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DETERMINING DYNAMIC PROCESSES IN A TANK AFTER ITS SEPARATION FROM THE BOTTOM DURING A FIRE

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The object of this study is the process of separating the body of a vertical steel tank from the bottom under the influence of emergency thermal and dynamic loads characteristic of fires at tank farms. The task addressed was to predict parameters of the trajectory of movement of a vertical steel tank with fuel when it is separated under the action of internal excess pressure due to the thermal effects of a fire.

The dynamic processes of destruction of the weld at the bottom of the tank enclosure and the processes of fuel leakage from it were investigated. During the research, a computer model of the process of separation of a part of the tank was substantiated, which takes into account the geometric and physical nonlinearity of the material behavior under such conditions, as well as hydrodynamic processes during fuel leakage. Computer simulation showed that the height of the tank's flight when it is separated from the bottom depends on its filling level and total volume. At the same time, a lower filling level of the tank and its smaller volume determine a lower height of its bouncing. This is explained by the fact that the increase in the weight of the mechanical system, which is a tank with an oil product, leads to an increase in energy for the corresponding bouncing height.

To describe the revealed patterns, a regression analysis was conducted. As a result, empirical dependences were established between the kinematic parameters of the bouncing trajectory, the design characteristics of the tank, and its filling level. The acceptable adequacy of the data obtained by the revealed regression dependence was shown.

The revealed patterns are a scientific basis for compiling practical recommendations on technological requirements for storing oil products in vertical tanks to reduce the risk of their bouncing over long distances during an internal explosion due to a fire

Keywords: tank separation, numerical modeling, finite element method, regression analysis

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1. Introduction

Predicting the danger of vertical steel tanks in emergencies, in particular fires, is a pressing issue for enterprises where liquid petroleum products are stored. Welded joints are the weak link in tank structures, especially at high temperature loads. The occurrence of separation of the tank body from the bottom during a fire could lead to structural failure, leakage of hazardous substances, and environmental disasters. To prevent such events, it is necessary to conduct detailed modeling of the processes of destruction of welded joints under dynamic and temperature influences. However, the main dangerous effect is the tank flying up after it is separated from the bottom. In this case, particularly dangerous consequences may arise that may threaten the life and health of people, the spread of fire to larger areas, an increase in the scale of pollution, etc. Therefore, it is important to design tools for predicting the trajectory and range of the tank flying up when it is separated from the bottom, depending on the structural features of the tank and its filling level.

The problem of the mechanics of separation of the tank body from the bottom is complex due to the need to take into account nonlinear deformation of the material and welds in the heated state during a fire. It also includes analysis of the processes of material destruction during separation and the influence of fuel that flows out after separation. Such a problem is science-intensive since its solution requires the use of a multicomponent mathematical model that includes a description of the simultaneous occurrence of several interconnected dynamic processes in solids and a hydrodynamic process. At the current stage of development of methods for mathematical description of dynamic systems, such problems can be solved only by numerical methods involving powerful computing equipment and productive computational algorithms. That is, there is an opportunity to use such an approach when solving this problem, taking into account all the most significant dynamic processes, including the hydrodynamics of the liquid, which is the fuel in the tank. This will make it possible to accurately determine the design parameters of the tank and its filling level to reduce the risk of flying up when separating from the bottom during a fire. The results could be taken into account when revising the standards and rules for fuel storage at tank farms in order to improve fire safety.

Therefore, research aimed at devising methods for predicting the kinematics of the fuel tank bouncing when it is separated from the bottom during a fire is relevant.

2. Literature review and problem statement

The results of the research reported in [1] concern the behavior of the enclosing structures of above-ground steel tanks with fixed roofs during fires, where they occur relatively often [1]. This paper examines the causes and consequences of fires at tank farms, including cases of separation of tanks from the bottom. However, there is no analysis and hypotheses regarding the occurrence of this phenomenon. Study [2] provides analysis of the features of the course of fires at oil storage facilities, but information on cases of internal explosions in tanks that cause their separation from the bottom is limited.

The results of the research reported in [3–7] focus on key aspects of fires in oil tanks in Ukraine, offering risk analysis and practical recommendations for improving the safety of such facilities. The general statistics of destruction of vertical steel tanks (VSTs) indicate that 46.4 % of cases were accompanied by large-scale fires with casualties. Of these, 6.4 % of destructions were the result of direct exposure to high temperatures and pressure. The mechanism of VST destruction is complex and not yet sufficiently studied. Also, the processes of movement of the tank and its main components when separated from the bottom as a result of the thermal effect of the fire are not taken into account.

In work [3], the specificity of combustion of petroleum products in tanks is analyzed in detail and measures are proposed to strengthen the fire protection of these structures. However, the work does not link combustion processes with the risk of internal explosions in tanks with their destruction. Work [4] considers combustion processes inside the tank but their connection with the heating of petroleum products and tank walls was not studied.

In study [5], the risk of fires at tank farms for the storage of petroleum products was assessed, taking into account various factors that affect the safety of operation of such facilities. The analysis provided does not contain data on the processes of tank destruction due to fire and does not consider the risks of tank bouncing as a result of an internal explosion.

Work [6] considers methods for increasing safety during fires in oil tanks, including recommendations for the selection of fire-fighting equipment and extinguishing agents, but it does not contain recommendations for preventing tank destruction due to depressurization or destruction as a result of internal explosion. Paper [7] reports the results of theoretical studies on the processes of tank destruction due to the thermal effects of fire, but this analysis is limited only to the strength of their elements. The processes of tank motion dynamics during their separation from the bottom and hydrodynamic processes during the leakage of oil products through the formed through holes were left out of consideration.

Study [8] is aimed at analyzing the influence of non-stationary thermal processes in the structures of vertical steel tanks that arise under the influence of thermal factors of fires, and their influence on the strength of structures. The study is limited to the conditions of occurrence of the limit values of the parameters of the stress-strain state of the tank enclosure. In this case, the processes of separation dynamics and flying up of the detached part were not considered.

According to the results of expert analyses, the main cause of VST destruction was determined to be damage to the most critical structural element – the junction of the tank wall with its bottom [9]. Work [9] gives a detailed analysis of the processes of strength loss, which causes separation from the bottom, but does not take into account the dynamics of the destruction process together with the dynamic processes that occur when liquid fuel leaks through the slots during separation from the bottom.

During VST explosions, the housing is often separated from the bottom, accompanied by its movement over a considerable distance. Thus, in the case of the VST-5000 explosion, the housing was thrown back approximately 50 meters, the VST-700 explosion led to the housing moving 25 meters, and the VST-3000 explosion caused the housing to overturn without further bouncing [9]. Such events indicate a violation of the strength balance between the weak seam between the roof and the housing and the strong seam between the housing and the bottom. Due to design, manufacturing or operational errors, a weak seam may turn out to be stronger, leading to the housing being torn off along with the roof instead of its separation.

Summarizing the results of the studies reported in [10], it can be noted that they are aimed at analyzing explosions and fires, determining that the tank body is most often moved in the direction of the strapping by the receiving and dispensing devices. It is noted that the separation of the tank from the bottom and the flying up of its detached part of the body occurs provided that the liquid level in them does not exceed half the height of the tank. These data emphasize the need to take into account the nature of the explosion and the trajectory of the body movement when assessing emergencies and planning fire extinguishing in the tank farm. In this case, it is necessary to take into account all the processes related to the dynamics of movement of tank parts during its separation, as well as the movement of the liquid when it flows out through the openings of the destroyed tank.

