vmatrix} = \begin{vmatrix} P_{1mn}R \\ P_{2mn}R \\ P_{3mn}R \end{vmatrix} \quad (2.106)$$

$$\left. \begin{aligned} T_{xmn} &= -\frac{E\delta R\lambda^2}{n}v_{mn} \\ M_{ymn} &= -\frac{E\delta^3}{12R^3}n(n^2-1)v_{mn} \end{aligned} \right\} \quad (2.107)$$

For the coefficients of equations (2.107) we have:

$$\left. \begin{aligned} T_x &= \sum \sum T_{xmn} \cos n\varphi \sin \lambda x \\ M_y &= \sum \sum M_{ymn} \cos n\varphi \sin \lambda x \end{aligned} \right\} \quad (2.108)$$

Equivalent stresses are calculated according to the deformation energy criterion according to the formula:

$$\sigma_e = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2}, \quad (2.109)$$

To ensure the required strength of the boiler shell, the condition must be met $\sigma_e \leq [\sigma]$, according to [1], and individual components of the equivalent stress (2.109) are determined by the system of equations of the form:

$$\left. \begin{aligned} \sigma_x &= \sigma + \frac{T_x}{\delta} \\ \sigma_y &= \frac{T_y}{\delta} \pm \frac{6M_y}{\delta^2} \\ \tau_{xy} &= \frac{S_y}{\delta} \end{aligned} \right\} \quad (2.110)$$

Hydrostatic pressure q (Fig. 2.2) distributed according to the law:

$$q_1 = \gamma R (\cos \varphi - \cos \beta_0), \quad (2.111)$$

where γ - specific weight of cargo;

β_0 - the angle that determines the position of the free surface of the load.

When bearing loads are applied, the angular width of the planes is taken into account $\beta_2 - \beta_1$ in cities, leaning on horizontal supports, and the load is distributed q oriented along the radius.

Load factors P_{1mn} , P_{2mn} and P_{3mn} for the supporting parts of the boiler, without taking into account tangential loads, will be determined by the formula:

$$\left. \begin{aligned} P_{1mn} &= \frac{4}{mn} q (\cos \lambda a - \cos \lambda b) (\sin n \beta_2 - \sin n \beta_1) \\ P_{2mn} &= \frac{4}{mn} r (\sin \lambda d - \sin \lambda c) (\sin n \beta_4 - \sin n \beta_3) \\ P_{3mn} &= 0 \end{aligned} \right\} \quad (2.112)$$

where r is the intensity of the distributed longitudinal load on the contact surface of the cylindrical shell and the legs.

The longitudinal load distributed over the contact surface of the cylindrical shell and legs is determined by the formula:

$$r = \frac{T_1 (m_\kappa + m_\epsilon)}{4m_{op} R (d - c) (\beta_4 - \beta_3)}, \quad (2.113)$$

where m_{κ} – tank wagon boiler mass;

m_{ϵ} – the mass of cargo transported in a tank wagon;

m_{op} – gross weight of the tank wagon;

$d - c$ – paw length;

$\beta_4 - \beta_3$ – the angle of the boiler shell envelope with a shaped leg.

According to the presented methodology, the stress-strain state of the tank wagon boiler for improved sulfuric acid model 15-1548-02 was calculated. The calculation scheme of the cylindrical part of the boiler takes into account its geometric dimensions and operating loads presented in table 2.1.

Table 2.1. Input data for calculation

Parameter, dimension	Size
Tank wagon carrying capacity, kg	67000
Gross wagon weight, kg	90300
Wagon base, see	780
The length of the cylindrical part of the boiler, cm	927
Radius of the cylindrical part of the boiler, cm	110
The inner angle of the girth of the supine support, degrees	34
The outer angle of the girth of the supine support,	36

degrees	
The inner angle of the girth of the shaped support, degrees	5
The outer angle of the girth of the shaped support, degrees	9
The distance from the extreme point of the cylindrical part of the boiler to the outer part of the lying support, see	50
The distance from the extreme point of the cylindrical part of the boiler to the inner part of the lying support, see	150
The distance from the extreme point of the cylindrical part of the boiler to the outer part of the shaped support, see	378.5
The distance from the extreme point of the cylindrical part of the boiler to the inner part of the shaped support, see	448.5
The thickness of the boiler shell, cm	0.7-1.1
Longitudinal force, kg	350,000
Modulus of elasticity of the material, kg/cm ²	2.1·10 ⁶

The calculation of the strength of the tank wagon boiler is carried out according to the I mode, in which, according to the requirements [1], a longitudinal force of 3.5 MN acts on the wagon. The thickness of the boiler shell is a variable parameter that takes into account the amount of its change due to surface corrosion damage. At the same time, in the calculation, the thickness of the shell is assumed to be the same in all sections, that is, it is assumed that corrosion is evenly distributed over the entire surface of the metal at the same depth.

In addition to the given calculation of the tank wagon for improved sulfuric acid, model 15-1548-02, in section 2.3 of this report, studies of other models of tank wagons for the transportation of chemical cargoes are presented from the point of view of the influence of the operational loads of the wagons on the stress-strain state of the cylindrical shell of the boiler under the accepted assumptions .

2.3 Determination of the stress-strain state of the cylindrical shell of the boiler in the mathematical package MATHCAD

Before starting the calculations of the stress-strain state, the calculation scheme of the boiler of the wagon is formed (Fig. 2.4), which is considered as a

beam on two supports with a rigid contour of the cross section, and the bending moments of the boiler are determined. The values of these moments depend on the longitudinal coordinate x , which determines the length of the cylindrical part of the boiler on the cross-section section in question, and the stresses in the cross-sections change in proportion to the bending moments.

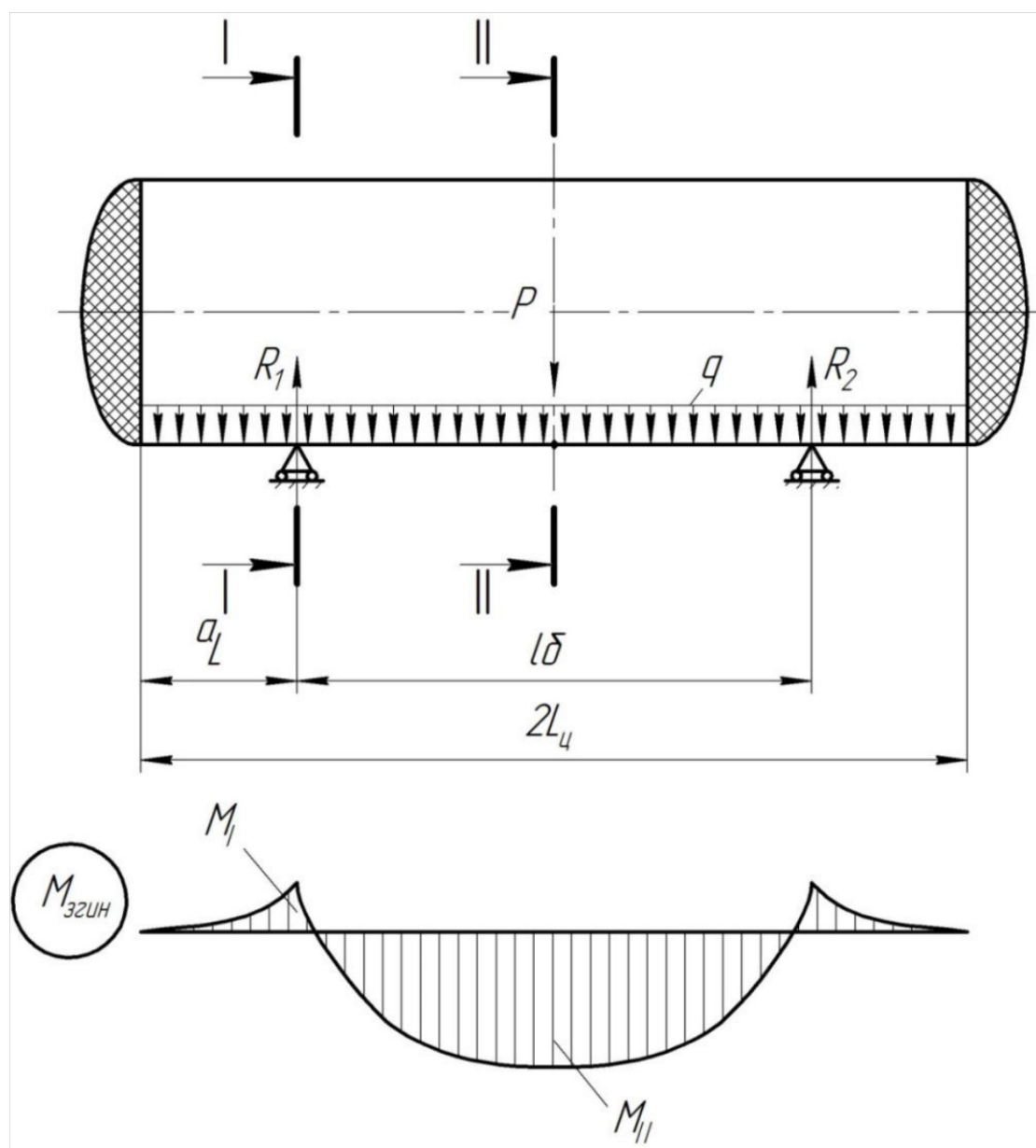


Figure 2.4 – Simplified calculation diagram of a tank wagon boiler

With the help of MathCAD software, a plot of bending moments (Fig. 2.5) was constructed for individual sections of the cylindrical part of the boiler based on the equation written according to the syntax of the calculation program:

$$M(x) := \begin{cases} q \frac{x^2}{2} & \text{if } 0 \leq x \leq a_L \\ q \frac{x^2}{2} - \frac{P}{2}(x - a_L) & \text{if } a_L \leq x \leq a_L + l\delta \\ q \frac{x^2}{2} - \frac{P}{2}(x - a_L) - \frac{P}{2}(x - (l\delta + a_L)) & \text{otherwise} \end{cases}, \quad (2.114)$$

where q – distributed load acting on the cylindrical shell of the boiler;

x – coordinate of the length interval of the cylindrical part of the boiler;

$l\delta$ – tank wagon base;

a_L – the length of the cantilever part of the cylindrical part of the boiler,

which is outside the base;

P – vertical load from the weight of the cargo.

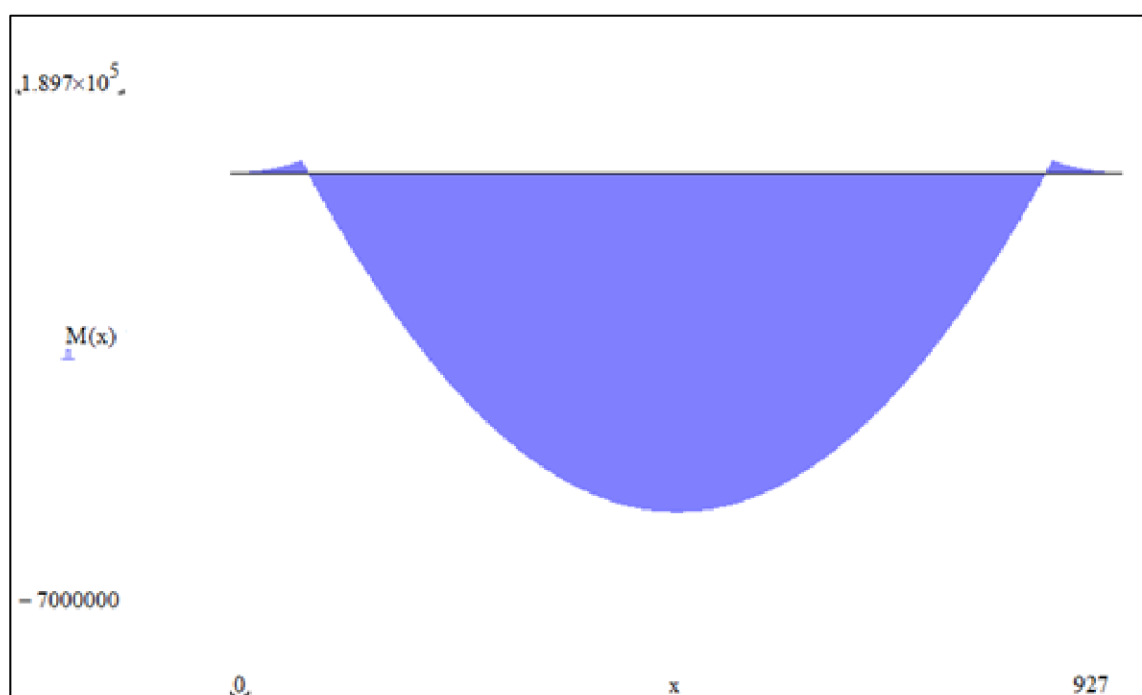


Figure 2.5 – Diagram of bending moments of the length of the cylindrical part
of the tank wagon boiler

According to the set input data, the calculated maximum values of the bending moments of the shell at the supporting points of support for the case of the thickness of the boiler shell $\delta = 0,7$ cm at $a_L = 73,5$ cm and in the middle part of the boiler at the length of the section, which takes into account the cantilever part and the semi-base of the wagon $a_L + l\delta / 2 = 463,5$ cm constitute $M(x)_I = 1,952 \cdot 10^5$ кг · см and $M(x)_{II} = 5,301 \cdot 10^6$ кг · см in accordance.

Defined components of the tangent $V(\varphi)$ and radial $W(\varphi)$ movements according to formulas (2.115-2.116) and (2.117-2.118) are presented in Figure 2.6.

$$V(m, n, \varphi) = X(m, n)_0 (\sin(n \cdot \varphi) \cdot \sin(\lambda(m) \cdot x)), \quad (2.115)$$

$$V(\varphi) = \sum_m \left(\sum_n V(m, n, \varphi) \right), \quad (2.116)$$

$$W(m, n, \varphi) = X(m, n)_0 \cdot n \cdot (\cos(n \cdot \varphi) \cdot \sin(\lambda(m) \cdot x)), \quad (2.117)$$

$$W(\varphi) = \sum_m \left(\sum_n W(m, n, \varphi) \right), \quad (2.118)$$

According to the graph, the characteristic level of the maximum amplitudes is determined, which for radial movements under the given conditions exceeds the value of the tangential stresses in the supporting places of application of loads by approximately 4.5-4.9 times.

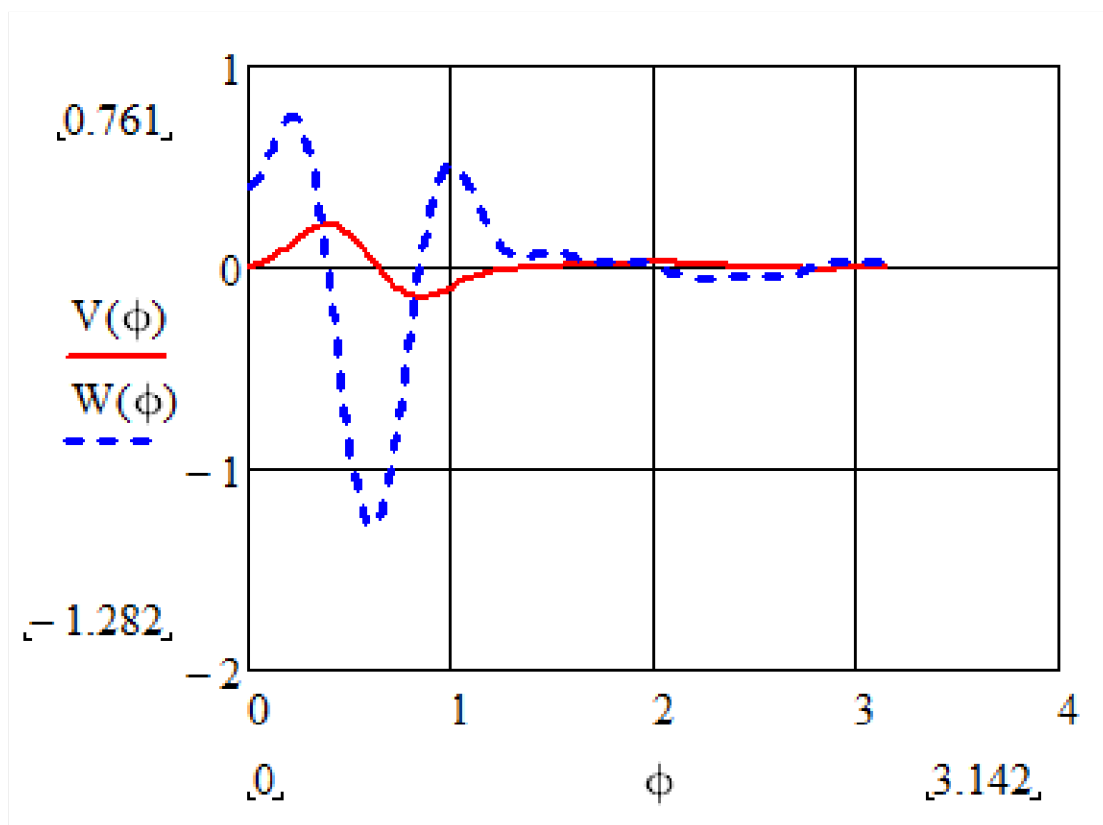


Figure 2.6 – Graphical dependence of tangent components $V(\varphi)$ and radial $W(\varphi)$ movements from the coordinate φ

Figure 2.7 shows the normal forces on the transverse $Tx(\varphi)$ and longitudinal $Tt(\varphi)$ planes, which are calculated by formulas (2.119-2.120) and (2.121-2.122).

$$Tx(m,n,\varphi) = X(m,n)_0 \cdot \frac{E \cdot \delta \cdot R \cdot \lambda(m)^2}{n} (\cos(n \cdot \varphi) \cdot \sin(\lambda(m) \cdot x)), \quad (2.119)$$

$$Tx(\varphi) = \sum_m \left(\sum_n Tx(m, n, \varphi) \right), \quad (2.120)$$

$$Tt(m, n, \varphi) = X(m, n)_2 \left(\cos(n \cdot \varphi) \cdot \sin(\lambda(m) \cdot x) \right), \quad (2.121)$$

$$Tt(\varphi) = \sum_m \left(\sum_n Tt(m, n, \varphi) \right), \quad (2.122)$$

At the same time, there is no phase shift due to the action of normal forces on different planes. The level of maximum amplitudes of normal forces on the transverse plane at the point of contact of the shell with the support exceeds the level of normal forces on the longitudinal plane by 4.1-4.3 times.

In accordance with the method of calculated intersections to determine the forces and stresses acting on the boiler shell, the intersection point is first chosen and the angular reference in the polar coordinate system is determined. The cross-section of the boiler has seven main positions, which correspond to a certain angle of inclination, in relation to the center in steps of 30° . Positions are numbered clockwise. The angle, which determines the coordinate, oriented along the cross section of the cylindrical part of the boiler is indicated φ . The number of intersections is chosen depending on the task, and is determined by the direction coordinate x .

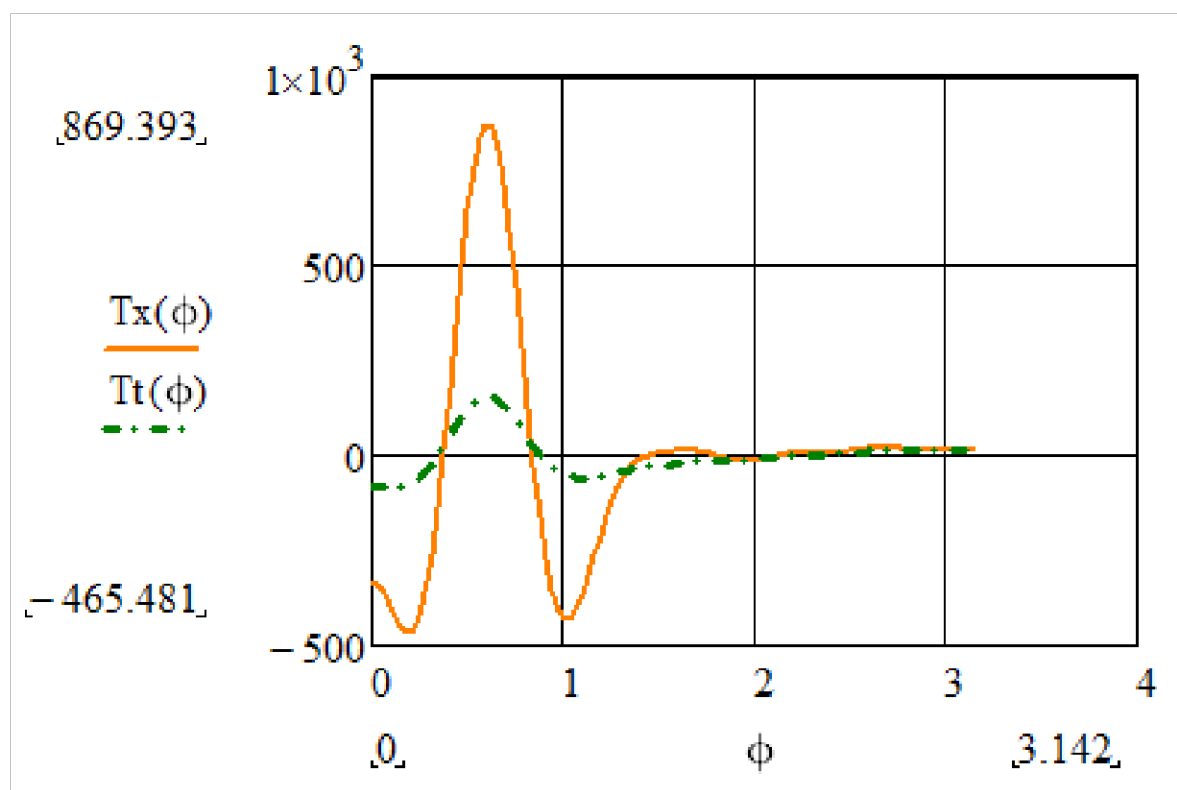


Figure 2.7 – Graphical dependence of normal forces $T_x(\varphi)$ on the transverse plane and normal forces $T_t(\varphi)$ on the longitudinal plane from the coordinate φ

According to the described calculation algorithm based on the presented method, the pivot points of the boiler on the frame of the wagon and its middle part are considered as the main calculation sections. Taking into account that the places of the greatest deformations and stresses occur in the contact zone of the boiler and supporting parts, the greatest attention is focused on the areas of positions 5, 6, 7 within the corner $\varphi = 120 \dots 180^\circ$.

Determining the most stressed areas, taking into account the decrease in the thickness of the metal shell, is a priority task when calculating the strength of a tank wagon boiler, therefore, changing the parameter δ is carried out from the permissible value to the minimum possible.

So for the case of the thickness of the boiler shell $\delta = 0,7$ cm it was established that the maximum values of tangential and radial displacements in the place of the supine support of the boiler on the frame are 1.95 mm and 10.54 mm, respectively. At the same time, the action of normal forces in the specified places corresponds to the values of 1.2 kN for the longitudinal direction and 1.76 kN for the transverse direction. For the section in the middle part of the boiler, the maximum values of tangential movements are 1.91 mm, and radial movements are 6.13 mm. The maximum values of normal forces in this section for the longitudinal direction are equal to 0 kN, and for the transverse direction 0.025 kN.

For cases of changes in the thickness of the boiler shell in the range from 1.1 to 0.7 cm in various design sections, according to the results of the calculations, it was established that the equivalent stresses (Fig. 2.8 - Fig. 2.9) exceed the permissible values of the yield strength of the material 09Г2С $[\sigma_m] = 325$ MPa at the minimum value of the shell thickness $\delta = 0,7$ cm in the pivot section at the point of support of the boiler with mass characteristics similar to model 15-1443-14 on the bearing supports and are 330.1 MPa.

As can be seen from fig. 2.8, for the pivot section, the largest equivalent stresses of the boiler shell are in the range from 290° to 310° of the polar coordinate system, while their values at the accepted lower and upper limits of the shell thickness differ by a factor of 2.2. For the middle part of the boiler (Fig. 2.9), the maximum values of the equivalent stresses are in the range from 270° to 260° of the polar coordinate system and have a similar level of growth.

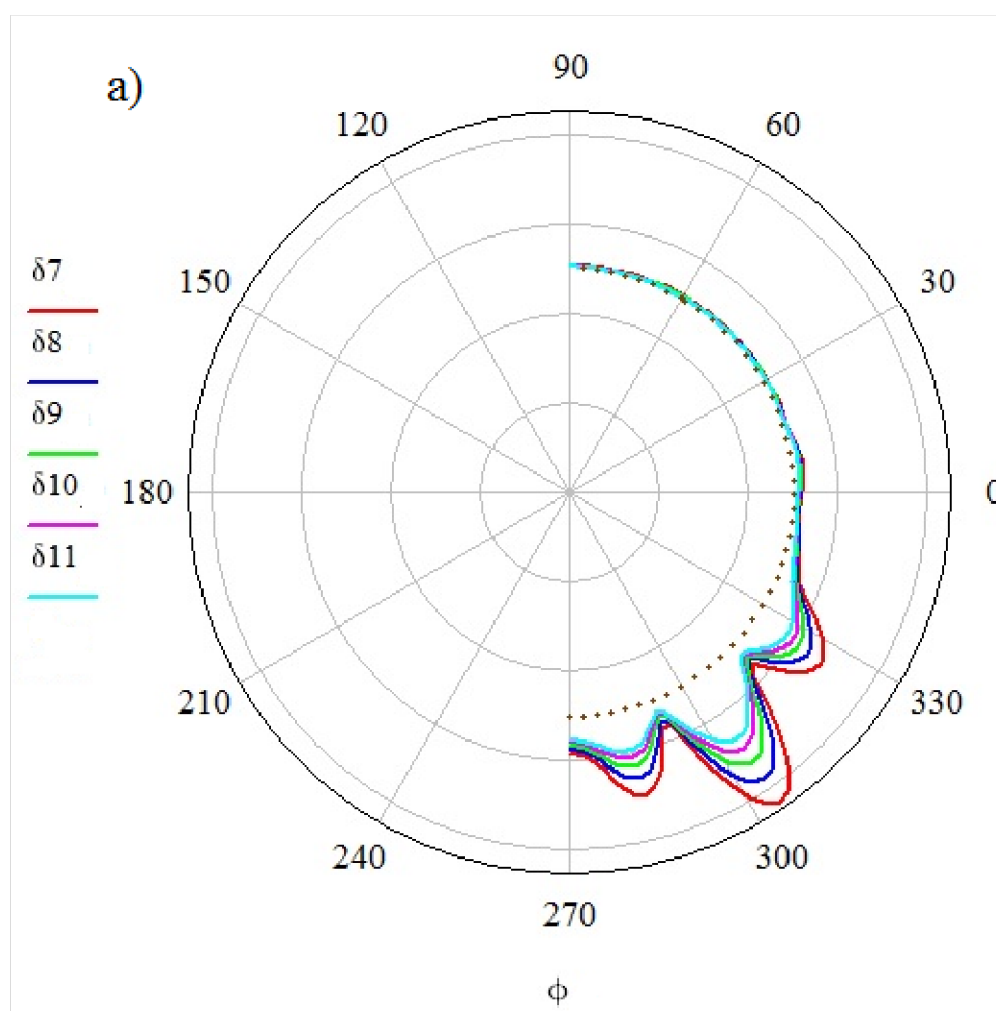


Figure 2.8 – Diagram of the distribution of equivalent stresses of the tank wagon boiler shell in the pivot section

Taking into account the variability of the nature of the loads of tank wagons for the transportation of chemical cargoes, but those that have similar geometric dimensions of structures in relation to the model 15-1443-14, it is appropriate to determine the equivalent stresses at the minimum permissible thickness of the boiler shell $\delta = 0,7$ cm.

