Assessment of damage in accidents and development of technical solutions to ensure safety on the railroad transport

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Abstract. A significant portion of hydrocarbons is transported by rail. At the same time petroleum products are classified as hazardous cargoes, accidents during transportation of which may lead to emergencies. The article gives an assessment of damage from emergencies in the transportation of petroleum products by rail. Assessment of economic losses, as well as damage to the environment. At damage assessment analysis of dependence of environmental damage from the time elapsed from the moment of emergency situation till the beginning of localization and liquidation of transport emergency was conducted. Technical solutions to ensure safety have been developed and proposed. The use of the proposed devices will increase the safety of transportation of petroleum products by rail. As a result of the conducted calculations the possibility of using a complex consisting of two proposed devices to ensure safety during transportation of dangerous goods has been established. Keywords: damage; environment; emergency; localization; elimination; runoff control; sorbent; safety

1 Introduction

In today's world, the railroad is one of the country's largest freight carriers. Every day more than 100,000 people in the country and a huge number of companies use rail transport services to transport goods [1-5]. Unfortunately, this mode of transportation, like any other, does not do without casualties, because sometimes various kinds of accidents occur on the railway transport. These accidents are related, among other things, to the transportation of poisonous and hazardous substances, after which damage is caused to the environment and a set of reclamation measures is required. Let's consider one of such situations caused by depressurization of a tank car with oil products, which resulted in environmental damage.

Emergencies at the objects of railway transport (hereinafter ES), associated with the release of hazardous substances, pose a danger to the population and territories [6-11]. Prevention and elimination of emergencies at the objects of transport, namely the railroad, is one of the main tasks of ensuring safety of potentially hazardous objects. In addition, in accordance with the Federal Law "On protection of population and territories from...
emergencies of natural and technogenic character", one of the main tasks of operation of any objects is prevention of occurrence and development of emergencies, as well as development of technical solutions aimed at improving safety.

In this connection, based on the results of the situation forecast and the structure of emergency response activities, it is necessary to analyze preventive measures to prevent and reduce the impact factors of emergencies on the railroad with the participation of fire-explosive cargo.

2 Materials and methods

Let us assess the damage caused by depressurization of a tank wagon and the subsequent release of an oil product into a water body within three hours of the accident.

1) Assessment of environmental damage from an emergency

In case of the emergency caused by the depressurization of a tank wagon with oil product there is a leakage of the oil product on the ground surface with the subsequent contamination of the water body. Hydrocarbons evaporating from the spill surface also pollute the surface layers of the atmosphere.

The degree of pollution of water bodies with oil products to be compensated is calculated as a fee for over-limit discharge of pollutants with application of an increasing coefficient equal to 5 [12]:

$$C_w = 5 \cdot K_i \cdot K_{ew} \cdot H_{bw} \cdot M_{ow}, \text{ rub},$$  \hspace{1cm} (1)

Where $K_i$ – indexing factor;
$K_{ew}$ – coefficient of ecological situation and ecological significance of the state of water bodies;
$H_{bw}$ – basic standard fee for discharge of one ton of hydrocarbons into water within the established limit, rubles/t;
$M_{ow}$ – mass of petroleum products polluting the water body, t.

Pollution of the atmosphere as a result of an oil product spill is calculated as the mass of hydrocarbons evaporated from the spill area to be compensated:

$$C_a = 5 \cdot K_i \cdot K_{ea} \cdot H_{ba} \cdot M_{oa}, \text{ rub},$$  \hspace{1cm} (2)

Where $K_i$ – indexation coefficient of pollution charges;
$K_{ea}$ – coefficient of ecological situation and ecological significance of the state of the atmosphere;
$H_{ba}$ – basic standard fee for emission of one ton of hydrocarbons into the atmosphere within the established limit, rubles/t;
$M_{oa}$ – is the mass of evaporated hydrocarbons, t.

The degree of land contamination by petroleum products to be compensated is calculated as a fee for contamination of the territory:

$$C_l = K_i \cdot H_l \cdot K_{el} \cdot S_l, \text{ rub}$$  \hspace{1cm} (3)

Where $K_i$ - indexation coefficient of pollution charges;
$H_l$ - standard cost of agricultural land, rubles/m$^2$;
$K_{el}$ - the coefficient of ecological situation and ecological significance of the territory of the economic district;
$S_l$ - area of contaminated land, m$^2$. 
1) Assessment of economic damage from emergencies

Damage from irretrievable losses of petroleum products is calculated according to the formula:

\[ D_o = M_o \cdot C_o, \text{rub} \]  \hspace{1cm} (4)

Where \( M_o \) – mass of irretrievably lost petroleum products, \( t \);
\( C_o \) – price of one ton of petroleum products, rubles/t.