According to [10], increasing the distance between the tanks or predicting a safe place for the body to land is impossible, such an approach is ineffective. Therefore, the structure of the tank should prevent its separation and bouncing. However, the possibility of a tank separation from the bottom due to an explosion due to technological errors and imperfections should still be predicted.

Analysis of studies [9, 10], which focus on studying the strength of welded joints of vertical steel tanks under extreme load conditions, reveals a high level of attention to the problem of reliability of such structures in emergencies. In work [9], the effect of fires on the strength of steel tanks was investigated using experimental and numerical methods to assess the stability of different types of welded joints. Study [10] analyzes the thermal behavior of steel tanks under the influence of fires, paying special attention to welded joints and their ability to withstand high temperatures and loads. This approach is used in work [11], which reports the results of computer simulation of damage to large oil tanks during a fire, taking into account the thermal and structural characteristics of welded joints, which makes it possible to improve the accuracy of predictions regarding the strength of tank shells.

In the presence of a rigid base, it is likely that the destruction and bouncing of the tank can be caused by the occurrence of a reflected wave, which with doubled force pushes the body upwards, simultaneously pressing the bottom to the base according to work [11]. However, even in this case, the most effective technique of protection is the presence of a weak seam on the roof and additional anchoring of the tank body, although the risk of technological miscalculations, as experience shows, is high.

A likely option for overcoming the difficulties is to avoid the separation of the body from the bottom; it is important to ensure that at the time of destruction of the weak seam on the roof, the weld near the bottom remains sufficiently strong with the necessary margin of safety, as recommended in works [11, 12]. However, to establish a safe strength ratio, it is necessary to analyze the forces acting on both welds during an explosion and the additional influence of the liquid present in the tank when it is not fully loaded.

In addition, study [12] is aimed at analyzing the impact of explosive loads on welded joints of large tanks, with an emphasis on their strength and possible failure mechanisms.

Therefore, it is possible to note a large body of research into the thermal impact of fires on the behavior of tank housing structures and the nature of their failure. However, aspects of the interrelated processes of the fracture mechanics of welded tank joints, separation, and movement of the tank housing with simultaneous leakage of liquid petroleum products through the formed defects have not been studied in detail. In addition, the impact of these processes on the kinematic characteristics of the movement of the detached part of the tank housing has not been thoroughly investigated. Acquiring data on such processes will make it possible to compile scientifically based recommendations on the technological aspects of storing liquid petroleum products in vertical steel tanks at enterprises equipped with them.

3. The aim and objectives of the study

The purpose of our study is to identify patterns in the change in the parameters of movement of a part of the tank after separation from the bottom depending on its design parameters and the conditions of its filling. The identified patterns are a scientific basis for compiling practical recommendations on technological requirements for storing petroleum products in vertical tanks to reduce the risk of their flying over long distances during an internal explosion due to a fire.

To achieve the goal, the following tasks were set:

– to conduct computer simulation of dynamic processes that occur when the tank is separated from the bottom during a fire and to qualitatively assess the influence of design and technological parameters on the nature of their course;

– to conduct a numerical experiment to study the influence of the design parameters of the tank and the level of its filling on the kinematic characteristics of the tank movement during its separation from the bottom and bouncing under conditions of increased internal pressure inside due to heating during a fire;

– based on a full factorial numerical experiment, determine a regression relationship that makes it possible to predict the height of tank bouncing depending on the design and operational parameters defined as factors.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of separation of the body of a vertical steel tank from the bottom under the influence of emergency thermal and dynamic loads characteristic of fires at tank farms.

The basic hypothesis assumes that a mathematical description of dynamic processes in the system "tank body-bottom-liquid" using models of interaction of solids, contact and hydrodynamic phenomena could make it possible to accurately predict the moments of occurrence of critical stresses in welded joints. Optimization of the parameters of structural elements, such as the strength of welds and the rigidity of the body, provides the opportunity to reduce the risk of separation of the body from the bottom by adapting the geometry and materials to conditions of increased pressure and temperature. Taking into account the dynamic characteristics of the liquid inside the tank, in particular its pressure on the walls and interaction with the surface, makes it possible to model the mechanism to form pressure waves that contribute to the separation of the bottom, and to devise measures to neutralize them. Improvements in modeling techniques, such as the use of the AIRBAG model to reflect the impact of an explosion, as well as penalty function methods for analyzing contact interaction, could ensure a high level of accuracy of the results of numerical experiments.

The data can be used to justify design solutions aimed at preventing the separation of the tank body by optimizing the weak seam between the body and the roof, additional anchoring of the body, and ensuring the reliability of the connection of the body to the bottom.

4. 2. The methodology of the study

The research methodology is based on the use of numerical modeling to analyze dynamic processes occurring during separation of the tank body from the bottom under fire conditions. The study begins with the statement of the problem, which includes the determination of the physical and mechanical characteristics of the tank structural elements and the conditions of exposure to high temperatures and pressures. The main approach is based on the use of finite difference method (FDM) and finite element method (FEM) to describe the stress-strain state (SSS) of the tank. The structure is modeled using Belichko-Tsay shell elements [13] taking into account real geometric parameters, and the behavior of the fluid is modeled using the smooth particle hydrodynamic model SPH.

An important aspect is the modeling of interaction of the fluid with the tank structure using the penalty function method, and the dynamic explosion pressure is taken into account using the AIRBAG model. Numerical experiments are performed in the LS-DYNA software package, which makes it possible to model various scenarios of the influence of temperature, pressure, the level of filling the tank with liquid, as well as material properties. Analysis of the obtained data makes it possible to determine critical conditions under which weak connections of the body with the bottom and roof of the tank are destroyed.

Petroleum products are usually stored at specialized facilities, such as oil depots and parks equipped with tanks. The most common are vertical tanks, a schematic representation of which is shown in Fig. 1. The structure of this type of tank meets the requirements specified in standards.

As shown in Fig. 1, the tank structure consists of vertical walls, a bottom, and a cover made of steel sheets connected by welds.

To simulate the process of separation of a tank with petroleum products from the bottom, a tank with a typical structure was chosen, as indicated in [11, 13]. This design is one of the most common at oil depots and parks for storing petroleum products in Ukraine.

Fig. 2 shows the geometric parameters of the structural elements of the tank used in the study.

To perform the simulation, the geometry and components of the model were considered in two typical variants, which are depicted in the diagrams in Fig. 3.

In Fig. 3, the first variant is a tank not filled with oil products, the second variant is a tank filled with oil products to different levels.

To model the process of separation of the bottom from the tank, key provisions were formulated, which include the following:

1. For the mathematical description of the stress-strain state in the structural elements of the tank, when separation from the bottom occurs, an engineering-theoretical approach is used, based on the explicit method of integrating the equations of the mechanics of interaction of deformed solids.

2. The general engineering-theoretical approach involves determining the displacements of the points of the structure from solid deformed elements. For this purpose, numerical integration of the general equations of dynamics by the finite difference method and the equations of the stress-strain state using the finite element method is used.