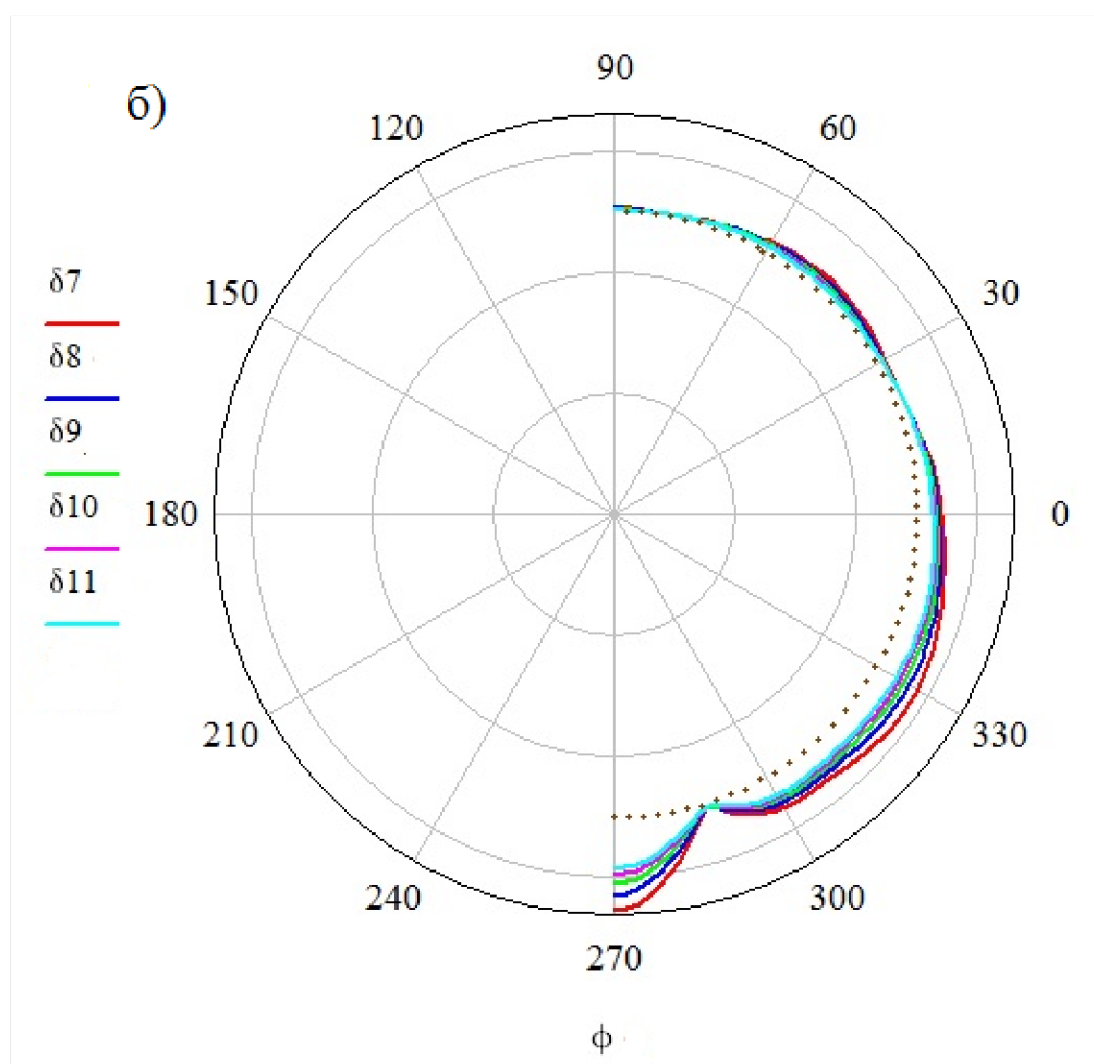


Figure 2.9 – Diagram of the distribution of equivalent stresses of the shell of a tank wagon boiler in the cross section of the middle part of the boiler

Table 2.2 shows models of tank wagons for the transportation of chemical cargoes, which have an internal diameter of the boiler $D = 3000$ mm and the base of the wagon $2l = 7800$ mm.

Table 2.2. Estimated loads of tank wagons

Tank wagon model	Target destination	Carrying capacity, i.e	Tara, t
15-1443-14	4-axle tank for N-methylaniline, aniline, cascade-3, ashless high-octane additive	66	25.8
15-1454-11	4-axle tank for methanol	56.6	24.4
15-1520	4-axle tank for pentane	40	23.4
15-1520-01	4-axle tank for pentane	42	27.1
15-1527	4-axle tank for benzene	62.3	26.4
15-1568	4-axle tank for acetaldehyde	53.2	25.87
15-1570	4-axle tank for Heptyl	54.4	26,29

According to the results of calculations in fig. 2.10 presents the determined maximum equivalent stresses in the pivot sections and the middle part of the boiler

of the tank wagons selected for research. With the determined minimum permissible thickness of the tank wagon boiler shell 15-1443-14 due to the action of corrosion, the most dangerous from the point of view of further safe operation under active loads are also considered models 15-1454-11 and 15-1527.

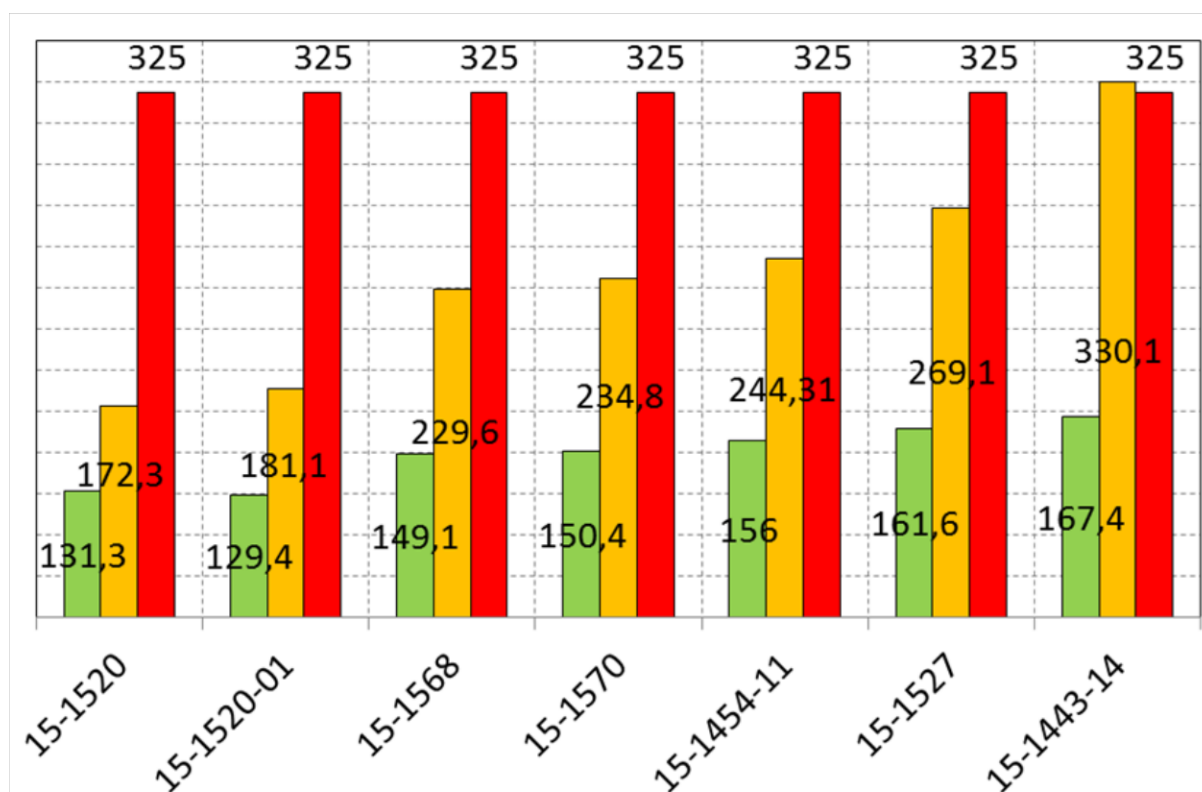


Figure 2.10 – Diagram of the maximum values of the equivalent stresses in the accepted design cross-sections at the thickness of the boiler shell $\delta = 0,7$ sm.

The calculated values of stresses in the directions of action for the tank wagon model 15-1443-14 at the minimum value of the thickness of the boiler shell are presented in table 2.3.

Table 2.3. Estimated values of the investigated values for the case of the thickness
of the boiler shell $\delta = 0,7$ sm

Parameter, dimension	Number of the position where the measurement is performed						
	1	2	3	4	5	6	7
Angular position of the measurement point in the polar coordinate system, degrees.	90	60	30	0	330	300	270
Normal stresses in the transverse direction in the cross-section of the middle part of the boiler, MPa	3.45	13.36	11.31	44,54	57.47	30,33	84.05
Normal stresses in the longitudinal direction in the cross-section of the middle part of the boiler, MPa	3.99	7.15	4.71	34.56	29.04	35.15	89.55
Tangential shear stresses in the cross-section of the middle part of the boiler, MPa	0	0	0	0	0	0	0
Equivalent stresses in the	6.45	18.04	14,26	40,48	76.25	56,76	150.4

cross-section of the middle part of the boiler, MPa							
Normal stresses in the transverse direction in the pivot (support) section of the boiler, MPa	5.46	2.96	1.92	2.81	51,56	106.1	92,91
Normal stresses in the longitudinal direction in the pivot (support) section of the boiler, MPa	2.71	2.41	0.82	18.68	115.1	202.8	32,35
Tangential shear stresses in the pivot (support) section of the boiler, MPa	0	2.88	3.71	3.51	11.61	15.96	0
Equivalent stresses in the pivot (support) section of the boiler, MPa	7.21	6.83	6.64	18.47	149.2	273.2	81.68

Figures 2.11 - 2.14 show the stress state diagrams obtained in the process of mathematical calculation for the pivot section (I-I). The maximum values of the equivalent stresses (Fig. 2.11) correspond to the value of 285.11 MPa. The

level of the greatest stresses occurring in the transverse direction (Fig. 2.12) is 122.14 MPa.

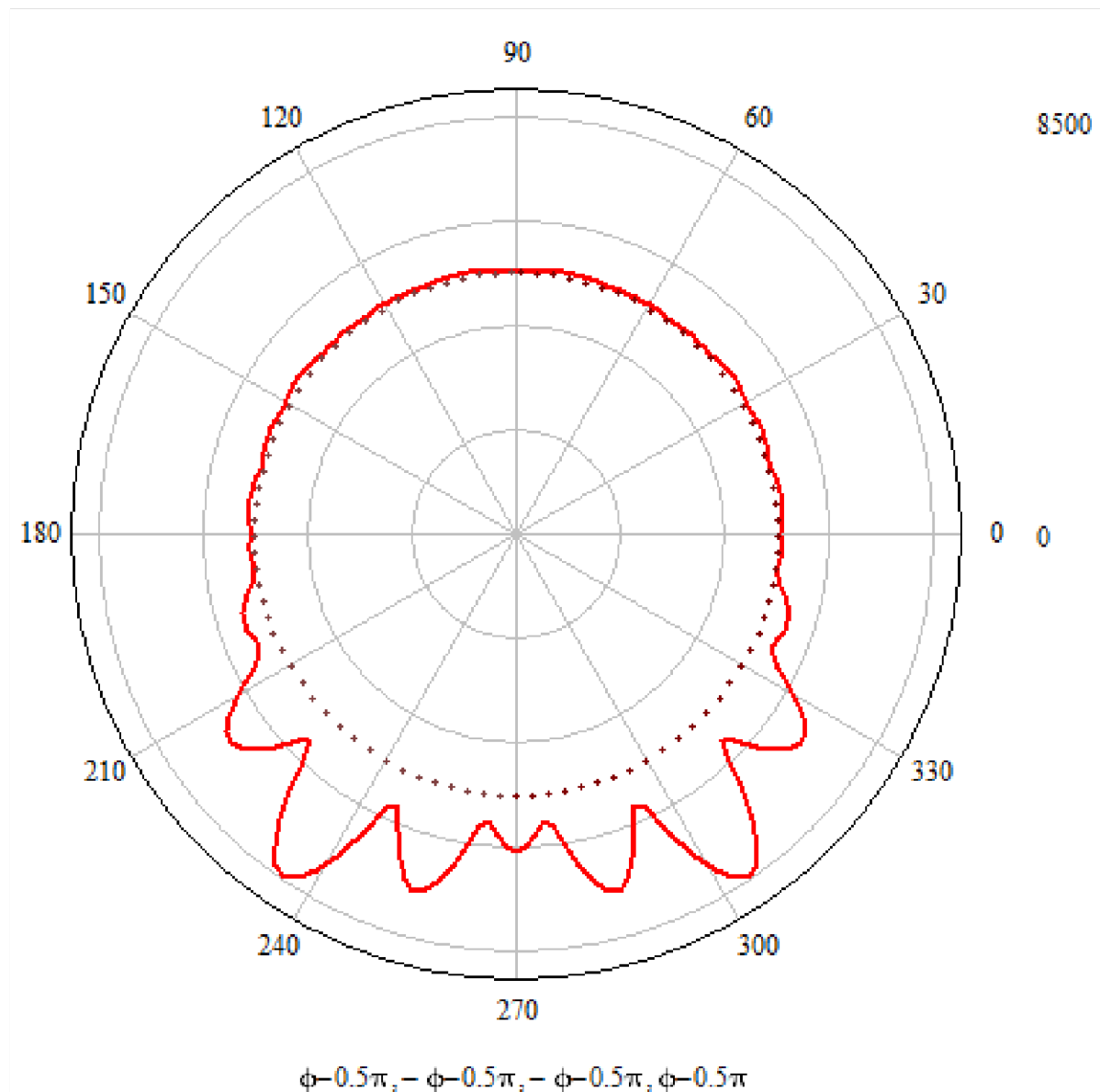


Figure 2.11 – Diagram of the distribution of equivalent stresses in the pivot
 section of the boiler

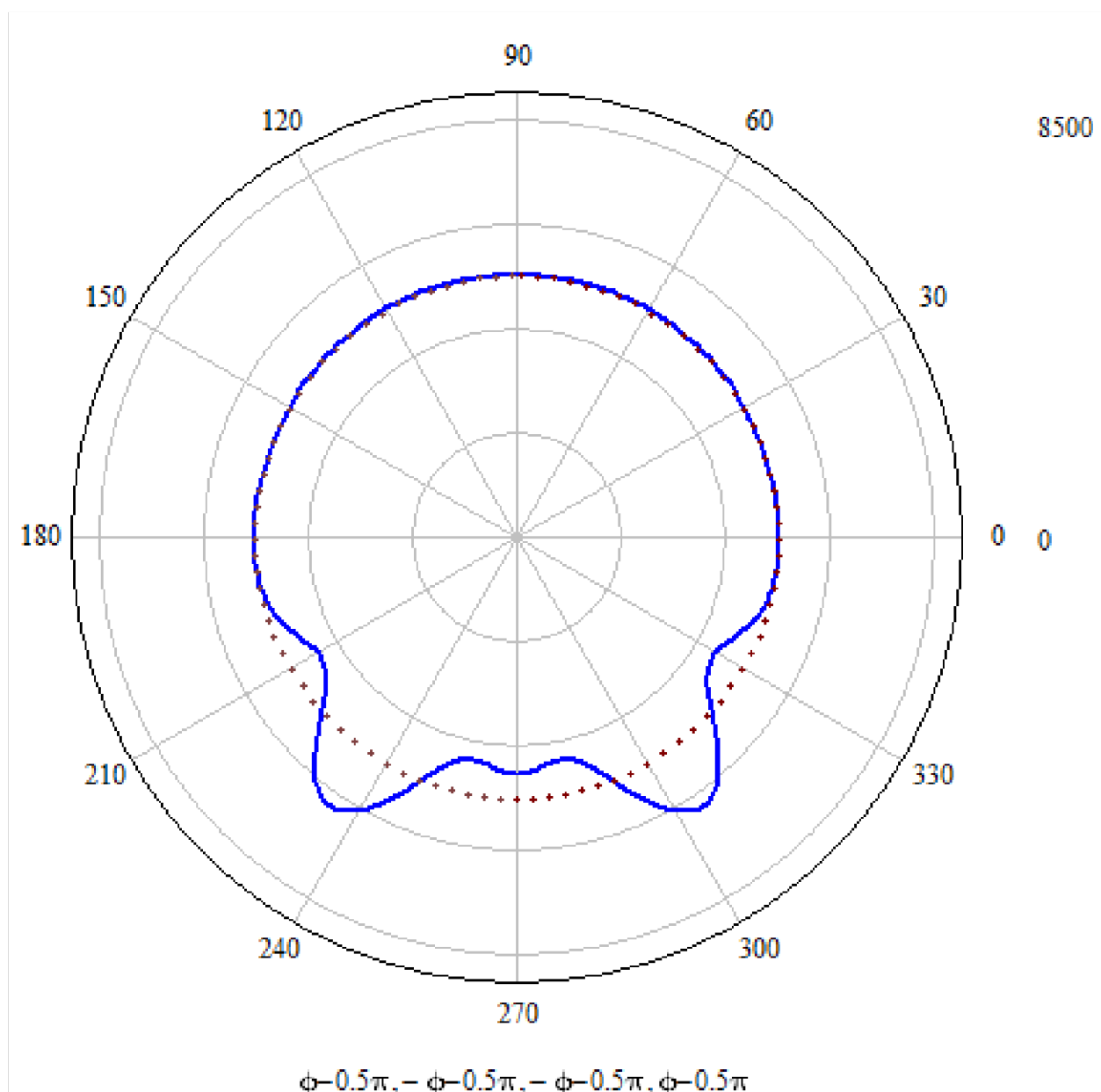


Figure 2.12 – Diagram of the distribution of normal stresses in the transverse
 direction in the pivot section of the boiler

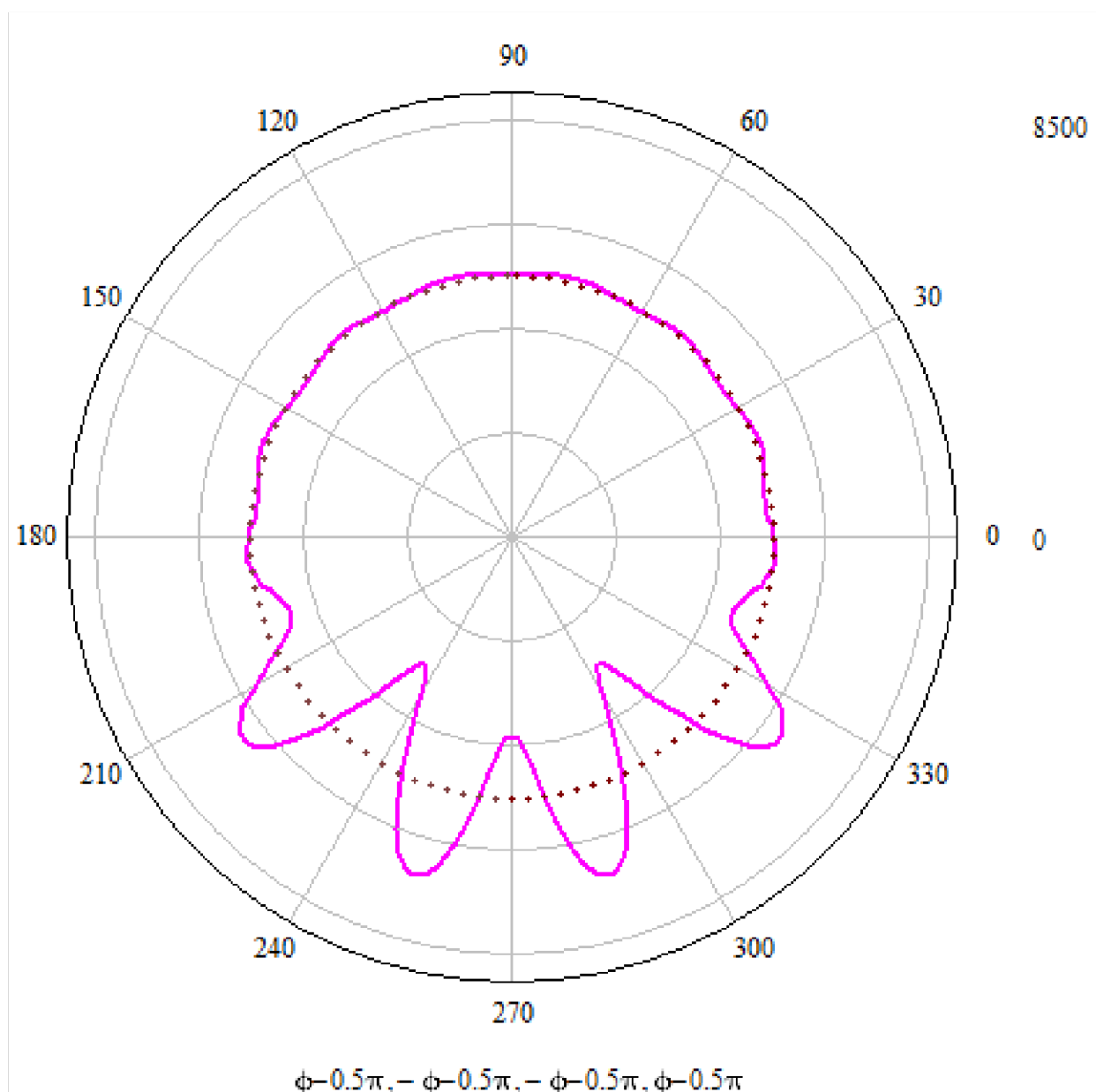


Figure 2.13 – Diagram of the distribution of normal stresses in the longitudinal
 direction in the pivot section of the boiler

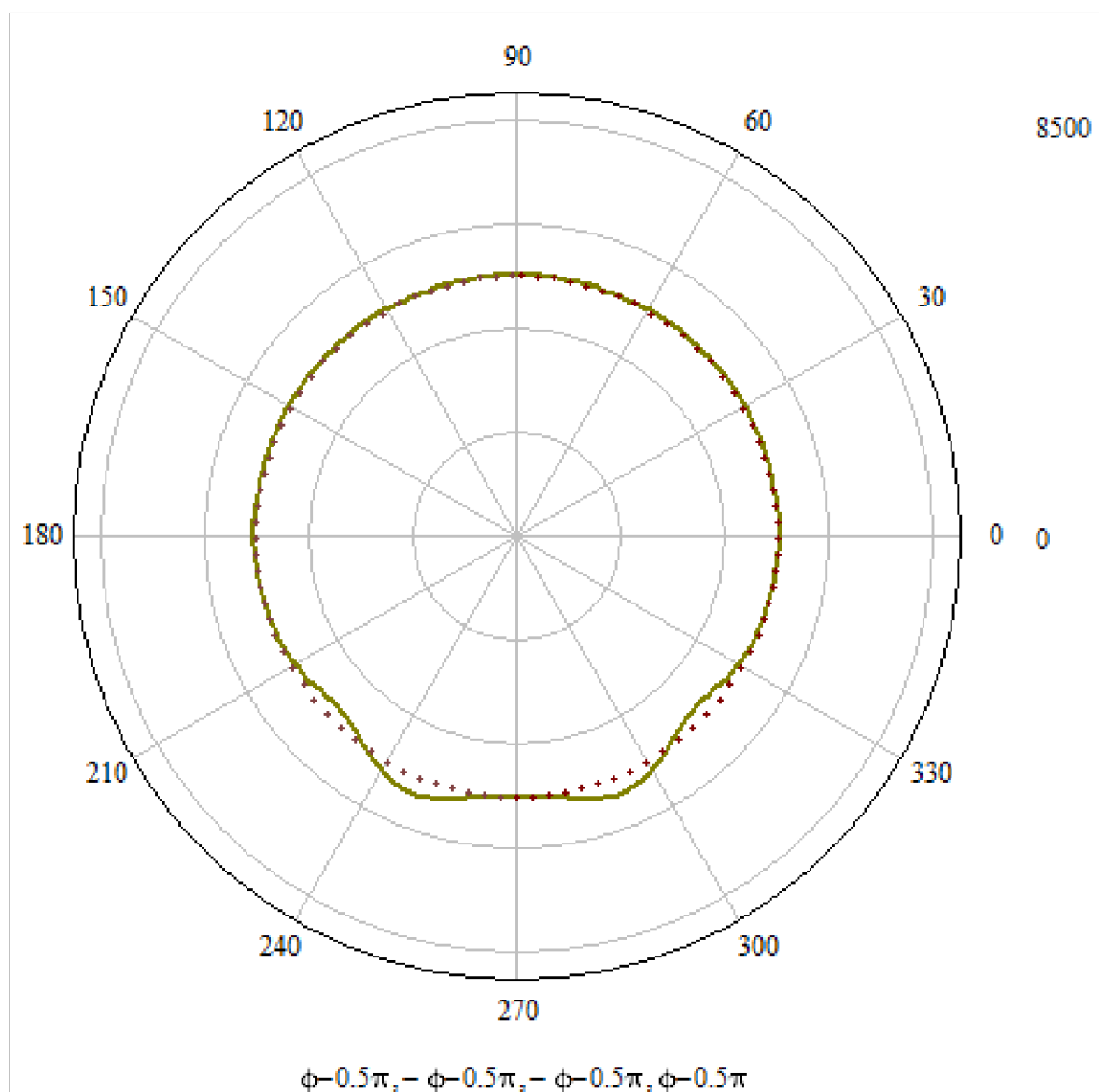


Figure 2.14 – Diagram of the distribution of tangential shear stresses in the pivot
section of the boiler