Let us analyze the predicted oil product spill situation for the first, second and third hour of the emergency before taking measures for containment and elimination of the spill - installation of booms [13]. The results of forecast assessment of oil product spill scale (52.7 tons of oil products) are presented in Table 1.

**Table 1.** Results of oil spill indicators for the first three hours after the accident.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>For an hour</th>
<th>For 2 hours</th>
<th>For 3 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of oil products spill. m²</td>
<td>1247679.00</td>
<td>2472300.00</td>
<td>2472300.00</td>
</tr>
<tr>
<td>Length of the shoreline polluted by oil products. m</td>
<td>6357.60</td>
<td>12684.20</td>
<td>17510.80</td>
</tr>
<tr>
<td>Area of oil-saturated soil. m³</td>
<td>8904.00</td>
<td>17757.88</td>
<td>24515.12</td>
</tr>
<tr>
<td>Amount of petroleum products soaked into the ground. t</td>
<td>0.93</td>
<td>1.86</td>
<td>2.57</td>
</tr>
<tr>
<td>Quantity of hydrocarbons evaporated into the atmosphere from the surface of the water body. t</td>
<td>0.18</td>
<td>0.71</td>
<td>0.86</td>
</tr>
<tr>
<td>Evaporation time of hydrocarbons. h</td>
<td>2.40</td>
<td>4.70</td>
<td>5.70</td>
</tr>
</tbody>
</table>

The table shows that it is most effective to install booms as early as possible, for example during the first hour after the accident.

Using the above dependencies, let us estimate the environmental damage caused to the components of the environment during the first three hours after the accident. The results of the calculations are presented in Table 2.

**Table 2.** Results of damage assessment during the first three hours after the accident.

<table>
<thead>
<tr>
<th>Time. h</th>
<th>Damage to water resources. million rubles.</th>
<th>Damage to the atmosphere. million rubles.</th>
<th>Damage to land resources. million rubles.</th>
<th>Total environmental damage. mln.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.08</td>
<td>4.59</td>
<td>1.69</td>
<td>22.36</td>
</tr>
<tr>
<td>2</td>
<td>16.08</td>
<td>18.10</td>
<td>3.37</td>
<td>37.55</td>
</tr>
<tr>
<td>3</td>
<td>16.08</td>
<td>21.93</td>
<td>4.65</td>
<td>42.66</td>
</tr>
</tbody>
</table>

Analysis of Table 2 shows the importance of minimizing environmental damage when carrying out prompt measures to eliminate an oil product spill as soon as possible. It is possible to carry out emergency response measures successfully and promptly only when all the units involved are coordinated [14]. The involvement of fire trains plays a special role in the rapid localization and elimination of an oil product spill.

The Federal State Enterprise "Departmental protection of railway transport of Russia" (FGP VO ZHDT) in Russia, using fire trains to localize and eliminate emergencies. There are 313 fire trains in Russia's Federal State Unitary Enterprise VO ZHDT of Russia.

Analysis of the practice of fire trains shows that fire trains were most often used to extinguish fires, eliminate emergencies, assist Russian EMERCOM fire brigades, and conduct drills. Fire train departures were distributed as follows (Figure 1).
As part of the Unified State Emergency Prevention and Response System (RSChS), as well as territorial and local fire and rescue garrisons, fire trains assist territorial fire and rescue units of the Russian EMERCOM in extinguishing natural fires and fires in populated areas and at facilities not part of the railway infrastructure.

Fire trains assisted in extinguishing fires with the territorial fire and rescue units of EMERCOM of Russia in 23.2% of the total number of missions [15-17]. In 52.6% of cases, they were involved in extinguishing natural fires (forests, peat, grass, etc.) and in 19.6% of cases they were involved in extinguishing other fires.

The distribution of emergency extinguishing missions was as follows: stationary objects of railway transport - 11.8 % of the total number of emergencies extinguishing missions, rolling stock - 88.2 % [18-23].