3. To model the walls of the tank and welded joints, flat four-node finite elements of the Belichko-Tsay shell type are used [13]. This makes it possible to reduce the dimensionality of the problem based on the accepted hypotheses, using five integration points along the thickness of the element.

4. For modeling welded joints and steel tank enclosures, an elastic-plastic material model is used. It makes it possible to describe deformations through bilinear diagrams, such as Prandtl, which include a section of elasticity and a slope of hardening with a limiting deformation [11].

5. Mathematical modeling of a liquid, which is an oil product, is carried out using particles characterized only by mass and having extremely small geometric dimensions. To describe the motion of particles and their contact interaction, the hydrodynamic model SPH (Smooth Particles Hydrodynamics) is used, which is implemented using the Monaghan model [14], which describes the interaction between particles with the viscosity inherent to liquids.

6. The system is considered under normal atmospheric conditions, taking into account gravity and temperature. Heat exchange between the oil product liquid and the tank walls is not taken into account.

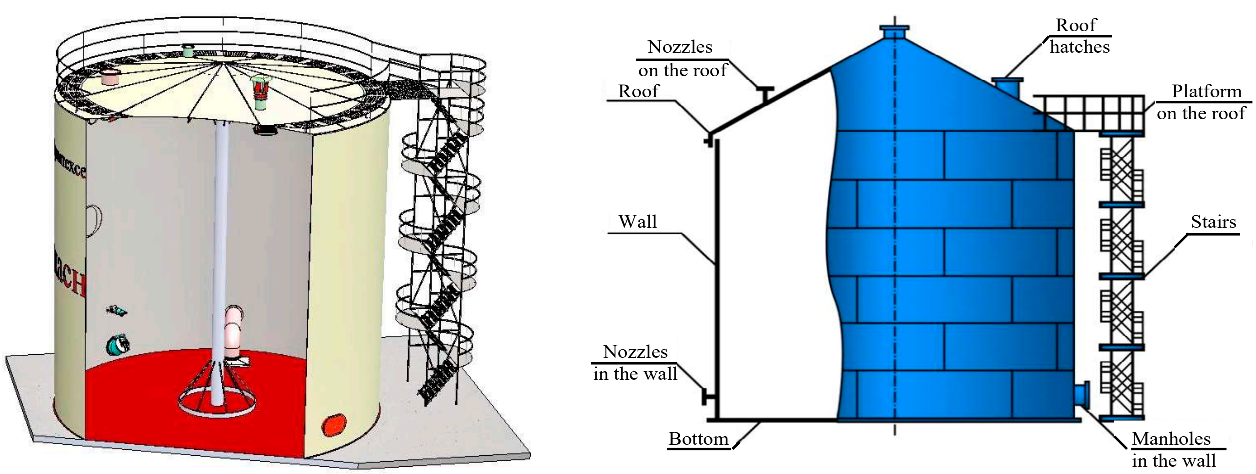
7. To analyze the contact interaction of particles with the enclosing surface, a mathematical contact model based on the penalty function method is used.

8. The application of pressure to the tank walls and the liquid surface is modeled using the AIRBAG model, which is implemented in the LS-DYNA software package [15].

The initial data for modeling the separation of the tank from the bottom under the influence of fire were obtained during the study of the destruction processes of welded joints [16], carried out for tanks using electric arc welding. In this work, the mechanical characteristics of welded joints are determined by the strength identification method based on the results of mechanical tests of samples of these joints.

The method was investigated from the point of view of the accuracy of the obtained results. This has made it possible to justify its use for the analysis of the strength of welded joints.

The test model consists of two rods that simulate the walls of the tank, connected by a weld. When modeling this structure, it was taken into account that the material of the rods and the welded joint is characterized by geometric and physical nonlinearity. The possibility of large deformations, plastic deformations, and element failure when critical deformation values are reached was also taken into account. The law of material deformation is described by the corresponding diagram, similar to those obtained in experimental studies [11]. The main characteristics of the sample materials are given in study (Tables 1, 2) [13].



a *b*

Fig. 1. Design and internal structure of a tank for storing petroleum products: *a* – image of the tank and its internal structure; *b* – structural diagram of the tank

The calculation was carried out until the moment of fragmentation of the sample, which reflects the destruction of the welded joint, as shown in Fig. 4. After achieving fragmentation, which means the destruction of the finite elements of the welded joint, further calculations become impractical.

As can be seen in Fig. 4, the fracture of the specimen occurred along the weld seam, since its strength was lower than that of the base material of the rods that were connected by welding. This is consistent with the results of practical experiments reported in [11].

Fig. 5 shows the distribution of the principal, highest stresses at the moment of fracture of the weld seam.

Based on our calculations, plots were constructed that demonstrate the dependence of the largest normal stresses on relative displacement.

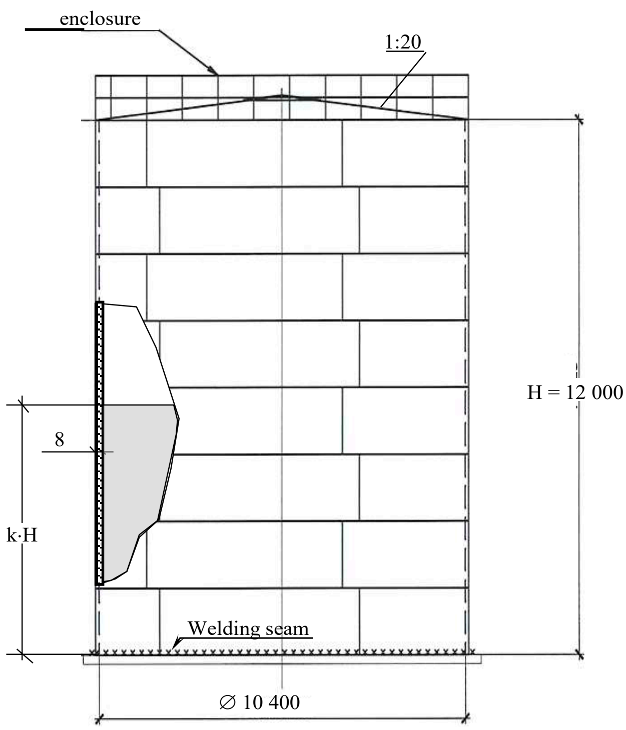


Fig. 2. Geometric parameters of structural elements of a tank for storing petroleum products, adopted for mathematical modeling of its separation from the bottom

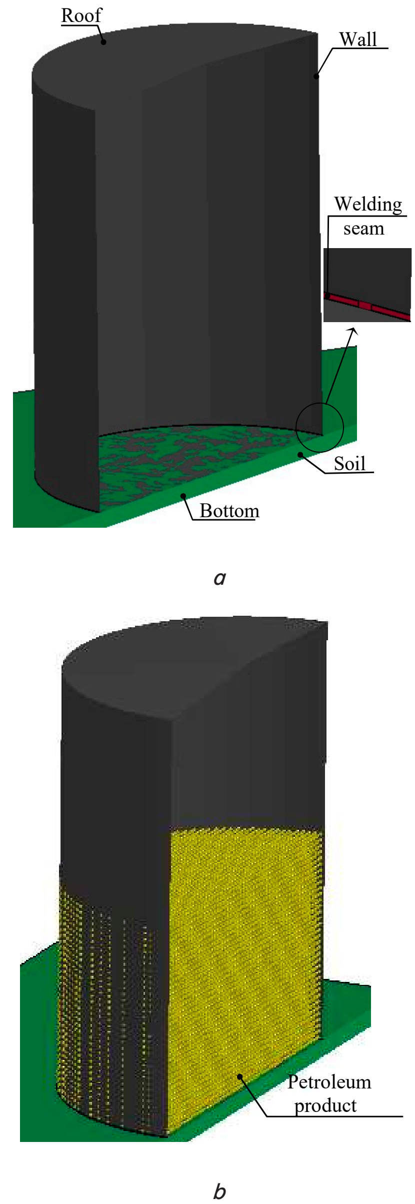


Fig. 3. Initial tank diagrams for modeling the bottom separation process: *a* – first variant; *b* – second variant