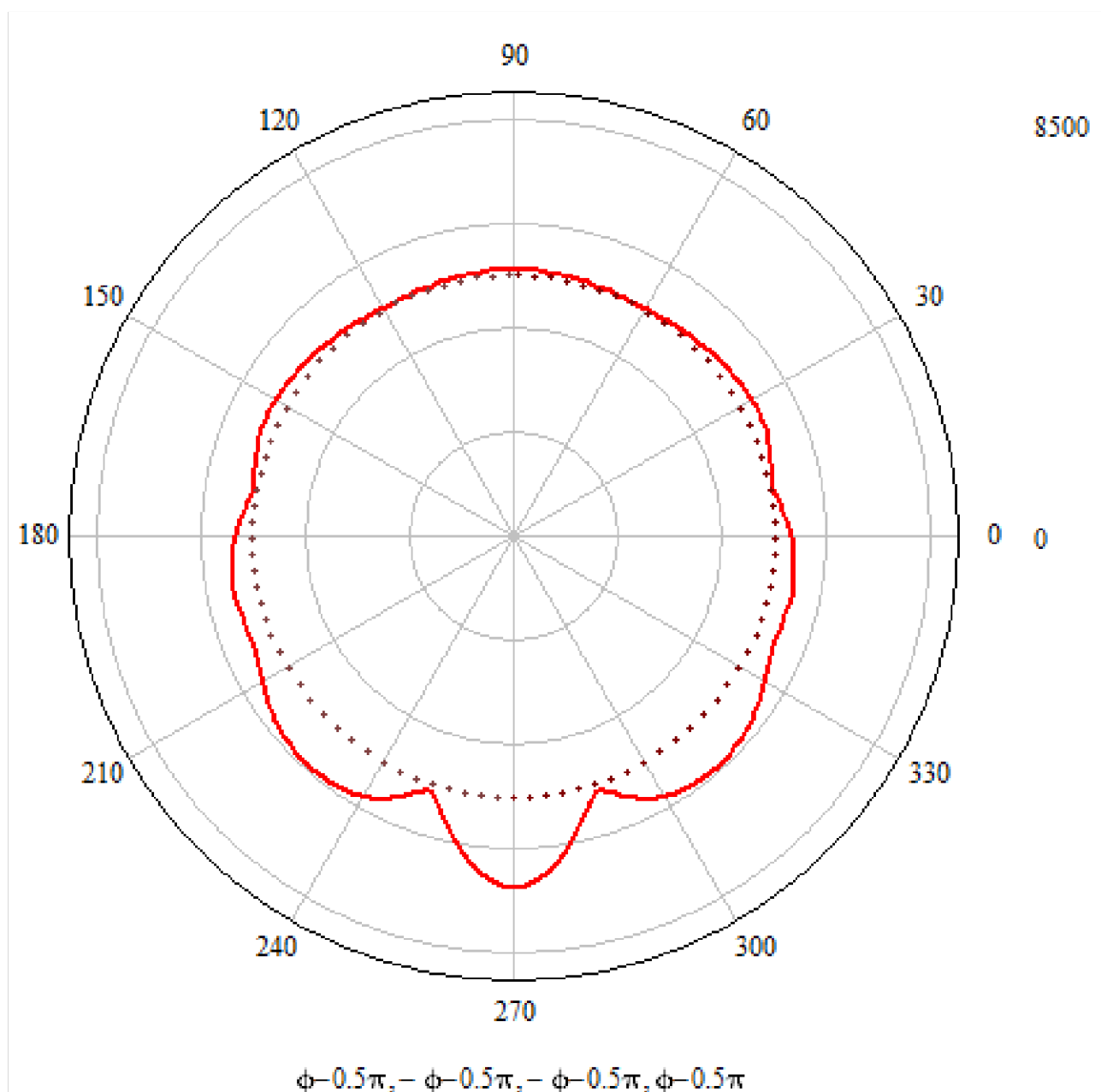


Figure 2.15 – Diagram of the distribution of equivalent stresses in the pivot
 section of the boiler

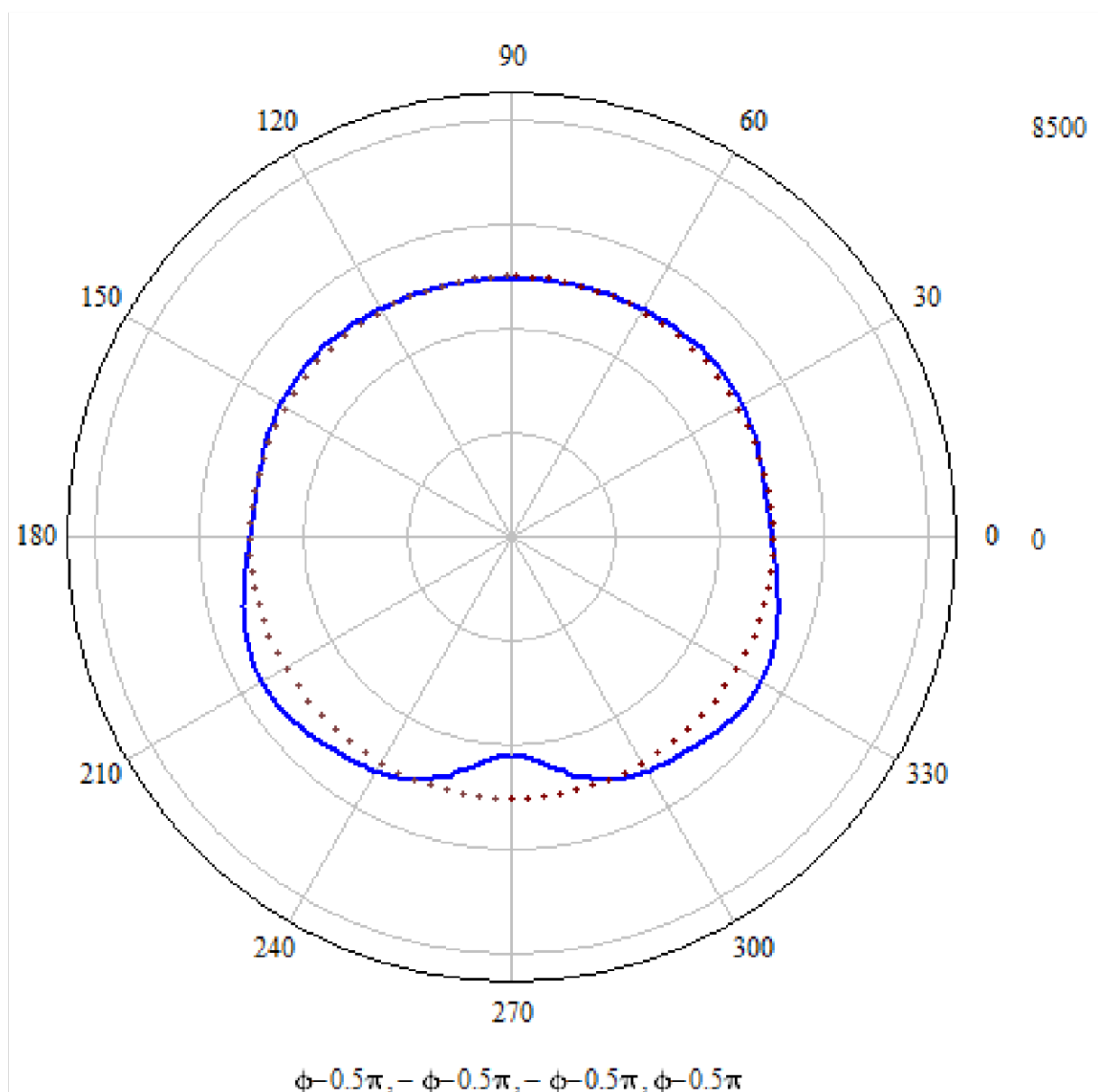


Figure 2.16 – Diagram of the distribution of normal stresses in the transverse
 direction in the pivot section of the boiler

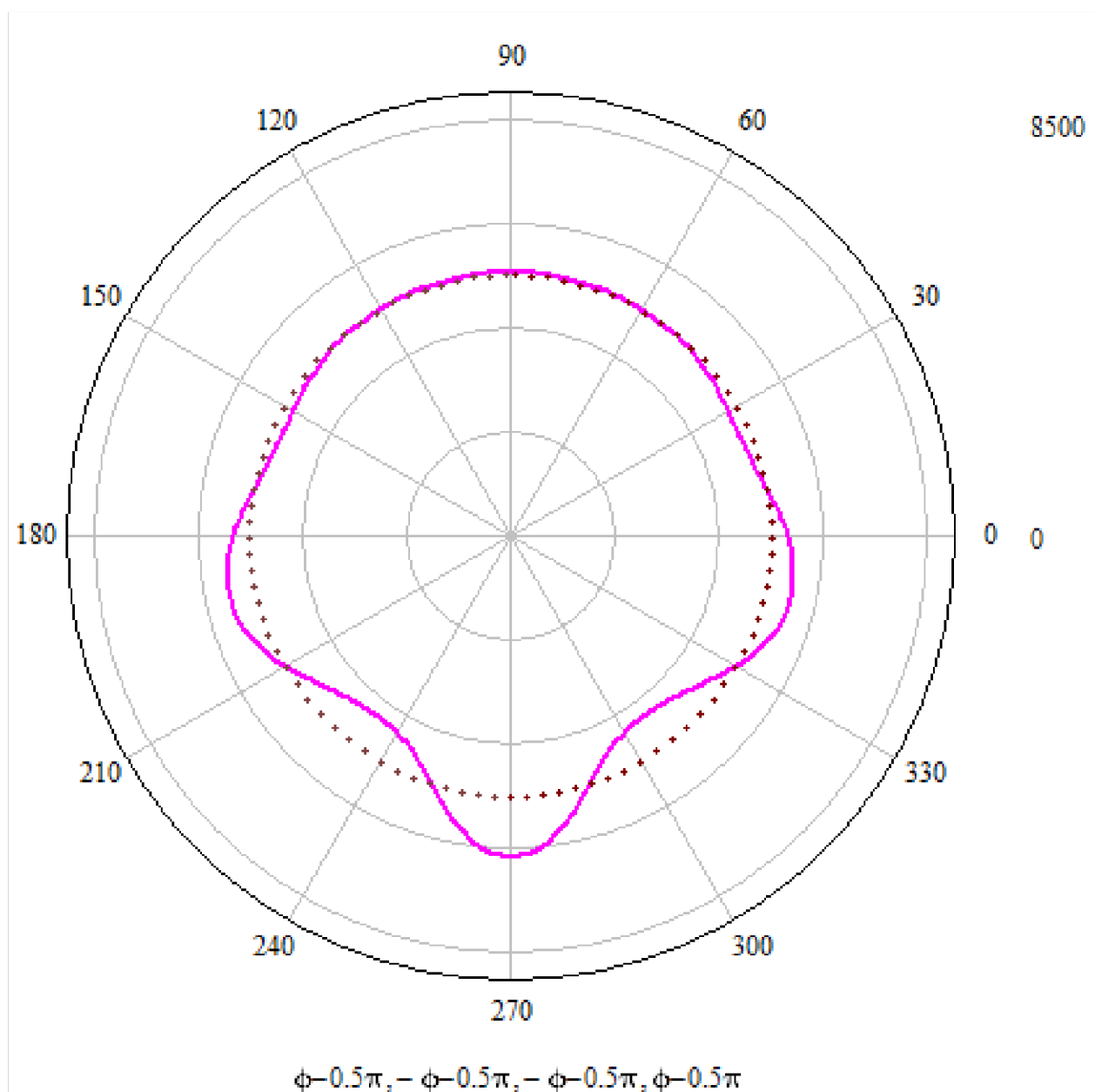


Figure 2.17 – Diagram of the distribution of normal stresses in the longitudinal
 direction in the pivot section of the boiler

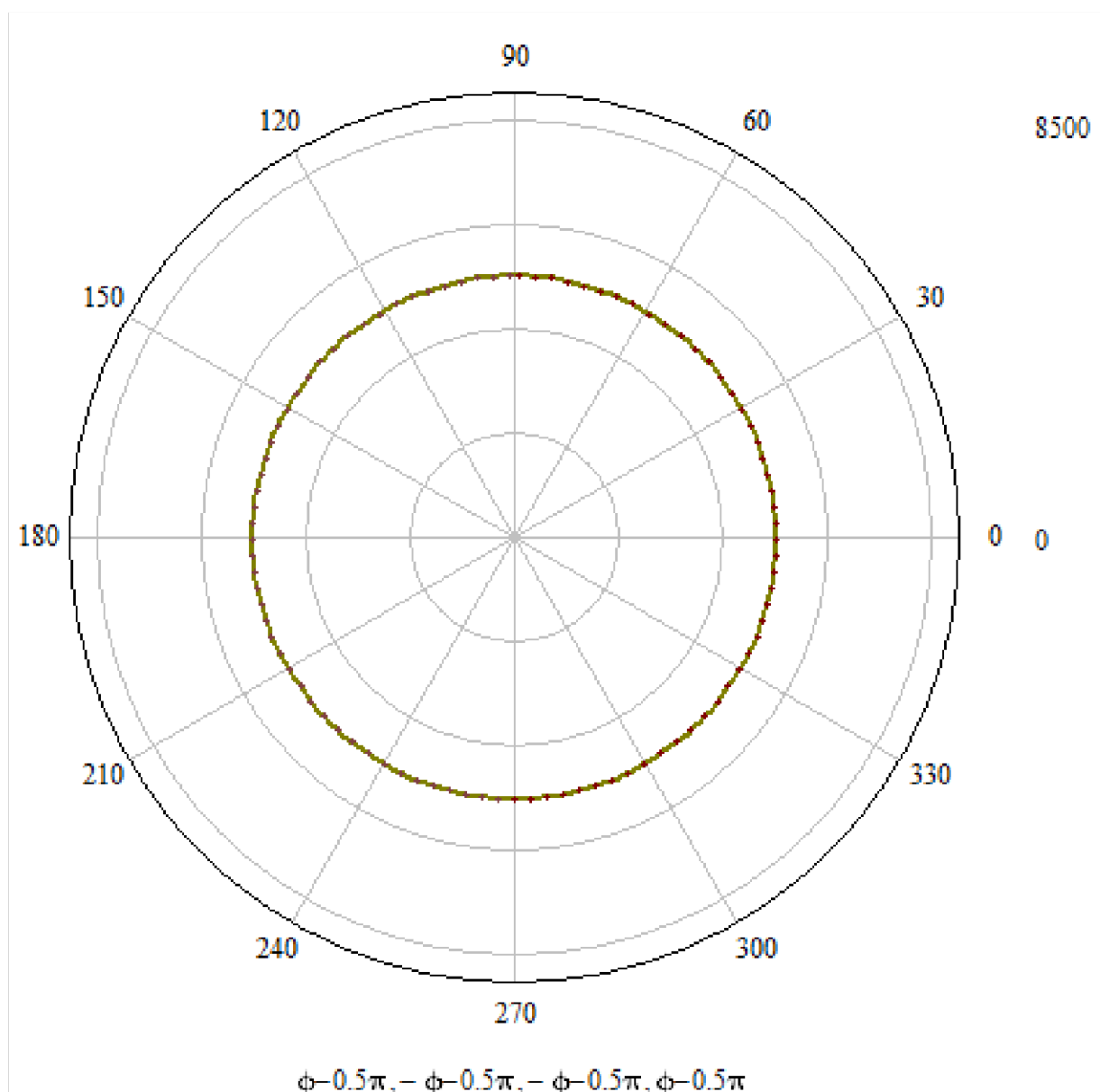


Figure 2.18 – Diagram of the distribution of tangential shear stresses in the pivot section of the boiler

At the same time, it should be noted that the values of the maximum equivalent stresses and stresses that occur in the transverse direction are in the range $\varphi = 305^\circ - 307^\circ$ of the polar coordinate system of the fourth quadrant.

For normal stresses acting in the longitudinal direction (Fig. 2.13), the maximum values are equal to 171.47 MPa at $\varphi = 284^\circ - 286^\circ$. The limit values of tangential shear stresses for the pivot section of the boiler (Fig. 2.14) are within 30.85 MPa at the angle $\varphi = 288^\circ - 291^\circ$.

Figures 2.15 – 2.18 show the resulting stress state diagrams for the section (II-II) of the middle part of the boiler. The maximum values of the equivalent stresses (Fig. 2.15) correspond to the value of 167.42 Mpa, which act in the lower part of the section at $\varphi = 270^\circ$. The level of the largest stresses in the transverse direction is distributed within $\varphi = 328^\circ - 332^\circ$ (Fig. 2.16) is 51.78 MPa.

The maximum values of normal stresses acting in the longitudinal direction (Fig. 2.17) are equal to 112.56 MPa at $\varphi = 270^\circ$. Limit values of tangential shear stresses for the middle part of the boiler across the entire cross-section (Fig. 2.18) are less than 0.001 Mpa.

Conclusions according to section 2

The section presents the results of the theoretical calculation of the deformed state of the cylindrical shell of the tank wagon boiler using the MathCAD mathematical package. The semi-momentless shell theory, which has the smallest calculation error based on the asymptotic analysis of the equations of the theory of isotropic shells, was used as the basis, compared to the moment technical theory and the edge effect theory.

Determination of the stress-strain state of the cylindrical part of the tank wagon boiler is performed under the conditions of reducing the average thickness of the shell to the maximum allowable values on the basis of regulatory requirements, taking into account the operating loads. The algorithm for calculating the stress state of the cylindrical part of the tank wagon boiler shell involves the use of the method of calculated sections, which allows you to effectively determine the stress in the most dangerous places where the boiler shell receives loads from various types of cargo. According to the methodology described in the section, the calculation of the stress-strain state of the tank wagon boiler for improved sulfuric acid model 15-1548-02 was performed. The calculation scheme of the cylindrical part of the boiler takes into account the geometric dimensions of the model and the load within the nominal values.

The studies of the stress-deformation state of the cylindrical shell of the boiler presented in this section based on the accepted assumptions of other models of tank wagons for the transportation of chemical cargoes, taking into account changes in the loads of the wagons, show that at the minimum permissible thickness of the boiler shell with mass-geometric characteristics close to the tank wagon 15- 1443-14 stresses exceed the allowable values of yield strength in pivot sections, and the most dangerous from the point of view of further of safe operation with significant corrosion and operating loads, models 15-1454-11 and 15-1527 are also considered.

3 STUDY OF THE STRESSED AND DEFORMED STATE OF THE BOILER SHELL OF A TANKER WAGON AND ASSESSMENT OF ITS FATIGUE STRENGTH IN CASE OF CORROSION WEAR BY COMPUTER SIMULATION MEANS

When extending the service life and types of repair of tank wagons, it is important to study the influence of corrosive-active loads on the strength characteristics of their structural elements. However, the existing methods of calculating the elements of these tanks are based on the simplest models that do not take into account the specifics of their operation, the peculiarities of interaction with a corrosive-active environment, as a result of which the strength of the structure is significantly reduced when the thickness of tank wagon boiler shells is reduced.

In this regard, the issue of development and implementation of stress-strain state assessment methods taking into account the impact of corrosion and finding technical solutions to increase the reliability of wagon structures during the transportation of corrosive-active cargoes is of urgent importance.

3.1 Calculation method

The method of researching the fatigue strength of a tank wagon boiler is based on the principle of calculation using generalized approaches related to nodes and parts of wagons that work under conditions of prolonged and intensive action of dynamic loads. The following assumptions were made for calculations in this work:

- the parameter that determines the cyclic strength is the coefficient of the reserve of fatigue resistance;
- the accumulation of fatigue damage is carried out according to the linear hypothesis of the summation of fatigue damage;
- corrosion wear of the tank wagon boiler metal is evenly distributed over its surfaces;
- fatigue damage to the material of the wagon boiler occurs under conditions of elastic deformation.

In accordance with the method of researching the fatigue strength of a tank wagon boiler, the calculation of fatigue resistance is performed with the determination of the coefficient of resistance reserve according to the expression:

$$n = \frac{\sigma_{a,N}}{\sigma_{a,e}} \geq [n], \quad (3.1)$$

where $\sigma_{a,N}$ is the endurance limit for the control zone at the base number of cycles

$N_0 = 10^7$ for wagon body elements;

$\sigma_{a,e}$ – the estimated value of the amplitude of the dynamic stress of a conditional symmetrical cycle, reduced to the basic number of cycles, which is equivalent to the damage effect of the actual mode of operational loads for the estimated service life;

$[n]$ is the minimum allowable coefficient of fatigue resistance margin.

Estimated endurance limit value for the control zone $\sigma_{a,N}$ is determined by the following formula:

$$\sigma_{a,N} = \overline{\sigma}_{a,N} \cdot (1 - z_p \cdot v_{\sigma_{a,N}}), \quad (3.2)$$

where $\overline{\sigma}_{a,N}$ – the median value of the endurance limit of the control zone;

z_p is the quantile of the distribution corresponding to the one-sided probability $p = 0,95$, $z_p = 1,645$;

$v_{\sigma_{a,N}}$ – coefficient of variation of endurance limit, $v_{\sigma_{a,N}} = 0,07$.

The average value of the endurance limit of the control zone $\overline{\sigma}_{a,N}$ determined by the formula:

$$\overline{\sigma}_{a,Ni} = \frac{\overline{\sigma}_{-1}}{(\overline{k}_{\sigma})_k}, \quad (3.3)$$

where $\overline{\sigma}_{-1}$ is the median value of the endurance limit of a smooth standard sample made of tank wagon boiler material under a symmetrical bending cycle on the base N_0

$(\overline{k}_{\sigma})_k$ is the average value of the overall coefficient of reduction of the endurance limit in the selected control zone in relation to the endurance limit of the smooth standard sample.

For tank wagon boiler sheets made of steel 09G2S $\overline{\sigma}_{-1} = 210$ МПа, for metal seams $\overline{\sigma}_{-1} = 245$ МПа.

Average values of coefficients $(\overline{k}_{\sigma})_k$ adopted in accordance with [1]. For elements made of low-alloy steels, the coefficients are given in table 3.1.

Table 3.1 - Coefficients of reduction of endurance limit

Control zone	Normalized value
Hatch	4.5
Shaped paws	5.2
Lying supports	1.5
Bottoms	2.0

The value of the amplitude of the dynamic stress of the conditional symmetrical cycle $\sigma_{a,e}$ is calculated by the formula:

$$\sigma_{a,e} = \sqrt[m]{\frac{N_c}{N_0} \sum_{i=1}^n \sigma_{a,i}^m \cdot p_i}, \quad (3.4)$$

where N_c – the total number of dynamic stress cycles for the estimated service life of the tank wagon boiler;

$\sigma_{a,i}$ – level of stress amplitudes in the i th interval;

m – degree indicator in the equation of the fatigue curve;

p_i – probability of appearance of amplitudes with the level of stress amplitudes in the i th interval;

n is the number of stress intervals.

The total number of dynamic stress cycles for the estimated service life of the tank wagon boiler is determined by the formula:

$$N_c^I = f_e \cdot 365 \cdot \frac{Z_c \cdot 10^3}{v_T} \cdot T_K, \quad (3.5)$$

where f_e – central (effective) frequency of the dynamic stress change process, Hz;

Z_c – average daily mileage of the wagon;

v_T – the average technical speed of the wagon;

T_K – estimated calendar service life.

The effective frequency of the dynamic stress change process is calculated by the formula:

$$f_e = \frac{a}{2\pi} \sqrt{\frac{g}{f_{cm}}}, \quad (3.6)$$

where a is the coefficient accepted for the body of the freight wagon $a = 1,4$;

f_{cm} – static deflection of the spring suspension.

The level of stress amplitudes must take into account the effect of vertical dynamic loads during operation and the effect of longitudinal impact forces, so it is determined separately for different blocks of loads.

Under the action of vertical dynamic forces, the level of stress amplitudes is found by the formula:

$$\sigma_{a,i}^I = \sigma_{cm} \cdot k_{\partial \partial i}, \quad (3.7)$$

where σ_{cm} – static stress from the gross gravity of the boiler, MPa;

$k_{\partial \partial i}$ is the coefficient of vertical dynamics in the i th interval.

The coefficient of vertical dynamics in the i th interval is determined by the formula:

$$k_{\partial \partial i} = \frac{\bar{k}_{\partial \partial i}}{\beta} \sqrt{\frac{4}{\pi} \ln \frac{1}{1 - P(k_{\partial \partial i})}}, \quad (3.8)$$

where $\bar{k}_{\partial \partial i}$ – the average probable value of the coefficient of vertical dynamics;

β is the distribution parameter, $\beta = 1,13$;

$P(k_{\partial \partial i})$ is a random function with a probability distribution, $P(k_{\partial \partial i}) = 0,97$.

When the condition is met $v < 15$ m/c

$$\bar{k}_{\partial \partial i} = a \frac{v_i}{15}, \quad (3.9)$$

where a – coefficient for body elements $a = 0,05$;

v_i – speed in the i th interval, m/s.

In quality v_i average speeds in the distribution interval according to [1] are used in the calculation.

When the condition is met $v > 15$ m/c

$$\bar{k}_{\partial \partial i} = a + 3,6 \cdot 10^{-4} \cdot \frac{v_i - 15}{f_{cm}}, \quad (3.10)$$

where f_{cm} – static deflection of the spring suspension, $f_{cm} = 0,05$ m.

For the zone of lying supports, the average probable value of the coefficient of vertical dynamics is determined taking into account the transshipment of the tank wagon boiler according to the formula:

$$\bar{k}_{\partial \partial i}^P = \bar{k}_{\partial \partial i} (1 + \gamma), \quad (3.11)$$

where γ – coefficient, according to [1] $\gamma = 0,2$.

When the longitudinal shock forces of the tank wagon are acting, as a result of its interaction with adjacent wagons, oscillatory processes occur, the amplitude levels of which can be determined by the following formula:

$$\sigma_{a,i}^{\text{II}} = \frac{\sigma_{\text{IY}}}{N} F_{ai}^y, \quad (3.12)$$

where σ_{IY} – calculated equivalent stresses that occur during impact interaction of a tank wagon with adjacent wagons, MPa;

N is the longitudinal impact force that acts on the wagon and corresponds to the calculated stresses σ_{IY} , MN;

F_{ai}^y is the amplitude level of the impact longitudinal force transmitted to the autocoupling in the i -th interval, MN.

The total number of cycles of longitudinal forces transmitted to the autocoupling during the estimated service life is determined by the formula:

$$N_c^{\text{II}} = N_p \cdot T_K, \quad (3.13)$$

where N_p - the number of impact forces transmitted to the truck coupling per year,

$N_p = 20197$ according to [1].

The calculation of the total equivalent stress amplitudes is performed according to the following formula:

$$\Sigma \sigma_{a,e} = \sqrt[2]{\frac{N_c^{\text{I}}}{N_0} \sum_{i=1}^n (\sigma_{a,i}^{\text{I}})^m \cdot p_i^{\text{I}} + \frac{N_c^{\text{II}}}{N_0} \sum_{i=1}^n (\sigma_{a,i}^{\text{II}})^m \cdot p_i^{\text{II}}}, \quad (3.14)$$

3.2 Development and description of the calculation model of the boiler based on the model 15-1443-14 tank wagon in the SolidWorks software complex

The built calculation model of the boiler takes into account: geometric dimensions of the research object, mass-inertial characteristics of the boiler in the loaded state (with the load carrying capacity of the wagon regulated by the design documentation), physical and mechanical properties of the material, thickness of individual components of the boiler, depending on the amount of corrosion damage.

The tank wagon boiler model is made using spatial solid finite elements in the form of tetrahedrons with six degrees of freedom in each of the nodes [21]. The edges of the finite elements are described programmatically in the form of a parabolic function. At the detailed level, the geometric features of the creation and connection of the sheets of the construction of the boiler casing with each other and their combination with the bottoms are taken into account. Shaped legs and bearing supports on which the boiler of the tank wagon rests are represented in the calculation model as simplified elements that perform the function of limiting the movements of the boiler in space in the longitudinal, transverse and vertical directions. The constructed grid of the boiler shell model consists of 540440

elements, 1015310 nodes, the maximum element size is 48 mm, the minimum element size is 8 mm, and the element size increase ratio is 1.4.

In fig. 3.1 shows the calculation scheme of the applied forces from the action of static loads.