Therefore, the functioning of fire trains plays an important role not only within Russian Railways, but also throughout the country. Successful extinguishing of fires and elimination of emergencies with dangerous goods at stationary objects and in rolling stock of railway transport crucially depends on coordination of actions of management bodies, forces and means of departmental fire protection of railway transport, territorial fire, rescue and medical divisions, engineering and technical services of objects, as well as internal affairs bodies on transport.

3 Results

One of the most important tasks to ensure the safety of railway transport facilities in accordance with the "Strategy for the development of railway transport in the Russian Federation until 2030" is the development of automated systems for monitoring the derailing of rolling stock, which makes relevant the development of the proposed system to ensure safe transportation of petroleum products by rail.

The problem is solved by the fact that the authors propose a device that consists of a sensor skidding rolling stock and warning system. As a sensor is used contact, electromechanical type. The device (utility model patent No. 122953 2012 "Mobile device for monitoring the derailment of a rolling stock car") consists of a frame, wheel set, axleboxes with a cassette bearing and control and identification units, and is fixed to the side frame of the rolling stock car and has an independent permanent power supply. The essence of the proposed device is explained in Figure 2.
The proposed device is explained in Figure 2.

The rolling stock car and has an independent permanent power supply. The essence of the device (utility model patent No. 122953 2012 “Mobile device for monitoring the derailment of a rolling stock car”) consists of a frame, wheel set, axlebox units, sensor unit and power supply unit, is attached to the side frame of the carriage with the screw device, made in such a way as to not form contacts with the wheelset of the car. Block sensor is placed in the housing, attached to the frame. The operation of the device consists in creating an electrical closed loop, through the rail line, or loop B.

Condition control and identification of a rolling stock car derailment is carried out by creating a closed electrical circuit. When the car moves along the rail track in the power unit an alternating current is generated, which is converted into direct current. The current is then fed by an insulated conductive wire to the node, where the charge is separated into the block sensor and the conductive parts of the device. To protect against foreign particles in the elements of the proposed utility model, all elements are placed in a special housing. The housing can be made of metal or polymeric materials.

Use of the offered device allows to automate completely the process of identification of a derailment and provides possibility of continuous control of a car wheel pair on a rail track which allows to prevent derailment of the whole rolling stock and occurrence of transport emergency.

In addition, the use of the device is particularly relevant to monitor the condition of the rolling stock used to transport hazardous goods, which include petroleum products.

It is also advisable to develop and implement a device for neutralizing oil spills in case of accidents on the railway transport. Occurrence of an oil product spill in some cases leads to ignition and fire of the spill. In this regard, one of the preventive measures ensuring localization of oil products and prevention of fire is application of sorbents to the surface of the spill, which absorb oil products. However, it is not always possible prompt arrival of teams to the place of emergency due to the length of the railroad, in this regard requires the stationary installation of the sorbent device on tank wagons with oil products and other fire-explosive substances.

The sorbent device in the case under consideration is a sealed container made of polyethylene, the characteristics of which are given in Table 3.

Table 3. Characteristics of the proposed device for neutralization of oil product spill in railway accidents.

<table>
<thead>
<tr>
<th>Length. m</th>
<th>Width. m</th>
<th>Height. m</th>
<th>Packaging density. kg/m³</th>
<th>Temperature limits of use. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.2</td>
<td>0.4</td>
<td>960</td>
<td>-45; +50</td>
</tr>
</tbody>
</table>
The device is installed on the tank boiler on both sides, using tie rods, as shown in figure 3.

![Diagram of device installation](image)

1 - device for oil product spill containment; 2 - tank boiler; 3 - attachment of the device to the tank boiler.

**Fig. 3.** The external view of the device for neutralization of oil product spill in case of accidents on the railway transport.

For localization of the spill, it is possible to use a hydrophobic peat-mineral oil sorbent, which characteristics are given in Table 4.

**Table 4.** Characteristics of a hydrophobic peat-mineral oil sorbent.

<table>
<thead>
<tr>
<th>Quality indicator, units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance, color</td>
<td>Powder, brown or black in color</td>
</tr>
<tr>
<td>Particle size, mm</td>
<td>0.2-1.0</td>
</tr>
<tr>
<td>Oil capacity, kg oil/kg sorbent</td>
<td>60</td>
</tr>
<tr>
<td>Degree of purification, %</td>
<td>98-99.5</td>
</tr>
<tr>
<td>Conglomerate formation time, sec</td>
<td>60-90</td>
</tr>
<tr>
<td>Buoyancy, day</td>
<td>30</td>
</tr>
<tr>
<td>Bulk density of the sorbent, kg/m³</td>
<td>350</td>
</tr>
<tr>
<td>Operating temperature range, °C</td>
<td>-25 to +300</td>
</tr>
</tbody>
</table>

The sorbent is designed to absorb and fix liquid hydrocarbons immiscible with water (oil, oils, gasoline, fuel oil, kerosene, benzene and other products) on water and solid surface for the time of cleaning activities.