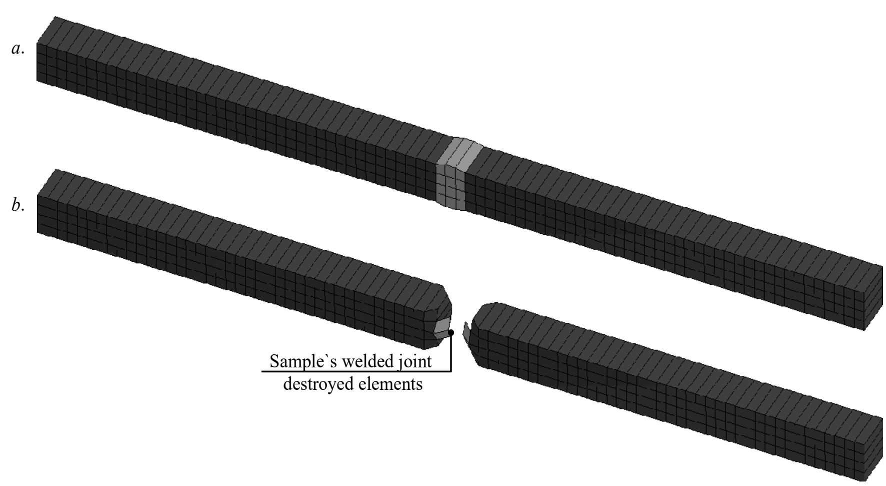


Fig. 4. Finite element models of the structural system of the welded joint for testing: *a* – before applying the load; *b* – after applying the destructive load

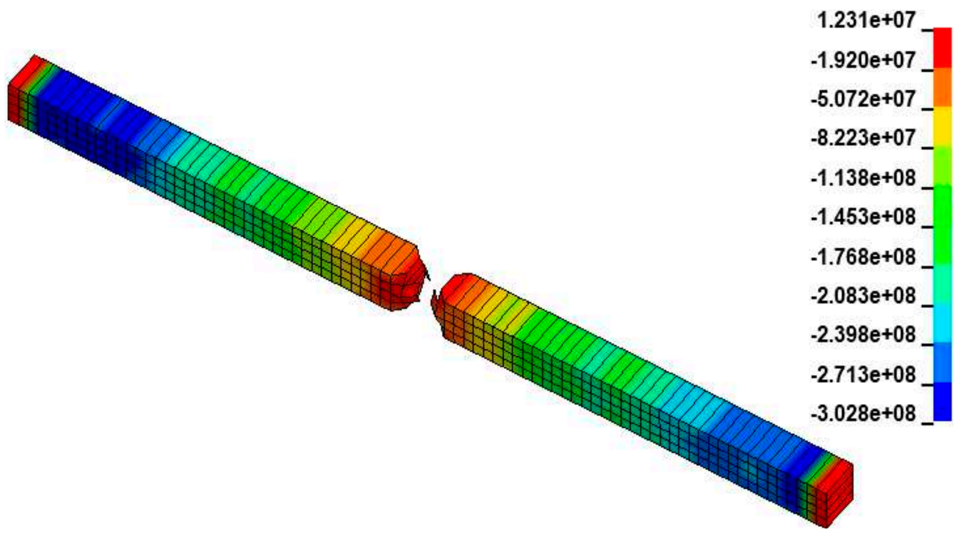


Fig. 5. Distribution of longitudinal stresses in a welded joint specimen during testing

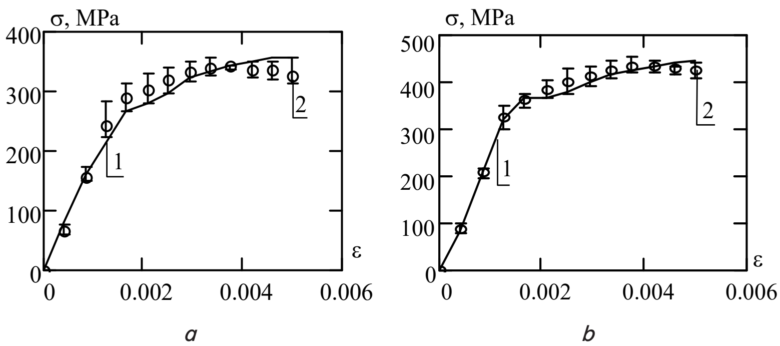


Fig. 6. Weld steel deformation diagrams: *a* – ordinary structural steel; *b* – high-strength steel; 1 – experimentally acquired data; 2 – averaged curve

The resulting curves demonstrate a high correspondence of the calculated results with the experimental data, which confirms the correctness of the selected mathematical models for calculating the fuel tank during its separation from the bottom. Lines 1 and 2 on the plots represent the results obtained from modeling and experimental studies, respectively.

Using the experimental data (Fig. 6) given in [11], to obtain the dispersion of reproducibility that was obtained when testing 6 identical weld samples and using the calculated data obtained using the calculation schemes given in Fig. 4, 5, the Fisher criterion was analyzed. Thus, for different weld strengths, the Fisher criterion values of 0.64 and 0.91 were obtained, which is significantly less than the tabular values. This means that this calculation method is acceptable for use in mathematical modeling of tank walls and welds.

The main purpose of calculations for our study of the separation of a part of the tank from the bottom, its movement, and the movement of the oil product liquid when flowing through the formed defects, is the kinematic parameters of the separated part of the tank. Also important is the modeling of the load from the internal excess pressure in the tanks when the temperature of the steam-air mixture inside increases and the processes of weld destruction. To reproduce all the main processes, an appropriate problem must be stated, where all the listed processes must be taken into account. In addition, the interaction of the liquid with the solid walls of the tank must be taken into account, and the corresponding properties of substances and materials, such as the viscosity of the liquid, the rigidity of the surface of the solid material, the inertial characteristics of substances, and the mathematical description of the interaction of the liquid in its internal layers, must be taken into account.

The features of the dynamic problem statement for such mechanical systems have been outlined; the mathematical model that can be used to describe dynamic processes under such conditions becomes very complex. To substantiate the conceivable method of calculation, it is necessary to form a system of basic assumptions and references regarding the studied dynamic processes that occur in a tank with a liquid petroleum product during its deformation, separation, and bouncing after separation with simultaneous outflow of the petroleum product from it. It is also necessary to establish computational tools for the calculation. Thus, the following assumptions and hypotheses were adopted to state the problem:

1. The mechanical system is considered to consist of steel walls of the tank enclosure, a weld, the soil on which the tank is installed, as well as the liquid petroleum product inside the tank. The process of destruction of the weld and separation of the tank from the bottom occurs in several stages. First, a gravitational load is gradually applied, and then a comprehensive excess pressure is gradually applied to the internal surfaces of the tank with the acquisition of critical values, at which the destruction of the lower weld occurs. When the weld is destroyed and through holes are formed due to the impulse action, the detached part of the tank begins to move upwards with simultaneous leakage of liquid from it. The bouncing of the detached part is observed until it reaches the highest height.