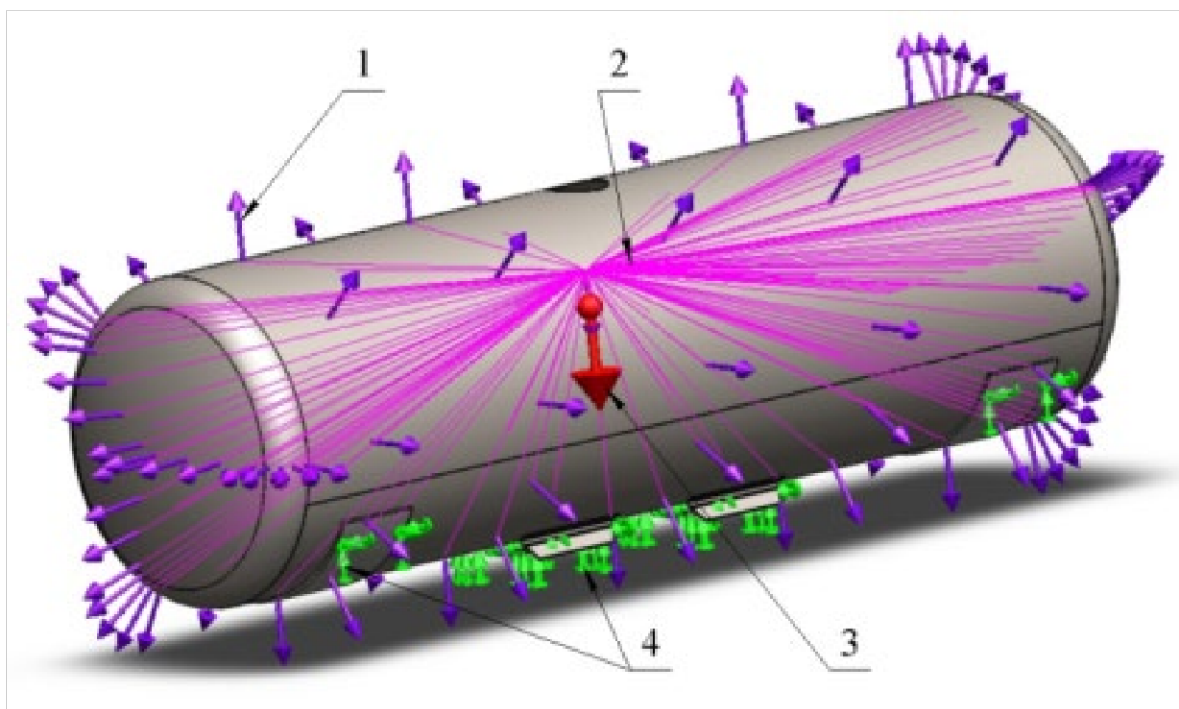


Figure 3.1 – Calculation scheme of support and application of forces acting on static loads:

1 – working pressure in the boiler; 2 – weight of cargo; 3 – acceleration of free fall; 4 – fixation of the boiler on the support elements.

The calculation of the equivalent stresses from the action of the longitudinal impact force of 3.8 MN, as in the case of the calculation of the static load from

the action of the gross gravity of the tank wagon boiler, was performed according to four calculation options.

The calculation scheme of the tank wagon boiler from the action of the longitudinal impact force is shown in fig. 3.2:

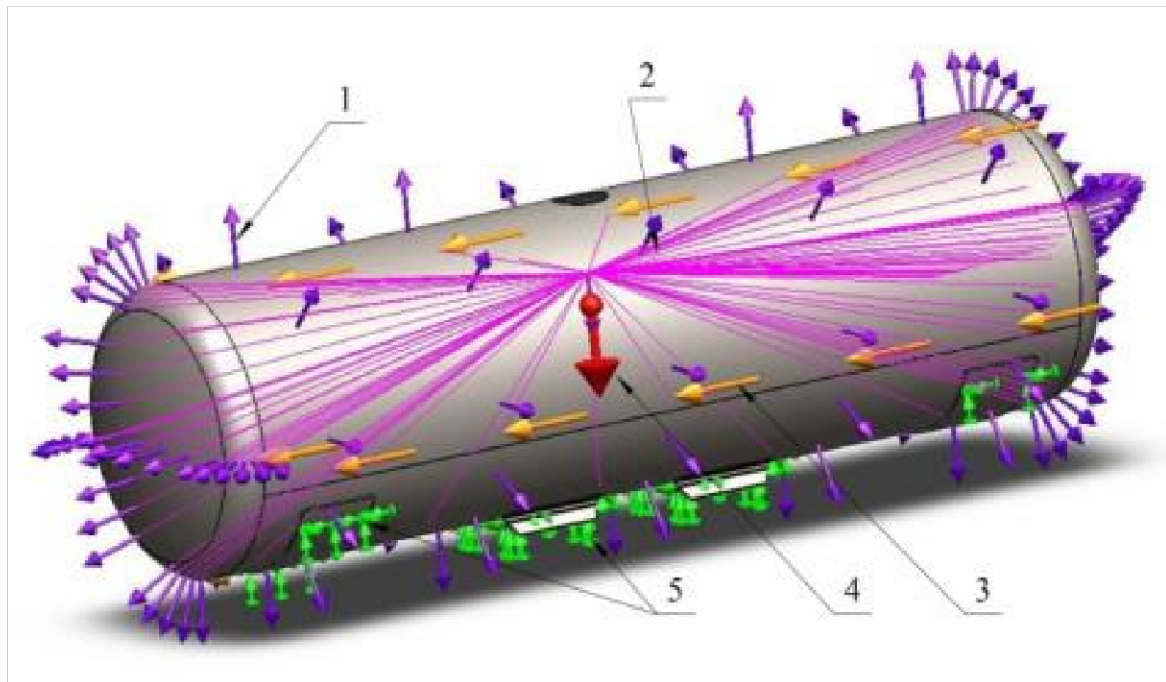


Figure 3.2 – Calculation scheme of a tank wagon boiler for assessing the stress-strain state due to the action of a longitudinal impact force:

1 – working pressure in the boiler; 2 – weight of cargo; 3 – longitudinal impact force; 4 – acceleration of free fall; 5 – fixation of the boiler on the support elements.

The probability of occurrence of amplitudes p_i' with the level of stress amplitudes in the i -th interval of speeds is presented in the table. 3.2 for the studied options depending on the speed of movement:

Table 3.2 – Distribution of probability of occurrence of amplitudes p_i' with the level of stress amplitudes in the average interval of movement speeds.

Movement speed interval, m/s	The average technical speed of the wagon, m/s	The probability of action of the level of amplitudes p_i' , %		
		$V = 90$ km/ hours	$V = 100$ km/ hours	$V = 120$ km/ hours
0÷12.5	6.25	8	5	3
12.5÷15.0	13.75	17	12	7
15.0÷17.5	16.25	22	15	9
17.5÷20.0	18.75	30	20	12
20.0÷22.5	21.25	18	25	16
22.5÷25.0	23.75	5	15	19
25.0÷27.5	26,25	-	6	16
27.5÷30.0	28.75	-	2	10
30.0÷32.5	31.25	-	-	6
32.5÷35.0	33.75	-	-	2

Frequency of amplitudes p_i'' in the i th interval of forces is presented in the form of a histogram in fig. 3.3:

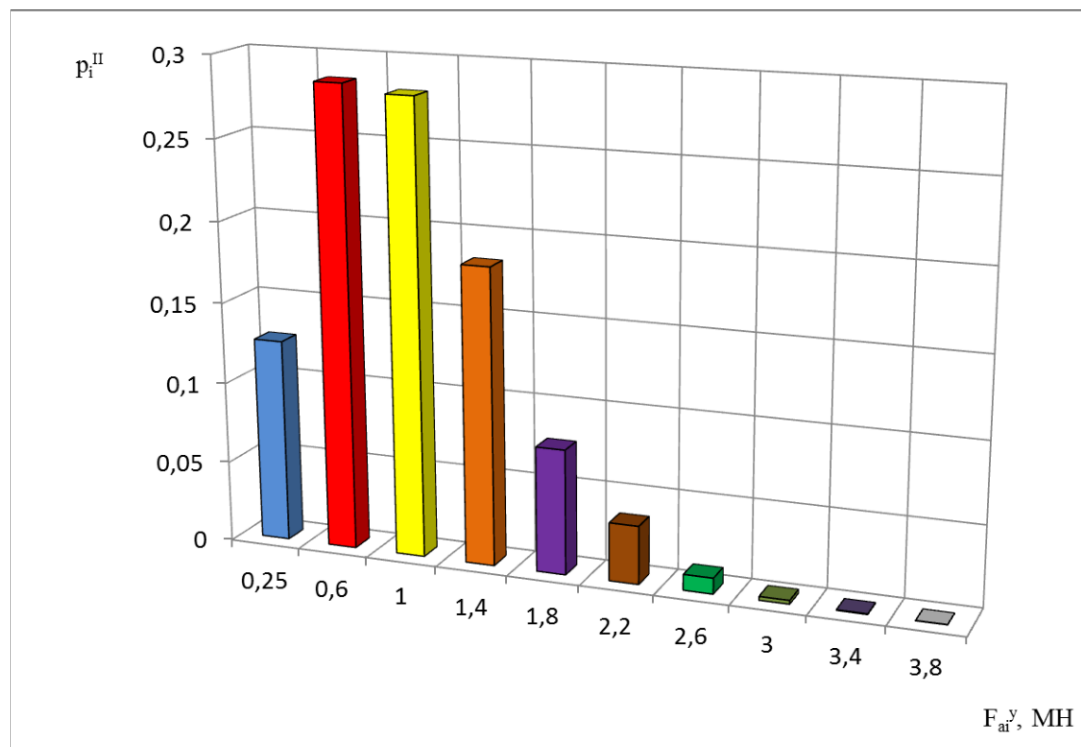


Figure 3.3 – Histogram of frequency dependence of impact force amplitudes in the range of action

The following are considered as calculation options:

option 1 - no corrosion;

option 2 - appearance of metal corrosion up to 1 mm deep;

option 3 - appearance of metal corrosion up to 2 mm deep;

option 4 - appearance of metal corrosion up to 3 mm deep.

The thicknesses of the boiler shell elements for the calculation options are presented in the table. 3.3.

Table 3.3 – Thicknesses of metal elements of a tank wagon boiler

Structural element of the boiler	The size of the thickness of the element, mm			
	option 1	option 2	option 3	option 4
Bottom sheet	12	11	10	9
Side sheet	9	8	7	6
Top sheet	9	8	7	6
The bottom	10	9	8	7

3.3 Results of the conducted research

According to the calculation method, it is determined calculated values of strength limits $\sigma_{a, Ni}$ for control zones of the boiler, which are presented in table.

3.4.

The total number of cycles of dynamic stresses from the action of vertical dynamic forces N_c^I for the one and a half service life of the tank wagon model 15-1443-14, taking into account changes in the average technical speed of the wagon, is presented in the table. 3.5.

Table 3.4 – Strength limits of boiler measurement zones

Control zone	Calculated value, MPa
Hatch	48.2
Shaped paws	41.7
Lying supports	123.9
Bottoms	92.9

Table 3.5 – Calculation results of the total number of cycles of dynamic stresses
due to the action of vertical dynamic forces

Total service life of the tank wagon, years	The average technical speed of the wagon, m/s		
	$V = 17,0 \text{ м/с}$	$V = 19,2 \text{ м/с}$	$V = 22,4 \text{ м/с}$
24	308783758.5	273402286.2	234344816.7
26	334515738.4	296185810.1	253873551.5
28	360247718.3	318969333.9	273402286.2
30	385979698.2	341752857.8	292931020.9
32	411711678.1	364536381.6	312459755.7
34	437443657.9	387319905.5	331988490.4
36	463175637.8	410103429.3	351517225.1

In the course of conducting research on the tank wagon boiler model, stress values in the most loaded zones due to the action of static forces were obtained, which are presented in Table 3.6. Arithmetic average values among the highest stresses for 5-8 sections around the stressed zones were calculated using the probing method.

Table 3.6 – Calculated stresses of tank wagon boiler elements obtained from the action of static load

Control measurement zone	The magnitude of the equivalent stresses σ_{cm} , MPa			
	option 1	option 2	option 3	option 4
Hatch	25.7	28.9	32.9	36.4
Shaped paws	16.9	18.4	26.1	29.5
Lying supports	71.4	80.1	89.2	97.2
Bottoms	73.8	82	93.2	114

The results of the calculation of the level of stress amplitudes in the i th interval of the 1st regime for options 1-4 with the probability of the action of the amplitude level p_i^I , calculated by formula (3.7) are shown in the table. 3.7-table 3.10:

Table 3.7 – Calculation of the level of stress amplitudes for option 1

Movement speed interval, m/s	Coefficient of vertical dynamics $k_{\partial ai}$	The level of stress amplitudes in the i-th interval for the i-th mode:			
		$\sigma_{a,j1}^I$	$\sigma_{a,j2}^I$	$\sigma_{a,j3}^I$	$\sigma_{a,j4}^I$
		Hatch area	Paw area	The area of lying	Bottom area
0÷12.5	0.039	1.001	0.658	3,338	2,875
12.5÷15.0	0.086	2,203	1,448	7,343	6,325
15.0÷17.5	0.110	2,835	1,864	9,453	8,142
17.5÷20.0	0.144	3,700	2,433	12,336	10,626
20.0÷22.5	0.178	4,565	3,002	15,220	13,110
22.5÷25.0	0.211	5,430	3,571	18,104	15,594
25.0÷27.5	0.245	6,295	4,140	20,988	18,078
27.5÷30.0	0.279	7,160	4,709	23,872	20,562
30.0÷32.5	0.312	8,025	5,277	26,756	23,046
32.5÷35.0	0.346	8,890	5,846	29,639	25,530

Table 3.8 – Calculation of the level of stress amplitudes for option 2

Movement speed interval, m/s	Coefficient of vertical dynamics $k_{\partial ai}$	The level of stress amplitudes in the i-th interval for the i-th mode:			
		$\sigma_{a,j1}^I$	$\sigma_{a,j2}^I$	$\sigma_{a,j3}^I$	$\sigma_{a,j4}^I$
		Hatch area	Paw area	The area of lying	Bottom area
0÷12.5	0.039	1,126	0.717	3,744	3,194
12.5÷15.0	0.086	2,477	1,577	8,238	7,028
15.0÷17.5	0.110	3,188	2,030	10,604	9,047
17.5÷20.0	0.144	4,161	2,649	13,840	11,807
20.0÷22.5	0.178	5,134	3,269	17,075	14,566
22.5÷25.0	0.211	6,107	3,888	20,310	17,326
25.0÷27.5	0.245	7,079	4,507	23,545	20,086
27.5÷30.0	0.279	8,052	5,127	26,780	22,846
30.0÷32.5	0.312	9,025	5,746	30,016	25,606
32.5÷35.0	0.346	9,997	6,365	33,251	28,366

Table 3.9 – Calculation of the level of stress amplitudes for option 3

Movement speed interval, m/s	Coefficient of vertical dynamics $k_{\partial ei}$	The level of stress amplitudes in the i-th interval for the i-th mode:			
		$\sigma_{a,j1}^I$	$\sigma_{a,j2}^I$	$\sigma_{a,j3}^I$	$\sigma_{a,j4}^I$
		Hatch area	Paw area	The area of lying	Bottom area
0÷12.5	0.039	1,282	1,017	4,170	3,631
12.5÷15.0	0.086	2,820	2,237	9,174	7,988
15.0÷17.5	0.110	3,630	2,879	11,809	10,282
17.5÷20.0	0.144	4,737	3,758	15,412	13,419
20.0÷22.5	0.178	5,844	4,636	19,015	16,556
22.5÷25.0	0.211	6,952	5,515	22,617	19,693
25.0÷27.5	0.245	8,059	6,393	26,220	22,830
27.5÷30.0	0.279	9,166	7,272	29,823	25,967
30.0÷32.5	0.312	10,274	8,150	33,426	29,104
32.5÷35.0	0.346	11,381	9,029	37,028	32,241

Table 3.10 – Calculation of the level of stress amplitudes for option 4

Movement speed interval, m/s	Coefficient of vertical dynamics $k_{\partial \theta i}$	The level of stress amplitudes in the i-th interval for the i-th mode:			
		$\sigma_{a,j1}^I$	$\sigma_{a,j2}^I$	$\sigma_{a,j3}^I$	$\sigma_{a,j4}^I$
		Hatch area	Paw area	The area of lying	Bottom area
0÷12.5	0.039	1,418	1,149	4,544	4,441
12.5÷15.0	0.086	3,120	2,528	9,996	9,770
15.0÷17.5	0.110	4,016	3,255	12,868	12,577
17.5÷20.0	0.144	5,241	4,247	16,794	16,414
20.0÷22.5	0.178	6,466	5,240	20,720	20,251
22.5÷25.0	0.211	7,691	6,233	24,646	24,088
25.0÷27.5	0.245	8,916	7,226	28,572	27,925
27.5÷30.0	0.279	10,142	8,219	32,498	31,762
30.0÷32.5	0.312	11,367	9,212	36,423	35,599
32.5÷35.0	0.346	12,592	10,205	40,349	39,436

According to the known values of the total number of cycles of dynamic stresses due to the action of vertical dynamic forces N_c^I (Table 3.5) we define and

present the components in Table. 3.11-table 3.22 for calculation $\sigma_{a,e}^I$, which has the form:

$$\sigma_{a,e}^I = \sqrt[m]{\frac{N_c^I}{N_0} \sum_{i=1}^n \left(\sigma_{a,i}^I \right)^m \cdot p_i^I}, \quad (3.15)$$

Table 3.11 – Calculation of the components of the amplitude of the dynamic stress of the conventional symmetrical cycle during the impact interaction of the tank wagon at $V = 90 \text{ km/ hours}$ (option 1).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,i1}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,i2}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,i3}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,i4}^I \right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	2	3	4	5
1	0.080	0.015	9,929	5,465
2	4,001	0.748	494,267	272,063
3	14,218	2,659	1756,377	966,775
4	56,245	10,517	6948,182	3824,537
5	78,193	14,621	9659.485	5316,938

6	43,480	8,130	5371,194	2956,504
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I \right)^m \cdot p_i^I$	196,217	36,690	24239,435	13342.282

Table 3.12 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 90 \text{ km/hours}$ (option 2).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I \right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I \right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	2	3	4	5
1	0.129	0.021	15,727	8,330
2	6,398	1,051	782,887	414,667
3	22,735	3,736	2781.986	1473,518

4	89,938	14,778	11005,466	5829.198
5	125,034	20,545	15299.992	8103,853
6	69,526	11,424	8507,619	4506,179
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,i}^I \right)^m \cdot p_i^I$	313,759	51,556	38393.677	20335,744

Table 3.13 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 90 \text{ km/hours}$ (option 3).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	2	3	4	5
1	0.216	0.085	24,187	13,901
2	10,746	4,256	1204.005	692,002
3	38,184	15,124	4278,429	2459.029
4	151,056	59,830	16925.355	9727.854
5	210,000	83,176	23529.926	13523.833
6	116,771	46,250	13083.906	7519,979
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	526,973	208,721	59045.807	33936.599

Table 3.14 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 90 \text{ km/hours}$ (option 4).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.323	0.140	34,102	31,118
2	16,101	6,946	1697,595	1549,042
3	57,214	24,682	6032,398	5504,519
4	226,339	97,643	23864.010	21775.733
5	314,660	135,745	33176.166	30273.007
6	174,968	75,482	18447.735	16833.422
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	789,606	340,638	83252.006	75966.841

Table 3.15 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at at $V = 100 \text{ km/hours}$ (option 1).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.050	0.009	6,206	3,416
2	2,824	0.528	348,894	192,044
3	9,694	1,813	1197,530	659,165
4	37,497	7,011	4632.122	2549,691
5	108,602	20,307	13415.952	7384.636
6	130,439	24,391	16113.582	8869,512
7	94,241	17,622	11641.890	6408,127
8	52,575	9,831	6494,745	3574.948
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	435,921	81,512	53850.920	29641.539

Table 3.16 – Calculation of the components of the amplitude of the dynamic stress of the conventional symmetrical cycle during the impact interaction of the tank wagon at $V = 100 \text{ km/hours}$ (option 2).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.080	0.013	9,829	5,206
2	4,516	0.742	552,626	292,706
3	15,501	2,547	1896,809	1004,671
4	59,959	9,852	7336,977	3886.132
5	173,658	28,535	21249.989	11255,352
6	208,577	34,272	25522.858	13518,536
7	150,694	24,762	18439.991	9766.997
8	84,069	13,814	10287,251	5448.785
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	697,054	114,537	85296.331	45178.386

Table 3.17 – Calculation of the components of the amplitude of the dynamic stress of the conventional symmetrical cycle during the impact interaction of the tank wagon at $V = 100 \text{ km/hours}$ (option 3).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.135	0.053	15,117	8,688
2	7,585	3,004	849,886	488,472
3	26,035	10,312	2917,111	1676,610
4	100,704	39,886	11283.570	6485.236
5	291,667	115,522	32680.452	18783.101
6	350,314	138,751	39251.717	22559.938
7	253,098	100,246	28358.944	16299.313
8	141,198	55,925	15820.809	9093.016
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	1170,736	463,700	131177.606	75394.376

Table 3.18 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 100 \text{ km/hours}$ (option 4).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.202	0.087	21,314	19,449
2	11,365	4,903	1198,302	1093,442
3	39,010	16,829	4112.999	3753.081
4	150,893	65,095	15909,340	14517,155
5	437,028	188,535	46078.008	42045.843
6	524,904	226,445	55343,204	50500.266
7	379,237	163,604	39984.871	36485.900
8	211,568	91,271	22306.649	20354,653
9	0	0	0	0
10	0	0	0	0
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	1754,207	756,769	184954,688	168769.788

Table 3.19 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 120 \text{ km/hours}$ (option 1).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.030	0.006	3,723	2,050
2	1,648	0.308	203,522	112,026
3	5,816	1,088	718,518	395,499
4	22,498	4,207	2779,273	1529,815
5	69,505	12,997	8586.209	4726,167
6	165,222	30,895	20410.537	11234.715
7	251,308	46,992	31045.040	17088.338
8	262,873	49,154	32473.727	17874.741
9	248,897	46,541	30747,102	16924,343
10	124,945	23,363	15434.905	8495,943
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	1152,743	215,549	142402.556	78383.635

Table 3.20 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 120 \text{ km/hours}$ (option 2).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.048	0.008	5,898	3,124
2	2,634	0.433	322,365	170,745
3	9,301	1,528	1138,085	602,803
4	35,975	5,911	4402,186	2331,679
5	111,141	18,262	13599.993	7203,425
6	264,197	43,412	32328.954	17123.479
7	401,852	66,031	49173.310	26045,326
8	420,345	69,069	51436.256	27243.927
9	397,995	65,397	48701.396	25795.370
10	199,792	32,829	24447.879	12949,158
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	1843,280	302,880	225556,321	119469.037

Table 3.21 – Calculation of the components of the amplitude of the dynamic stress of the conditional symmetrical cycle during the impact interaction of the tank wagon at $V = 120 \text{ km/hours}$ (option 3).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.081	0.032	9,070	5,213
2	4,425	1,752	495,767	284,942
3	15,621	6,187	1750,267	1005,966
4	60,422	23,932	6770.142	3891,141
5	186,667	73,934	20915,489	12021,185
6	443,731	175,751	49718.842	28575.922
7	674,929	267,323	75623.851	43464.835
8	705,989	279,625	79104.047	45465.079
9	668,452	264,758	74898.093	43047.706
10	335,560	132,907	37598.501	21609.752
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	3095,876	1226,202	346884.069	199371.742

Table 3.22 – Calculation of the components of the amplitude of the dynamic stress of the conventional symmetrical cycle during the impact interaction of the tank wagon at $V = 120 \text{ km/hours}$ (option 4).

Interval number	The level of stress amplitudes in the i-th interval for the i-th regime, MPa			
	$\left(\sigma_{a,j1}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j2}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j3}^I\right)^m \cdot p_i^I$	$\left(\sigma_{a,j4}^I\right)^m \cdot p_i^I$
	Region hatch	Region paw	The area of lying	Bottom area
1	0.121	0.052	12,788	11,669
2	6,630	2,860	699,010	637,841
3	23,406	10,097	2467,799	2251,849
4	90,536	39,057	9545.604	8710,293
5	279,698	120,662	29489.925	26909,339
6	664,878	286,830	70101,392	63967.003
7	1011,300	436,277	106626.323	97295.733
8	1057,840	456,355	111533,246	101773,264
9	1001,594	432,090	105603.036	96361,991
10	502,796	216,907	53012,243	48373.280
$\sum_{i=1}^n \left(\sigma_{a,j}^I\right)^m \cdot p_i^I$	4638,798	2001,189	489091,367	446292.264

The level of the stress amplitudes from the shock interaction of the tank wagon with neighboring wagons in the i th interval is interconnected with the equivalent stresses σ_{ry} for the studied zones, which are determined according to the scheme (Fig. 3.2) and presented in Fig. 3.4 - 3.7. The values of the largest stresses are presented in the table. 3.23.