**4 Analysis of results**

Using the proposed devices to ensure oil products transportation safety by railroads involves modification of the existing elements of the rolling stock, so it is necessary to justify the safety of introducing such changes in the design of wagons and bogies.

Wheelset is the most loaded, structural element, which cannot be made with an excessive safety margin, so there are high requirements to its reliability. The use of the proposed device for monitoring and identifying the derailment of a rolling stock car (figure 2) undoubtedly creates additional loads, first of all, on the axle of the car wheel pair. In this regard, in order to assess the safety of the proposed derailment control and identification device application, wheel set axle strength calculation has been performed.

Wheelset axle operates in the mode of alternating deformations, the number of cycles during the service life is high, and the loading has a probabilistic nature. It is established that
mechanical properties of material change with time. At the same time, the allowable stress in the middle part of the axis is 155 MPa, in connection with this the strength properties are observed.

Thus, on the basis of calculations it is established that when creating additional load on the car wheel pair axle in the form of a device for identification of rolling stock derailment fixed on the side frame of the bogie, stresses in the considered sections do not exceed the normatively permissible ones. In this connection the use of the device does not pose a threat of emergency situations and the car axle meets the strength conditions of the allowable stresses.

According to the requirements of railway transport standards, the steady movement of the wheels on the rail track must be ensured. However, under unfavorable conditions, when the horizontal force of dynamic pressure of the wheel on the rail head is high and the vertical force is low, the wheel crest will not slide on the rail head. In connection with this, to prevent derailment in operation, the wheel stability on the rail was checked.

Calculated stability factor is higher than standard one, so it can be concluded that the wheel stability of the device for detecting run-off of the rolling stock while running along the rails is ensured.

The operation of the device is based on the creation of a closed electrical circuit. The functioning of the sensor unit in the normal state of the wheel pair is possible, if the resistance in the resistor in the electrical circuit is less than the resistance of the car wheel pairs, the railroad track, the wheel pair of the derailment control device.

The DC resistance of rails is mainly determined by the type of rails, as well as the type and condition of the junction connectors, since the intrinsic resistance of a solid rail is small. The resistance of a rail loop is equal to the sum of the resistances of both rail strands.

The value of rail loop resistivity depends on the type and condition of ballast, type and condition of sleepers. The condition of the ballast is determined by the temperature and humidity of the air, as well as the degree of contamination. The maximum ballast resistance occurs at low temperatures and humidity. In addition, contamination of ballast with salt-containing substances (salinity) reduces its resistance.

The use of safety systems is essential for the uninterrupted and safe operation of the derailment control device. In this regard, there is a safety node in the power unit (utility model patent No. 122953 2012 "Mobile device for monitoring the derailment of a rolling stock car"). In order to increase the reliability of the device functioning the safety node was backed up, as a result of which the average time between failures increased by 1.5 times, and the probability of no-failure operation by 1.9 times.

In order to provide an effective and safe usage of the oil product spill neutralization device for the accidents on the railway transport (picture 3) the loading of the cistern boiler was estimated at installation of this device.

The activation of the device is possible with the help of the device for controlling the derailment of the rolling stock (figure 2). The sorbent is dispersed over the contaminated water or solid surface by pneumatic means.

Based on geometrical characteristics of the device given in Table 3, the volume of sorbent placed in the device on one tank is 1.28 m3. In this connection the mass of the sorbent is 448 kg with the mass of oil product in the tanker of 52.7 tons.

Thus, the mass of the sorbent in the device is enough to absorb 50% of the tank mass. Based on this it is established that complete localization of oil products will not happen, however, partial localization will significantly reduce the probability of a spill fire and reduce the negative impact on the environment when oil products enter the water body.