2. To describe the part of the dynamic system, which is a tank with a liquid, the method of explicit integration of dynamics equations is used in conjunction with the finite element method [17].

3. The enclosing elements of the tank structure and the weld are represented as a deformable solid body consisting of an elastic-plastic material with the possibility of destruction when critical deformations are reached. The soil is represented as an absolutely solid body, and its material has elastic characteristics, which are taken into account only when contact interaction occurs between it and the enclosure [17].

4. The liquid in the oil product is represented by a certain number of discrete particles, determined only by mass. To reproduce the motion of particles and their contact interaction, the hydrodynamic model of smooth particles SPH (Smooth Particles Hydrodynamics) [18] is used. To describe the interaction between particles, the Monaghan hydrodynamic model is used [18].

5. The motion of the system is considered under normal atmospheric conditions, gravity, and temperature. In this

case, heat transfer between the liquid petroleum product and the tank walls is not considered.

6. When analyzing the contact interaction of particles and the enclosing surface, an appropriate mathematical model of contact is used, based on the penalty function method [18].

The interaction between particles is described according to the scheme shown in Fig. 7.

To model the components of a dynamic system, which is a tank with a liquid petroleum product, three types of materials are used: the material of the particles, the material of the tank enclosure, and the material for the soil on which the tank is installed. To describe SSS of the tank enclosure, the elastic-plastic material described above is used.

For discrete liquid particles, a material model is used designed to determine the characteristics of an idealized material, in which it is not necessary to calculate the internal stresses that are components of the stress deviator. In this case, the strength of the material can be ignored. Viscous stresses are calculated using the expression:

$$\sigma_{ij} = \mu\varepsilon'_{ij}, \quad (1)$$

where ε'_{ij} is the growth rate of deviatoric deformations.

The use of this material is also due to the possibility of identifying the contact interaction between particles and an adjacent solid body.

To describe the soil, a model of a completely solid material is used. The material model is used when it is not necessary to determine the stress-strain state in the internal layers of the sludge included in the dynamic system. In this case, it is possible to condition the inertial characteristics of bodies. For this material, it is also possible to condition its elastic characteristics when describing the elastic interaction during contact of bodies with this material model and other component bodies of the system.

Such a material can be used to condition the previously specified conditions of the motion of the entire system, since it is possible to optionally specify their degrees of freedom and their laws of motion.

To describe the contact between particles and the tank enclosure, the theory of contact interaction between nodes and surfaces of finite elements is used. To identify the contact interaction between the node and the finite element surface, the penalty function method is used, and to describe the conditions of the force interaction between them, predefined mechanical characteristics of materials are used.

Applying a composite geometric model of the tank without and with liquid petroleum product, a finite element diagram was constructed, shown in Fig. 7.

Fig. 8 shows the boundary conditions and contact interaction conditions between the model components.

According to Table 2, materials were selected for the components of the reservoir model. Fig. 9 shows a diagram of the components of the reservoir model with material models used to describe the behavior of the model components.

The characteristics of the materials used to build the tank model were adopted according to DSTU B V.2.6-183:2011.

Table 1 gives values of adopted parameters for material properties.

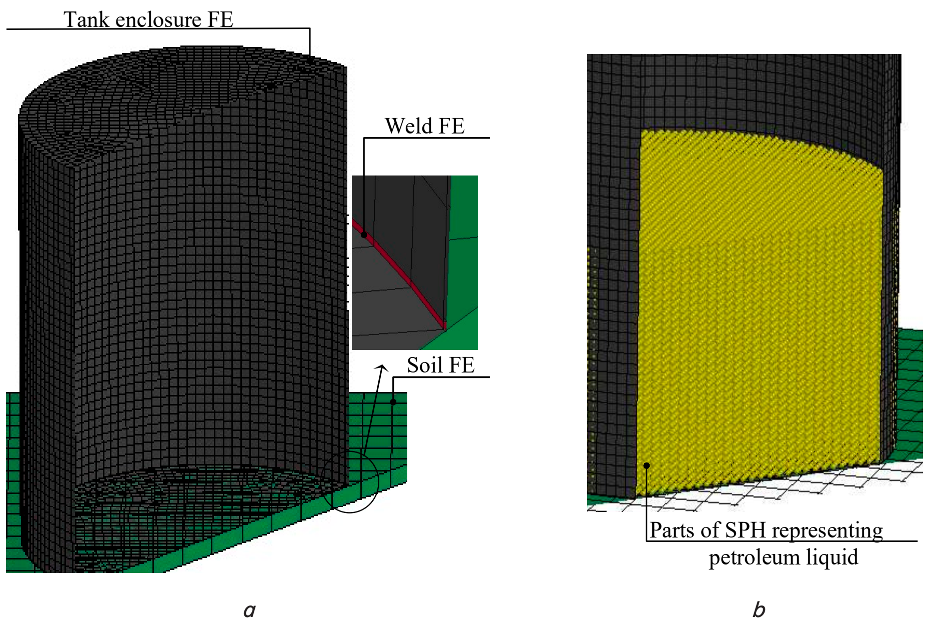


Fig. 7. Finite element diagrams of the components of a tank model for modeling the bottom separation process: *a* – first variant; *b* – second variant

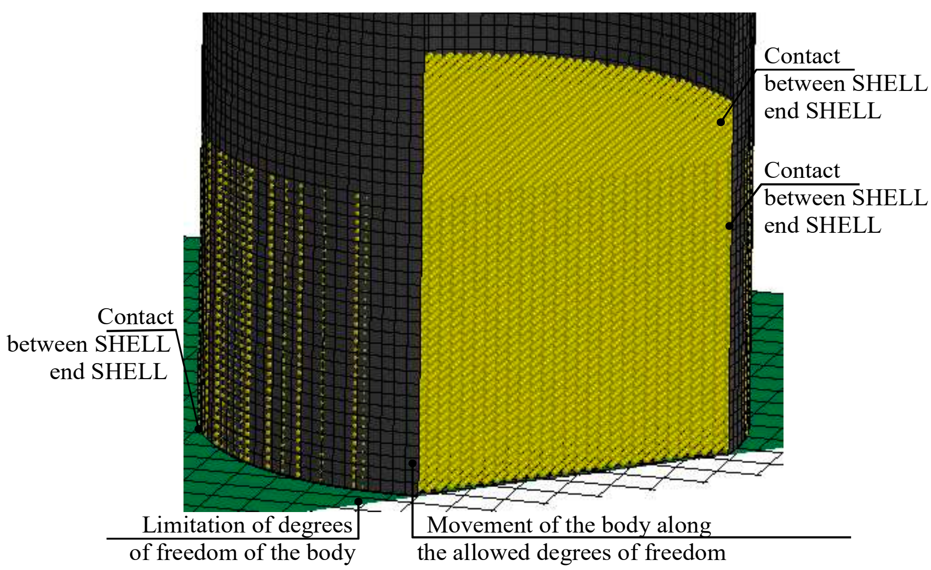


Fig. 8. Finite element diagram of the tank model components for modeling the bottom separation process with boundary conditions