Table 3.23 – Values of equivalent stresses in the most stressed places of the tank wagon boiler

Zone Version	Region Luka, MPa	Region paw, MPa	Lezhniy Oblast, MPa	Bottom area, MPa
1	121	85.8	123	152
2	126	93.2	135	170
3	144	97.6	149	186
4	156	119	167	210

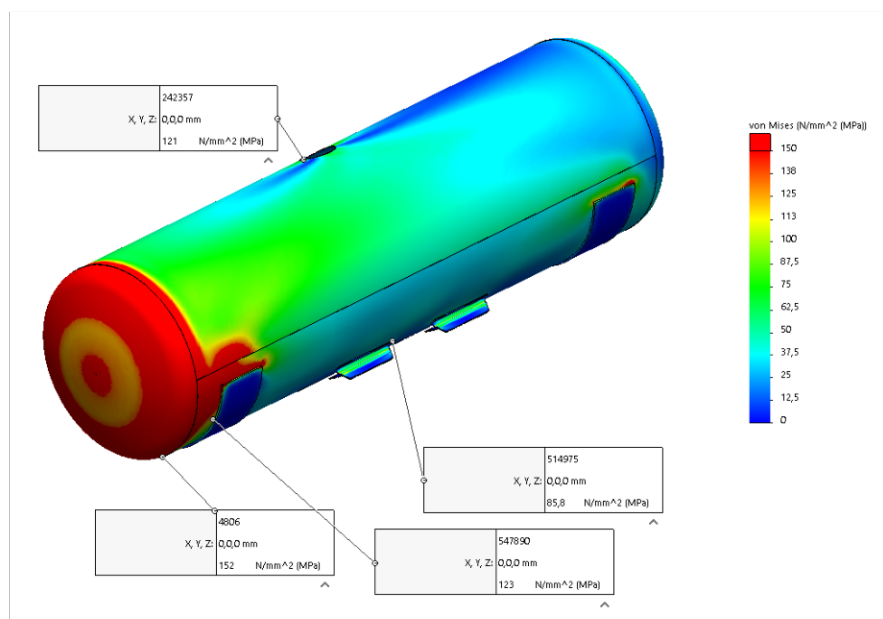


Figure 3.4 – Diagram of the stress-strain state of the boiler as a result of the longitudinal impact force $N = 3.8$ MN in the absence of corrosion of the boiler metal (option 1)

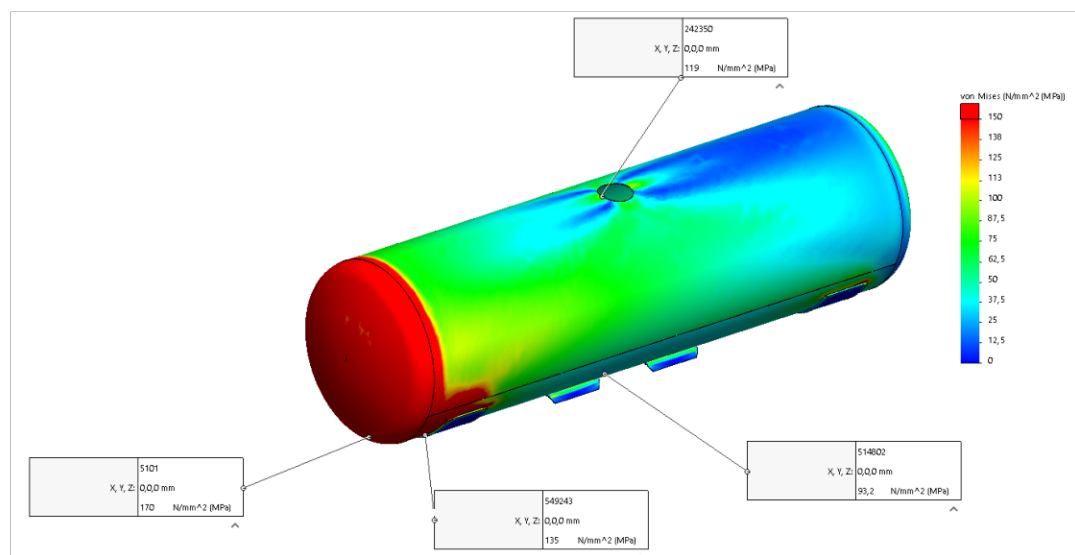


Figure 3.5 – Diagram of the stress-strain state of the boiler under the action of the longitudinal impact force $N = 3.8$ MN during corrosion of the boiler metal 1 mm deep (option 2)

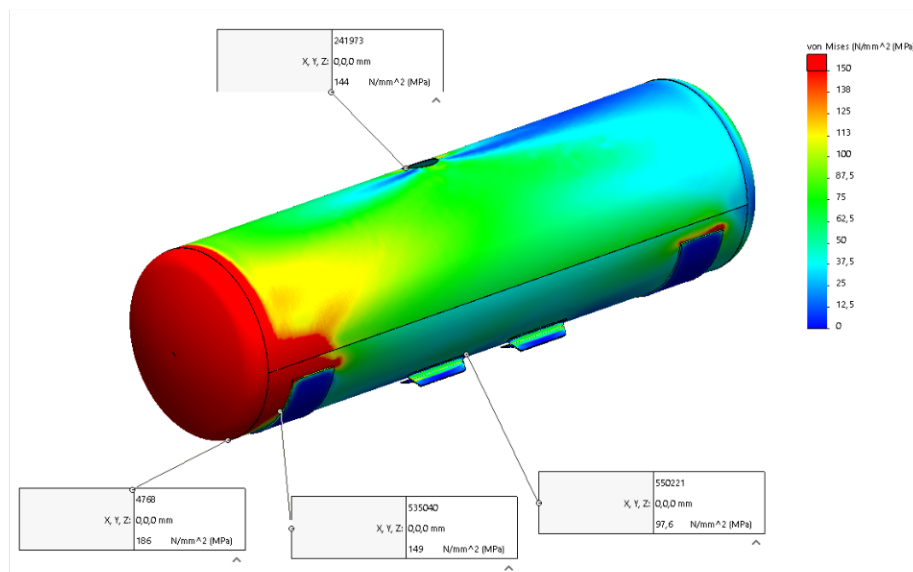


Figure 3.6 – Diagram of the stress-strain state of the boiler under the action of the longitudinal impact force $N = 3.8$ MN during corrosion of the boiler metal 2 mm deep (option 3)

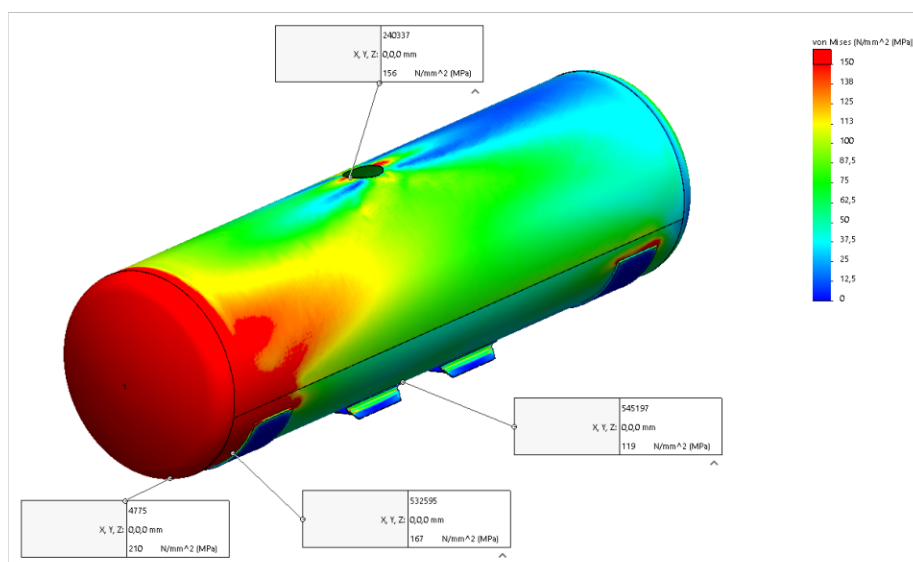


Figure 3.7 – Diagram of the stress-strain state of the boiler under the action of the longitudinal impact force $N = 3.8$ MN during corrosion of the boiler metal 3 mm deep (option 4)

The movement of the tank wagon boiler for the established research options is presented in fig. 3.8 - fig. 3.11.

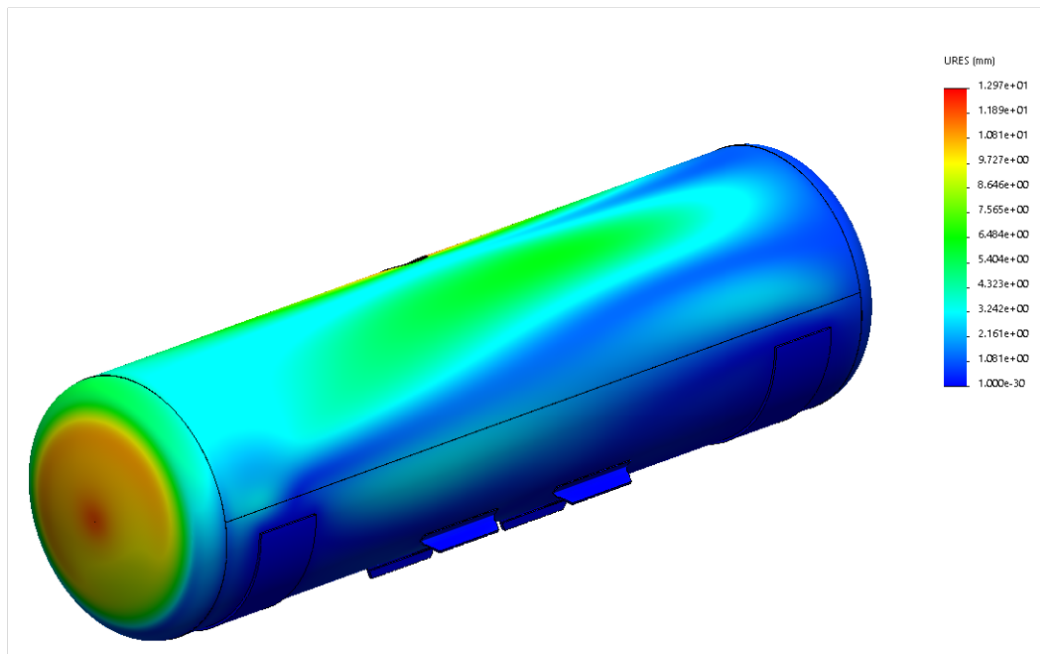


Figure 3.8 – Diagram of displacements due to longitudinal impact force
 $N = 3.8 \text{ MN}$ in the absence of corrosion of the boiler metal (option 1)

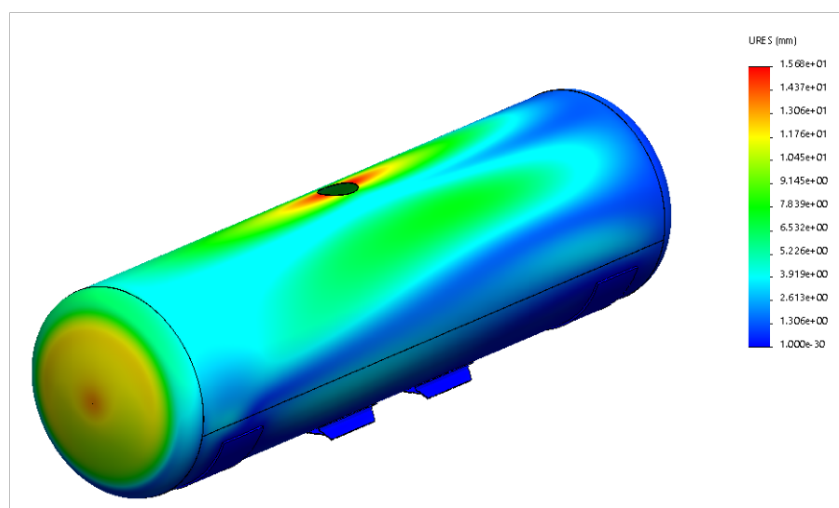


Figure 3.9 – Diagram of displacements due to longitudinal impact force
 $N = 3.8 \text{ MN}$ with corrosion of the boiler metal with a depth of 1 mm (option 2)

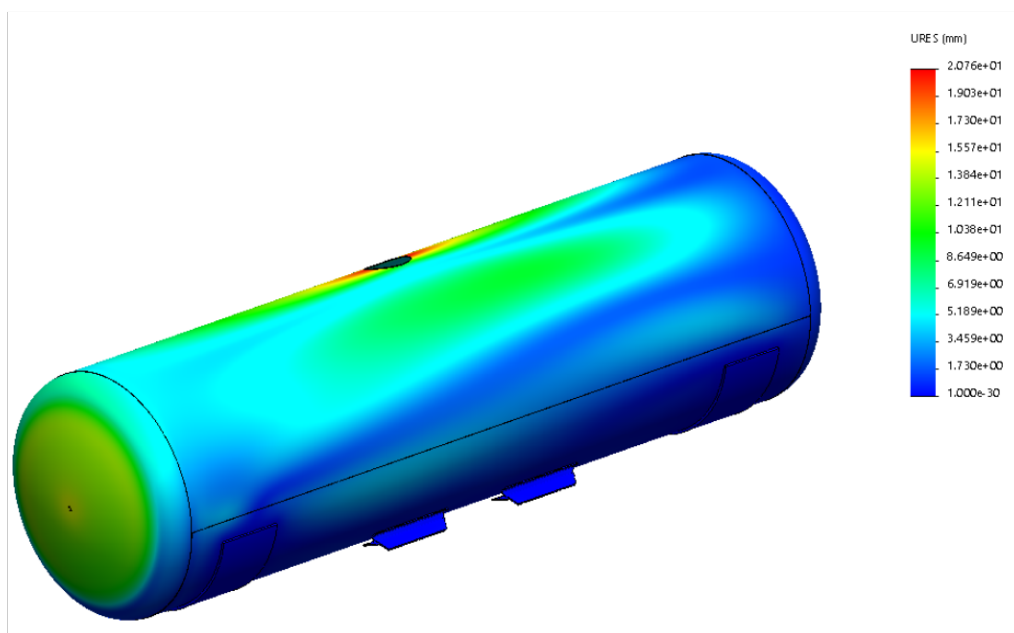


Figure 3.10 – Diagram of displacements due to longitudinal impact force
 $N = 3.8 \text{ MN}$ in the case of corrosion of the boiler metal with a depth of 2 mm
(option 3)

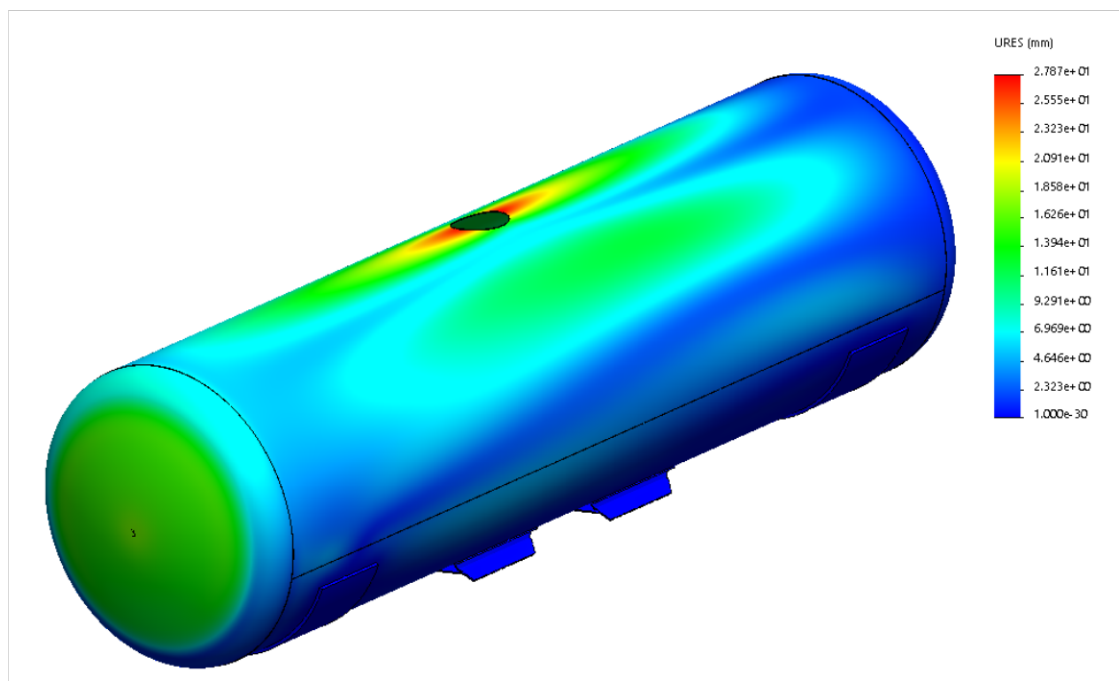


Figure 3.11 – Diagram of movements due to longitudinal impact force
 $N = 3.8 \text{ MN}$ with corrosion of the boiler metal with a depth of 3 mm (option 4)

The deformations that arise from the action of the longitudinal impact force for the calculation options are shown in fig. 3.12 - 3.15.

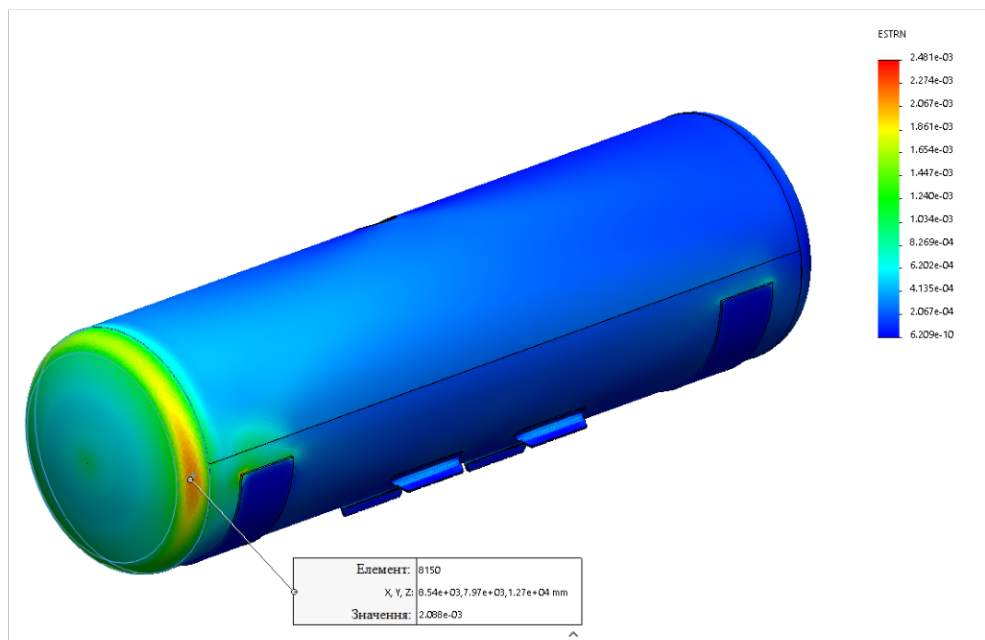


Figure 3.12 – Diagram of deformations due to longitudinal impact force
 $N = 3.8$ MN in the absence of corrosion of the boiler metal (option 1)

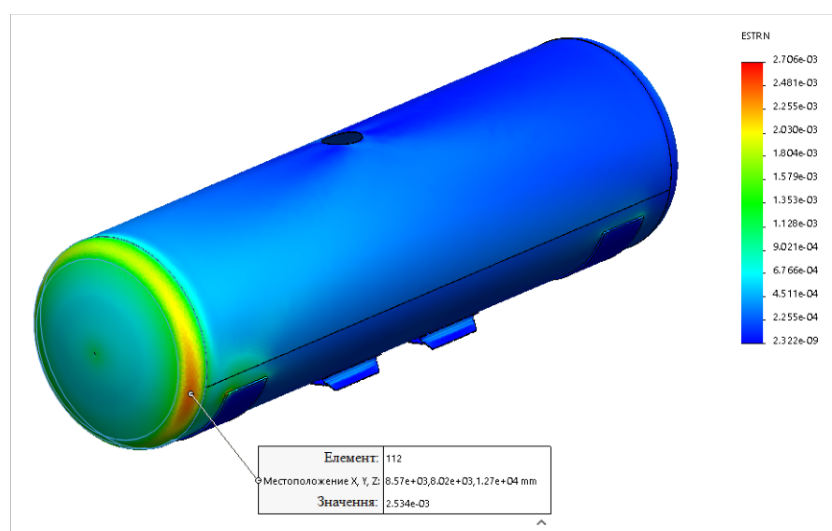


Figure 3.13 – Diagram of deformations due to longitudinal impact force
 $N = 3.8$ MN with corrosion of the boiler metal with a depth of 1 mm (option 2)

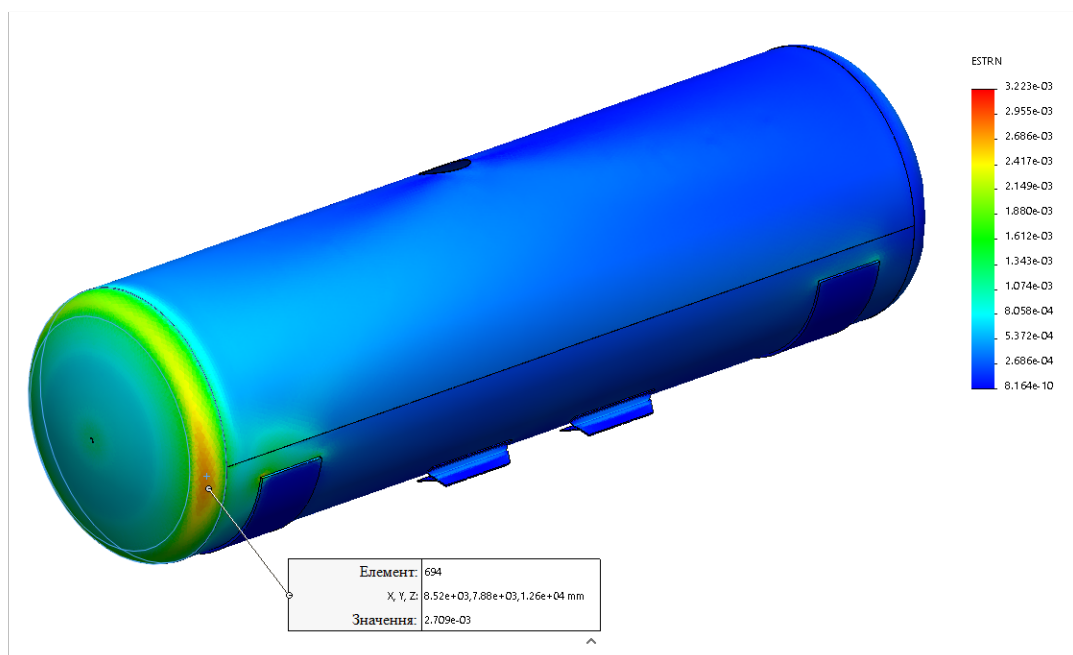


Figure 3.14 – Diagram of deformations due to longitudinal impact force
 $N = 3.8 \text{ MN}$ in the case of corrosion of the boiler metal with a depth of 2 mm
 (option 3)

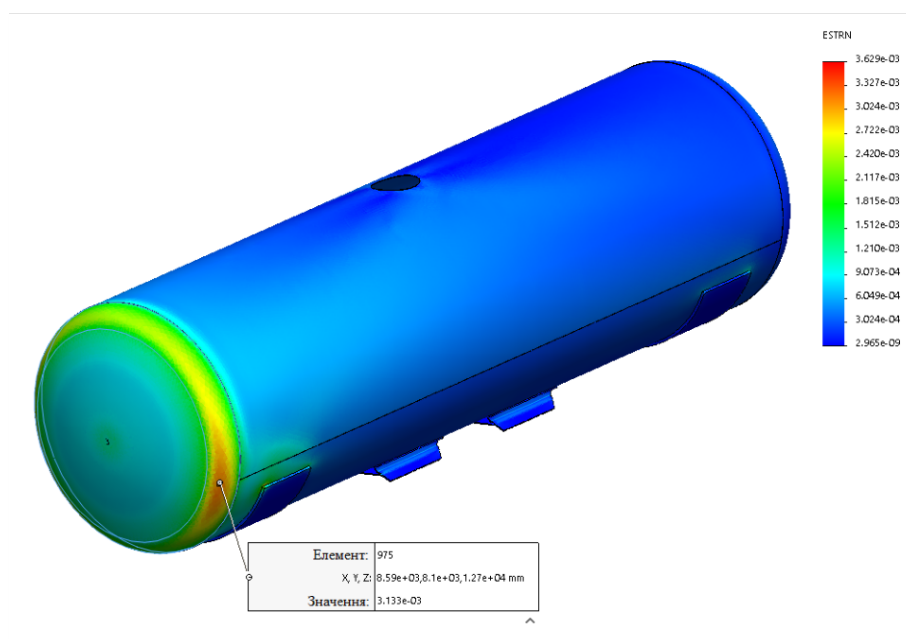


Figure 3.15 – Diagram of deformations due to longitudinal impact force

$N = 3.8$ MN with corrosion of the boiler metal with a depth of 3 mm (option 4)

The total number of cycles of longitudinal forces N_c'' , which act on the coupling for the estimated service life is determined by formula (3.13) of the report, taking into account the annual number of cycles (Table 3.24) for the force interval, depending on the cycle amplitudes and their frequency.

Table 3.24 – Distribution of longitudinal impact forces

Power interval	Amplitude cycle, MN	Frequency of amplitudes	Number of cycles per year
	F_{ai}^y	p_i''	N_p
0.1 - 0.4	0.25	0.1258	2539
0.4 - 0.8	0.6	0.2852	5761
0.8 - 1.2	1	0.2802	5661
1.2 - 1.6	1.4	0.1832	3699
1.6 - 2.0	1.8	0.0772	1554
2.0 - 2.4	2,2	0.0359	725
2.4 - 2.8	2.6	0.0098	202
2.8 - 3.2	3	0.0023	48
3.2 - 3.6	3,4	0.0003	6
3.6 - 4.0	3.8	0.0001	2
Together:		1	20197

The level of stress amplitudes in the i-th interval for the II-th mode, which is determined by formula (3.12), is presented for calculation options 1-4 in the table. 3.25 - 3.28.

Table 3.25 – Calculated amplitude levels according to II mode (option 1)

Interval number	Hatch area, MPa	Paw area, MPa	Lezhniy Oblast, MPa	Bottom area, MPa
	$\sigma_{a,j1}^{II}$	$\sigma_{a,j2}^{II}$	$\sigma_{a,j3}^{II}$	$\sigma_{a,j4}^{II}$
1	2	3	4	5
1	7,961	5,645	8,092	10.0
2	19,105	13,547	19,421	24.0
3	31,842	22,579	32,368	40.0
4	44,579	31,611	45,316	56.0
5	57,316	40,642	58,263	72.0
6	70,053	49,674	71,211	88.0
7	82,789	58,705	84,158	104.0
8	95,526	67,737	97,105	120.0
9	108,263	76,768	110,053	136.0
10	121.0	85.80	123.0	152.0

Table 3.26 – Calculated amplitude levels according to II mode (option 2)

Interval number	Hatch area, MPa	Paw area, MPa	Lezhniy Oblast, MPa	Bottom area, MPa
	$\sigma_{a,j1}^{II}$	$\sigma_{a,j2}^{II}$	$\sigma_{a,j3}^{II}$	$\sigma_{a,j4}^{II}$
1	8,289	6,132	8,882	11,184
2	19,895	14,716	21,316	26,842
3	33,158	24,526	35,526	44,737
4	46,421	34,337	49,737	62,632
5	59,684	44,147	63,947	80,526
6	72,947	53,958	78,158	98,421
7	86,211	63,768	92,368	116,316
8	99,474	73,579	106,579	134,211
9	112,737	83,389	120,789	152,105
10	126.0	93.20	135.0	170.0

Table 3.27 – Calculated amplitude levels according to II mode (option 3)

Interval number	Hatch area, MPa	Paw area, MPa	Lezhniy Oblast, MPa	Bottom area, MPa
	$\sigma_{a,j1}^{II}$	$\sigma_{a,j2}^{II}$	$\sigma_{a,j3}^{II}$	$\sigma_{a,j4}^{II}$
1	2	3	4	5
1	9,474	6,421	9,803	12,237
2	22,737	15,411	23,526	29,368
3	37,895	25,684	39,211	48,947
4	53,053	35,958	54,895	68,526
5	68,211	46,232	70,579	88,105
6	83,368	56,505	86,263	107,684
7	98,526	66,779	101,947	127,263
8	113,684	77,053	117,632	146,842
9	128,842	87,326	133,316	166,421
10	144.0	97.60	149.0	186.0

Table 3.28 – Calculated amplitude levels according to II mode (option 4)

Interval number	Hatch area, MPa	Paw area, MPa	Lezhniy Oblast, MPa	Bottom area, MPa
	$\sigma_{a,j1}^{II}$	$\sigma_{a,j2}^{II}$	$\sigma_{a,j3}^{II}$	$\sigma_{a,j4}^{II}$
1	10,263	7,829	10,987	13,816
2	24,632	18,789	26,368	33,158
3	41,053	31,316	43,947	55,263
4	57,474	43,842	61,526	77,368
5	73,895	56,368	79,105	99,474
6	90,316	68,895	96,684	121,579
7	106,737	81,421	114,263	143,684
8	123,158	93,947	131,842	165,789
9	139,579	106,474	149,421	187,895
10	156.0	119.0	167.0	210.0

The calculated total number of cycles of longitudinal forces, taking into account the service life of one and a half years (36 years), is presented in the table.

3.29.

Table 3.29 – Dependence of the total number of cycles of longitudinal forces on the increase in the service life of the wagon

N_c^{II} , units	484728	525122	565516	605910	646304	686698	727092
T_K , years	24	26	28	30	32	34	36

The obtained values of the fatigue strength reserve coefficients according to formula (3.1) for the tank wagon boiler, which may have deviations in metal thickness, in the range of one and a half years of service - from 24 to 36 years for the considered options 1 - 4, taking into account changes in the probability of action of the amplitude level p_i^I at different speeds of movement, presented in fig. 3.16 - 3.27.