In addition, it is necessary to determine the load on the cysteine boiler when installing this device. Vertical loads acting on the boiler can be considered as evenly distributed with a total intensity and are determined by the formula:
\[ Q = \frac{P_c + P_b + P_d + P_{dev}}{2L_c} \]  \hspace{1cm} (5)

Where \( P_c \) – cargo weight, is 52.7 tons;
\( P_b \) – the weight of the boiler, is determined by the formula:
\[ P_b = P_{con} - 2P_{cart} - P_{fr} - 2P_{cou} \]  \hspace{1cm} (6)

Where \( P_{con} \) – weight of the tank, 36.8 tons;
\( P_{cart} \) – cart weight, is 4.8 tons;
\( P_{fr} \) – weight of the frame, is 7 tons;
\( P_{cou} \) – weight of coupling and braking device, 0.52 t.
Accordingly, the weight of the boiler is 19.16 tons.
where \( P_d \) – dynamic load, taken as 0;
\( L_c \) – the length of the cylindrical part of the boiler, is 4.85 m
\( P_{dev} \) – the weight of the device, is determined by the formula:
\[ P_{dev} = 2 \cdot (M_{sor} + M_{con}) \]  \hspace{1cm} (7)

Where \( M_{sor} \) – mass of the sorbent in the container, 448 kg;
\( M_{con} \) – tare weight, equal to 325.5 kg.
The weight of the device is 1547 kg.
Thus, the boiler load is 76 kH/m.
The stresses in the cross section of the boiler are:
\[ \sigma = \frac{M}{W} \]  \hspace{1cm} (8)

Where \( M \) – bending moment in the design section of the boiler, kH·m;
\( W \)– bending resistance moment of the boiler cross section, m³.
The bending moment in the middle of the boiler is:
\[ M = q \cdot \frac{(l + 2L_c)^2}{2} - R \cdot L_c \]  \hspace{1cm} (9)

Where \( l \) – the length from the end of the boiler to the section in question, is 6.01m;
\( R \) – the reaction in the center of the boiler, according to is 360 kH.
Accordingly, the bending moment is 2735.7 kH·m.
Moment of resistance to bending of the boiler cross section:
\[ W = W_{out} - W_{in} = 0.1 \cdot d_{out}^3 - 0.1 \cdot d_{in}^3 \]  \hspace{1cm} (10)

Where \( d_{out} \) – external diameter of the tank boiler, equal to 3.22 m;
\( d_{in} \) – inside diameter of the tank boiler, equal to 3 m.
Accordingly, the bending moment of resistance of the boiler cross section is 0.064 m³
Thus, the stress in the boiler cross section is 42.75 MPa.
Standard stress in the boiler cross section should not exceed 120 MPa. In this regard,
since the calculated stress is less than the normative stress, there is no violation of the integrity
of the boiler when installing the device.
Thus, the use of this device on railway tanks is appropriate when transporting cargoes
that pose a particular risk of an emergency situation.
5 Conclusion

Thus, as a result of the assessment of various components of damage from accidents during transportation of oil products by railway transport it is revealed that the value of damage depends to a large extent on the time from the moment of the accident and the entry of oil products into the water body. Apart from the damage to water resources there is the contamination of the atmospheric air by hydrocarbon vapors, as well as negative impact on the ground, as a consequence of oil products spreading on it.

It is shown that it is possible to promptly carry out measures to eliminate the emergency situation only if the actions of all the involved formations are coordinated. Moreover, a special role in localization and liquidation of oil spills is played by the fire-engine trains. Therefore, increasing the number, re-equipping and expanding the functionality of fire trains plays an important role not only within Russian Railways, but also for the entire country.

In order to solve the problem of safety at railway transport facilities, a device for monitoring the derailment of rolling stock was developed. The device consists of a sensor of convergence of the rolling stock and a warning system. The use of the proposed device allows to automate the process of identification of a derailment and provides the ability to continuously monitor the status of the wheel set of the car on the rail track, which prevents the convergence of the rolling stock and the emergence of transport emergencies.

In addition, the use of the device is particularly relevant to monitor the state of the rolling stock wagons used to transport hazardous goods, which include petroleum products. Also developed a device for neutralizing oil spills in accidents on the railway transport. When the proposed device triggers, sorbents are applied to the surface of the spill, with which the absorption of petroleum products occurs.

The use of the proposed device will increase the safety of oil products transportation by railroad transport, but it is connected with the modification of the existing elements of the rolling-stock. Therefore, the axle of the wheelset has been calculated for the strength, the stability of the wheel on the rail has been tested and the loading of the cistern boiler has been estimated while installing the device. As a result of the conducted calculations, the possibility of using this complex, consisting of two devices, to ensure safety during the transportation of dangerous goods on the railway transport has been established.

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