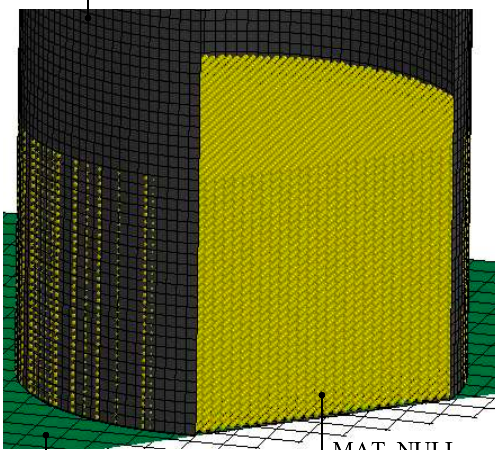


Fig. 9. Finite element diagram of the tank model components for simulating the bottom separation process with assigned material models

The parameters of the tank wall and weld material are given in [16] (Table 2).

Before applying pressure to the tank walls and the surface of the oil product liquid particles (diesel fuel) according to the AIRBAG model, it is necessary to apply gravitational forces to the model components. To avoid dynamic effects in the form of strong initial impulses, which are the cause of oscillatory movements with a large amplitude, the gravitational load should be applied slowly in the preliminary phase of the calculation. To do this, before carrying out the main dynamic calculation, the gravitational acceleration is applied to each model component at a time interval of 5 s with the general dynamic damping variant set. After applying gravitational accelerations to the system, the damping variant is turned off. At the end of this procedure, the corresponding pressure according to the AIRBAG model is applied to the tank walls and the surface of the oil product liquid.

Table 1

Parameter values for the properties of materials of a tank with petroleum products (diesel fuel)

Material	Density, ρ, kg/m^3	Modulus of elasticity, E, MPa	Poisson's ratio, ν	Viscosity (artificial), μ
Absolutely solid material	1,900	900	0.3	–
Null material	830	–	–	0.001

According to the finite element diagrams shown in Fig. 10, the quantitative characteristics of finite elements are summarized in Table 2.

Table 3 takes into account that according to the adopted methodology of numerical experiments for studying the dynamic characteristics of the tank and the liquid petroleum product, four variants for filling the tank are considered: 0 %, 25 %, 50 %, and 75 %.

Using the proposed approaches, a regression model was built for the dependence of the height of tank bouncing when it is separated from the bottom under fire conditions on the design parameters and the level of its filling. For this purpose, a full factorial experiment was conducted using the simplest orthogonal plan. This experimental plan was chosen due to the fact that the dependence of the height of bouncing on the level of filling the tank approaches linear.

Table 2

Basic quantitative data on the finite elements in a model of a reservoir with petroleum products

Reservoir filling type, %	Number of FE of type SHELL	Number of SPH of type particles	Number of solid FE of type SOLID
0	10 092	0	53
25		49 490	
50		98 980	
75		148 470	

Given the assumption that the larger the volume of the tank, the smaller the height of bouncing, the hypothesis was accepted that the dependence of bouncing height can be expressed through a linear polynomial dependence of the following type [18]:

$$y=b_0+b_1x_1+b_2x_2+b_3x_1x_2, \quad (2)$$

where x_1, x_2 are factors that correspond to the most significant parameters adopted, which are the level of filling the tank in relative units and the volume of the tank with the oil product (m^3). It should be noted that these parameters are independent in nature.

In this case, to construct the adopted regression dependence, an experimental design matrix can be established, corresponding to the symbolic entry in Table 3.

Таблица 3

Full-factorial experiment design matrix

No.	x_1	x_2	x_1x_2
1	+	+	+
2	+	-	-
3	-	+	-
4	-	-	+

Table 4 gives factor intervals for conducting a full factorial experiment.

Table 4

Intervals of variation of factors in a full factorial experiment

Tank fill level, γ			Tank volume, V_t, m^3		
The smallest value, γ_{-1}	Average value, γ_0	The greatest value, γ_1	The smallest value, V_{-1}	Average value, V_0	The greatest value, V_1
0.1	0.45	0.8	400	5200	10000

To obtain data for conducting a full-factorial numerical experiment, the most common characteristics of tanks and their filling level were adopted, in particular, the mechanical characteristics of concrete and reinforcing steel, and the geometric characteristics of the materials of the components of mathematical models of tanks with petroleum products.

5. Results of mathematical modeling of separation from the bottom of a tank with an oil product

5. 1. Results of computer simulation of dynamic processes occurring when a tank separates from the bottom during a fire

Varying the filling level, it was found that only 4 events are considered for numerical experiments. According to Table 4, 4 experimental cases are considered.

According to the first variant of no filling of the tank with oil product liquid, the case is considered when the tank has a very low filling level, due to the burning out of almost all the fuel with the gradual leakage of oil product liquid vapors. In this case, the oil product liquid level is so low that it can be neglected. Fig. 10 shows the position of the tank at certain points in time after applying pressure to the tank walls.

As can be seen from Fig. 10, when the pressure inside the tank increases, it detaches from the bottom and bounces to a certain height, and then falls to the ground surface, which is consistent with the observation data given in [8]. In this case, it can be noted that the walls of the tank and its coating have noticeable plastic deformation.

To analyze the mechanism of fracture of the welded joint, diagrams of the distribution of the largest principal stress in the tank enclosures were constructed. These diagrams are shown in Fig. 11.

From Fig. 12 it is seen that the separation of the upper part of the tank occurs along the weld since it is less strong than the base material.

In order to analyze the trajectory of bouncing of the upper part of the tank using the LS-Dyna software, a plot of change in the maximum vertical displacement of the tank depending on time was constructed. The resulting plot is shown in Fig. 12.

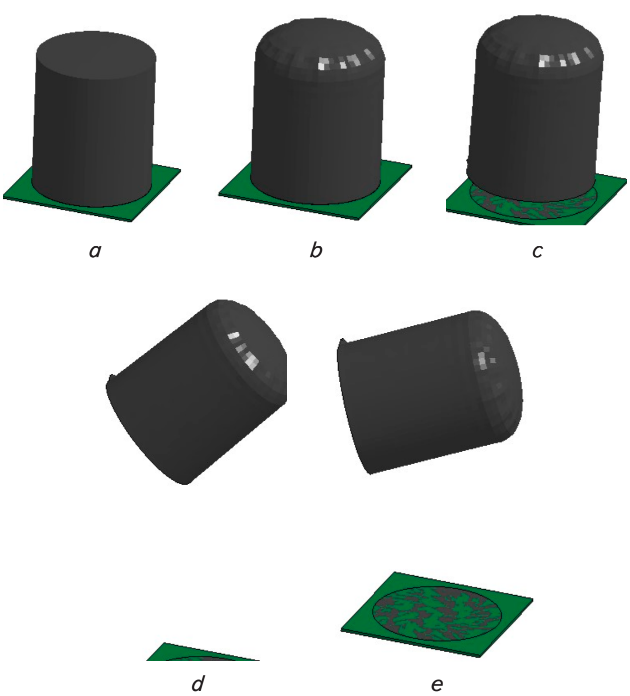


Fig. 10. Position of the upper part of the tank separated from the bottom at different times: *a* – after the application of gravitational forces; *b* – before separation from the bottom; *c* – 0.1 s of bouncing; *d* – at the highest point of bouncing; *e* – at the stage of descent