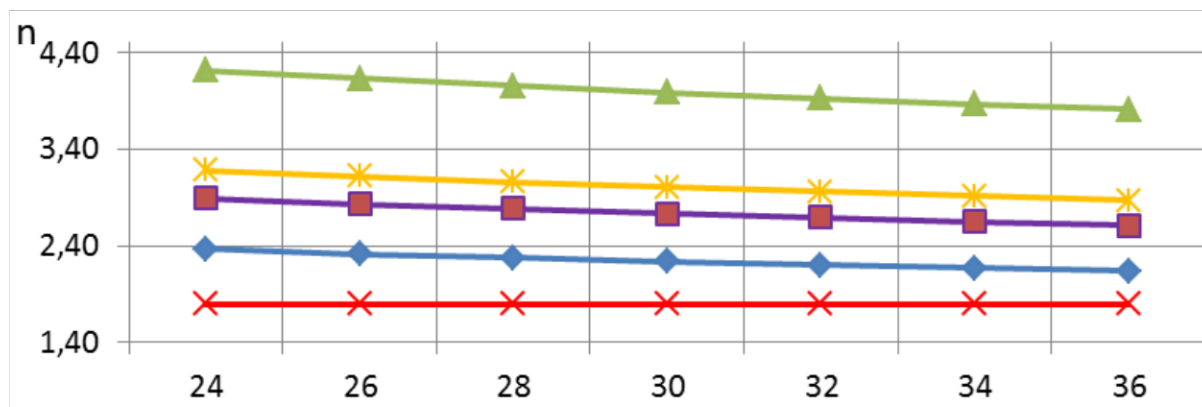


Figure 3.16 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 90 \text{ km/ hours}$ (option 1)

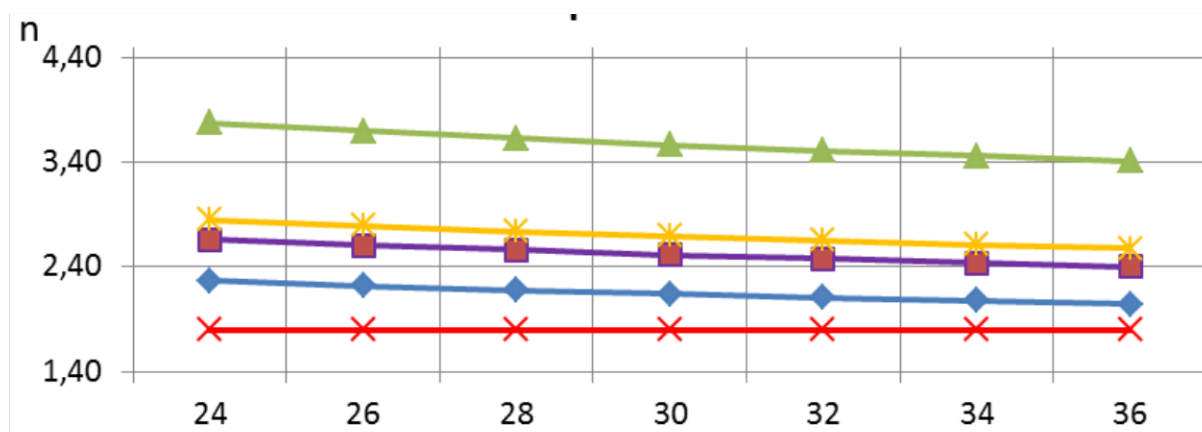


Figure 3.17 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 90 \text{ km/ hours}$ (option 2)

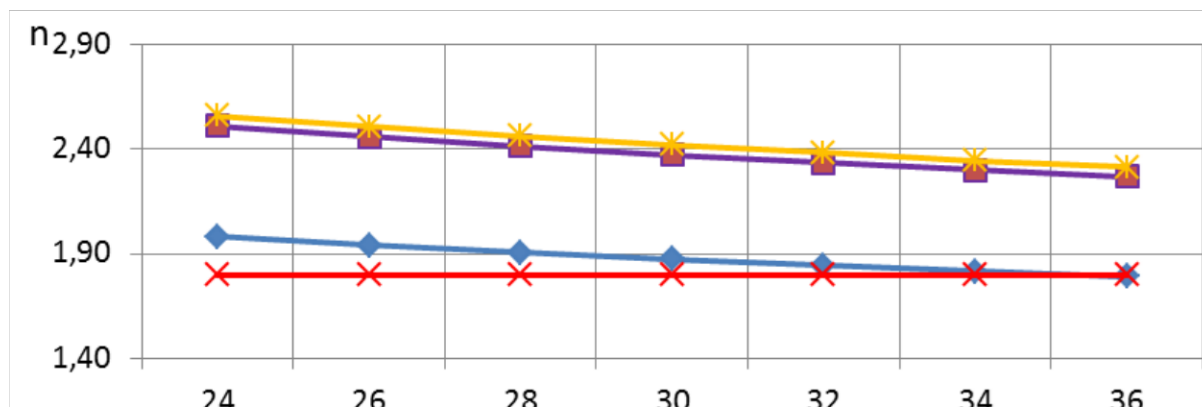


Figure 3.18 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 90 \text{ km/ hours}$ (option 3)

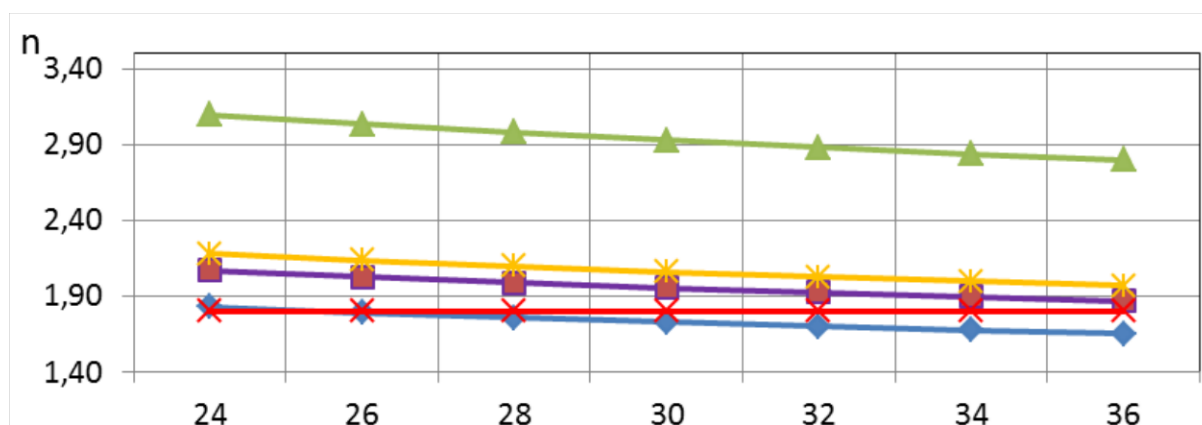


Figure 3.19 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 90 \text{ km/ hours}$ (option 4)

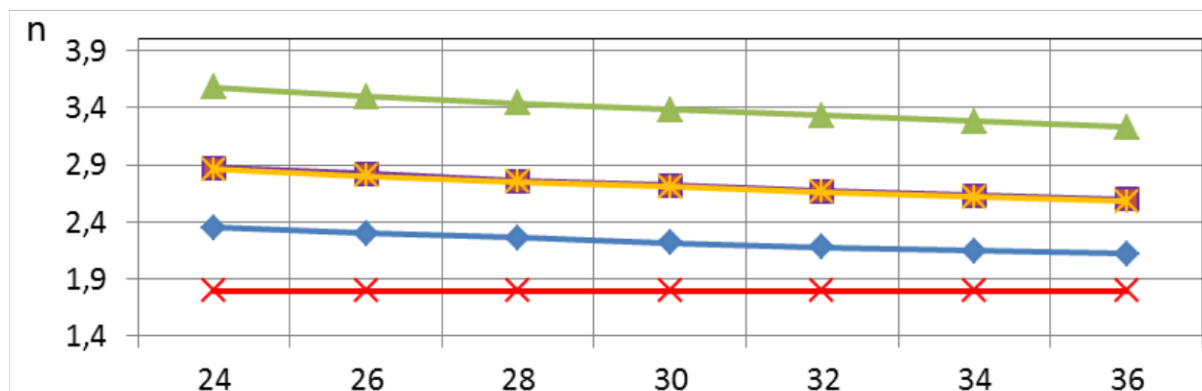


Figure 3.20 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 100 \text{ km/ hours}$ (option 1)

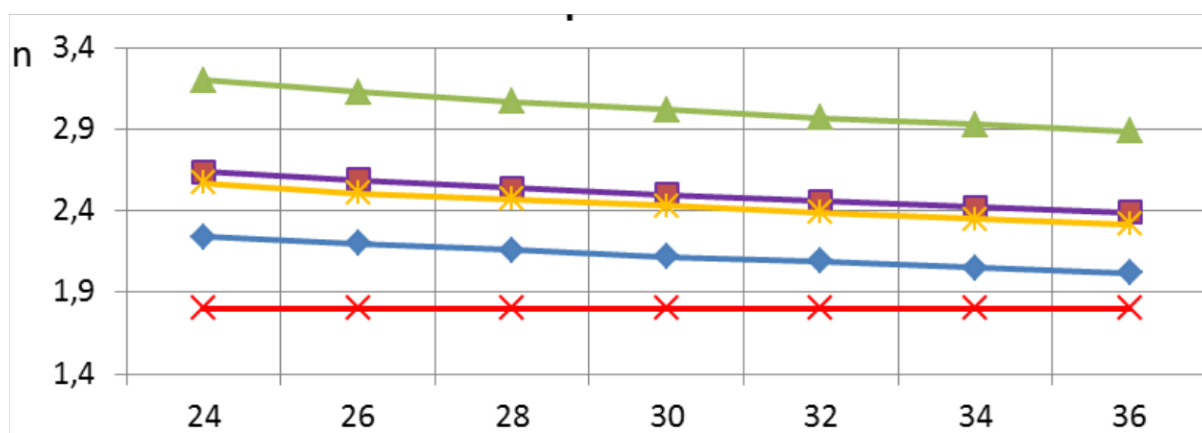


Figure 3.21 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 100 \text{ km/ hours}$ (option 2)

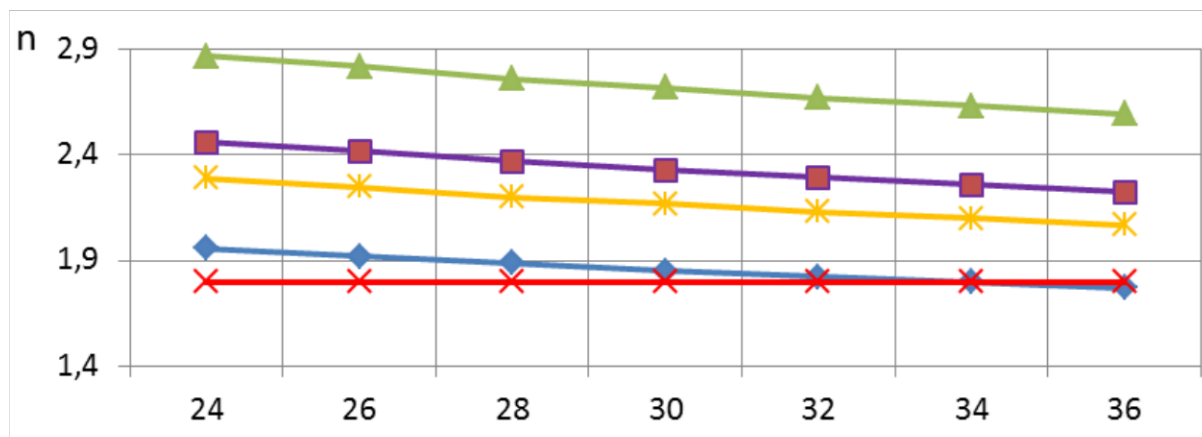


Figure 3.22 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 100 \text{ km/hours}$ (option 3)

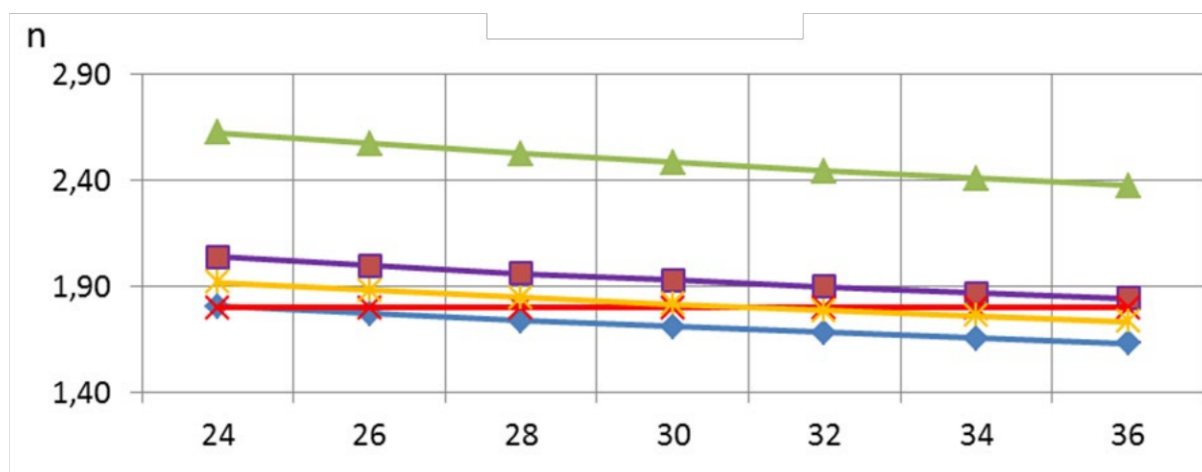


Figure 3.23 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 100 \text{ km/hours}$ (option 4)

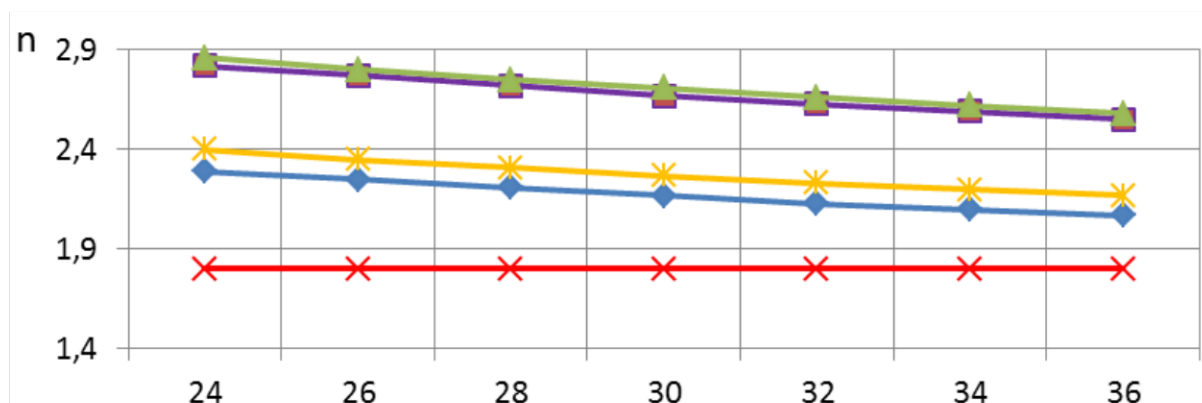


Figure 3.24 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 120 \text{ km/ hours}$ (option 1)

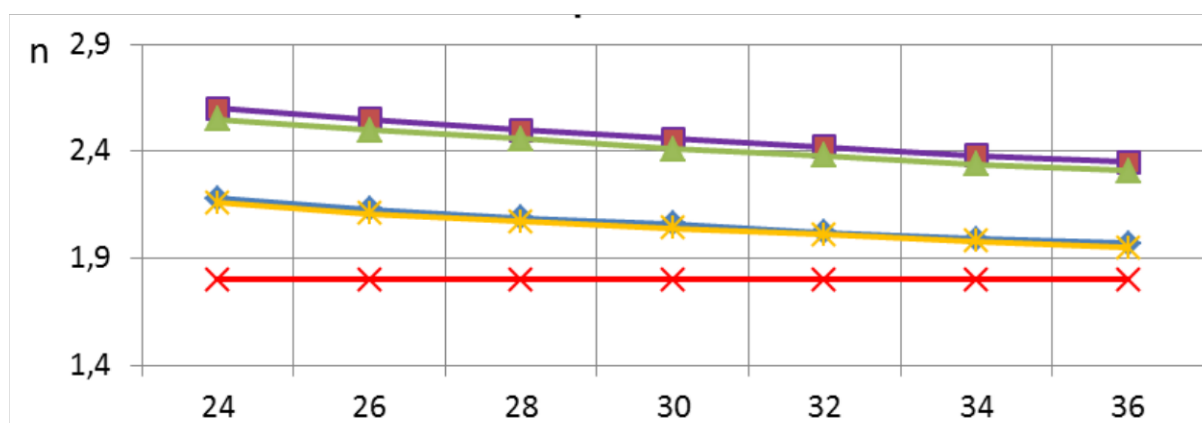


Figure 3.25 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 120 \text{ km/ hours}$ (option 2)

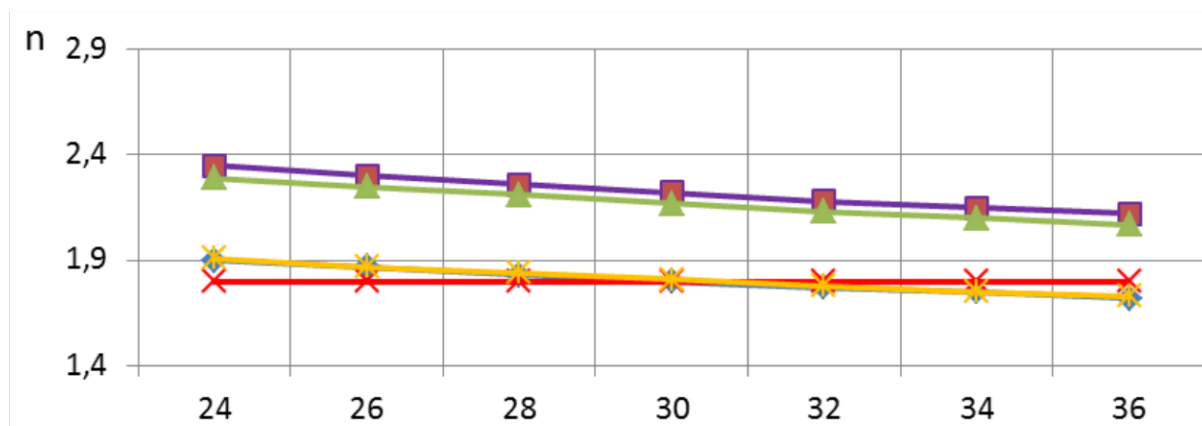


Figure 3.26 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 120 \text{ km/ hours}$ (option 3)

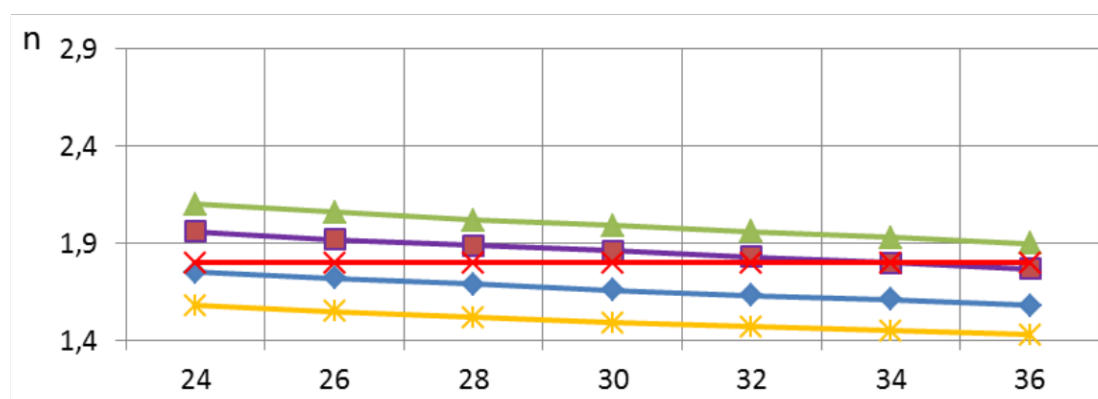


Figure 3.27 – Graph of the dependence of the coefficients of the reserve of fatigue strength on the service life of the tank wagon boiler in the absence of metal corrosion and the speed of movement $V = 120 \text{ km/ hours}$ (option 4)

Analyzing the results of the study of calculation option 1 for movement speeds – $V = 90 \text{ km/ hours}$, $V = 100 \text{ km/ hours}$ and $V = 120 \text{ km/ hours}$, it was established that the coefficients of the reserve of fatigue strength are within the

permissible limits for the considered period of operation (from 24 to 36 years) for the adopted control zones.

As evidenced by the results of the study of calculation option 2 in the considered speed limits $V = 90 \div 120 \text{ km/ hours}$ compared to option 1, the coefficients of the reserve of fatigue resistance are reduced by approximately 8 – 11% for all control zones, but do not cross the limit of the minimum permissible value in the entire range of one and a half service life.

The nature of the change in the studied indicator of fatigue strength for option 3 (Fig. 3.18, Fig. 3.22, Fig. 3.26) provides grounds for asserting that the level of the permissible value in the area of the boiler hatch is exceeded when the boiler service life is 34 years in the range of driving speeds $V = 90 \div 120 \text{ km/ hours}$, in the area of the boiler hatch and bottoms during boiler operation for 30 years under the conditions of speed of movement $V = 120 \text{ km/ hours}$. At the same time, the value of the coefficients of the reserve of fatigue resistance for the area of shaped legs and the area of lying supports corresponds to the conditions of safe operation.

The obtained research results for option 4 indicate an unacceptably low level of the values of the coefficients of the fatigue strength reserve: for the hatch area – starting from 26 years at $V = 90 \text{ km/ hours}$, for the area of bottoms – from 30 years at $V = 100 \text{ km/ hours}$, for shaped paws – upon reaching 34 years of operation and speed $V = 120 \text{ km/ hours}$.

Conclusions according to section 3

The results of the technical diagnostics of tank wagons for the transportation of chemical wagoes with an overestimated service life indicate that they have significant corrosion damage to the load-bearing elements and the body, which directly affects the safety of the operation of the moving units and requires a comprehensive review, conducting comprehensive measures to study the consequences of reducing the thickness of the main of metal, forecasting the final resource of individual elements of the wagon structure and making proposals regarding the implementation of additional measures for increased control of the most dangerous areas.

The presented section presents the results of the study of the stress-strain state of the cylindrical shell of a tank wagon boiler using the SolidWorks software complex. The conducted theoretical research on the determination of the stress-strain state of the tank wagon boiler shows that the depth of metal corrosion and the place of occurrence are significant factors that must be taken into account when assessing the strength of structural elements. In the course of the calculations, it was established that the most dangerous areas in the event of corrosion with a depth of 3 mm or more include the areas of the bottoms and the hatch, which makes it impossible to extend the life of the boiler. In case of

corrosion up to 2 mm deep, the maximum service life of the boiler can be 30 years.

In case of complete absence of corrosion, the service life can be extended by 12 years, i.e. up to one and a half years (36 years) of the designated service life.

The patterns of changes in the coefficients of the reserve of fatigue strength of the most stressed parts of the tank wagon boiler when corrosion damage occurs reflect how significant the value of the thickness of the metal shell is, which can be used when monitoring tank wagon structures for the transportation of chemical corrosive-active cargoes, the service life of which has already been exhausted , and determining the possibility of their further exploitation with an extension of the service life according to the methodology presented in the report.

This method of determining the fatigue strength of a tank wagon boiler allows predicting the further possibility of operating the structure beyond the intended service life, taking into account the appearance of corrosive wear and local places of the structure where the most dangerous stresses occur. This approach to assessing the residual resource of individual elements of a tank wagon can be applied both based on the results of simulation and experimental research data, which will make it possible to reasonably determine the permitted period of operation.

4 PROPOSALS FOR INCREASING THE RESOURCE OF TANK WAGON BOILERS

Electrochemical protection is a universal method of protection against corrosion of metal coatings. This method of corrosion protection can be used in places where there is contact between metal and electrolyte.

The essence of all electrochemical methods of corrosion protection consists in shifting the potential of the protected metal to the range of values at which its ionization is difficult or impossible at all. Depending on the side of the potential shift (positive or negative), protection is divided into anodic and cathodic.

Cathodic protection is the most common. The essence of protection is to connect the protected object to the negative pole, while the positive pole is connected to the anode. With this method, corrosion of the product is almost completely stopped.

Cathodic protection is possible both with the help of protection units connected to an external power source and with the help of autonomous protective units.

When using protective protection, a metal with a more electronegative potential is attached to the object being protected. At the same time, the metal of the protector is destroyed. Over time, the protector corrodes and is replaced with

a new one. Tread protection is effective in cases where there is little transient resistance between the tread and the environment. Each protector has its own radius of protective action, which is determined by the maximum possible distance at which the protector can be installed near the object without losing the protective effect. Protectors are usually made of magnesium, zinc, iron, aluminum.

Anodic electrochemical protection is used for titanium metals, low-alloy stainless steels, carbon steels, high-alloy alloys, dissimilar metals that are passivated. Anodic protection is used in electrically conductive corrosive environments.

With anodic protection, the potential of the protected metal shifts to a more positive side until the system reaches a passive stable state. Anodic protection can be implemented in several ways: by shifting the potential to the positive side with the help of an external electric current source or by introducing oxidizing agents (or elements in the alloy) into the corrosion environment, which increase the efficiency of the cathodic process on the metal surface.

The installation for anodic electrochemical corrosion protection consists of an external current source, a reference electrode, a cathode and the protective object itself.

For each case of anodic protection, the layout of the cathodes is designed individually.

4.1 Selection of the method of protection against metal corrosion

Among the existing best-known methods of corrosion protection of metal surfaces (anodic and cathodic methods), the most simple and sufficiently effective in the framework of research on corrosion control and reducing its consequences is the protector method of corrosion protection, as a type of cathodic method, therefore for the inner surface of tank wagon boilers , which are used for the transportation of chemical cargo, it is advisable to use this method.

Due to the fact that a potential difference occurs between the protector and the metal structure due to the electrolytic connection, an electric current passes. At the same time, the active material - the protector (galvanic anode) dissolves, while the cathode (protective structure) remains inert.

With the help of a projector, the metal structure is subjected to polarization, which in turn leads to a displacement of the potential of the structure in the negative direction. Surface shielding occurs on the metal of the protective structure (hydroxide deposit), which makes it difficult for oxygen to diffuse and increases the thickness of the protective layer.

This method allows you to use the electrochemical protection of the galvanic anode against corrosion using the protective properties of the precipitate

of the dissolved surface of the anode, which is formed on the cathodically polarized surface of the metal.

The use of active corrosion protection with galvanic anodes (protectors) is recommended to be combined with the use of protective paint coatings, which allows you to significantly reduce current consumption and anode alloy consumption and extend the service life of protective protection. In the case of applying protective protection without paint coatings and preliminary surface preparation, cleaning from rust and other surface defects, will provide surface protection for approximately 11-14 years (with the application of protective paint coatings, the validity period is practically doubled).

The protective effect causes inhibition of the work of corrosive microelements due to the polarization of the corroding surface. The corroding system as a binary short-circuited galvanic element (K-A) is presented in Figure 4.1, to which the third electrode (Zn) is added as the most effective protector. On the polarized corrosion diagram (Figure 4.2) point S determines the corrosion potential V_x and corrosion current without the use of electrochemical cathodic protection (without contact with the anode); V_y is the total potential of the three-electrode system after connecting the protector.

On the diagram it is shown that after joining the protector, the corrosion current significantly decreases compared to the initial current ($V_x S$). Therefore, the more negative the initial potential of the protector and the flatter the anodic

polarization curve of the protector is, the more the potential of the three-electrode system shifts to the negative side and the smaller the final corrosion current of the microcouples. With a sufficient displacement of the total potential of the system V_y in the negative direction (to the potential V_a^0) the corrosion current can be zero - complete protection occurs.