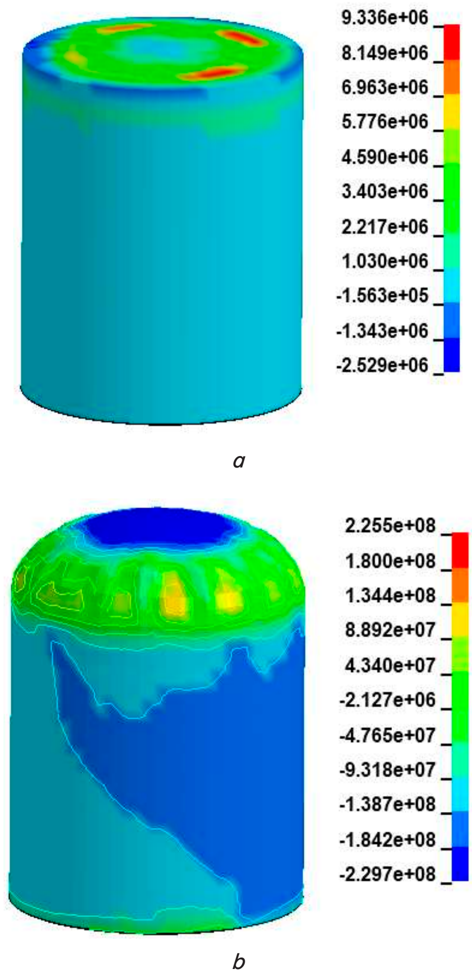


Fig. 11. Distribution of the greatest principal stress in the tank's enclosing structures: *a* – after application of gravitational forces; *b* – before separation from the bottom

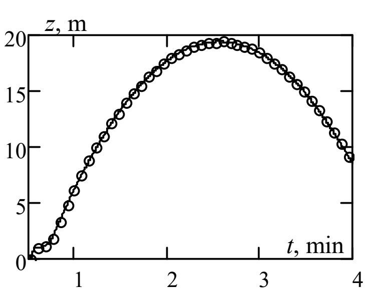
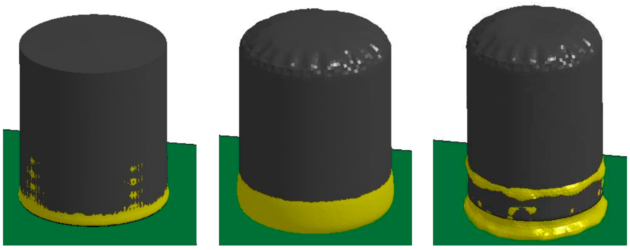


Fig. 12. Dependence of the maximum vertical displacement of the upper part of the tank on time when it is separated from the bottom

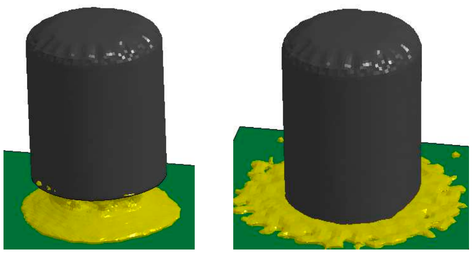
According to the plot shown in Fig. 13, the upper part of the tank, when it is separated from the bottom, rises up to a maximum height of about 20 m.

When studying cases of separation of the tank from the bottom due to an increase in pressure in it due to heating of the gas in the cavity between the liquid and the tank enclosure, three other variants were considered. Fig. 13, 14 show the position of a half-filled tank at certain points in time after applying pressure to the tank walls and the liquid surface.



a *b* *c*

Fig. 13. Position of the upper part of a half-filled tank separated from the bottom at different times: *a* – after the application of gravitational forces; *b* – before separation from the bottom; *c* – 0.1 s of bouncing



a *b*

Fig. 14. Position of the upper part of a half-filled tank detached from the bottom at different times: *a* – after the application of gravitational forces; *b* – at the highest point of bouncing; *c* – at the moment of landing

In Fig. 13, 14, one can see the features of the process of movement of the part of the tank detached from the bottom with the simultaneous leakage of liquid fuel from it. When the tank is filled by 50 %, it flies up only 4 meters. This result is consistent with practical observations

5. 2. Results of investigating the influence of structural and technological parameters of a steel tank on the kinematic characteristics of its movement when detached from the bottom during a fire

In order to analyze the trajectory of bouncing of the upper part of a half-filled tank, a plot of the maximum vertical displacement of the tank depending on time was constructed using the LS-Dyna software package. The resulting plot is shown in Fig. 15.

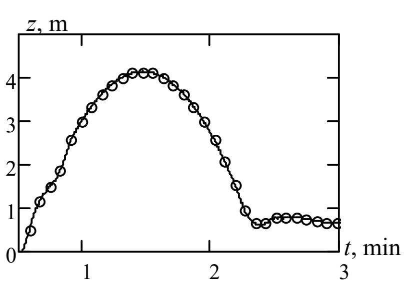


Fig. 15. Dependence of the maximum vertical displacement of the upper part of the tank on time when it is separated from the bottom

Similar plots were constructed based on the results of mathematical modeling of the separation from the bottom of tanks filled by 25 % and 75 %, according to Table 4. The resulting plots are shown in Fig. 16.

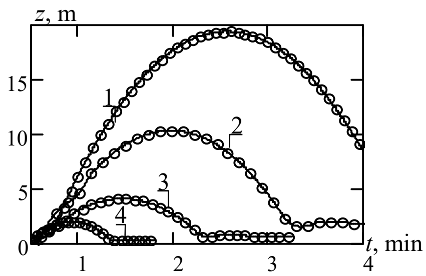


Fig. 16. Dependences of maximum vertical displacement of the upper part of the tank on time when it is separated from the bottom at different levels of its filling: 1 – 0 %; 2 – 25 %; 3 – 50 %; 4 – 75 %

In Fig. 16, one can see the dependence of maximum bouncing height on the tank filling level. It can be noted that the higher the tank filling level, the lower the bouncing height. This can be explained by the fact that when the tank is separated from the bottom, energy is spent on lifting the part of the liquid that has not yet flowed out of the tank. Fig. 17 shows the dependence of the bouncing height of the part of the tank separated from the bottom on its filling level. This plot was constructed based on the data given in Fig. 16.

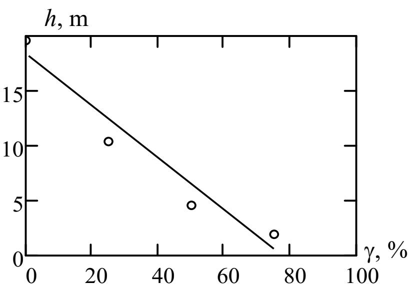


Fig. 17. Dependence of the bouncing height of the part of the tank detached from the bottom on its filling level

According to the plot shown in Fig. 18, the bouncing height of the upper part of the tank when it is separated from the bottom significantly depends on the level of its filling and monotonically decreases with an increase in the level of the liquid petroleum product stored in the tank.

Our data could become part of the generalization of similar studies for other tanks and be taken into account when compiling recommendations established by regulatory guidelines for enterprises where fuel and lubricants are stored.

5. 3. Results of a full factorial numerical experiment on the influence of the structural and operational parameters of a tank on the bouncing height of its body when separated from the bottom during a fire

By changing the described parameters according to the matrix of the full factorial experiment plan according to Table 3 and Table 4 and performing calculations based on the above-substantiated computer model for the analysis of dynamic systems and their components, the corresponding data were obtained as a result of conducting a full factorial experiment under the established conditions. The results are given in Table 5.

Using the data from Table 5, the coefficients of the adopted regression were calculated; they are given in Table 6.

Table 5

The height of tank bouncing when it is separated from the bottom due to an increase in internal pressure under fire conditions

Experimental case	1	2	3	4
Height of tank bouncing when it is separated from the bottom, *h*, m	0.8	3.2	6.1	34

Table 6

Regression coefficients for determining the bouncing height of a tank with an oil product when it is separated from the bottom due to an internal explosion

Regression coefficients (2)	b_0	b_1	b_2	b_3
Coded values	11.025	–9.025	–7.575	6.375
Real values	39.714	–45.518	–0.0033	0.0038

Thus, the regression equation takes the final form:

$$h=39.714-45.518\cdot\gamma-0.0033\cdot V_t+0.0038\cdot\gamma\cdot V_t, \quad (3)$$

where γ is the tank filling level; V_t is the total tank volume (m^3).

The constructed regression establishes the pattern of changes in the bouncing height of oil product tanks due to an internal explosion depending on their filling level and total volume. The nature of the revealed pattern can be traced using the constructed surface for this regression, which is shown in Fig. 18.

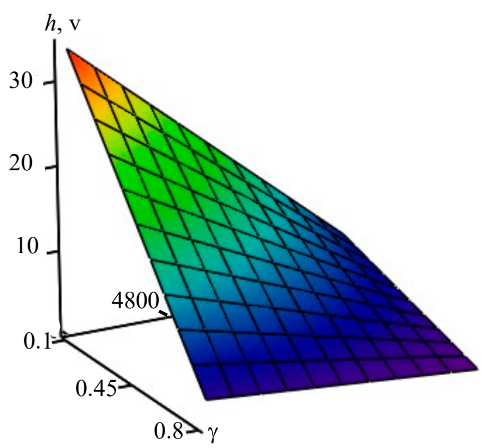


Fig. 18. A surface corresponding to the dependence of the bouncing height of oil tanks due to an internal explosion on their filling level (γ) and total volume (V_t)

It is convenient to determine the bouncing height of oil product tanks due to an internal explosion based on their most significant design parameters: filling level and total volume, using the nomogram shown in Fig. 19.

When checking the adequacy of results from determining the bouncing height of oil tanks by regression dependence, they were compared with the results obtained using a computer model (Fig. 6–9, Tables 1, 2). In this case, statistical criteria were analyzed, namely the absolute deviation and relative deviation as adequacy criteria. The calculated data to check the adequacy of the results obtained when using regression with coefficients corresponding to Table 6 are given in Table 7.

The data on the adequacy analysis, given in Table 7, show that the average error of the results obtained by the regression dependence is less than 12 %, which is insignificant, and the determined regression dependence of the bouncing height of tanks with petroleum products due to an internal explosion on the filling level and total volume can be used to assess the danger of a tank separating from the bottom.

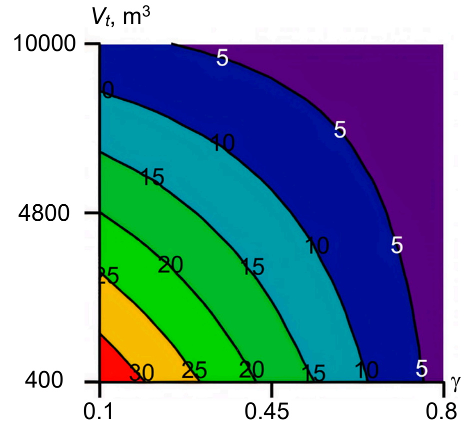


Fig. 19. Nomograms of the dependence of the bouncing height of tanks with petroleum products due to an internal explosion on their filling level (γ) and total volume (V_t)

Table 7

Adequacy of the results based on the determined indicators of the bouncing height of tanks with petroleum products due to an internal explosion according to the regression dependence

Bouncing height, m	Bouncing height calculated by regression dependence, m	Absolute deviation, m	Relative deviation, %
Filling level γ=0.25, Tank volume V_t=4,800 m^3			
15.705	17.117	1.412	8.25
Filling level γ=0.5, Tank volume V_t=4,800 m^3			
11.438	10.291	1.147	11.146
Filling level γ=0.75, Tank volume V_t=4,800 m^3			
3.974	3.465	0.509	14.691
Average			
–	–	1.023	11.362

6. Discussion of results based on the study of dynamic processes occurring when a tank is separated from the bottom during a fire

We have substantiated a calculation methodology based on the explicit method of integrating the dynamics equations for the processes of deformation and destruction of the tank and the weld when the excess pressure inside increases due to the thermal effect of the fire. In addition, this methodology was supplemented with computational procedures that make it possible to take into account the leakage of petroleum product liquid using the hydrodynamics of smoothed particles when the tank is separated from the bottom. It has been shown that the model data are adequate (Table 7).

Based on calculations of the stress-strain state of the tank body when it is separated from the bottom, the hydrodynamic processes of liquid leakage from the tank, as well as the kinematics of bouncing of the separated part of the tank, it was established that bouncing height depends on the level of fuel stored in it (Fig. 12–17). Thus, the bouncing height of the tank body is from 2 to 20 m. This is explained by the fact that for the tank with a higher level to bounce, a larger impulse must be applied, which weakly depends on the tank filling level. This result is consistent with observational data.

Using the results of our calculations, a dependence was investigated that reproduces the regularity of dependence of the height of tank bouncing on its filling level. This dependence is defined in the form of a regression, the coefficients of which are given in Table 7. This dependence is shown in Fig. 18 in the form of a response surface and in Fig. 19 in the form of a contour distribution. These dependences show a decrease in the bouncing height with an increase in the total volume of the tank and its filling level. This is also explained by the fact that when the tank is separated from the bottom, energy is spent on lifting part of the liquid that has not yet flowed out of the tank. This dependence can be used to establish bouncing height and can be used to compile recommendations for enterprises that store fuel and lubricants.

The application of this regression dependence is limited to one type of tank that was investigated. This limitation can be overcome by conducting similar studies for other types of tanks.

7. Conclusions

1. We have performed computer simulation of dynamic processes occurring during separation of a tank from the bottom during a fire, taking into account the destruction of the weld and the hydrodynamics of leakage of the oil product liquid through the formed holes. It was found that the volume and filling level of the tank affect the bouncing height of tank body when it is separated from the bottom.

2. Our numerical experiments have made it possible to determine the range of tank bouncing height (2–20 m) depending on filling level. It was found that the bouncing height of the upper part of a tank decreases with increasing filling level, demonstrating a direct relationship between the liquid level and kinematic characteristics.

3. During the study, a regression model was built that makes it possible to estimate the height of tank bouncing depending on the filling level (γ) and the total volume of the tank (V_t); it takes the form h=39.714–45.518·γ–0.0033·V_t+0.0038·γ·V_t.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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