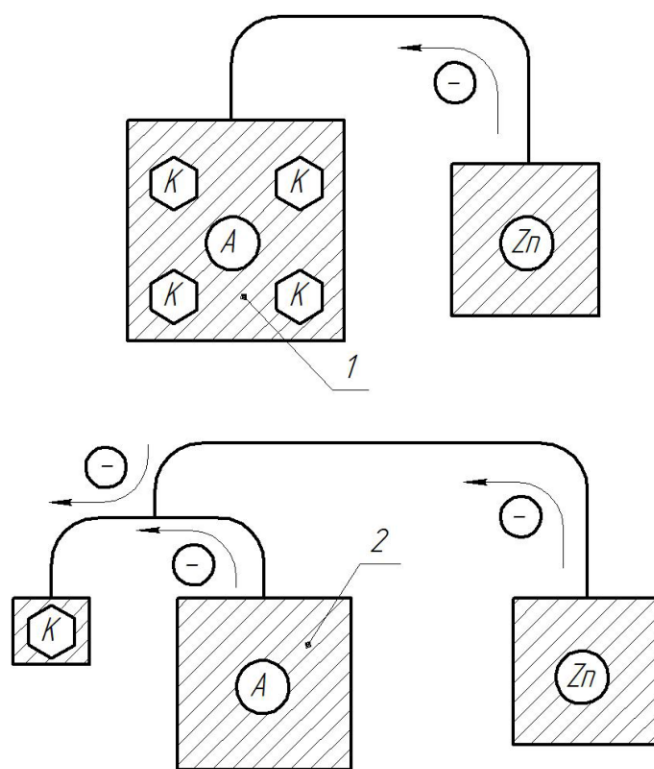


Figure 4.1 – Corrosive system:

1 - contact of the corroding metal (K-A) with the anode (Zn); 2 – equivalent three-electrode model of the protective system.

According to the phenomenon of differential effect, there is a need to introduce a coefficient of protective effect K when reducing the work of corrosive

microcouples due to an increase in the current density of the external cathodic polarization by one unit. At the same time, the dependence of the constant of the protective effect on the value of the cathodic and anodic polarization of the system when the polarization curves are close to straight lines K will be approximately constant and the overall protective effect is proportional to the cathode current density.

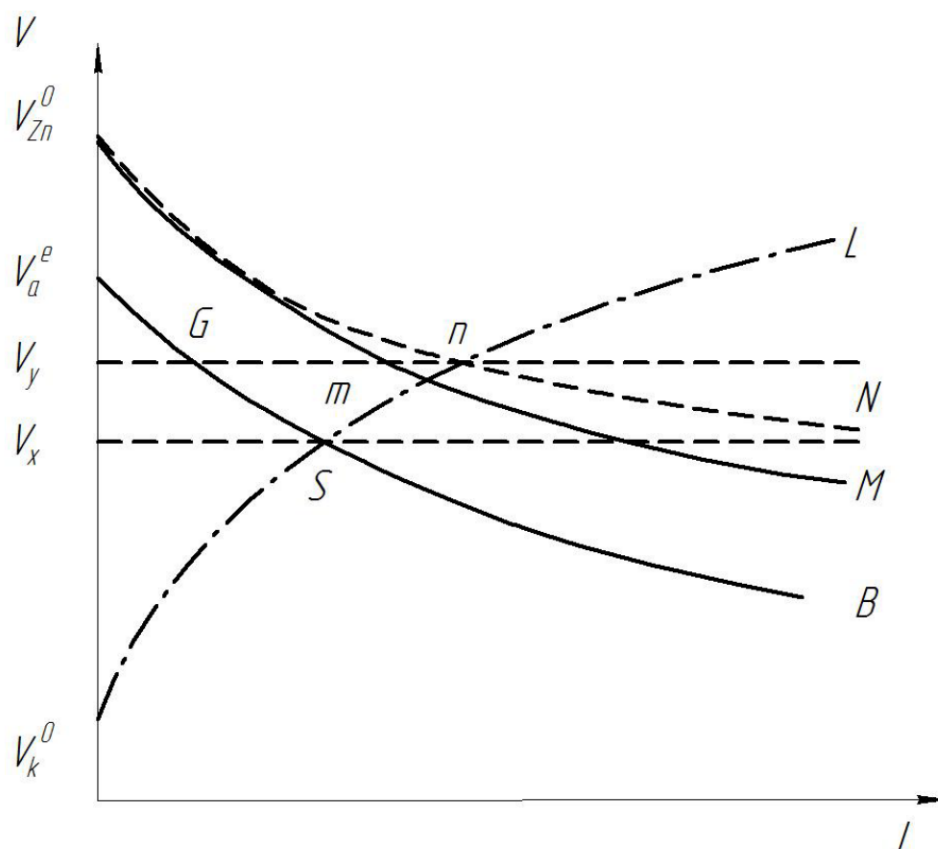


Figure 4.2 – Polarization diagram of corrosion:

$V_a^e B$ – anode curve of a complex electrode; $V_K^0 L$ – cathode curve of a complex electrode; $V_{Zn}^0 M$ – curve for anode contact; $V_{Zn}^0 N$ – general anode curve.

Ondiagram (Fig. 4.3) $V_K^0 C$ and $V_a^e A$ ideal cathode and anode curves for the investigated corrosion system under the given conditions, and V_x is the potential of the corrosion system in the absence of electrochemical protection. If you use electrochemical protection by connecting a protector or cathodic polarization from the outside by applying voltage, then the potential of the corroding system will have a shift towards a more negative value V'_x . At the same time, the corrosion current will decrease from the value $V'_x b$ to $V'_x a$ and the external cathode current will be equal to ac . Full protection will be provided if, during the process of cathodic polarization, the potential of the corroding system becomes more negative than the value of the initial potential of the anodic process V_a^e .

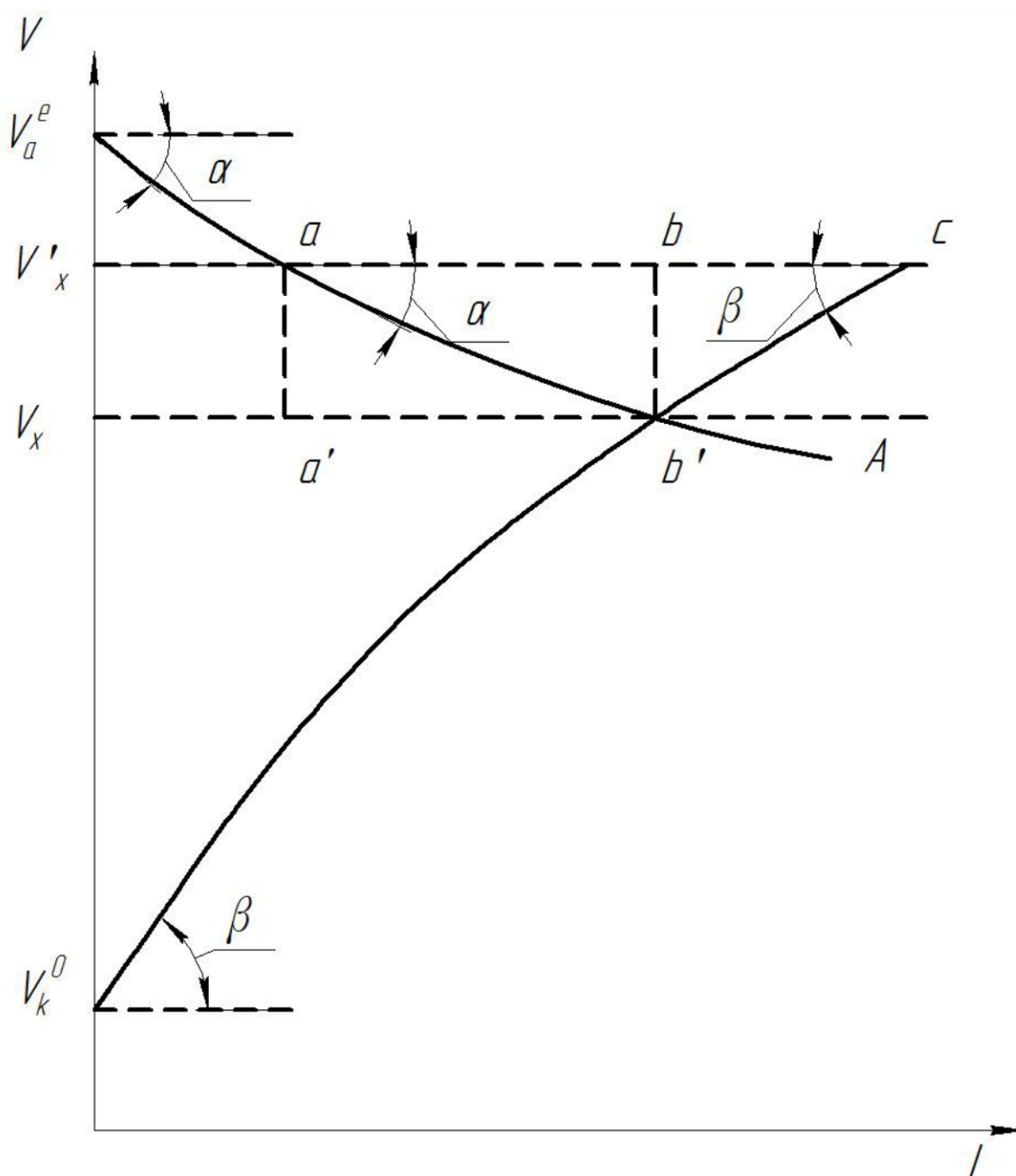


Figure 4.3 – Polarization diagram for graphical calculation of the coefficient of protective effect

If we consider the polarization curves at the point of their intersection b' as straight lines, it is possible to show the existence of a direct proportionality

between the protective effect and the density of the imposed cathodic current. This condition is fulfilled with a high degree of probability at a low value of the external cathode polarization current.

Based on the graphic construction (Fig. 4.3), it is possible to write the voltage potential according to the following expressions:

$$\Delta V = b \cdot c \cdot \operatorname{tg} \beta, \quad (4.1)$$

$$\Delta V = a \cdot b \cdot \operatorname{tg} \alpha, \quad (4.2)$$

Dividing the first expression by the second, we get:

$$\frac{bc}{ab} = \frac{\operatorname{tg} \alpha}{\operatorname{tg} \beta}, \quad (4.3)$$

After transformations, we can write this expression as follows:

$$\frac{bc}{ab} + 1 = \frac{\operatorname{tg} \alpha}{\operatorname{tg} \beta} + 1,$$

or otherwise:

$$\frac{bc + ab}{ab} = \frac{tg\alpha + tg\beta}{tg\alpha}, \quad (4.4)$$

Segment aa' is a protective effect during cathodic polarization by an external current I , which is graphically represented by a segment $ac = ab + bc$.

Then for the segment aa' we will have the ratio:

$$\frac{I}{aa'} = \frac{tg\alpha + tg\beta}{tg\beta}, \quad (4.5)$$

Where will we get:

$$aa' = \frac{tg\beta}{tg\alpha + tg\beta} I, \quad (4.6)$$

or otherwise:

$$aa' = K_{\text{зax.эф.}} \cdot I, \quad (4.7)$$

At constant values α and β the coefficient of the protective effect will be constant in value. If we consider that the cathode and anode polarization are linearly dependent on the current density, i.e. $tg\alpha = P_a$ and $tg\beta = P_\kappa$, then the protective effect coefficient can be written in the form:

$$K_{\text{ax. eq.}} = \frac{P_{\kappa}}{P_{\kappa} + P_a} = \frac{1}{1 + \frac{P_a}{P_{\kappa}}}, \quad (4.8)$$

Therefore, the protective effect, that is, the reduction of the local current with an increase in the external cathodic-polarized current, will be greater, the greater the cathodic polarization of the corrosion protection system.

If the polarization curves are close to straight lines, this rule will be valid over the entire range of the polarization current. If the polarization curves cannot be considered as straight lines, then the specified rule will be observed only at relatively small values of the external current compared to the value determined by the abscissa of the point of intersection of the polarization curves.

4.2 Development of a set of technical solutions to protect the inner surface of the tank wagon boiler from corrosion

Using in the protective protection project should be based on a technical calculation.

To basic requirements for the development of a protection system include:

- 1) protective protection of boilers can be designed both as a built-in block and as an individual structural design independent of the standard dimensions of the boiler.
- 2) protective protection can be applied as a backup when using cathodic-protective protection schemes.
- 3) protection with the help of protectors should be used with the specified calculated specific electrical resistance in accordance with the type of protectors, their number, material and electrolytic medium;
- 4) protector protection installations must be equipped with control and measuring devices and, if necessary, regulating resistors or shunts;
- 5) provision of protective protection should consist of single or group installations, while the choice of the type and layout of the protectors should be carried out taking into account the specific conditions of installation at the object;
- 6) the protective current density on the surface of the tank wagon boiler from the projectors must be taken into account during the design calculation.

The set of technical solutions includes:

- proposals for the creation of a block system of tank wagon boiler protection;
- development of drawings for the protection mechanism;
- creating a layout of the protection system;

- development of a schedule for carrying out planned diagnostic works to determine the technical condition of the internal surface of the tank wagon boiler after the introduction of anti-corrosion protection systems;
- application of the ultrasonic method of controlling the metal thickness of the boiler shell according to the developed measurement scheme.

In accordance with the proposals, the tank wagon boiler protection system for the transportation of chemical wagongo looks like this:

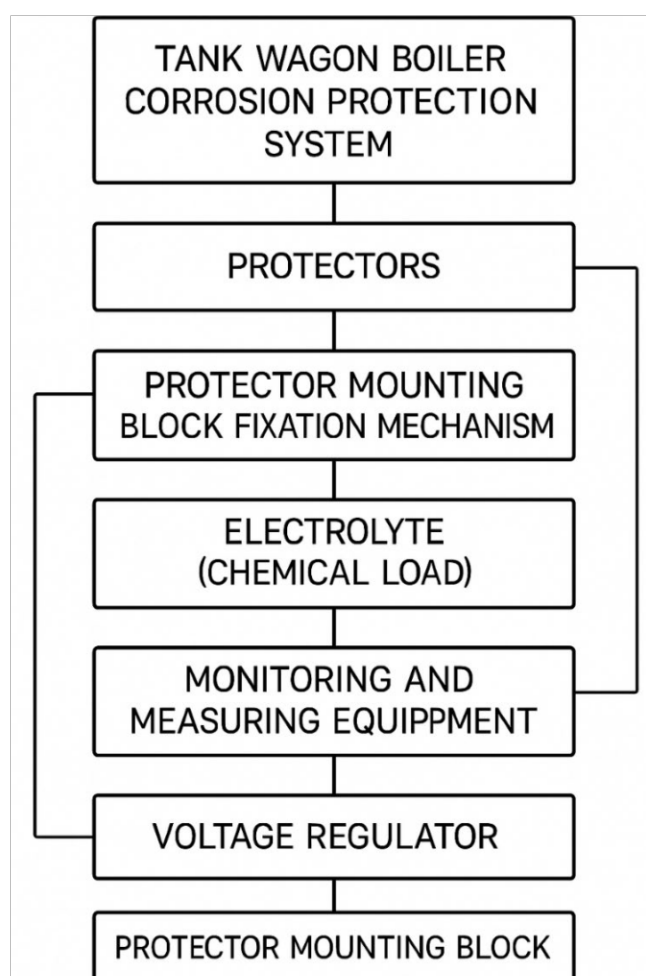


Figure 4.4 – Block diagram of the tank wagon boiler protection system

The protection system is presented in the form of a complex that contains two blocks of protectors with galvanic anodes, united in independent groups, located at a certain distance from each other inside the tank wagon boiler. Such groups are mixed in the lower part of the boiler and fixed with the help of the fixing mechanism of the protector placement block in the selected spatial position. Assembly and disassembly of protectors of the block part is performed at the place of their installation. The anodes can be connected using a parallel or series connection scheme to the active group.

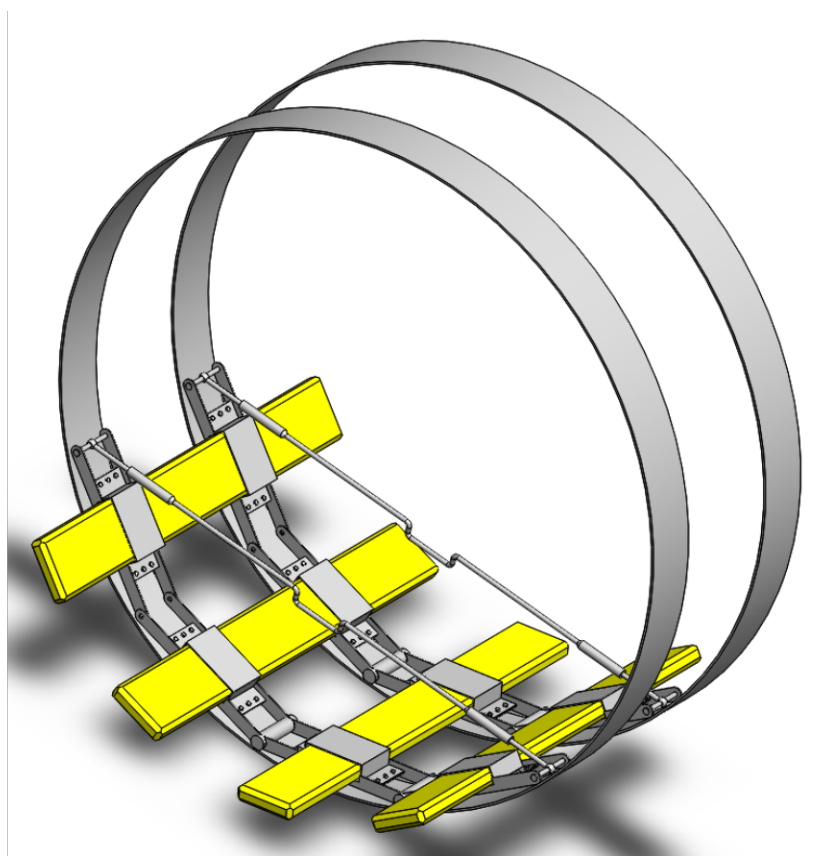


Figure 4.5 – The basic layout block of the anti-corrosion protection system of
the tank wagon boiler

The protectors are connected to the body of the tank wagon boiler with the help of resistors, the resistances of which must be calculated depending on the type of chemical cargo in order to limit the maximum current of the protector. A voltage regulator is connected to the resistors according to the scheme to determine the potential difference between the cathode (inner surface of the boiler body) and the anode (protector). The effectiveness of protective protection is determined by the amount of cathodic polarization (displacement of the electrolyte potential), which is measured relative to the working electrodes, or by means of a potential measurement unit (control and measurement equipment) brought outside and mounted on the tank wagon boiler frame.

Drawings of the tank wagon boiler protection mechanism are presented in Appendix A of this report, and the basic layout block is shown in Figure 4.5. Conducting planned diagnostic work to determine the technical condition of the internal surface of the tank wagon boiler after the introduction of anti-corrosion protection systems involves working according to the developed schedule presented in Figure 4.6.

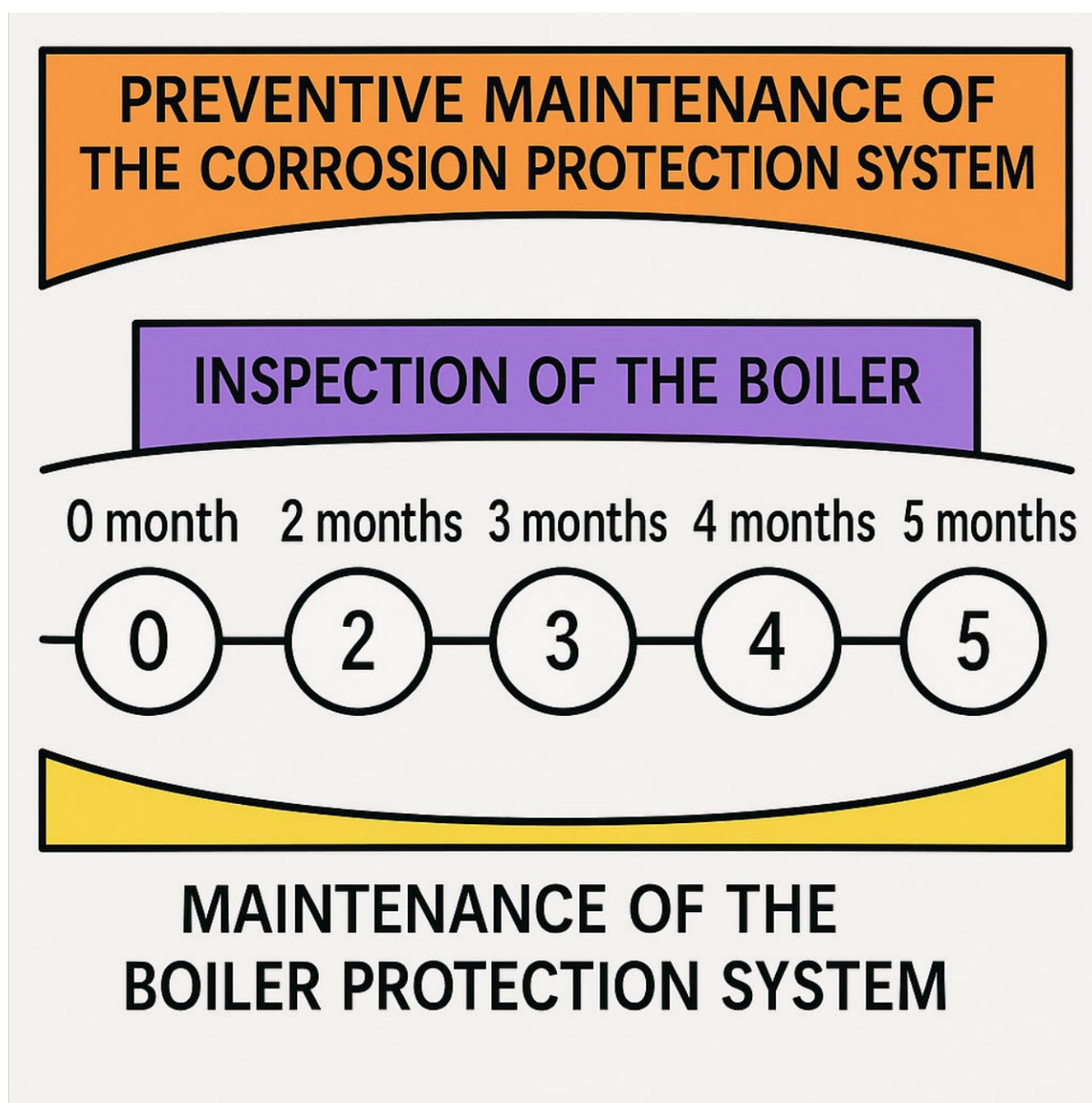


Figure 4.6 – Schedule of planned diagnostic works of boilers of tank wagons for
the transportation of chemical wagongo ($\text{pH} = 6\div 8$).

The scope of work during technical diagnostics of the tank wagon boiler
and checking the current state of the protection system must take into account the
following operations:

- a clear sequence of actions to be followed during the actual inspection of the boiler surfaces according to the established work schedule;
- checking the metal thickness of the research object using non-destructive testing methods (visual and ultrasonic);
- accumulation of data on the technical condition of individual elements or parts of the research object;
- forecasting data regarding the possibility of changing the resource of boiler operation using computer analysis of the stress-strain state of the boiler;
- diagnosing the technical condition of protective anti-corrosion equipment;
- carrying out preventive measures for the repair of protective protection systems.

Introduction of the ultrasonic method of metal thickness control can be carried out according to the proposed scheme (Fig. 4.7).

In accordance with the presented scheme (Fig. 4.7), measurements must be carried out in different sections of the boiler, which belong to separate groups. The first group contains five control zones in the lower, side and partially upper part of the cylindrical shell of the boiler. Measurement operations for this group are performed in six geometrically defined vertical sections: four of them are

located near the bearing supports, and two more are located near the middle of the cylindrical part of the boiler.

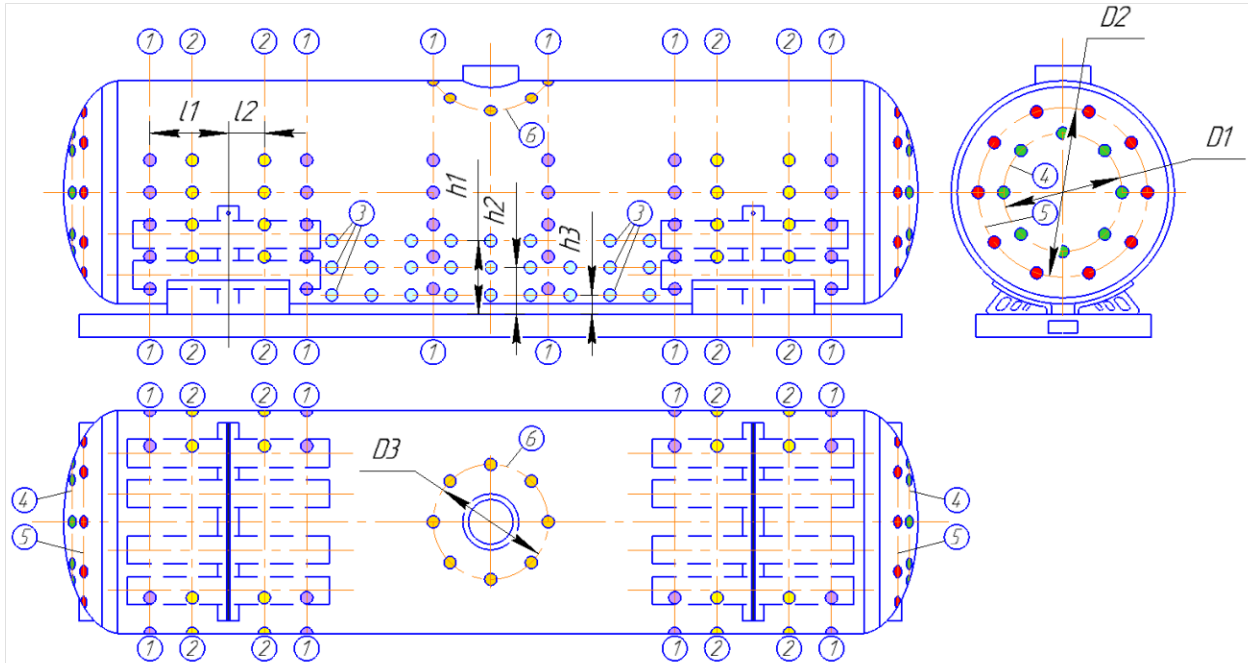


Figure 4.7 – Scheme of detection of changes in metal thickness due to corrosion.

The second group has four control zones in the lateral and partly upper part of the boiler shell. Measurement operations for this group are carried out near the location of the clamps in the four vertical sections. The third group includes control zones in the lower and side parts of the boiler along the cylindrical part in three horizontal sections. The fourth and fifth groups take into account places on the bottom of the boiler where corrosion is possible, along the average radius of the ellipsoid bottom and $3/4$ of the radius from its center, respectively. The sixth group consists of eight control zones, which are located in a circle relative to the boiler hatch and are located at a distance that is approximately twice its diameter.

On the basis of the conducted ultrasonic control method, collection and analysis of the received data, relying on the results of stress-strain state calculations based on stress state assessment methods based on the created mathematical model of the cylindrical shell of the boiler, it is possible to assert the feasibility of using a protective protection system and its effectiveness in reducing the impact of corrosion for tank wagons carrying chemical cargo (for which $\text{pH} = 6\div 8$) for a certain period of operation.

4.3 Algorithm for calculating the tread protection system

Proposed variant of protector protection of boilers of tank wagons involves the use of groups of protectors, which are placed in the boiler in blocks (Fig. 4.8). The purpose of calculating the protective protection parameters is to determine the number of extended protectors installed in parallel and their total weight, which provide a given degree of tank protection.

For simplification of calculation, we will divide it into separate stages.

Stage 1.

Calculation of protective cathodic polarization, B :

$$\Delta\varphi_{II} = 0,081g(1 - P_3), \quad (4.9)$$

where P_3 – the degree of protection of the tank wagon boiler against corrosion, $P_3 = 0,95 - 0,99$.

$$\Delta\varphi_{II} = 0,081g(1 - 0,95) = -0,104 \text{ B.}$$

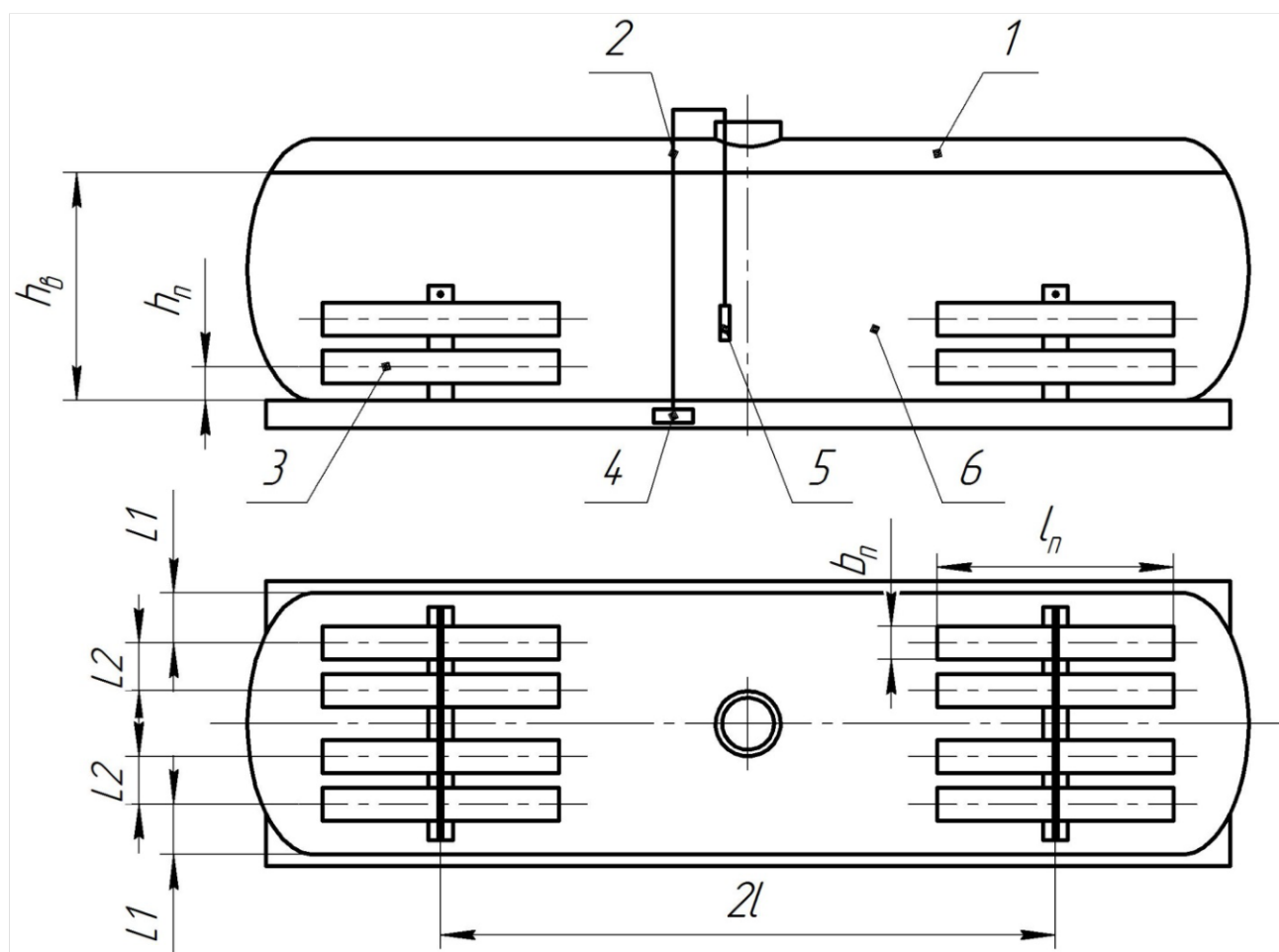


Figure 4.8 – Scheme of protective protection of the tank wagon boiler for the transportation of chemical cargoes:

1 – tank wagon boiler; 2 – electrical conductor; 3 – block of protectors; 4 –
control and measuring equipment; 5- electrode;
6 – liquid chemical cargo.

Stage 2.

Calculation of the minimum required protective current density on the surface of
the tank wagon boiler, A/m²:

$$j_3 = \frac{|\Delta\varphi_{II}|}{P_c}, \quad (4.10)$$

where P_c – polarization resistance of steel, $P_c = 1 \text{ Ом} \cdot \text{м}^2$.

$$j_3 = \frac{|-0,104|}{1} = 0,104 \text{ A/м}^2.$$

Stage 3.

The arc angle of the tank wagon boiler circle (degrees), which is wetted by the
liquid phase, is calculated by the formula:

$$\psi = 360 - 2 \arccos \frac{2h_6 - D}{D}, \quad (4.11)$$

where h_g – the level of the liquid phase in the tank wagon boiler, $h_g = 2,85$ м.

$$\psi = 360 - 2 \arccos \frac{2 \cdot 2,85 - 3,0}{3,0} = 308^\circ$$

Calculation of the area of the inner surface of the tank wagon boiler, which is in contact with the water phase, m^2 :

$$S_u = \frac{\psi}{360} \cdot \pi D L_u + 1,3 \left(\frac{\pi D^2 \psi}{2 \cdot 360} + \frac{D^2}{2} \cdot \sin \frac{(360 - \psi)}{2} \cdot \cos \frac{(360 - \psi)}{2} \right), \quad (4.12)$$

where D – the inner diameter of the tank wagon boiler, $D = 3,0$ м;

L_u – the length of the cylindrical part of the tank wagon boiler, $L_u = 9,614$ м

;

ψ is the angle of the arc of the circumference of the boiler of the tank wagon wetted by the liquid phase, $\psi = 308^\circ$.

$$S_u = \frac{308}{360} \cdot \pi \cdot 3,0 \cdot 9,614 + 1,3 \left(\frac{\pi \cdot 3,0^2 \cdot 308}{2 \cdot 360} + \frac{3,0^2}{2} \cdot \sin \frac{(360 - 308)}{2} \cdot \cos \frac{(360 - 308)}{2} \right) = 92,94 \text{ м}^2$$

Stage 4.

The protective surface area of the tank wagon boiler (m²) is calculated according to the formula:

$$S_3 = S_y \cdot S_0, \quad (4.13)$$

where S_0 – coefficient of defectiveness of the anti-corrosion protective coating of the tank wagon boiler, $S_0 = 0,1$.

$$S_3 = 92,94 \cdot 0,1 = 9,294 \text{ m}^2.$$

Stage 5.

Determination of the current required to protect the inner surface of the tank wagon boiler is performed according to the formula:

$$I_{II} = j_3 \cdot S_3, \quad (4.14)$$

$$I_{II} = 0,104 \cdot 9,294 = 0,967 \text{ A}.$$

Stage 6.

Let's calculate the current that can be provided by one row of protectors according to the formula:

$$I = \frac{m_0 \cdot N \cdot L_y \cdot K_g}{T_{\Pi} \cdot q}, \quad (4.15)$$

where m_0 - the mass of one linear meter of tread rod, $m_0 = 8,3 \text{ кг/м}$;

N - the number of rows of projectors, $N = 1$;

L_y - the length of the cylindrical part of the tank wagon boiler, $L_y = 9,614 \text{ м}$

;

K_g - coefficient of use of the tread mass, $K_g = 0,75$;

T_{Π} - the design service life of the protectors, $T_{\Pi} = 5 \text{ років}$;

q - speed of anodic dissolution of the protector, $q = 11,9 \text{ кг/А} \cdot \text{год}$.

$$I = \frac{8,3 \cdot 1 \cdot 9,614 \cdot 0,75}{5 \cdot 11,9} = 1,01 \text{ А}$$

Stage 7.

We will calculate the number of rows of protectors that provide the required current strength to protect the inner surface of the tank wagon boiler according to the formula:

$$N = \frac{I_{II}}{I}, \quad (4.16)$$

$$N = \frac{0,967}{1,01} = 0,957 \text{ A}$$

We accept $N = 1$.

Stage 8.

Calculation of the total resistance between the tread and the tank wagon, with the estimated number of rows of treads N .

The area coefficient of the use of protectors is calculated according to the formula:

$$A = \frac{2h_{II}(D - h_{II})}{D \cdot A_{II}}, \quad (4.17)$$

where h_{II} – the height of the location of the tread in the tank wagon, $h_{II} = 0,1 \text{ м}$;

A_{II} – cross-sectional area of the tread rod, $A_{II} = 0,021 \text{ м}$.

D – the inner diameter of the tank wagon boiler, $D = 3,0 \text{ м}$;

$$A = \frac{2 \cdot 0,1 \cdot (3,0 - 0,1)}{3,0 \cdot 0,021} = \frac{0,58}{0,063} = 9,21$$

$$R = \frac{1}{\psi} \left[\frac{4(\rho_B \delta_{II} + P_c)}{(2L_y + D)DS_0} + \frac{\rho_B}{\sqrt{N}} \ln(A + \sqrt{A^2 - 1}) \right], \quad (4.18)$$

where ψ is the angle of the arc of the circumference of the boiler of the tank wagon wetted by the liquid phase, $\psi = 0,9$ рад;

ρ_B – specific resistance of the liquid phase of the chemical mixture in the tank wagon boiler, $\rho_B = 0,15$ Ом · м;

δ_{II} – the thickness of the anti-corrosion coating of the inner surface of the tank wagon boiler, м, $\delta_{II} = 1,5 \cdot 10^{-4}$ м;

P_c – polarization resistance of the steel from which the boiler is made, $P_c = 1$ Ом · м²;

L_y – the length of the cylindrical part of the tank wagon boiler, $L_y = 9,614$ м ;

S_0 – coefficient of defectiveness of the anti-corrosion coating, $S_0 = 0,1$ м²/м²;

N – the number of rows of protectors, $N = 1$.

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{1}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 1,149 \text{ Ом}$$

Stage 9.

Calculation of protective current strength of the tank wagon boiler.

$$I'_B = \frac{\Delta\varphi_e + \Delta\varphi_{\Pi}}{R + \frac{P_{\Pi}}{\pi A_{\Pi} L_y N}}, \quad (4.19)$$

where $\Delta\varphi_e$ – the difference between the natural potentials of the protector and the boiler for AC5Mn5, $\Delta\varphi_e = 0,3 \text{ В}$;

$\Delta\varphi_{\Pi}$ – protective cathodic polarization, $\Delta\varphi_{\Pi} = -0,104 \text{ В}$;

P_{Π} – polarization resistance of the steel from which the boiler is made,

$$P_{\Pi} = 0,1 \text{ Ом} \cdot \text{м}^2.$$

$$I'_B = \frac{0,3 - 0,1}{1,149 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 1}} = 0,150 \text{ А}.$$

Stage 10.

Checking the sufficiency of the mass of the estimated number of protectors to ensure the strength of the protective current I_B'' during the design life of the treads T_{II} .

$$I_B'' = \frac{m_0 \cdot N \cdot L_y \cdot K_\epsilon}{T_{II} \cdot q}, \quad (4.20)$$

$$I_B'' = \frac{8,3 \cdot 1 \cdot 9,614 \cdot 0,75}{5 \cdot 11,9} = 1,01 \text{ A}$$

Because I_B'' more than I_B' ($1.01 \text{ A} > 0.150 \text{ A}$) then the mass of the estimated number of protectors is sufficient.

Stage 11.

Calculation of protective current density in the lower part of the tank wagon boiler.

$$j = \frac{4 \cdot I_B' \cdot K_T}{(2L_y + D) \cdot D \cdot S_0 \cdot \psi}, \quad (4.21)$$

where K_T – coefficient of non-uniformity of the distribution of current density along the perimeter of the boiler shell of the tank wagon.

The coefficient of the area of the lower part of the boiler is calculated according to the formula:

$$\lambda = \frac{(D - 2h_{II})}{D}, \quad (4.22)$$

$$\lambda = \frac{(3,0 - 2 \cdot 0,1)}{3,0} = 0,93$$

The coefficient of specific resistance of the boiler with liquid is determined by the formula:

$$C = \frac{4 \cdot \pi \cdot P_c}{\rho_B \cdot D \cdot \psi \cdot S_1}, \quad (4.23)$$

S_1 – coefficient of defectiveness of the anti-corrosion coating of the lower part of the tank wagon boiler, $S_1 = 0,3 \text{ м}^2/\text{м}^2$;

$$C = \frac{4 \cdot 3,14 \cdot 1}{0,15 \cdot 3,0 \cdot 308 \cdot 0,3} = 0,302.$$

$$K_T = 1,5 - 1,3 |\lg C|, \quad (4.24)$$

$$K_T = 1,5 - 1,3 |\lg 0,302| = 0,824.$$

$$j = \frac{4 \cdot 0,150 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,082 \text{ A/m}^2.$$

$$\frac{j}{j_3} > 1,2, \quad (4.25)$$

$$\frac{j}{j_3} = \frac{0,082}{0,104} = 0,79 < 1,2$$

Since the condition $j / j_3 > 1,2$ does not comply, then we will increase it N per unit and perform the calculations again.

Let's calculate the total resistance between the tread and the boiler of the tank wagon, at $N = 2$.

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{2}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 1,007 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{1,007 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 2}} = 0,180 \text{ A}$$

$$j = \frac{4 \cdot 0,180 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,099 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,099}{0,104} = 0,95 < 1,2$$

Since the condition $j / j_3 > 1,2$ does not comply, then we will increase it N per unit and perform the calculations again.

Then at $N = 3$ we will have:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{3}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 0,944 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,944 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 3}} = 0,197 \text{ A}$$

$$j = \frac{4 \cdot 0,197 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,108 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,108}{0,104} = 1,03 < 1,2$$

As a condition $j / j_3 > 1,2$ is not executed, then we will increase it N per unit and perform the calculations again.

So at $N = 4$ we will get:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{4}} \ln \left(9,21 + \sqrt{9,21^2 - 1} \right) \right]$$

$$= 0,907 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,907 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 4}} = 0,207 \text{ A}$$

$$j = \frac{4 \cdot 0,207 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,113 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,113}{0,104} = 1,09 < 1,2$$

Based on the fact that the condition $j / j_3 > 1,2$ is not executed, then we will increase it again N per unit and repeat the calculations.

Then at $N = 5$ we will get:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{5}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right]$$

$$= 0,881 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,881 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 5}} = 0,215 \text{ A}$$

$$j = \frac{4 \cdot 0,215 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,118 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,118}{0,104} = 1,13 < 1,2$$

Given that the condition $j / j_3 > 1,2$ does not work, let's increase it again

N per unit and make calculations.

Then at $N = 6$ we will get:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{6}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 0,863 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,863 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 6}} = 0,220 \text{ A}$$

$$j = \frac{4 \cdot 0,220 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,121 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,121}{0,104} = 1,16 < 1,2$$

As a condition $j / j_3 > 1,2$ is not executed, then we will increase it N per unit and calculate again.

At $N = 7$ we will get:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{7}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 0,848 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,848 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 7}} = 0,225 \text{ A}$$

$$j = \frac{4 \cdot 0,225 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,123 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,123}{0,104} = 1,18 < 1,2$$

Condition $j / j_3 > 1,2$ is not executed, so let's increase it N per unit and perform repeated calculations.

At $N = 8$ we will get:

$$R = \frac{1}{0,9} \left[\frac{4(0,15 \cdot 1,5 \cdot 10^{-4} + 1)}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1} + \frac{0,15}{\sqrt{8}} \ln(9,21 + \sqrt{9,21^2 - 1}) \right] = 0,836 \text{ Ом}$$

$$I'_B = \frac{0,3 - 0,1}{0,836 + \frac{0,1}{3,14 \cdot 0,021 \cdot 9,614 \cdot 8}} = 0,229 \text{ A}$$

$$j = \frac{4 \cdot 0,229 \cdot 0,824}{(2 \cdot 9,614 + 3,0) \cdot 3,0 \cdot 0,1 \cdot 0,902} = 0,125 \text{ A/m}^2$$

$$\frac{j}{j_3} = \frac{0,125}{0,104} = 1,205 > 1,2$$

Condition $j / j_3 > 1,2$ is performed

Therefore, 8 rows are enough to ensure protective current density on the surface of the tank wagon boiler. With a tread length of 2 meters, the approximate weight of the tread protection will be:

$$M_{\text{защ.пог.}} = n \cdot b \cdot h \cdot l \cdot \rho, \quad (4.26)$$

where n - the number of rows of protectors, $n = 8$ рядів ;

b – tread width, $b = 0,28$ м ;

h - tread height, $h = 0,075$ м ;

l – tread length, $l = 2$ м ;

ρ – zinc density, $\rho = 7100$ кг/м³ .

$$M_{\text{захис.прот.}} = 8 \cdot 0,28 \cdot 0,075 \cdot 2 \cdot 7100 = 2385,6 \text{ кг} .$$

It should be noted that the approximate weight of the total number of protectors is a variable parameter and may change depending on the use of different types of profiled zinc pipes.

Conclusions according to section 4

The section presents information on the possibility of providing electrochemical protection of the tank wagon boiler against the appearance and spread of corrosion using various protection methods, among which preference is given to the protector method of protection using a galvanic anode. The considered issues are related to the theory of calculation of the coefficient of

protective effect based on the analysis of the polarization diagram of corrosion. It was established that the protective effect will be greater, the greater the cathodic polarization of the corrosion protection system when the local current decreases with an increase in the external cathodic-polarized current.

To develop a surface protection system for a tank wagon boiler, the requirements that should determine the principles of construction and its operation were considered, as well as a complex of technical solutions and measures aimed at wagonrying out diagnostics, checking the technical condition and performing repair work within the established time frame was proposed. The authors of the report suggest using an ultrasonic control method to detect changes in metal thickness according to the pattern of group intersections.

In order to determine the necessary degree of protection of the tank wagon boiler, an algorithm for calculating the protective protection system was developed: determination of cathodic polarization of the metal surface of the boiler; calculation of the minimum required protective density and amperage; ensuring the required number of rows of protectors.

CONCLUSIONS

The decrease in the technical resource of the wagon is associated with corrosion processes. Boilers of tank wagons are one of the most vulnerable parts that are subject to corrosion caused by physical processes of contacting different environments and chemical reactions that occur in them as a result of their direct interaction. Over time, corrosion reduces the integrity of the boiler, penetrating into its structure, which causes a change in thickness and leads to loss of strength properties of the shell metal. The occurrence of corrosion phenomena and their spread is a particularly dangerous factor during the transportation of chemical corrosion-active wagons in boiler tank wagons, as it significantly accelerates the chemical oxidation reactions of the metal of the boiler shell and carries the threat not only of premature repair or even replacement of the boiler, but also to be a factor in man-made disasters in case of leakage of chemicals into the environment.

The first section of the report presents a statistical analysis of tank wagon boiler malfunctions. For various types of corrosion of tank wagon boilers, approximate static relationships that arise between them are shown. Special attention is focused on pitting and ulcer corrosion of the boiler shell, because due to the small size of ulcers and their filling with corrosion products, such destruction is difficult to detect and eliminate in a timely manner. The thermodynamic processes of chemical corrosion of metal with various oxidants:

acids and alkalis are considered in detail. In order to rationalize the application to determine the thickness of the metal shell of the boiler, an analysis of active and passive methods of non-destructive testing was carried out. A description of the generalized implementation of ultrasonic thickness measurement at the hardware level is given due to the need to find options for conducting further experimental studies using optimal diagnostic solutions.

The second section of the report contains a mathematical description and theoretical bases for calculating the discrete model of the orthotropic shell of the cylindrical part of the tank wagon boiler according to the momentless and semi-momentless theory for solving the problems of axisymmetric deformation of the shells under the action of loads. The asymptotic analysis of the exact equations of the theory of isotropic shells shows that, depending on the variability of external factors and the stress state, they allow certain simplifications. The degree of simplification depends on the index of variability of the surface or edge load and, therefore, on the index of variability of the stress state. The stress-strain state of the shell can be asymptotically divided into elementary stress states, each of which is described by known approximate equations of the theory of shells and flat bodies. In the conducted study, to determine the stress-deformed state of the cylindrical part of the tank wagon boiler under the condition of reducing the thickness of the shell to obtain the values of its maximum allowable values, it is proposed to use the classical semi-momentless theory of shells, based on the

Kirchhoff-Leav hypotheses. The method of calculated intersections proposed by the authors of the report based on the semi-momentless shell theory provides an opportunity to determine the necessary parameters (displacement, stress) at individual points of the polar coordinate system. According to the presented method, the calculation of the stress-strain state of the tank wagon boiler for improved sulfuric acid model 15-1548-02 was carried out under the I load mode in the MATHCAD mathematical package. The work also presents studies of other models of tank wagons for the transportation of chemical cargoes (15-1443-14, 15-1454-11, 15-1520, 15-1520-01, 15-1527, etc.) from the point of view of the influence of operational loads wagons to the stressed-deformed state of the cylindrical shell of the boiler according to the accepted assumptions. For cases of changes in the thickness of the boiler shell in the range from 1.1 to 0.7 cm in different calculated sections, based on the results of the calculations, it was established that the equivalent stresses exceed the permissible values of the yield strength of the 09G2C material at the minimum value of the shell thickness $\delta = 0,7$ cm in the pivot section at the place of support of the boiler with mass characteristics similar to the model 15-1443-14 on lying supports. With the determined minimum permissible thickness of the shell of the tank wagon boiler due to the effect of corrosion and theoretical calculations, the models 15-1454-11 and 15-1527 are also the most dangerous from the point of view of further safe operation under active loads among the considered tank wagons.

The third section of the report is devoted to issues of development and implementation of stress-strain state assessment methods taking into account the impact of corrosion, finding technical solutions to increase the reliability of wagon structures during the transportation of corrosive-active cargoes. The development and description of the calculation model of the boiler based on the model 15-1443-14 tank wagon in the SolidWorks software complex was carried out. In the course of the calculations, it was established that the most dangerous areas are the areas of the bottoms and the hatch when corrosion with a depth of 3 mm or more occurs, which makes it impossible to extend the life of the boiler. In case of corrosion up to 2 mm deep, the maximum service life of the boiler can be 30 years. In case of complete absence of corrosion, the service life can be extended by 12 years, i.e. up to one and a half years (36 years) from the designated service life of 24 years. The authors of the report proposed a method for determining the fatigue strength of the tank wagon boiler, which allows predicting the further possibility of operating the structure beyond the intended service life, taking into account the appearance of corrosive wear and analysis of local places of the structure where the most dangerous stresses occur. This will contribute to a reasonable determination of the permissible period of operation of tank wagons, which have deviations of the thickness of the boiler elements from the normative values due to the action of corrosion.

In the fourth section of the report, the issue of choosing an effective method of protection against metal corrosion of the boiler surfaces is considered, among which preference is given to the protective method of protection using a galvanic anode. The theory of calculating the protective effect coefficient based on the analysis of the corrosion polarization diagram is presented. An assessment of the effectiveness of protection in case of a change in cathode polarization is given. The requirements that should determine the principles of the construction of the protection structure and its functioning were considered, and a set of technical solutions and measures aimed at conducting diagnostics of the metal surfaces of the research object and its protection systems, checking the technical condition within the specified maintenance periods and introducing the implementation of repair works. As a basic method of control, the working group of researchers of this report proposes to use the ultrasonic method to detect the change in metal thickness according to the developed scheme of group intersections. The algorithm for calculating the protective protection system presented in this section provides for the implementation of a set of measures aimed at ensuring the required degree of anti-corrosion protection of the tank wagon boiler and ensuring an increase in its resource as a whole.

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Фомін Олексій Вікторович; Ловська Альона Олександрівна; Фоміна Анна

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202101164; заявка 03.04.2022; публ. 02.11.2022, Бюл. № 44

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B61D 3/08 (2006.01) Фомін Олексій Вікторович; Ловська Альона

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B61D 17/00 Фомін Олексій Вікторович; Ловська Альона

Олександрівна; Фоміна Анна Миколаївна; Климаш Андрій Олександрович;

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Фомін Олексій Вікторович; Ловська Альона Олександрівна; Фоміна Анна
Миколаївна; Сергієнко Оксана Олександрівна; Сова Сергій Сергійович;
Литвиненко Андрій Сергійович Універсальний критий вагон. (Україна);
власник: Східноукраїнський національний університет імені Володимира
Даля № u 202101172; заявка 04.04.2022; публ. 02.11.2022, Бюл. № 44

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Фомін Олексій Вікторович; Ловська Альона Олександрівна; Сова Сергій
Сергійович; Литвиненко Андрій Сергійович Вагон-хопер. (Україна);
власник: Східноукраїнський національний університет імені Володимира
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Фомін Олексій Вікторович; Ловська Альона Олександрівна; Сова Сергій

Сергійович; Литвиненко Андрій Сергійович Вагон-хопер для мінеральних

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(2006.01) B61D 3/00 Фомін Олексій Вікторович; Ловська Альона

Олександрівна; Сова Сергій Сергійович; Литвиненко Андрій Сергійович

Універсальний піввагон. (Україна); власник: Східноукраїнський

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Фомін Олексій Вікторович; Ловська Альона Олександрівна; Сова Сергій

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STUDY OF THE STRESSED AND DEFORMED STATE OF A TANK WAGON
BOILER FOR TRANSPORTATION OF CHEMICAL CARGO
UNDER THE INFLUENCE OF CORROSION

Monograph

This monograph is dedicated to the pressing issue of ensuring the reliability and safety of the operation of tank wagons intended for the transportation of chemical cargo under conditions of corrosion wear. The work comprehensively investigates the influence of corrosion on the stressed and deformed state of the tank wagon boiler.

Chapter 1 assesses the effect of corrosion on the operability of boilers of tank wagons intended for the transportation of chemical loads. The mechanisms of corrosion damage to the inner surface of the boilers are analyzed, statistical information on corrosion-related malfunctions is presented, and the behavior of metals and alloys in aggressive chemical environments is considered. The application of non-destructive testing methods for determining the actual thickness of the boiler metal is substantiated.

Chapter 2 focuses on the theoretical foundations for calculating the stressed and deformed state of a tank wagon boiler using the Mathcad software environment. The basic principles of calculating discrete models of physical shells are outlined, the calculation method and necessary input data are defined. An algorithm for determining the stress-strain state of the cylindrical shell of the boiler in the Mathcad environment is presented.

Chapter 3 presents a study of the stressed and deformed state of the boiler shell of a tank wagon and an assessment of its fatigue strength in case of corrosion wear using computer simulation. The calculation method is described, and a computational model of the boiler based on the 15-1443-14 tank wagon model in the SolidWorks software complex is developed and described. The results of the conducted research are provided and analyzed.

Chapter 4 offers proposals for increasing the service life of tank wagon boilers. Methods of protection against metal corrosion are considered, a set of technical solutions for protecting the inner surface of the tank wagon boiler from corrosion is developed, and an algorithm for calculating the tread protection system is proposed.

This monograph is intended for researchers, engineers, postgraduate students, and students specializing in the fields of railway transport, materials science, metal corrosion, and structural strength.

It can also be used as a учебное пособие (teaching aid/textbook) for relevant academic disciplines.

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